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FIRE ENDURANCE IN BUILDINGS

by

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RESEARCH SPONSORED BY:
NATIONAL SCIENCE FOUNDATION
DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT
NATIONAL FIRE PREVENTION AND CONTROL ADMINISTRATION
AND
NATIONAL BUREAU OF STANDARDS

REPORT NO. UCB FRG 76-16 NOVEMBER 1976

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By

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A.B. (Swarthmore College) 1968
M.S. (University of California) 1972

DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Fire Protection Engineering

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA, BERKELEY

Approved: Robert Brady Williamson

Robert F. Sawyer

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Committee in Charge

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ABSTRACT

This work is a study on the methods for designing and analyzing fire endurance in buildings. Fire endurance is a property of a building element, termed a barrier, that enables it to stop or delay the spread of fire in a building after the room of fire origin has become fully involved in fire. The physics of fully involved room fires is studied. Variables controlling the fire behavior are elucidated and a model for determining the expected fire is offered which is useful for design purposes. From that basis several techniques for simplified design fires are developed and their usefulness examined.

A set of firesafety goals is given, and criteria for evaluating fire endurance are generated from the goals. The role of materials used in the barrier and the manner of their arrangement is treated in a way that can lead to identifying of reliability problems. Means of both measuring and calculating the response of a structure to a given fire are examined. The technique of critical temperature design, which is partly based on measured behavior and partly on calculated response is considered in detail. The problems associated with furnace testing of building components are examined and improved operating procedures are set forth.

The historical development of fire testing is investigated and the background of the accepted method in the United States, Standard E-119 of the American Society for Testing and Materials, is traced. The shortcomings of the standard and means for minimizing them are pointed out. The development in the U.S. of building codes related to firesafety is outlined and a technical analysis of the fire endurance provisions in the Uniform Building Code, a model building code used in many locales, is given. The impact on endurance design of insurance ratings is also treated.

Some newer design methods already in use are analyzed from theoretical and effectiveness standpoints. Proposals are given for ways of designing and analyzing fire endurance in buildings that are consistent with the best applicable knowledge of behavior of fire and materials.

KEYWORDS: Fire resistance; fire tests; fire protection; buildings --fire protection; fire walls; safety engineering--fires.

ACKNOWLEDGEMENTS

Professor Brady Williamson first interested me in the problems of fire in buildings. At his suggestion I delved into the vast, but hardly organized, area of fire endurance. His instruction, encouragement, and support enabled me to undertake and to finish the present work. His unfailing belief that fire protection can and should be an engineering discipline, not just a technology guided by traditional rules and *ad hoc* methods convinced me that it will be an inspiring profession.

Professor Boris Bresler questioned my results, challenged my presumptions and provided insights that improved my appreciation of numerous areas of fire protection.

Professors Robert Sawyer, Alan Searcy, and John Daily likewise provided guidance and inspiration.

To Dr. Paul Croce, of the Factory Mutual Research Corporation, I am grateful for providing unpublished data that were useful in validating the theoretical aspects of compartment fires.

Fred Fisher, Robert Draemel, and Harry Hasegawa helped capably in conducting the experimental work. Cecile Grant aided my bibliographic searches and procured essential documents.

The research was made possible by grants from the RANN Program of the National Science Foundation, and additional funds from the Department of Housing and Urban Development, The National Bureau of Standards, and the National Fire Prevention and Control Administration.

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NOTATION USED

A = area (m^2)

b_p = incomplete mixing factor (-)

B = width (m)

Bi = Biot number (-)

C_d = discharge coefficient (-)

C_p = specific heat (kcal/kg-°K)

D = fuel thickness (m)

E = flux ratio (-)

F = configuration coefficient (-)

F = water flow (ℓ/sec)

F_a = air changes per hour (hr^{-1})

Fo = Fourier number (-)

g = gravitational acceleration (m/sec^2)

h = convective coefficient (kcal/hr-m^2-°K)

h = enthalpy (kcal)

h = height (m)

ΔH_c = calorific value (kcal/kg)

k = attenuation coefficient (m^{-1})

k = thermal conductivity (kcal/hr-m-°K)

L = wall thickness; span length (m)

m = mass (kg)

P = pressure (Pa)

P = probability of success (-)

q = heat (kcal)

r = air/fuel mass ratio (-)

R = universal gas constant

t = time (hr)

T = temperature (°K or °C)

v = velocity (m/sec)

V = volume (m^3)

W = molecular weight (kg/mole)

ε = emissivity (-)

ϕ = equivalence factor (-)

ρ = density (kg/m^3)

σ = Stefan-Boltzmann constant ($kcal/hr\text{-}m^2\text{-}°K^4$)

τ = time constant (min)

Subscripts

b = band

c = combusted; crack; critical

e = endurance

f = fire gases; outflow; fuel

i = incident

n = net

o = inflow

p = pyrolyzed

R = radiated

s = fuel surface; stoichiometric; soot

t = thermocouple

v = window (ventilation)

w = wall

x = furnace wall; species x

∞ = undisturbed ambient

Superscripts

$\cdot$ = time rate

$'''$ = volume rate

CHAPTER 1

INTRODUCTION

The standard fire resistance test, as conducted in the United States and in most other parts of the world, is among the most costly of physical tests associated with building construction. Similarly, the expenditures for fire endurance constitute, over-all, the greatest fraction of the national investment in building firesafety features. One can also observe that the mandated tests and the underlying building code provisions have not significantly changed since the turn of the century. One might then be led to think that the fundamental correctness of the procedures involved has been so well founded and so highly developed as to be beyond dispute. One would be wrong to think so.

The present work attempts to examine the major aspects of fire endurance in buildings and provide a self consistent rationally based framework for design and analysis. Four broad areas of concern are developed. These are the physics of compartment fires, test requirements, design procedures, and history of fire endurance requirements and standards. The latter is pivotal for understanding of the status quo, since it will be shown that the present building code provisions are founded largely on studies reported in the 1920's and earlier--their relationship to the present state of engineering and economics knowledge is not notably strong.

The role of fire endurance will be developed in greater detail in Chapter 2, but since the study of any subject should begin with its description, a brief definition must be given here. Fire endurance is the length of time that a building component can contain a fire without propagating its ill effects. These ill effects must be defined by specific criteria. Fire resistance is the general ability of a component to withstand some effect of fire. Fire resistance rating is generally used to mean the fire endurance when tested under a standard fire exposure. The components considered include all load carrying members and those members that divide a building into compartments. A member possessing non-trivial fire endurance will be called a barrier. It follows that by this definition a building must consist of at least one compartment; open structures, such as derricks or bridges are excluded. Open-air parking structures would be hard to classify except that tests indicate that fires in them do not behave in a manner associated with compartment fires.

Extinguishment devices, such as sprinklers, are alternate means for achieving firesafety but are not considered to be barriers. Principles for requiring or designing extinguishment systems will not be treated here. If a sprinkler system is properly designed and operated, then fire will not threaten, and generally not even reach, the barriers. Conversely, if sprinklers fail to control a fire, and once a fire becomes large enough to threaten the barriers, the effect of the sprinklers on reducing the fire intensity is (with the exception of massive discharge deluge systems) negligible. Considered deterministically, it would then seem that to provide both automatic extinguishment and fire endurance is redundant. The correct viewpoint, of course, is a probabilistic one. If both measures are provided, in a certain fraction of expected fires, the extinguishment system will put out the fire and the barriers will not come into play. In the remaining number, the extinguishment system will fail and the fire spread will be governed by the barrier success.

CHAPTER 2

FIRESAFETY IN BUILDINGS

2.1. Firesafety Goals

The most generalized goal for firesafety in buildings is simply to avoid fire-related losses. Building codes have typically taken as justification such a phrasing, or even a more general "for the public benefit" and proceeded to directly produce minutely detailed requirements. Having only a vaguely and generally stated goal is a hindrance--it encourages the confounding of means and goals. Fire endurance, for instance, should be provided only when it demonstrably promotes the goal of firesafety.

To make it easier to determine what promotes that general goal it should be broken down into more specific goals. There is no one correct way of making the subdivision. Any set of goals that does not exclude known significant factors can be satisfactory. The goals must be specified, prescribed, or quantified by either the building owner or a governmental body. It is inappropriate extension of prerogative for the designer to determine the goals for the owner. Once the goals are clarified the designer can marshall forth a number of means to accomplish the goals. To enable the process to be clearly conceived the goals should be as non-overlapping as possible. The means will, in many cases, be overlapping with respect to the goals. Their effectiveness may be radically different for several goals and thus will need to be evaluated separately.

The three primary losses to be avoided are: life, property (building and contents), and operation (loss of business is the main example).

Thus the safety of the above three items can be postulated as three goals. In practice, several observation can be made. If ignition is prevented or if extinguishment is successful, then all three goals are aided. Also, losses of property and of operation are controlled by exactly the same means, although the various means may differ in relative importance. Thus it can be useful to combine property and operation loss into one item. Further, the gains from ignition prevention and from extinguishment can be deleted from the above and put into separate categories. The following set of four goals then results. Commonly available means are given for each below.

Goal 1. <u>Reduce risk of fire outbreak</u>

A. Training of occupants and maintenance personnel in firesafety.

B. Restrictions on fuel properties, particularly fuels likely to be exposed to ignition sources.

C. Control over properties of the building and its equipment which can lead to fire outbreak (e.g., electrical installations, heating appliances).

Goal 2. <u>Provide for safety of occupants in case of fire</u>

A. Provisions for safe occupant and visitor movement

i) Effective warning and instructions (alarms, signs, P.A. systems),

ii) Suitable physical routes of escape.

iii) Control over availability of escape routes (e.g., doors unlocked, elevator control)

iv) Suitable end destination (refuge area, street).

B. Restriction of fire movement

i) Limited speed of flame spread along surfaces.

ii) Time to flashover.

iii) Limitation of post-flashover fire spread (fire endurance).

iv) Control of smoke and toxic products evolution from materials and flow through building (control over materials, HVAC operation).

C. Provision for building structural integrity

Adequate fire endurance of loadbearing members.

Goal 3. <u>Reduce probable property damage, potential for conflagration, and operation losses</u>

A. Damage within building

i) Control of fuel load or ventilation.

ii) Division of building into smaller areas (compartmentation).

iii) Effectiveness of barriers (fire endurance).

B. Fire spread to and from the outside

i) Sufficient separation between buildings.

ii) Roof properties: containment of interior fire and resistance to external flame spread and brand production

iii) Facade properties: materials and construction to limit ignition and flame spread.

C. Prevent structural collapse

Adequate fire endurance of loadbearing members.

Goal 4. Provide for safe and successful firefighting

A. Methods for early detection.

B. Adequate firefighting resources (water supply, standpipes, automatic extinguishment).

C. Provisions for interior firefighting

i) Minimize danger of unexpected collapse of structure on firefighters.

ii) Suitable physical routes.

iii) Control over availability of routes.

iv) Provision for communication.

D. Provisions for exterior firefighting

i) Adequate access to site.

ii) Architectural design to facilitate firefighting (e.g., window arrangements).

2.2. Firesafety Design

The usage of the term, "firesafety design," is quite new when applied to fire endurance. It implies that there are alternatives that must be considered and that the process of specifying fire endurance may not be sufficiently well accomplished by merely mechanically applying some prescribed regulations. At this time there are in existence some design methodologies which are widely used and long established. These will be termed "traditional." Other methodologies exist that have been introduced only in the last few years and approach the problem from a different viewpoint. They will be termed "innovative."

Traditionally there have been only two methodical bases for treating firesafety--building codes and similar laws, and insurance rating regulations. A building code is a technical expression of a building safety policy. That policy is (ideally!) the local expression of the people for a given minimum of safety in their buildings. A building code does not need of itself to be prescriptive. It could say simply, "provide this given level of safety against this particular hazard." The rest could be left up to the discretion of a licensed design professional. Unfortunately, this is rarely done; it tends to be approached only when the governing principles involved are well known and accepted. The fact that in firesafety matters totally prescriptive regulations are given can be taken to reflect the scarcity of knowledge in the field.

Another traditional force, although not binding, has come from the insurance industry. In the 19th century the insurance industry provided almost the sole technical input into fire protection. The development of automatic sprinklers and of "mill type" construction were two outstanding accomplishments due largely to insurance company work. In the 20th century technical development efforts by the insurance industry have been fewer, due to the establishment of laboratories by manufacturers, governmental agencies, and other bodies.

The insurance industry has continued to exert an influence through its rating procedures. To enable prudent underwriting, insurance carriers must be able to evaluate the firesafety of buildings. The procedures for making the evaluations stem from the same traditional knowledge and similar premises as incorporated in the building codes.

However, while the building code is phrased in go/no-go terms, an insurance rating schedule must evaluate qualitatively every possible design. At least potentially, then, it offers more room for a broader approach. It does not, however, address itself to all the firesafety goals. Fire insurance provides only for property and business loss. Life safety aspects are not treated except when incidental to property safety.

Many suggestions for innovative design have been made in the course of the last decade. Two innovative approaches will be considered which are rapidly assuming importance because of their thoroughness and their accessibility to the designer. The systems approach of the General Services Administration is based on an explicitly probabilistic view of the entire building fire process. It has already received some use in the U.S., mainly by GSA designers. Another new methodology is the one contained in the Swedish manual, *Fire Engineering Design of Steel Structures*. While less comprehensive, since it treats only the endurance problem in steel-framed buildings, it is more directly based than any of the other methods on recent theoretical studies of combustion and structural response.

In the course of the present work both the advantages and the shortcomings of the four above methodologies will be presented. While no new unique method will be delineated, the emphasis will be placed on investigating those areas where accuracy or validity of existing methods is most questionable.

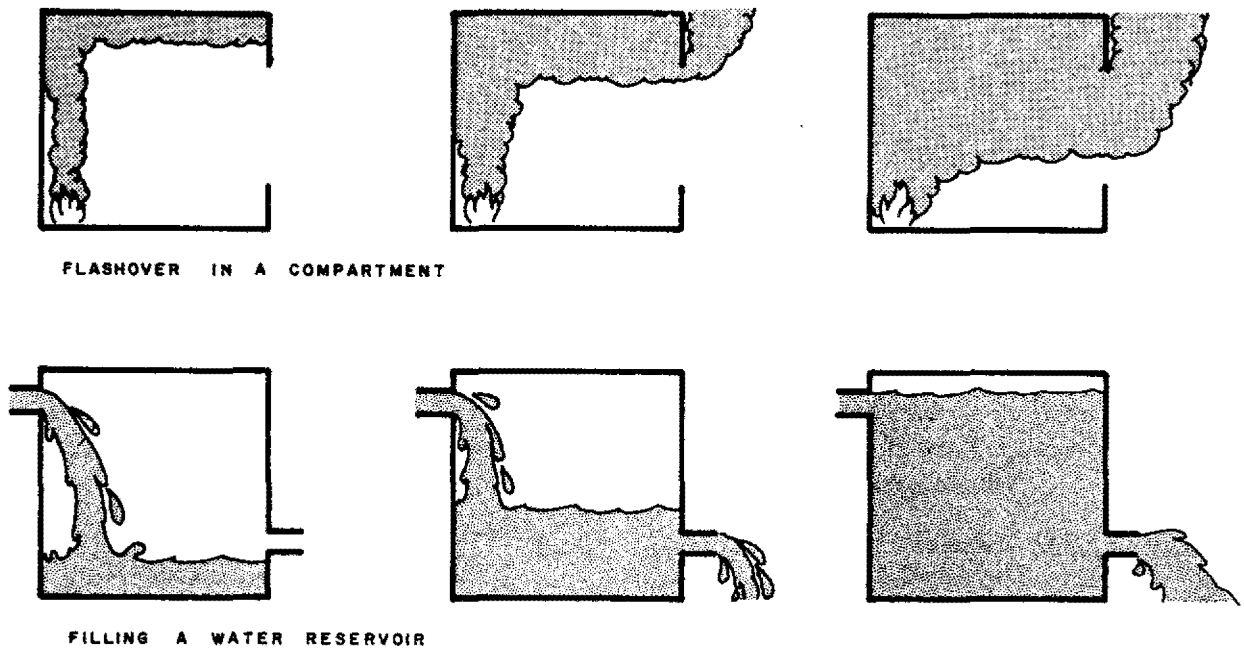
2.3. Course of Fire in a Building

2.3.1. Flashover and the Stages of a Fire

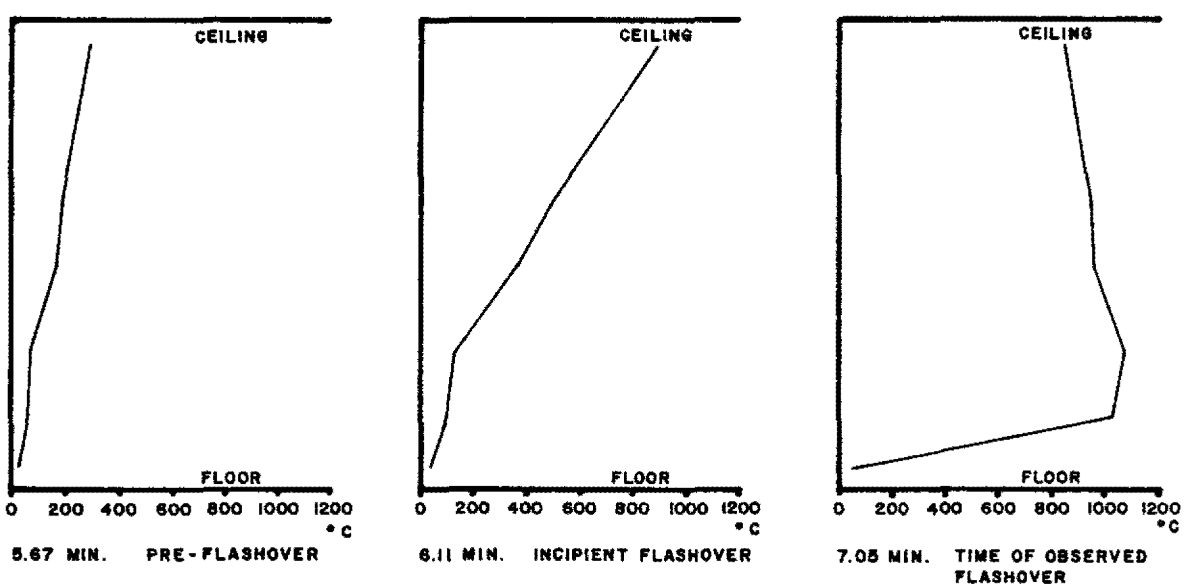
Before the role of fire endurance can be discussed it is necessary to understand the development of fire in a building. A critical event, generally called flashover, must be described. (The event sometimes goes by other names, such as full-room involvement, flameover, or spreadover. These alternate terms may imply a slightly different fire growth pattern, but not one which is germane to the present study.)

Fires usually start in buildings with one small item in flames, such as a waste paper basket or chair, and then grow in size. If it is going to become a serious fire, the small fire which began with a single item eventually grows to involve the whole room. On the other hand, the initially small fire may expend itself. It is noticed that usually, in the former case, the fire involvement becomes suddenly uniform, and the oxygen levels start to drop, while CO and CO_2 levels rapidly rise. That instant is called "flashover."

It can be hypothesized that the flashover process is analogous to the filling of a water reservior as shown in Figure 1a. First a stable layer is formed with no outflow and then outflow can begin while the water level continues to rise. Finally, the reservoir is filled to the top and a quasi-steady state begins. The fire development in a room follows a similar course although it is a much more complex process. A hot mixture of both combustion products and unburned pyrolysis products begins to stack up near the ceiling. When the depth reaches the window or door top, outflow begins. The hot gas layer continues to deepen until its bottom reaches the lower third of the room. When the layer no longer descends, flashover has been



(a) RESERVOIR ANALOGY FOR COMPARTMENT FLASHOVER



(b) VERTICAL TEMPERATURE DISTRIBUTION FROM REF. 228

FIGURE 1 THE PROCESS OF FLASHOVER

reached, provided sufficient heat has built up in the compartment. Waterman,[1] however, observed the flashover phenomenon in situations where there probably were very few pyrolyzed gases in the compartment, but the accumulation of relatively inert hot gases in the upper portions of the space led to the rapid kindling of cellulosic fuels. Quintiere[2] has recently attempted to provide a quantitative fluid mechanical model of the flashover process. Controlled experiments in the area, however, are not yet available--the existing knowledge has come mainly from empirical observations.

Flashover can be defined as the time when flames cease to be localized and flaming can be observed throughout the whole volume of the compartment. This definition is useful since it is not necessary to describe the cause of flashover to be able to distinguish it. Another way of viewing the situation is that burning changes from a surface phenomenon to a volume process. Flashover is then used as a demarcation point between two stages of a room fire: pre-flashover and post-flashover.

One of the most important characteristics of the post-flashover fire is that it can be considered a volume process where average temperatures and heat fluxes within the compartment are meaningful concepts. This is directly contrasted with the pre-flashover period, during which time flames are either localized to stationary sources or else characterized by flame fronts advancing along the surfaces, and the gas temperatures have extreme spatial variations--flame temperature in some areas and near-ambient temperature everywhere else.

A somewhat startling implication of the definition of flashover is that it represents a sudden jump from one relatively stable mode to a different but also stable one. This transition does not always occur. Occasionally, a fire will flash momentarily then go out or drop back to being of a two-dimensional, surface-burning character. Other times, a fire may be noticed to oscillate rapidly between vigorous burning and slower burning. This behavior is not fully understood; however, it has been observed only in fires of low intensity (< 500° C). Thus, the assumption of quasi-steady (temperatures and other variables change only slowly with time) post-flashover behavior will be made since the low intensity fire is not of major concern.

After flashover large-scale turbulence is the means through which the condition of flaming throughout the volume of the room is maintained. Fuel is pyrolyzed from the solid combustibles but cannot fully burn in the immediate vicinity of the fuel pile. The process of mixing the pyrolysis gases with oxygen then takes place in a highly irregular fashion throughout the compartment. It is this turbulence which can be viewed as the reason for the experimental observation that after flashover gas temperatures become quite uniform throughout the compartment The spatial variations usually amount to no more than 20% (see Figure 1b) and thus, for practical purposes of analysis, it is assumed that in the post-flashover stage the gas temperature is a function only of time and not of location.

Furthermore, the description of flashover as given here applies only to moderate-sized spaces. A large space, such as a factory, will not necessarily behave as a single simple reservoir. Travel times which are long compared to mixing times and the possibility of multiple outlets for the hot gases will make behavior non-uniform. Indeed, the main reason for roof venting in a large undivided building is to localize the gas flow and prevent the total space from uniformly flashing over. Neither reliable experimental work nor an adequate theory is available for describing flashover in a large undivided space; thus this topic remains outside the scope of the present work.

2.3.2. Role of Fire Endurance

When the concept of a fire in a room was discussed the word "room" was used in a more limited sense than ordinarily meant by it. Architects consider a room a space with a specific function and one which is visually or physically separated from other building spaces. In fire protection engineering the room of interest is often called a "compartment" to emphasize that it must have physical barriers surrounding it. The barriers, except in a vault, are not expected to be fully complete but must be complete enough to serve one function: prevent a simultaneous flashover of more than one room. If several rooms are separated by barriers which are so incomplete as to flash over simultaneously, then they are counted as one compartment.

A barrier is considered successful if it restricts the propagation of harmful effects of fire through the building. Barriers can be of two types: planar (walls, floors, doors, etc.) and lineal (columns, beams). "Wall" will be used hereafter synonymously with "planar barrier" except where clear from content that other room surfaces are excluded. Active devices for restricting fire spread (sprinklers, fans) are not considered barriers in the sense used here, although barriers may contain active elements (e.g., door actuators).

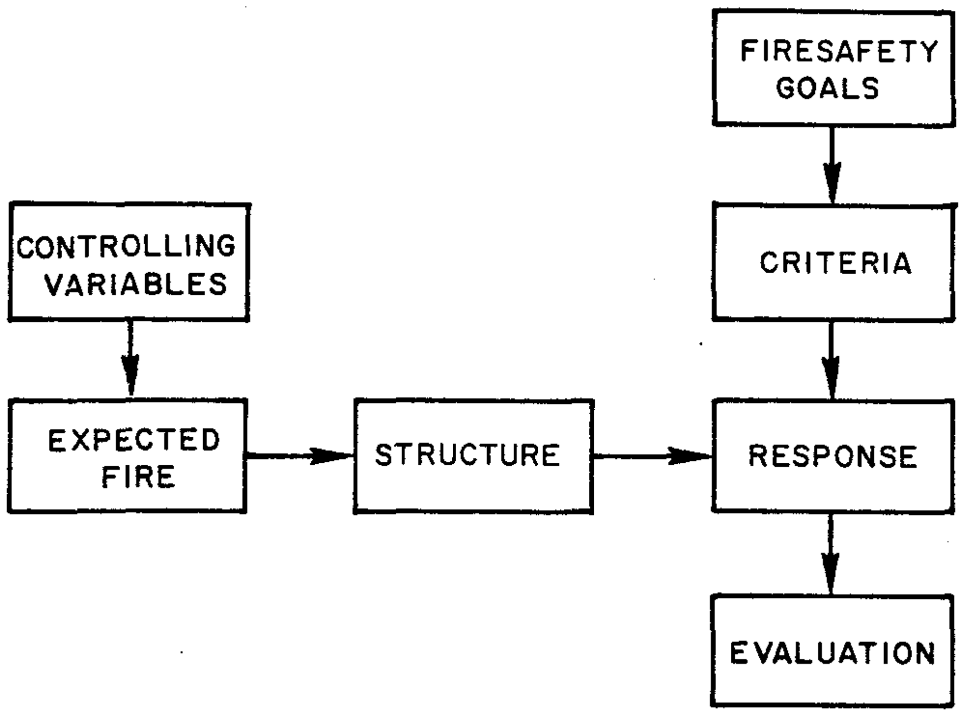


FIGURE 2 FRAMEWORK FOR FIRE ENDURANCE ANALYSIS

A fundamental tenet of firesafety design is that barriers are threatened only by a post-flashover fire. Three factors are needed to threaten a barrier--temperature, area, and time. To induce damage one must apply a high enough temperature over a large enough area for a sufficiently long time. This combination is potentially available only in a post-flashover fire. Thus, endurance time is measured from flashover, not from ignition, and flashover will in the present work be set as $t = 0$. The point especially bears emphasis in interpreting burnout experiments. If wall collapse is reported as occurring at, say 45 min. after ignition and flashover took place at 20 min., then wall endurance to collapse was 25, not 45, minutes.

2.4. Framework for Analysis

From a physical viewpoint the procedures in analyzing endurance must be systematically organized to ensure that meaningful results are obtained. Figure 2 gives one possible framework. The compartment fire theory is developed (Chapter 6) to identify the controlling variables and generate a prediction of an expected fire history. The fire impinges on a structure (Chapter 7), which is usually a complex assembly of materials and connections. The action of fire on the structure generates a response (Chapter 9) which can either be obtained by actual test or by calculation. To evaluate response, firesafety goals (Section 2.1) are established and are used to produce a set of relevant performance criteria (Chapter 8). The systematic techniques which are already in use are presented in Chapters 3-5, while an evaluation of their effectiveness is given in Chapter 10.

2.5. Limitations of Scope of Present Work

The present work attempts to treat in some detail the foundations of the entire process of designing, analyzing, and testing for fire endurance in buildings. Nonetheless, to keep the scope manageable, certain problems associated with fire endurance are omitted.

Automatic extinguishment is not treated since, as mentioned in the introduction, in a deterministic treatment it interaction with endurance is of a simple go/no-go character. In a probabilistic treatment the best available model is the one used in the GSA systems method. Despite its shortcomings no better technique can currently be offered. Sprinkler/endurance tradeoffs can be analyzed on that framework.

Further, "active" barriers are not considered here. These are devices to make a barrier more complete (detector-actuated fire doors) and devices to change the ventilation (thermoplastic skylights). The same theory developed here is applicable to their use. The main problems associated with these devices are operational ones and have to be solved on an individual basis.

Facade and roof fires are two closely related external fires that can cause or be caused by internal fires. Since the methodology for treating them is quite different than for internal fires, it is reasonable to exclude their consideration here. The internal fire, it must be nonetheless noted, is the prime determinant of the facade fire; the concept of the excess unburnt pyrolysates, developed in Chapter 6, is expected to be of practical importance in determining the intensity of a facade fire.

Finally, excluded from consideration are situations where intense fires can develop that do not fulfill the definition of a post-flashover fire. These include fires in semi-open structures, as well as in very large undivided spaces.

CHAPTER 3

EVOLUTION OF ENDURANCE TESTING AND STANDARDS

3.1. Development of Fire Testing

The ASTM Standard E-119[4] has been used in the U.S. for nearly 60 years. While numerous minor changes have been made, the time temperature curve and the basic geometry and criteria have remained unchanged. Component test methods established in other parts of the world have, until recently, likewise been modeled on the E-119. Thus it is illuminating to outline the course of development of fire testing and its standardization. Subsequently its relation to actual fire behavior will be taken up in detail.

In the present section all the creditable efforts at quantitative large-scale fire testing prior to 1918 known to the author will be discussed. Tests which do not model a realistic use condition will generally be excluded. A summary is given in Appendix A. The precursors to fire testing can be traced to the 1790's. Quantitative work began in Germany in the 1880's and in the U.S. and England in the 1890's. The latter 1890's saw intensive efforts in exploratory testing, leading gradually to standardization in the early 1900's. Efforts were also going on in other countries, but with a few exceptions they will not be considered here since they were not influential in the English speaking world and their records are not easily accessible.

Today the distinction between fire-resistive and non-combustible construction is clear. The fire-resistive assembly is engineered to withstand some specified effects of fire for a given time, while the non-combustible material is any which will not have a measurable heat of combustion at temperatures which can be expected in a fire. In the last century the two terms were initially presumed to be synonymous. Thus the early history of designing fire endurance into buildings began with efforts mainly to find useful non-combustible materials.

Load-bearing masonry systems were proving to be too costly for the increasingly high multi-story buildings in the 1870's. Their replacement was the skeleton frame construction. Developed in the 1880's, it replaced the heavy bearing masonry with skeletons of iron columns. Floors, meanwhile, had been evolving in 1870's from heavy all-brick arches which generally had good fire performance, into significantly lighter brick or terra-cotta arches sprung on iron beams, whose fire behavior was variable. There arose a lucrative field of designing and manufacturing ingenious patented floor systems and systems for fireproofing of columns.[18] Their merits were touted in florid terms, yet no basis existed for comparing their fire resistive performance. Indeed, not all owners were convinced that any fireproofing really needed to be added to iron columns, so long as combustible materials were not used. Many other methods of construction did involve the complete covering of all iron members with terra-cotta tile. However, in the poorer of these systems the terra-cotta would fall off very quickly in a fire. In some cases the assembly held together during the fire but shattered in a brittle manner as soon as firefighters started applying water.

Records of fires were mainly used in the 1880's and 90's to evaluate fire performance of different components of a building. Thus after major fires, such as the Horne Building in Pittsburgh[5] or the Home Life Insurance Building in New York,[6] extensive analyses were published showing what went wrong with their fire protection. The fires following the San Francisco earthquake of 1906 provided a veritable catalog[7] of fire protection lessons. Only a limited amount of construction underwent large fires; so comparative discussions of relative firesafety of various systems were still putative rather than factual. Codes were phrased in prescriptive, but vague, terms. For instance, prior to the inception of testing efforts there, the New York City Building Code required floors in fire-resistive buildings to be of brick or stone, "sectional hollow brick, hard-burnt clay, porous terra-cotta or some equally good fireproof material."

3.1.1. Tests of Floors

One of the earliest records of a test for fire endurance was for one conducted in London in the 1790's. An informal club of architects, The Associated Architects, conducted tests[8] to determine the relative merits of two floor fireproofing systems: one consisted of iron plates, the other of stucco covering. A fuel load of wood shavings and barrels was introduced and tests were run for one to two hours. The results showed that fire, but not smoke, was successfully contained. The test, of course, preceded the availability of equipment to measure fire temperatures.

Concrete was slowly coming into use in the 1870's. Thaddeus Hyatt was a strong exponent for the use of reinforced concrete as an engineered construction for floors in fire-resistive buildings. Widespread acceptance of concrete floors was not to come until two decades later, but in 1877 Hyatt published[9] a remarkable treatise on the design of reinforced concrete members. In addition to performing mechanical property tests and evolving a way of calculating their strength, Hyatt also performed fire tests on concrete floors. First he cast small blocks of concrete, heated them in a furnace for six hours, then plunged them into water. Concrete specimens did not disintegrate while brick did. Then he built a wood-fired furnace over which a specimen about 0.6 by 1.6 m clear was tested for twelve hours. The test specimen represented three sections of a floor slab, iron reinforcing bars being covered by 5, 7.5, and 10 cm of concrete, respectively. Hyatt had no way of recording the furnace temperature, but he obtained the iron (back face) temperatures by several means: melting of tin and lead squares, bulb thermometers, and, afterwards, immersion calorimetry. The results were surprisingly precise temperature plots of the back face. A second test was then made to test the load-bearing behavior. A 19 cm thick floor was loaded to 300 psf and tested for ten hours. Afterwards, a hose stream test of 15-20 minutes was conducted. Load was held and no collapse nor significant deflection occurred.

By 1890 it was becoming clear in the U.S. that tests rather than mere philosophical discussions were needed to compare the merits of various fireproofing systems. The pioneering work here was a series of tests on floors which were conducted in Denver[10] in that year. The architects for the Denver Equitable Building wanted to determine which of three competing floor systems was best, both from structural and fire considerations. To determine their fire performance 1.2 m by 1.5 m specimens of the three floor systems were given fire and hose stream tests. Two kinds of fire tests were conducted. In the first the floors were built up over a fire pit and loaded down to 300 psf.

A coal fire was stoked and its temperature taken by measuring the resistance of a platinum wire strung through the furnace pit. A temperature averaging 815° C was maintained for 24 hours. The second test entailed similar conditions as the first one, except that every 90 minutes a hose stream was applied for 3 minutes. Both tests continued until destruction. The available hose stream was recorded as unfortunately being a very feeble one, from a 1/4 inch nozzle. The floors lasted between three and fourteen such cycles.

The following year a similar test was made in St. Louis[11] by the architects for the Wainwright Building. Only one type of specimen, 1.4 m by 2.4 m, was tested. The construction involved a concrete arch floor protected by a separately hung clay tile ceiling. The fire test was performed only on the ceiling, with the beams only, but not the arches, installed. The specimen surmounted a furnace 27 cm deep, which was fed by 84 gas burners. This test thereby constituted one of the first known gas-fired tests. Furnace temperature was recorded with a thermocouple protected in iron pipe. A thermocouple was used also for measuring the exposed surface temperatures. The exposure temperature was around 815° C for 6½ hours, not including an initial period when readings were not taken. Immediately afterwards three cycles of hose stream testing, alternating with reheating, were applied. The water was from a garden hose and apparently of low pressure.

The next series of tests marked the inception of floor fire testing in Germany. During 1893 the Vereinigung von Feuerversicherungsgesellschaften (The German Association of Fire Insurance Companies) organized a series of tests[12,13] in a building to be demolished in Berlin. Several floors, doors, wired glass windows, and other components were tested. This series was notable mainly for the fact that doors were begun to be tested. The test conditions were not intended to be uniform enough to be considered standard tests, but were closer to what would now be considered burnout tests. Realistic furniture was used as fuel and temperatures in the range of 1000-1300° C were recorded using Seger cones.

An isolated floor test, one of 4 hours in duration and fueled by "a fierce wood fire," was conducted in 1894 in Trenton.[14] That same year a German fire test of a Monier arch floor[15] was recorded. A 0.70 m wide by 2.0 m long specimen was heated for 2 hours in a fire fueled by wood, coal, and coke. Temperatures, noted only with melting point indicators, stayed below 700° C.

The inception of systematic fire testing of floors was not begun until 1896. In that year and the following one, Stevenson Constable, the New York Superintendent of Buildings, conducted 16 tests[16,17] to determine quantitatively the merits of the various available floor systems and to obviate the need for subjective judgement by the Board of Examiners.

The tests were conducted in different ad hoc brick huts, usually 3.4 m by 4.3 m inside and 3.0 m high. Wood fuel was used since it was felt to more closely model actual fires. The tests were run for 5 hours, the first hour being considered warm-up time, while the temperatures in the last 4 hours were to average 1093° C. The poor control achieved with manual stoking of wood fuel was the main reason for the long required warm-up time. In this first series of tests the temperatures were measured with a single pneumatic pyrometer, supplemented by melting point indicators. The floors had a load of 150 psf applied. After the test a 15 minute hose stream was applied; unlike previous tests this involved a rigorous test with a 60 psi stream. The load was then raised to 600 psf and had to be carried for 24 hours. Deflection, which was not allowed to exceed 6.35 cm was recorded; fall-off or disintegration was noted.

At the same time the New York Building Department also conducted four tests on small 1.2 m square, specimens of wood floors,[18] such as typically used in mill construction. These lasted until flame-through occurred, periods of 29 minutes to 1 hour and 35 minutes.

After 1897 floor testing ceased in the U.S. until 1902 when it was resumed in New York. Starting in that year a measurement of temperatures on the steel of the floor beam was occasionally added. Readings were taken with a special glass bulb thermometer; yet no corresponding criterion for failure was added. Furnace temperatures were now being measured with from 2 to 5 platinum-rhodium thermocouples and the average temperature required was lowered to 926° C.

Although *ad hoc* tests[17] were still being conducted, 1902 marked the establishment of the first permanent station in the United States for testing fire resistance of building components. Professor Ira H. Woolson, a graduate of the School of Mines at Columbia University, first built fire testing facilities on the Columbia campus in Manhattan, then shortly afterwards relocated them to Greenpoint, Brooklyn. The work performed there was not basic research, but rather was conducted as a service to the New York Bureau of Buildings. Two large-scale furnaces[17] were erected--a floor-furnace 5.5 m by 6.7 m long and a wall furnace 3.0 m by 4.6 m wide. Woolson left Columbia after a few years to join the National Board of Fire Underwriters, but work at the station was

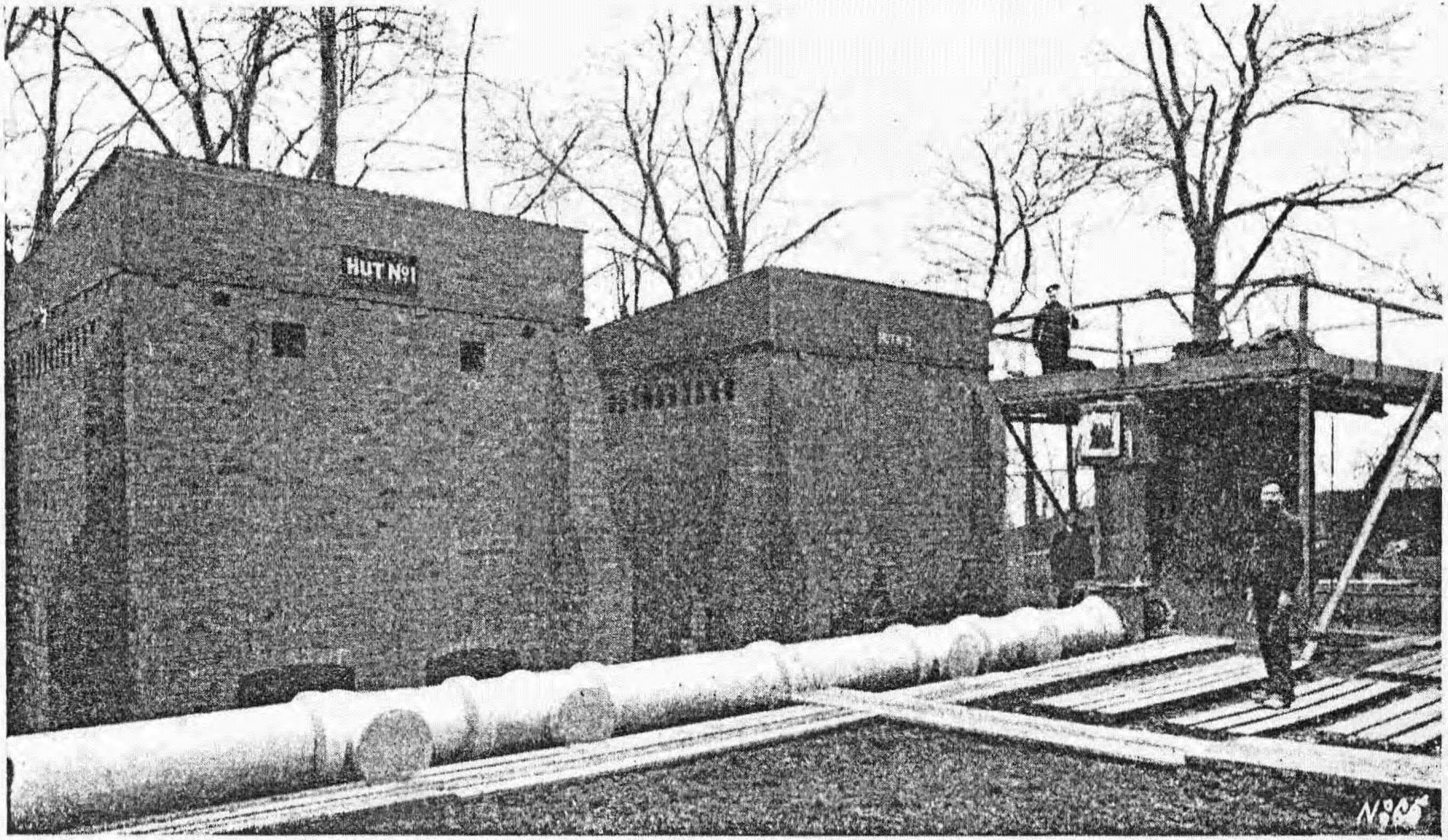


FIGURE 3 THE FIRST BRITISH FIRE PREVENTION COMMITTEE TESTING STATION

continued for several more decades. In addition to fire resistance testing, tests for fire retardancy of wood[274] were also developed at Columbia. Little published research resulted from the later efforts.

In Britain, meanwhile, the history of fire testing reads like the biography of Edwin O. Sachs. Trained as an architect and specializing in theater design, where safety is of utmost importance, Sachs soon realized that official British efforts for firesafety were weak and sporadic. Thus, in 1897 at the age of 27 he organized a group of public-minded citizens and formed the British Fire Prevention Committee. As has happened time and again, before and since, the precipitating event was a tragic conflagration, in this case the Cripplegate fire of November 1897. In two years time a facility containing three multi-purpose furnace "huts" was erected in London,[19] and the first test, a floor test, was conducted.[20] The average life of a test hut was said to be[21] about 10 tests, even though the walls were 36 cm thick masonry and the brick work was repaired frequently. Figure 3 shows this testing facility. By the end of 1899 thirty-six publications, later called "Red Books," had been issued and twenty-nine tests had been reported. In 1901 the facility was razed to make way for railroad construction and a new test station,[22] comprising four furnaces, was erected.

Initially the temperature curve for the producer-gas fired furnaces was not standardized. Tests began with a slow simulation of a smoldering period and then climbed to the vicinity of 1093° C. A hose stream test of several minutes then followed. The criteria for success consisted of avoiding collapse and flame-through. In 1906 deflection measuring was started, although deflection was not required to be limited.

In 1912 Woolson reported[17] that the Underwriters' Laboratories which were started in 1894 in Chicago to test electrical devices and had gradually expanded to other tests, had already tested six floors. No record appears to exist of the furnaces or the test method. It is known that in 1920 two identical floor furnaces were constructed. These could accommodate 16.7 m^2 specimens. In 1924 these furnaces were re-constructed, but very shortly fell into disuse. Floor testing was then discontinued at UL until 1939. The extensive ratings for building components now being published by the UL in fact did not come into being until the 1940's and 50's. Previously only tests of fire doors and windows were routinely being tested and listed. UL's reluctance to routinely test and rate other types of components stemmed from the fact that they were not factory manufactured. Unlike a door assembly, a floor did not leave a factory complete, inspected, and labeled. Thus, in the early days, the UL listings for building components tended to be simple, single-material systems from large manufacturers.

The British Fire Prevention Committee lost its momentum when Sachs died in 1919 and the following year it was merged into the National Fire Brigades Union. Testing in Britain was continued when the Fire Offices' Committee, analogous to our NBFU, which had already been conducting sprinkler, extinguisher and fire door tests since 1908, built a furnace at Cheetham Hill, Manchester, in 1927. Later in 1935, the FOC erected a fire testing station at Borehamwood (Elstree), equipped with three furnaces for wall, floor, and column tests.

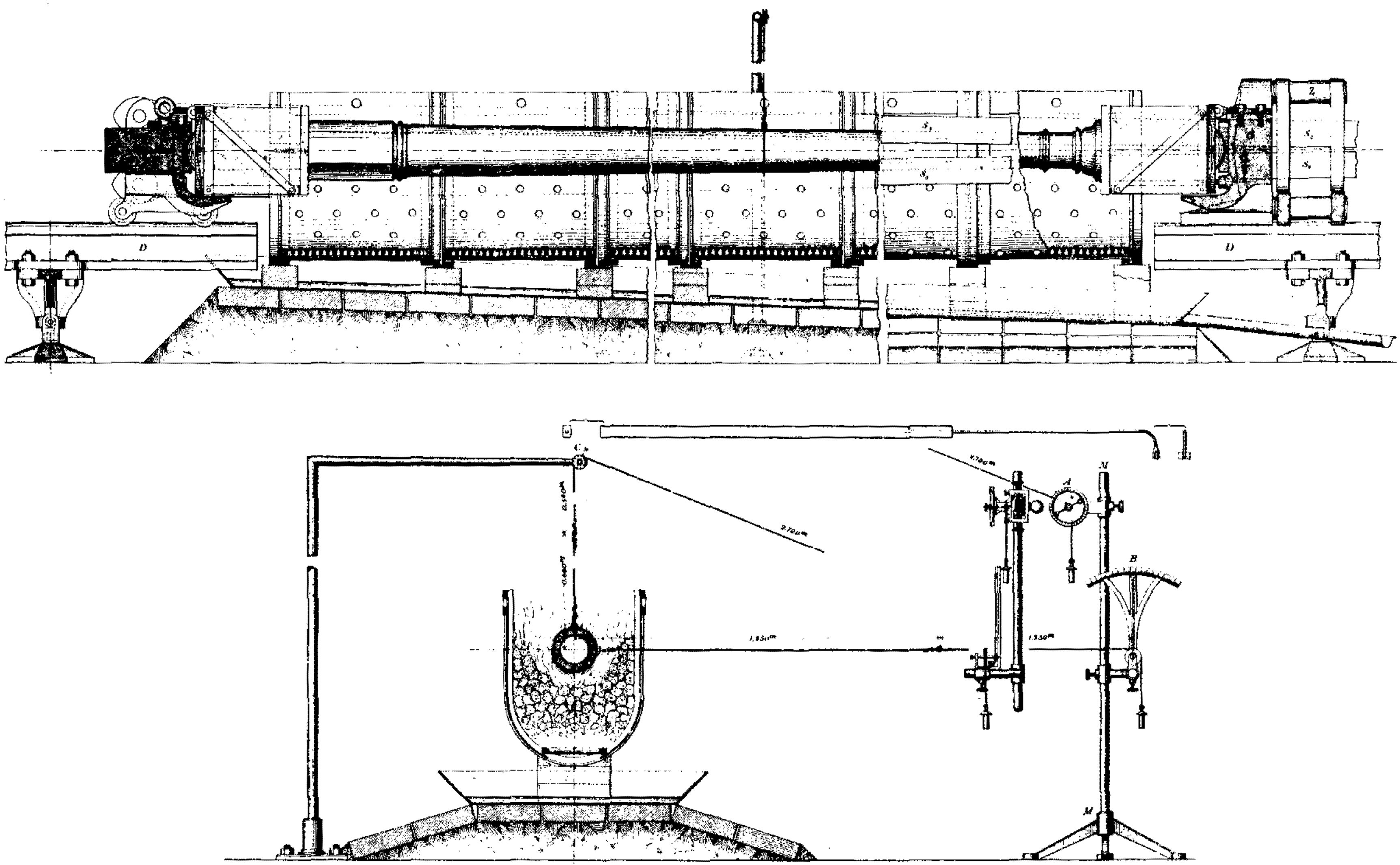


FIGURE 4 BAUSCHINGER'S COLUMN TEST FURNACE (1884)

3.1.2. Tests of Columns

Column testing was first recorded in Germany and Austria. During 1884 Professor J. Bauschinger, famed for his researches in materials science, conducted tests[23,24] at his laboratory in the Technische Hochschule of München on 11 unprotected cast or wrought iron columns and 12 brick, stone or plain concrete columns. The testing procedure consisted of heating the loaded columns in a horizontal position in a woodburning furnace. Figure 4 shows a cross section of this primitive furnace. Three successive fire and water tests were to be conducted. An unusual feature of these tests was that instead of measuring the fire temperature, Bauschinger measured the surface temperature of the columns using low melting point alloy probes. A column was heated until its surface reached 300° C, then doused with water, then raised to 400° or 500° C and then doused, and finally doused after reaching 600° C. The columns were loaded and their deflections were measured while being heated. After the columns were removed from the furnace, a complete stress-strain curve was run on them. A second series[25] of 12 iron columns was run in 1886 under similar conditions.

In 1887 Möller and Lühmann conducted a series of tests[26,24] in Hamburg, described by them in a paper which won a prize from a German construction promotion council. The fire test aspects were only secondary to a general structural column investigation, so an adequate description of the fire tests was not given. A coke and wood-fired furnace, possibly similar to Bauschinger's was used, but it is reported that the flame exposure was not solely on one side of the column. Unlike Bauschinger's procedure, only a single cycle of fire and hose stream testing was performed. The times were reported when the columns got red hot and when they failed. The tests were intended mostly to compare the differences between cast and wrought unprotected iron columns. The differences were slight, with most columns lasting between ½ and 1½ hours.

The next recorded column test was conducted[27] by the Building Department of Vienna in 1893 and represented an advance in furnace building. A single wrought iron column 3.5 m long and protected by brick masonry was erected in a furnace hut fired with wood fuel. The column was subjected to load and fire tested for 2½ hours. Column temperatures were measured with low melting point alloys, but furnace temperatures were not recorded. A hose stream was applied afterwards.

Testing activity continued in Hamburg. A municipal committee under the direction of F. Andreas Meyer, concerned with fire problems after the conflagration in Hamburg's warehouse district in 1891, organized two series[28,29,30,24] of tests of protected and unprotected iron columns, conducted in 1892-94 and 1895. The columns were full size, representing a distance of 3.5 m between floors. They were loaded in a hydraulic testing machine and a 1.0 m high split oven was clamped around the middle portion; illuminating gas was supplied to 12 burners at the bottom of the oven. Furnace temperatures were monitored both with Seger cones and with thermocouples. Unlike in earlier investigations, the column was erected upright and was heated symmetrically. A standardized temperature curve was not used. The columns were heated to 1200-1400° C for up to 7 hours if there was no failure. Both central and eccentric loadings were used. Most specimens failed much sooner. Unprotected iron ones tended to last ½ to 1 hour, at which time the furnace temperature was 800-850° C and the specimen was at

800° C. Other specimen temperatures were measured but not published. A hose stream portion was included, but it was not meaningful since most columns had already failed from the heat. For comparison several 30 cm square timber columns were tested at the same time. When unprotected they lasted just over 1 hour at temperatures of 900-1000° C.

In the United States, column testing dates from 1896. A committee[31,32] representing the Architectural League of New York, the American Society of Mechanical Engineers, and the Tariff Association of New York arranged to have a furnace, fueled by manufactured gas, constructed at the Continental Iron Works in Brooklyn. Five unprotected columns, two of steel and three of cast iron, were tested. The test procedure was not standardized, the tests lasting from 25 minutes to over two hours, and with temperatures ranging up to 840° C. Some columns were subjected to several cycles of fire and hose stream testing.

Column tests were again conducted in New York in 1902, this time by the Guy B. Waite Company[24] for the New York Building Department. In this series, floors, partitions, and columns were simultaneously tested. Tests were conducted for four hours, with the temperature averaging 930° C. The same hose stream test which was prescribed for floor tests in New York was applied. Some additional hose stream tests were also performed.

Reinforced concrete columns were coming into use at the turn of the century. These were first tested in 1904 by the National Fire Proofing Company[33] in Chicago. Three columns were tested unloaded in a woodburning furnace for three hours, the furnace temperatures ranging around 800-1000° C. A hose stream was applied afterwards; the next day the load carrying capacity was measured.

The next series of column tests, the first standardized one, was the famous series[24] of 1917-18 conducted at the Underwriters' Laboratory in Chicago. In addition to UL, the Factory Mutual companies, the NBFU and the Bureau of Standards, participated in the effort. Simon H. Ingberg, from the Bureau of Standards, was in charge of the program. These tests represented the first major fire testing effort, for both Ingberg--who became the American authority on fire testing--and the Bureau, which had started its fire testing program in 1914.

Over 100 steel, cast iron, reinforced concrete, and timber columns were tested, making it the largest testing effort to that date in the United States. The results are still being used in building codes; this acceptance was due mainly to the fact that furnace temperature control had been standardized. Platinum-rhodium furnace thermocouples sheathed in 2.0 cm O.D. porcelain tubes were used. The column specimens were 3.9 m long and were tested vertically under load in a furnace fired by city gas. A load 10% greater than the design working load was maintained for 8 hours, or until failure resulted. Some specimens were also subjected to a hose stream test afterwards. Temperatures of the column itself were also measured using thermcouples attached to the metal load-bearing portion in the columns containing iron or steel. This technique was much advanced over Bauschinger's crude use of low melting point alloys to indicate specimen temperatures.

Little additional column testing was done at the UL facility and the furnace was torn down about 1944. Column testing resumed in 1946, being at first conducted in a furnace normally used for testing of fire resistant safes.

3.1.3. Test of Walls

The first controlled tests of walls can be dated from 1891 in Germany. The fire test facility of the Königlichen Technischen Versuchsanstalten zu Berlin was established in 1884 in Charlottenburg; the first published report[33] gives results of a pair of tests conducted in 1891 by a Professor Böhme.

The tests were designed to compare the performance of wood walls against a proprietary wallboard system. Two identical test huts were erected. Each contained a burn room 2.01 by 2.63 m by 2.63 m high. The burn room was surmounted by a chimney and fueled by manually stoked fir logs, soaked in petroleum. Each test hut contained a smaller adjoining observation room. The test wall was erected as a partition between the burn room and the observation room. In addition, the same wall material as used in the test partition also lined the ceiling and other walls of the burn room. The test houses carried a fire window plus a loaded cast iron column and a timber column, both protected with wallboard.

Gas temperatures were monitored by multiple melting point indicators. Wall thermal performance was determined by several methods. A peak registering thermometer was attached to the unexposed face; sheets of thin paper were hung on the wall to check for ignition; and the wall was touched to determine if it was too hot to the touch. The temperatures underneath the column protection were determined by a buried peak thermometer plus samples of two low melting point materials.

A total of 275 kg of fuel were used for each test. Gas temperatures averaged 1000° C, the length of the test being one hour. Observations mentioned the window glass bursting at 5 minutes, and eventual slight cracking and crumbling of the walls. One column collapsed at 50 minutes. The other lasted a full hour. At the end of the test fire was extinguished by a feeble hose stream applied to both the inside and outside of the burn room causing some fall-off inside.

The Vienna column test[27] of 1893 also incorporated some test of wall panels. These panel tests cannot be considered quantitative building component tests since the panels were small and not erected in the manner of intended use.

Work was resumed at Charlottenburg in 1895. By 1900 Gary could report[35] a series of eleven wall tests. In each case an ad hoc test hut was erected and divided into two rooms by the test wall. For most of these tests the hut was framed with ordinary wood studs since it did not need to be re-used. The inside dimensions varied in each case. The fuel was petroleum soaked fir burned on a brick checkerwork.

In the new series gas temperature measurement was improved--both Seger cones and thermocouples were used. Only the maximum temperature was reported; it varied in the range 1000-1100° C for the series. A hose stream was applied after each test and was first directed at the test partition. Unexposed face conditions were recorded as earlier. In one case curtains were also hung on the back face. Observations included note of cracks and fall-off as well as the back face heating. The assemblies tested in the second series were mostly proprietary wallboard systems, many of them based on gypsum planks. They were not intended for fire-resistive buildings, but were merely viewed as more modern replacements of traditional plastered wood walls. The tests were all conducted for one hour. The successful systems were generally issued approval to be used as equivalent to plastered wood walls in residential occupancies.

The British Fire Prevention Committee testing of walls began in 1899, shortly after its initiation of floor testing. A non-load bearing specimen 3.0 m wide and 2.1 m high was constructed[36] dividing the space of one of the test huts. Similar temperature control as for floor tests was used; a hose stream was applied after the test. Burn-through and structural stability appear to have been the main criteria. By the next year,[37] temperature readings of the unexposed face were being taken, and shortly thereafter recording of deflections was also begun. At times a match would be held to the unexposed face to see if it would ignite.

In the United States testing of non-loadbearing walls (generally called partitions) was started by the New York Department of Buildings.[38] In 1901 thirty walls were tested in fifteen separate huts by W.W. Ewing. Each hut was 4.4 m long, 2.9 m wide and 2.9 m high. The test walls were erected in the long side. Mosts of the tests involved two slightly different assemblies by the same manufacturer. Underneath the hut was a grate on which kerosene-soaked wood fuel was burned.

Furnace temperatures were measured with platinum-rhodium thermocouples. The temperature control consisted of trying to reach 926° C at 30 minutes, then maintain that level until the end of the test. All tests were one hour in duration. A hose stream was applied to the fire side after the test. The criteria for success were that neither the fire nor the hose stream pass through the assembly.

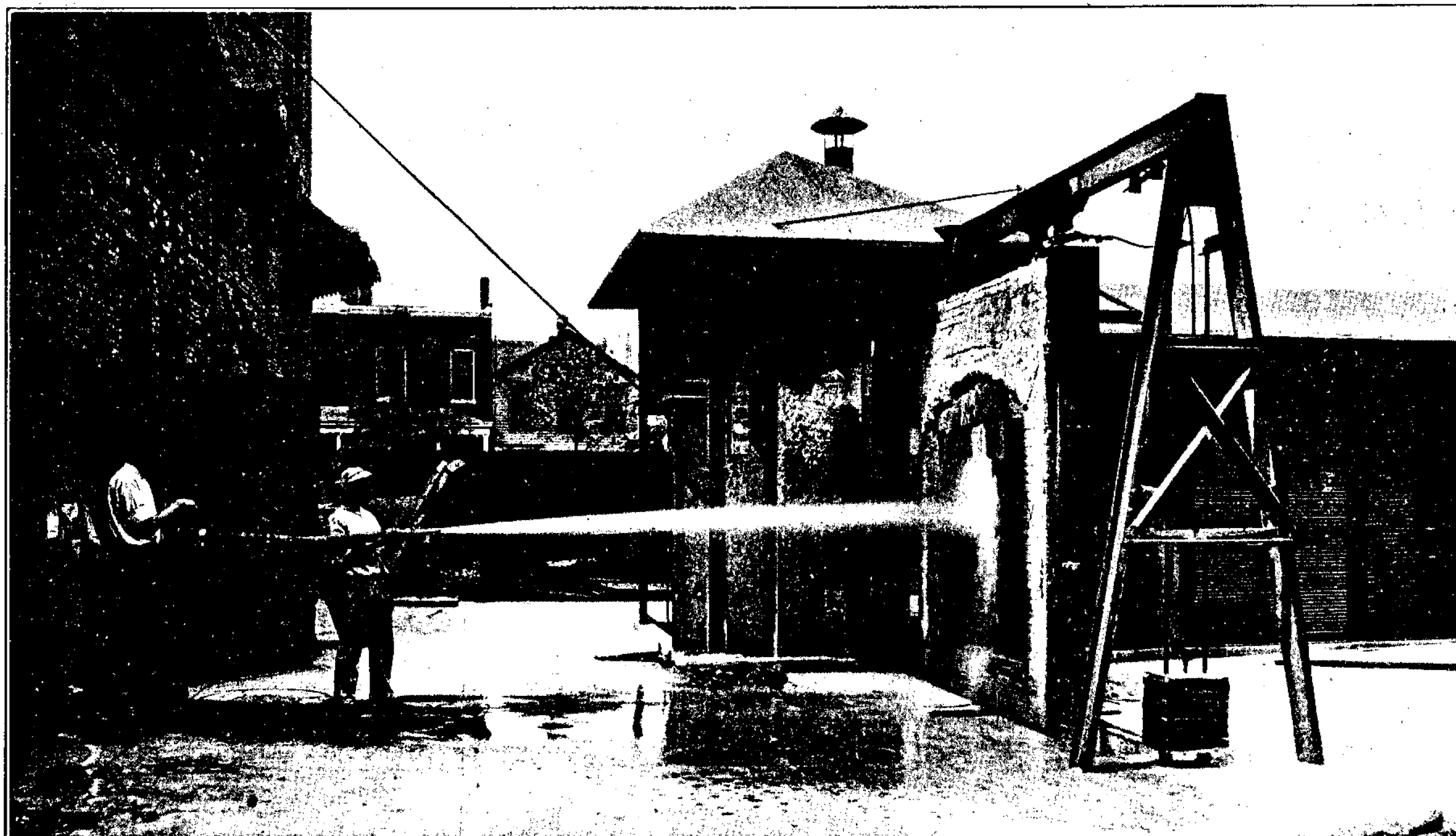


FIGURE 5 WALL PANEL FURNACE AT UNDERWRITERS LABORATORIES

The systems tested included plaster block, tile block, and concrete block walls and plaster on metal lath constructions. The walls which passed the test were approved for use wherever the New York Building Code allowed "other fireproof material." Those systems containing organic materials, however, were barred from use for shafts in tenements since the 1901 law specifically prohibited any combustible material there. The New York City testing was continued by Woolson when his station was built.

The U.S. Geological Survey had a mission at the turn of the century to evaluate building materials used in construction of government buildings. As part of that program they set about to evaluate the fire resistance of walls. A series of wall tests were conducted in 1907 by the USGS at the UL facility, and Humphrey reported the results[39] in 1909. These tests were intended to explore the physical properties of the materials, rather than to be directly used for regulatory purposes; nonetheless, the tests were standardized and the results are of interest.

The furnace used at UL (Figure 5) was their first fire test furnace, erected in 1903 for testing doors and windows. It may be considered the first modern furnace, more resembling current furnaces than the huts predominantly then used. The furnace was a gas fired chamber, only 32 cm deep inside and approximately 2.7 wide by 3.7 m high. Gas was fed through burners in the floor, while forced air was supplied through holes in the front. Furnace temperature was monitored with stubby shielded platinum-iridium thermocouples. A vertical specimen panel 1.8 m wide by 2.1 m high was tested for two hours at a temperature which rose to 926° C in the first half hour and was then held at that level. A hose stream test was applied immediately after the test. The panels were not loaded during testing since the furnace was not so equipped but were taken out and load tested the following day. Thirty panels in all were tested--bricks, concrete blocks, tile, concrete, and stone specimens were included. Backface temperatures were measured, and in addition, some interstitial temperature readings were taken.

The UL conducted its own series of tests on gypsum block walls[40] during the years 1909-1918. At first the furnace described above was used. Starting in 1915 a new larger furnace[41] was constructed. It was also gas fired, as had now become customary in the United States. The inside chamber was 40 cm deep, by 3.6 m wide and 4.5 m high. Furnace temperatures were measured by thermocouples sheathed in steel pipe. This furnace, like its predecessor, was not capable of testing load-bearing walls. Until 1927, when a test frame was built to perform load-bearing wall tests, if the UL wanted to test walls intended to be load-bearing they simply tested them unloaded, but for a 25% longer period. The UL did not carry out much routine testing and listing of walls or other building assemblies until the 1940's. Occasional large series of tests[42,43] would be sponsored at UL by trade associations, but most detailed ratings emerged from Bureau of Standards test programs.

3.1.4. Tests of Doors and Other Opening Protection

The 1892 investigations of fire door performance in Berlin has been discussed above in connection with floor tests. The first controlled fire tests on doors can be dated to 1899 when the British Fire Prevention Committee began door tests.[44] The initial series consisted of three wooden doors; mounted in the exitway of one of the test huts they were tested at temperatures rising to 900-1100° C until failure. The doors were mounted swinging outwards, but failed by collapsing into the furnace. A 5 cm solid teak door lasted 60 minutes, while standard pine paneled doors lasted 19-20 minutes before burn-through or collapse, which were the only criteria involved. Later a back face temperature measurement was added, but a hose stream was normally not used. Some tests were also run with doors swinging into the furnace. Furnace pressures were not measured or noted.

In the U.S. the earliest record of opening protection testing is of some tests of fire windows and shutters[45] conducted by the New York City Department of Buildings. Systematic testing of doors and windows was taken up by Columbia University when its test station was established in 1902. Testing by the UL of doors and windows began in 1903 in the furnace already described. Rating of doors, however, was begun earlier in 1901. This was possible because the doors were mainly investigated for conformance to the various prescriptive specifications set forth by the NBFU and the National Fire Protection Association, rather than being tested as a fire barrier. Very similar prescriptive specifications were adopted in Britain by the Fire Offices' Committee.[46] Woolson's report of 1912[17] states that by that date the UL had already tested 209 doors and 273 window frames. Despite this extensive activity

Freitag[47] could not list any American test results as having been published by that year. The first description of the UL testing program appeared in 1917. Carr[48] described how these tests were conducted in the wall testing furnace. A test was of one hour in duration, with a hose stream applied afterwards. An interesting set of additional measurements was involved: at distances of 81, 162, 243, and 324 cm horizontally away from the centerpoint of the unexposed face thermometers and cloth test strips were hung. It is not stated, however, what use was made of these measurements, which were taken after 1903. From a committee report[49] of 1915 it would appear that positive furnace pressure was maintained at that time. Woolson is quoted as saying,

> "I have been much interested during the past year or more in studying laboratory reports on tests of various types of fire doors, and I find that it is not unusual during a test of a device of that kind that flames anywhere from four inches to three feet issue from around the edges of fire doors. It seems to me that is a very decided danger point, and we ought to provide for it in some way by a regulation keeping combustible material away from the door. I think the public as a general thing expects that any fire door is going to keep fire out of the room. It is certain that a single door will not do it if there is a considerable amount of pressure on the fire side."

The testing of doors by the UL was not coordinated with the testing of other components. While other components were tested and rated for varying time periods, the pervasive influence of the early prescriptive specifications fixed these door tests to be 60 minutes in duration. The testing was changed in 1938 under the impetus of New York City Building Code Requirements, which provided for three rating periods:

3/4 hour for doors with glazing of greater than 645 cm^2 area

1-1/2 hour for exterior doors and vent shaft doors

3 hours for doors in fire walls

A standard door test was not available until the first edition of ASTM E-152[50] was adopted in 1941. A parallel standard by Underwriters' Laboratories, UL10b,[51] was adopted the following year.

3.1.5. Other Early Test Stations

By 1903 it was reported[52] that a fire test station existed at St. Petersburg and occasional testing was being done at Ghent,[53] Leipzig, Karlsruhe, and Stuttgart. An initial test had also been conducted[54] by C.L. Norton of the Massachusetts Institute of Technology. The next year Norton was associated with the founding of the Insurance Engineering Experiment Station by the Boston Manufacturers' Mutual Fire Insurance Co. This station conducted several fire tests then closed within a year's time. Ad hoc testing was occasionally done in other U.S. cities. These tests were generally not as well controlled as the ones in New York, and little record remains of their results.

TABLE 1

FIRE TEST STANDARD OF THE BRITISH FIRE PREVENTION COMMITTEE

CLASSIFICATION	SUB-CLASS	DURATION OF TEST	MINIMUM TEMPERATURE	LENGTH OF HOSE STREAM TEST	FLOORS		PARTITIONS		DOORS	
					Load	Minimum Area	Maximum Thickness	Minimum Area	Maximum Thickness	Minimum Area
		(min)	°C	(min)	(kg/m²)	(m²)	(m)	(m²)	(m)	(m²)
Temporary	A	45	816	2	not required	9.3	0.051	7.43	0.051	1.86
	B	60		2		18.6	not limited		not limited	
Partial	A	90	982	2	547	9.3	0.063	7.43	0.063	1.86
	B	120		2	820	18.6	not limited		not limited	
Full	A	150	982	2	1094	9.3	0.063	7.43	0.018	2.32
	B	240		5	1367	18.6	not limited		not limited	

3.2. Development of the Standard Time-Temperature Curve

Until 1903 each test laboratory used its own specifications for temperature, generally a prescription saying that the temperature will be maintained, on the average, above a certain level. As the most active testing organization, the British Fire Prevention Committee was the first to propose a widely accepted standard method. Their standard, as developed by Sachs, was issued at the 1903 International Fire Prevention Congress,[53] where its use was adopted by a resolution of the delegates. The standard consisted essentially of only a table, which is shown slightly condensed as Table 1.

Three main classes of endurance were established:

-- full protection
-- partial protection
-- temporary protection

These terms were perhaps somewhat ill-chosen. Temporary did not apply to temporary structures, but rather to endurance which would not be sufficient to endure a burnout of the contents. Full protection, on the other hand, was envisioned as providing such assurance. The main classes were each further divided into subclasses A and B. Prescribed temperatures for both classes were identical, but specimen size and loading and duration of hose stream application varied. The subclasses entailed quite different requirements but no record remains explaining the necessity for such subdivision.

In the U.S. the first test standard was promulgated as part of the New York building code in 1899. (See Appendix B.) It was not intended to be national in scope. A nationwide attempt at standardization came from the efforts by the American Society for Testing Materials. Prompted by the Baltimore conflagration of 1904, ASTM organized

Committee P, On Fireproofing Materials, which first met in May 1905. The committee, which was soon re-designated C-5 and later E-5, produced its first standard, A Standard Test for Fire-Proof Floor Construction[55] in 1907. Ira Woolson was the Chairman of Committee P and R.P. Miller, the New York Superintendent of Buildings, its secretary; thus it is not surprising that its recommendations consisted mainly of a re-wording of the New York procedure.

The test conditions envisaged a test hut similar to the ones used in New York and London. The grate area, flue construction, hut wall thickness, and inside clear height were all specified. The clear span of the floor was to be 4.3 m and the floor was to be loaded to 150 psf. A hose stream was to be applied afterwards. When cooled the floor was to be loaded to 600 psf.

The temperature control was the same as in the New York tests: an average of no less than 926° C was to be maintained for four hours.

Criteria consisted of the following:

(a) No flame-through or passage of smoke.

(b) No collapse

(c) A permanent deflection of no more than 1/96 the length.

In 1909 a separate test for walls was added, Standard Test for Fireproof Partition Construction.[56] With a few exceptions this test was to be conducted in a manner similar to the floor test. Only non-loadbearing partitions were considered; following New York practice, the specimen was to be at least 2.9 m high and 4.4 m long. The temperature was raised to 926° C in the first half hour and then maintained at 926° C until the end, the standard endurance being two hours.

Criteria consisted of the following:

(a) No flame-through or passage of smoke.

(b) Sustain the hose stream.

(c) Not "warp or bulge, or disintegrate under the action of the fire and water to such an extent as to be unsafe."

In other countries, meanwhile, the 1903 BFPC standard was being adopted. Woolson, at that time, was also the chairman of a similar standards committee of NFPA. Influenced by the increasing prestige of the BFPC standard, this NFPA committee recommended[57] in 1914 that instead of further developing an American standard, the 1903 international standard be adopted in the U.S. but with certain modifications. These modifications consisted of:

(a) Deleting the subclass A.

(b) Lowering the temperature requirements to 926° C in the "full" and "partial" classes.

(c) Increasing the duration of the hose stream, up to a maximum of 10 minutes for floors with "full" protection.

(d) Some modifications in specimen thicknesses, area, and loading.

This recommendation was not approved by NFPA.

Instead, in 1916 and 1917 two meetings were held for the purpose of determining U.S. fire test standards. These conferences were made up of representatives from ASTM, NFPA, UL, the Bureau of Standards, NBFU, Factory Mutual, American Institute of Architects, American Society of Mechanical Engineers, American Society of Civil Engineers, Canadian Society of Civil Engineers, and American Concrete Institute. The new standard, ASTM C-19 (later renumbered E-119), was issued at the 24 February 1917 meeting of that conference.

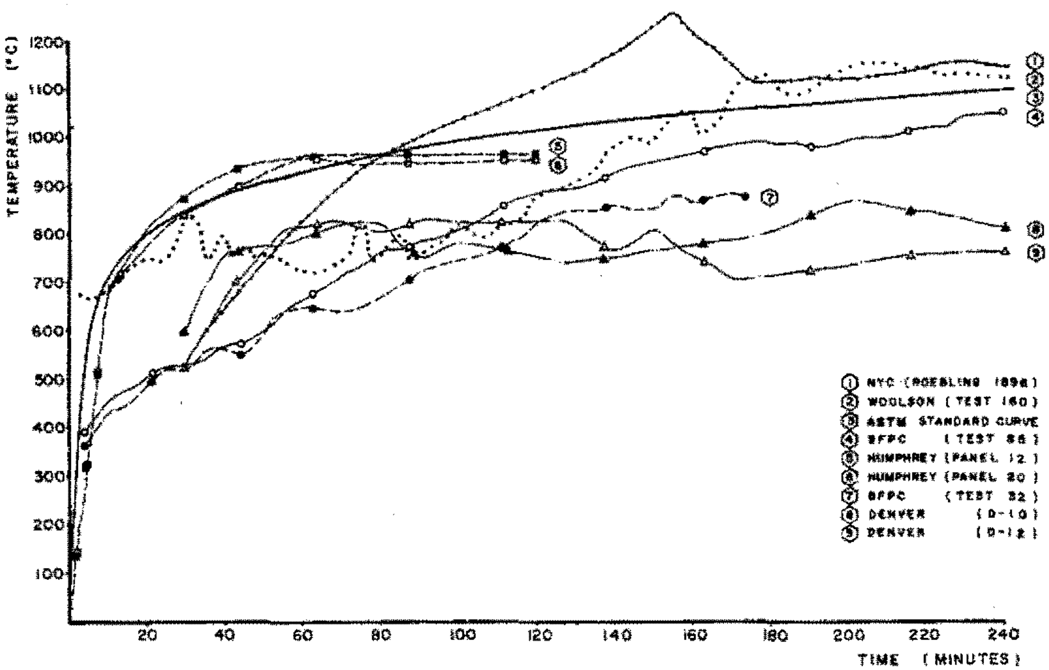


FIGURE 6 THE STANDARD ASTM CURVE COMPARED TO SOME EARLIER TEST CURVES

The most striking innovation of the new standard was its prescribed time-temperature curve. That curve (Figure 6) was first published in the 1916 description[58] of the proposed UL column tests and has not been changed since then. For years it had been called the "Columbia Curve" in honor of Woolson.

Its origin stemmed from the realization that it is not adequate to merely specify that the temperature must, on the average, be greater than some value. A furnace does not heat up instantaneously; for reproducible results this initial heating rate should be quantified. Figure 6 gives some results of early time-temperature curves; they show a rather gradually rising characteristic. At the conference meeting the members examined about a dozen such curves. The resulting standard curve was basically an idealization of these previous curves. It differed only because, at the insistence of William C. Robinson, who was in charge of fire testing at UL, the rise in the initial 10 minutes was made faster than in the earlier curves.[59] Robinson believed that in some occupancies a more rapid rise can be expected, and the test should reflect that fact. It is likely that this more rapid rise was made possible by the more modern gas-fired furnaces which had come into use. Earlier tests in the U.S., having used manually stoked wood fuel could not have produced a sufficiently fast rise. Of the existing curves, the one adopted was closest to those of the New York/Columbia tests after 1902, when the average temperature was dropped from 1093° C (2000° F) to 926° C (1700° F); thus the designation Columbia Curve was appropriate. The curve was specified for a period of 8 hours. Standard tests prior to 1916 were normally not over four hours. To leave an option for future testing, however, the curve was defined up to 8 hours, with a constant rise of 41.7° C (75° F) per hour prescribed after the first two hours. Ingberg[60] later reported some furnace tests up to 14 hours long.

It is important to realize that the standard curve was prescribed in 1917 without the knowledge of what actual temperatures in building fires might be. Although burnout experiments had already been conducted in Europe, as discussed above, Woolson and his fellow committee members were not aware of them. None had been conducted in the U.S. and the variables controlling fire temperatures were not known.

The first systematic effort at the measurement of fire temperatures was started by S.H. Ingberg at the National Bureau of Standards with the construction of their first test burnout building in 1922. This building was furnished with furniture and papers resembling office occupancies. Fires were started and their development noted; temperature measurements were made with thermocouples, sometimes bare but usually sheathed in heavy iron pipe. The program continued for many years. Some of the questions investigated included the differences between the fire behavior of steel and wood furniture, the temperatures of smoldering debris piles, and the fire damage to papers in safes and metal cabinets. Ingberg was particularly interested in the latter problem and worked, under the auspices of the NFPA, towards developing standards for fire testing of safes.

Some preliminary findings from the burnouts of the simulated offices were briefly given in 1927.[61] The main results, published in 1928,[62] included the first presentation of Ingberg's equal-area severity hypothesis, discussed below. The actual data from the burnouts were

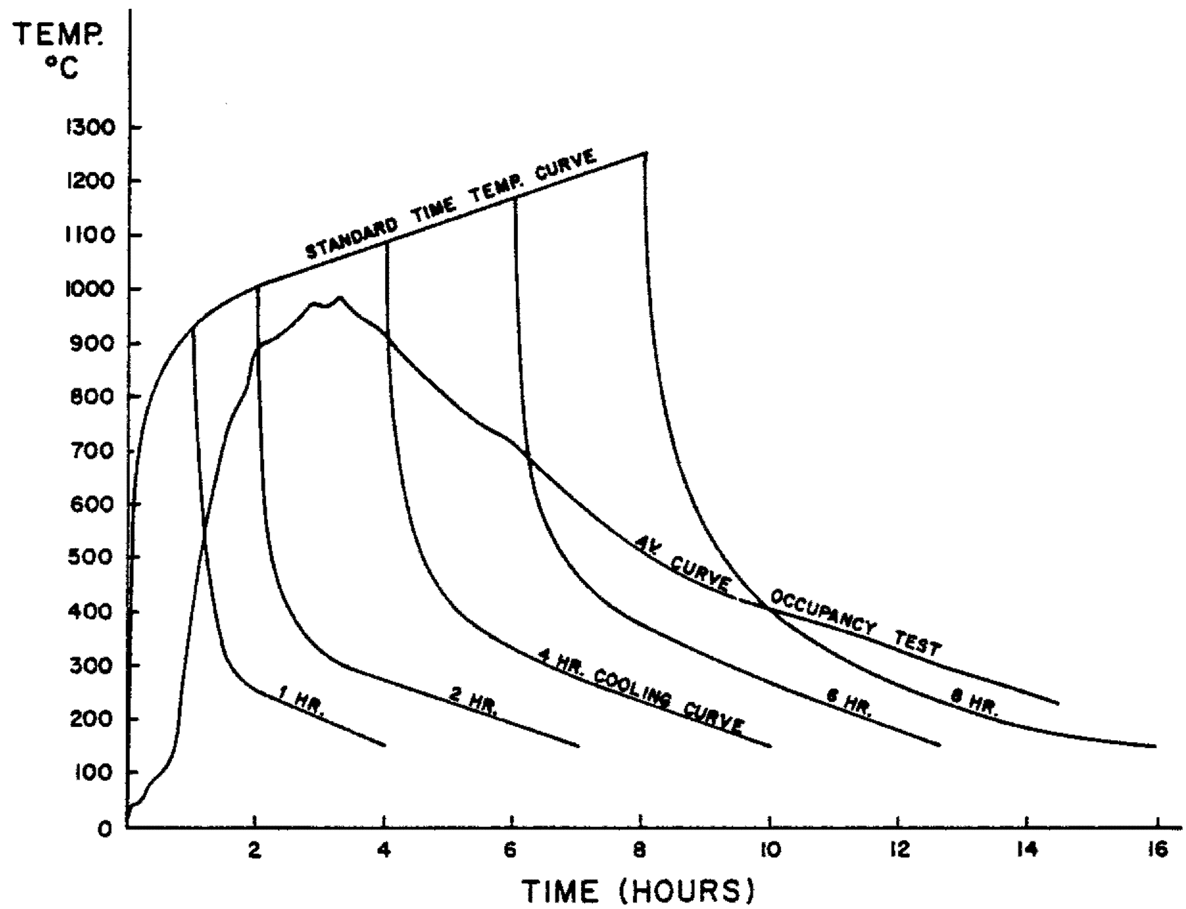


FIGURE 7 INGBERG'S RESULTS OF 1928 AND THE STANDARD ASTM CURVE

not published--only a single illustrative curve and the overall average curve were given (Figure 7). Burnout work continued at NBS in the 1930's and 1940's. Fires in residential occupancies were studied in 1939[63] and into the late 40's. These results were not published.

3.3. Equal-Area Concept of Severity

The early New York City philosophy of fire testing basically implied that there was no difference among fires. An assembly either withstood it or it did not. The 1903 International Standard proclaimed that it was desirable to have six different categories of protection. It was not based on six different possible expected fires; instead, the distinction was mainly economic--how good a protection can you afford? Later such a quantized scale of protection would be incorporated into building codes. In 1903, however, Sachs' work, done in London, was not even used by the London County Council.[52]

In the same year, Woolson was using 926° C as the test fire temperature[52] since as he stated, "This particular temperature was chosen because it is given by the New York Building Code as approximately the heat of a burning building." To complete the circle, one only needs to know that the New York Building Code used 926° C as the temperature of a burning building because Constable ran his fire tests at that temperature.

What emerges from this discussion is that fires were considered to have a single representative temperature and last for, perhaps, four hours. A building assembly passing a test under these conditions could withstand a fire burnout. An assembly qualifying for some lower classification could be used if failure would not be intolerable.

Ingberg's monumental contribution to fire endurance theory consisted of recognizing a quantitative variable in determining the expected fire, namely, the fuel load. As can be seen in Figure 7, his burnout results indicated that the expected fires could have temperatures quite different from the standard curve. One logical product

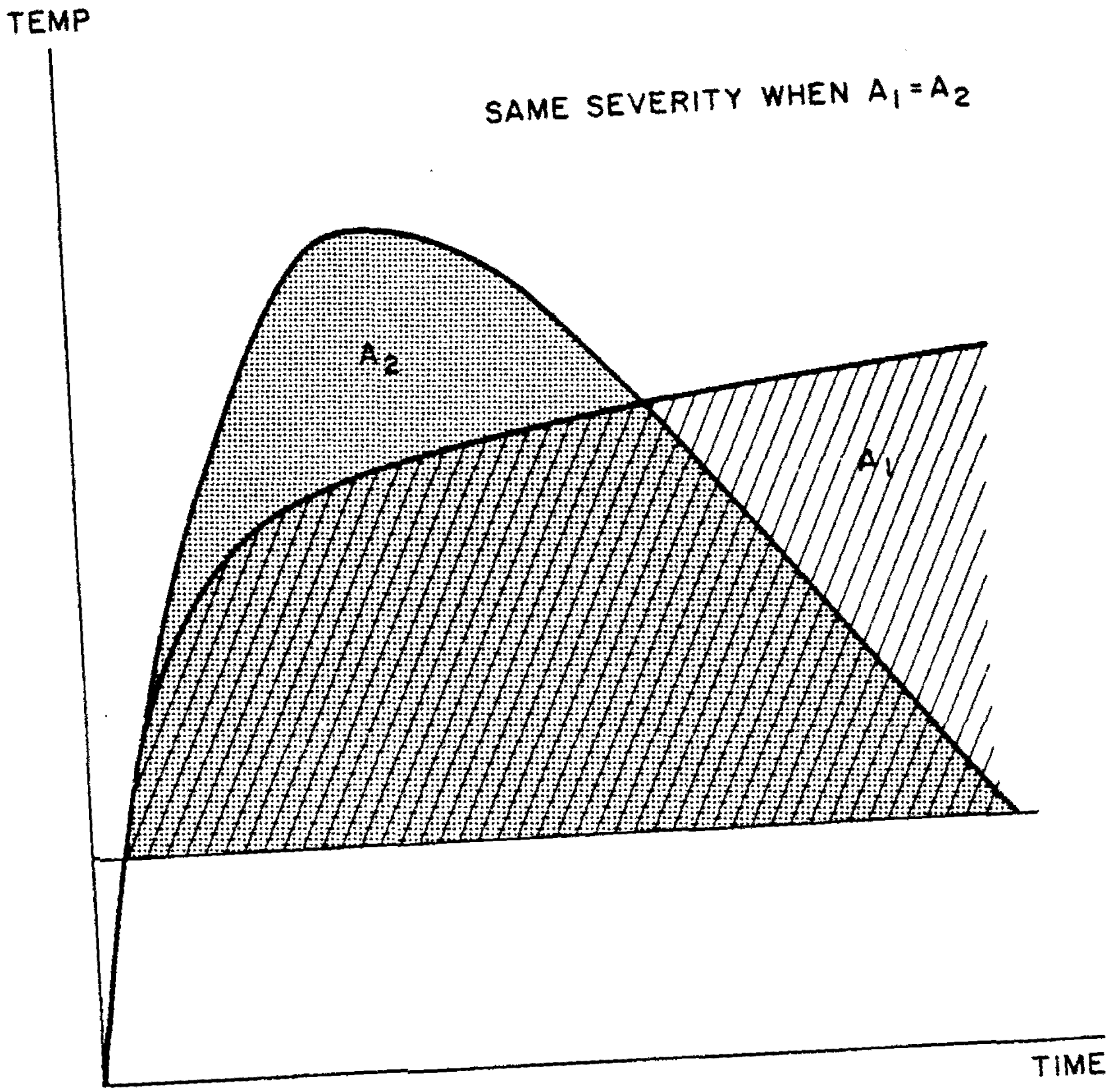


FIGURE 8 THE EQUAL-AREA CONCEPT OF SEVERITY AS PROPOUNDED BY INGBERG

would be a series of time-temperature curves for varying fuel loads. Ingberg realized the impracticality of making multitudinous endurance tests on assemblies under all the different possible curves. The simplest solution was to reduce the dimensionality of the problem (two: temperature and time) by one. There was no physical basis for doing that, so he provided a hypothesis: what mattered was not the entire time-temperature curve, but merely the integral under it. He defined this integral as the "severity" of the fire. The problem was now reduced to a single dimension, the severity.

The general topic of reducing the dimensionality of a problem is one of the key issues in all aspects of engineering. Unless a problem has been redundantly formulated, that is, unless there is a known physical connection between some supposedly unconstrained variables, then when a reduction of dimensionality is performed some information is unavoidably irretrievably lost. Much of the research of yesteryear can be re-evaluated on this basis because complex numerical models of an entire system can now often be evaluated on a computer which could not have been analyzed some decades ago. In fire endurance a simplifying hypothesis such as the equal-area one becomes unnecessary if the fire performance can be numerically evaluated by calculation. In that case it is no harder to use a well calculated curve than an approximate one. Some situations are still not amenable to this kind of numerical design, as will be discussed in Chapter 9.

Ingberg considered that the severity is to be calculated as the area above some baseline (see Figure 8). The baseline was to represent a temperature of negligible damange, either 150° C, or 300° C when dealing with protection for heavy noncombustible structural members.

Again, there is no physical reason why a given baseline should be selected; the negligible damage criterion is indeed irrelevant to a scaling of temperatures. The results then related fuel load, the main variable that he identified, to severity, where severity was expressed as the time on the standard curve which represented the same area as the burnout curve. The 1928 results, giving fuel load in equivalent wood fuel, were:

TABLE 2

Ingberg's Fuel Load - Fire Severity Relationship

Combustion Content (lbs/ft^2 of floor area)	Equivalent BTU/ft^2	Standard Fire Duration (hrs)
10	80,000	1
15	120,000	1½
20	160,000	2
30	240,000	3
40	320,000	4½
50	380,000	6
60	432,000	7½

The standard time-temperature curve was thus saved by Ingberg. He demonstrated that real fires are quite different from the temperatures of the curve, but at the same time provided a method for using the curve, even though it did not represent actual fire conditions.

To make use of fuel load as a fire variable required that the fuel loading of buildings be known. Surveys needed to determine fuel load distributions were started at NBS in 1928. The results were only published in 1942 in report BMS 92.[64] Additional fuel load surveys for different occupancies were presented in 1957.[65] A new series of office occupancy fuel load surveys[66,67,68] has just been completed, and a similar survey for residential occupancies is in progress.

Shortcomings of the Equal-Area Severity Concept

In Ingberg's time the fire endurance periods considered fell mostly in the one to four hour range. Also, the materials available on the market tended to be fairly massive, were unlikely to fail by local buckling or melting and generally had to reach fairly high temperatures before impairment. Today it is not unusual to see 1/6 hour fire tests and materials failing by collapse at low temperatures. Ingberg's hypothesis was no more true in his day than it is today; yet because of the above factors the repercussions from its inaccuracy were less important. Its utility was great and even though it was not an accurate method, no more accurate approach was available at that time. Thus, it was rightly considered valuable then. Now, however, lighter weight, short endurance materials are used, requiring less approximate methods. More accurate methods, as indicated later, are now available, and they should supplant the equal-area concept.

There are at least four main physical objections to the equal-area concept.

1) The outstanding example is when materials can undergo a phase change at some temperature T_c. Consider two fires, one which heats up some portion of a building assembly beyond its melting point and one which does not. It is clearly unreasonable to say that those two fires might somehow be equated.

2) If some building assembly is combustible, its rate of mass loss, and thereby degradation, can usually be expressed by an equation of the form

$$\dot{m} = Ae^{-E/RT}$$

This relationship is patently not linearly dependent on the gas temperature.

3) The main mechanism of heat transfer to the wall, at temperatures above about 500° C is radiation. The radiant flux is proportional to T^4, not T^1.

4) Finally, some building assemblies derive their protection primarily from a latent heat of hydration. Gypsum wallboard is the most common example of this kind of protection. For a material of that kind, degradation is proportional to the heat input, which is not a linear function of temperature.

Ingberg applied the equal-area hypothesis to all his data, although admitting that it might be inexact. The current version of the E-119 standard, however, permits a limited equal-area correction to be made to the furnace time-temperature curve. The correction is allowed only if the deviations are not over 10% for 1 hour tests and 5% for tests over 2 hours. The Russians,[69] similarly, considered the equal-area severity hypothesis to be reliable only if curves no farther than 10% apart are compared. To apply this equation only when the curves are so close together is of little benefit indeed. The whole field of fire endurance testing and calculation is not precise enough to warrant such an adjustment. Even 20% differences can be considered within the expected scatter. Any curve can be arbitrarily well approximated by a straight line if the interval of applicability is made small enough. The serious problems arise in trying to cross-compare very large, not very small deviations.

In certain countries, notably Japan, the approach taken in recent years was to produce accurately calculated curves of expected fire temperatures and then in the final step express the results as equivalent fictitious endurance of a standard curve. Thus while precision is seemingly maintained, the true accuracy of the results is seriously compromised. It appears better to use almost any other method to avoid multiple testing of components, even if the chosen method is highly approximate, provided it does not rely on an unphysical hypothesis of severity.

It is sometimes asserted that even though under many conditions the standard curve exposure will not be at all similar to the expected realistic exposure, it is still justified to use the curve. The argument usually runs, "we know the test results will not be the same as endurance time in a fire, but so long as the test exposure is fully standardized, all materials will be tested fairly and adequate ranking established." It should be adequately clear that such a viewpoint is untenable. Compare, for instance, an assembly using materials which are good insulators and have low T_c, with one using poorly insulating, high T_c materials. When tested under appropriately low temperatures the first assembly will prove superior, but at higher temperatures the second will be better. In general, there is no way of assuring that even relative rank will be preserved; in consequence testing under conditions greatly differing from those of the expected fire is not a suitable design philosophy.

CHAPTER 4

TRADITIONAL APPROACHES

4.1. Building Codes

4.1.1. Code Development in the United States

Laws regulating buildings for ensuring health, safety, and welfare of a community date from at least the Code of Hammurabi. In the United States building regulations date from the 1630's in Plymouth Colony, where thatched roofs and wooden chimneys were prohibited.[70] Each municipality made its own building regulations; these regulations usually tried to eliminate conditions that had caused large or tragic fires in the area.

Lashit[71] cites the building regulations of Salem, N.C., in 1788. The fire provisions include description of minimum sizes and clearances of chimneys; a restriction on where furnaces and other fire using appliances may be placed; and some design rules for furnaces and fireplaces.

It was not until the late nineteenth century that the first model building codes were published. In 1892 the National Board of Fire Underwriters published a short document entitled "Proposed Building Law for Medium Sized Cities."[72] This model code was written in such a form that it could easily be adopted by a municipality as a local ordinance.

Probably the most far-reaching of the early building laws was the 1901 Tenement House Act of New York.[73] The New York State Legislature was moved by the social consciousness of the times and desired to ameliorate the squalor prevalent in workers' housing. The resulting hotly-debated 1901 Act was applicable to cities of the first class, i.e., New York City and Buffalo, and consisted of provisions for improving lighting, ventilation, plumbing and general sanitation of tenement houses, regulations for minimum fire standards, and prohibition of prostitution (!) in tenements. Thereafter, apartments in New York City were categorized as "old law" or "new law," with the latter showing a noticeably superior fire record.[74]

The Act distinguished between two types of construction - "fireproof" and "non-fireproof." The definition of fireproof was " . . . built entirely of brick, stone, iron or other hard incombustible material, and in which no woodwork or other inflammable material is used in any of the partitions, furrings or ceilings." It would now be considered a definition of non-combustible, but in 1901 the distinction between fire resistance and non-combustibility was not fully established. The Act further provided that wooden finish-floors, stair treads, and handrails were not precluded from fireproof construction.

Within the fire limits of each city no new wood tenements were to be erected. Non-fireproof construction was implicitly divided into two groups: "ordinary" (all exterior walls are non-combustible, with floors and interior walls usually of wood) and wooden (wood framed). For existing tenements, the main fire provision was for the erection of fire escapes in non-fireproof buildings. Existing wooden houses outside the fire limits were not subject to fire escape requirements.

A limited set of occupancy separations, unusual for its narrow scope, was prescribed. Bakeries and other places of business where fat is boiled could only be maintained in fireproof tenements; or else, they had to be separated by fireproof walls unpierced by openings. Businesses

TABLE 3

MAIN FIRE PROVISIONS OF THE 1901 NEW YORK TENEMENT ACT

	EXISTING BUILDINGS			NEW BUILDINGS		
	Inside Fire Limits		Outside Fire Limits	Inside Fire Limits		Outside Fire Limits
Requirement	Fireproof	Non-fireproof	Wooden	Fireproof	Non-fireproof	Wooden
Fire escapes	-	yes	-	-	yes	-
Minimum size and number of stairs	-	-	-	yes	yes	-
Stair materials prescribed	-	-	-	yes	yes	-
Brick walls and opening protection for stair halls	-	-	-	-	yes	-
Protected horizontal exit	-	-	-	yes	yes	-
Cellar ceiling protection	-	-	-	yes	yes	-
Firestopping	-	-	-	yes	yes	-
All new ventilation shafts fireproof	yes	yes	-	yes	yes	-
Hazardous occupancy separations	-	yes	yes	-	yes	yes

storing flammable liquids required only fireproof doors and wire-glass in the transoms for separation.

New tenements were to be fireproof if five stories, or over, in height. New non-fireproof buildings had to have fire escapes. Minimum width (3 feet) and number of stairs were specified for all new tenements. Stair halls and entrance halls (horizontal exits) in non-fireproof buildings had to be fireproof and enclosed with brick walls. Self-closing fireproof stairway doors were required, and only wired glass could be used. Transoms were prohibited on stair halls.

Cellar stairs in non-fireproof buildings had to open only to the outside and to be fireproof. In fireproof buildings there had to be at least one entrance to the cellar from the outside. Closets underneath first story stairs in non-fireproof buildings were prohibited.

Because of the added hazards in cellars, all new tenements were required to either have fireproof first story floor construction or to have plastered the cellar ceiling. Fuel storage and boiler areas had to be separated by fireproof walls.

Firestops were required and wainscotting could be applied only over a plaster base.

The main provisions of the Act are summarized in Table 3.

The first model code of importance came a few years later with the publication of a Building Code Recommended by the National Board of Fire Underwriters in 1905.[75] The NBFU was headquartered in New York and their new code showed a strong influence of the New York City Building Code. Later named the National Building Code, it has been revised periodically to this day. Currently it is published[76] by the American Insurance Association, the organization NBFU merged into in 1966. The

TABLE 4

MAIN FIRE PROVISIONS OF THE 1905 NATIONAL BUILDING CODE

Occupancies

Defined only as needed.

Type of Construction

Fireproof
Non-fireproof
ordinary
wooden
Mill construction

Requirements for the different types of construction

Fireproof: Allowable materials enumerated; amoung of woodwork limited; plus an interesting provision requiring the tops of doors and windows to be at least 12" below the ceiling.
Mill construction: Minimum member thicknesses: 8" beams, 3" floor planks.

Area and Height Limitations

Construction	Allowable area if not sprinklered (sq. ft.)	Additional area allowed if sprinklered	Allowable height (ft)
Non-fireproof	5,000- 7,000	50%	55
Fireproof			
a) Stores, warehouses factories			
< 55' high	10,000-15,000	33%	
55' to 100' high	5,000- 7,000	33%	100
b) Others < 125' high	13,333-20,000	50%	125
Frame dwellings	3,500- 7,500	Not given	40

Occupancy Requirements

Theaters: An inordinately length list of provisions is spelled out if capacity > 300 persons.
Public assembly: Rules for keeping exits free.
Apartments and tenements: Similar provisions to the 1901 law.

Other Fire Resistance Requirements

Protection of floor openings
Fireproofing of hoistways
Fire shutters on windows required in most instances
Fire door requirements

Flame Spread, Firestopping, Ignition Requirements

Firestopping required in stud walls.
Shingle roofs and non-fireproof cornices prohibited within fire limits.
Storage of goods in attics forbidden.
Heat producting devices regulated - clearance and other prescriptions given for fireplaces, steam pipes, hot air flues, furnaces and ranges.

Exit Requirements

Number of stairs and fire escapes set forth, materials limited.
Protected horizontal exit on first floor required.

Fire Extinguishment Provisions

Standpipes described.
Automatic sprinklers required in cellars of certain buildings.
Assured water supply mandated.
Skylights required (for smoke control).

National Building Code has been mostly utilized by smaller municipalities.

The 1905 code was a lengthy and verbose document, consisting essentially of a concatenation of individual provisions -- over-all organization was lacking. There was no systematic differentiation of occupancies. Individual provisions specified if they were limited to stores or dwellings, or offices, etc. Recognized construction types were similar to the Tenement Act. Table 4 outlines some of the main provisions of this code.

Currently three more model building codes exist. The Uniform Building Code[77] was first published in 1927 by the Pacific Coast Building Officials Conference, now the International Conference of Building Officials. The Standard Building Code[78] was first issued in 1945 as the Southern Standard Building Code by the Southern Building Code Congress. The Basic Building Code[79] which first came out in 1950, was issued by the Building Officials Conference of America, now the Building Officials and Code Administrators International.

Larger cities have generally been slow to adopt model codes. Most large cities already had a viable building code by the time the model codes were making their appearance. Not only was there a reluctance to change but also the model codes were not initially aimed at the problems of high density areas and high rise buildings. Eventually most larger cities have adopted some model code, although often with extensive changes. New York City has remained a major exception to this trend.

It is striking that there is no Federal building code in the U.S. In most other countries building regulations are either promulgated by national laws, or a federally-authored model code. In Canada the National Building Code of Canada[80] was first issued in 1941 by a Committee of the National Research Council; individual municipalities, or provinces, may adopt it if they so choose. The U.S. Federal Government has promoted building safety in several ways. The earliest efforts were directed through the Building Code Committee of the Department of Commerce. Established in 1921 and chaired until his death in 1927 by Ira H. Woolson, the Committee issued several reports containing various recommend code provisions. Three reports are directly related to firesafety. Report BH1, Recommended Minimum Requirements for Small Dwelling Construction,[81] was first issued in 1923 and revised several times, the last publication[82] being issued as BMS 107. Report BH6, Recommended Minimum Requirements for Masonry Wall Construction,[83] was issued in 1925; and Report BH14, Recommended Minimum Requirements for the Fire Resistance in Buildings,[84] was issued in 1931. A final report, Design and Construction of Building Exits (M151)[85] was issued in 1935, after the Committee's dissolution. The work of this committee was especially valuable since a large part of each of their reports consisted of a commentary on the recommended requirements, a feature lacking in most codes.

BH1 summarized well the reasons model codes were an advance over unique city codes:

> ". . . local building laws required more material or refinements of workmanship than were justified, considering the purpose of the buildings affected. It was further disclosed that building codes and builders, either through ignorance or selfish motives, frequently failed to recognize modern methods of construction, thus denying the property owner such benefits as might accrue therefrom . . . The building codes of the country have not been developed upon scientific data, but rather on compromises; they are not uniform in principle and in many instances involve an additional cost of construction without assuring more useful or more durable buildings."

As is customary with regards to dwellings, fire resistance questions did not play a strong role. Some fire-resistance topics were discussed in BH1 and can be reviewed here. At the time BH1 was written a significant fraction of buildings was being built of bearing brick masonry. The preferred thickness had been 12 inches, but was generally being reduced to 8 inches for 1 and 2 story buildings. The committee considered that thicker masonry walls provided a better salvage value and were less hazardous to firefighters because of a decreased tendency to precipitously collapse. In addition the committee noted that the thicker walls have better endurance in fire tests, while noting the inconsistency of paying attention to wall endurance in dwellings yet not having any requirements for fire doors, shutters, or other protection of openings.

A definite firesafety prescription is given for party walls. No more than four families are permitted in attached dwellings before a party wall is required. The thickness of brick or hollow block are prescribed, but an alternate of fire-tested construction is allowed.

Required fire endurance in hours is given only for one situation--a garage attached to a dwelling has to have one-hour separation from the dwelling. In this case even the openings are restricted. The door has to be fire-rated and must not have glazing. In addition, if the garage is located below the dwelling, all garage windows must be fire-rated. Two additional provisions are given which could best be considered as limiting flame spread. The garage floor must be fire-resistive and impervious and it must be at least one foot below the floor of the dwelling at the doorway. The latter provision is intended to prevent gasoline vapors accumulated near the floor of the garage from spreading into the dwelling.

The next report, BH14, is important because it provides for fire resistance requirements that persist to this day in similar form in most U.S. building codes. The fact that a commentary is given for these requirements makes the report of even more value.

The system is based on a set of classifications. These include fire districts, occupancies, and types of construction.

Fire Districts

Each city adopting a code of this type would define upon a city map two limits, in order to dividethe city into three fire zones. BH14 does not describe this process since the methodology propounded by the NBFU had already been well established. The basic purpose of the fire zone system is to prevent conflagrations by excluding more hazardous constructions or occupancies from the more heavily built up areas. The first zone essentially represents the central business district, the second zone the outlying areas, and the third or unrestricted zone the rural areas.

Occupancies

Five classes are established:

1--Public (government buildings and public assembly buildings)

2--Institutional (hospitals, jails)

3--Residential (residences, hotels)

4--Business (factories, warehouses, stores, office buildings)

5--Garages, hangers, barns

Types of Construction

Six types are set out:

1--Fully protected

2--Protected

3--Heavy timber

4--Masonry wall and joist ("ordinary")

5--Wood frame

6--Unprotected metal

The definition of Type 1 construction is especially noteworthy--it must be made "of incombustible materials having an ultimate fire resistance sufficient to withstand the hazard involved in the occupancy, but not less than 4 hours for bearing walls . . ." This classification would seem to partly permit engineered fire design. Its scope is narrow, however, since by virtue of the minimum requirements it would only be applied in situations where very long hot fires were expected. Data cannot be found to indicate that any buildings of that period had indeed been built in accordance with such permission for engineered design.

Type 2 construction is defined by endurance limits on the structural members and is less demanding than Type 1.

Type 3 is the old "mill" construction. It is noted that this type has a good fire record when equipped with automatic sprinklers; however, no requirements for sprinklers are made. Columns at least 8 by 8 inches and girders at least 6 by 10 inches are required.

Type 6 is a category which has alternately been called unprotected non-combustible.

Within the above scheme endurance requirements in hours are only given for Types 1 and 2:

	Type 1	Type 2
Fire walls, party walls	>4	4
Bearing walls, columns	>4	3
Partition walls	>2½	2
Floors, beams	>2½	1½

The type of construction and the fire zone categories are used together to prevent conflagrations by excluding all Type 5 buildings from the first fire zone and all Type 5 buildings except dwellings from the second fire zone.

The main use that occupancy and construction classifications are put to in a traditional building code is to establish two tables. Thus in BH14 we find a table for "Allowable Heights of Buildings" and another for "Allowable Area of Buildings." They are divided according to occupancy and construction, with stricter limits being placed on less well-protected buildings and on hazardous or densely populated occupancies. Additional provisions are introduced to provide for buildings housing mixed occupancies. The reasons customarily adduced for having such regulations are two-fold: the less fire-safe structures should be limited in size in order not to encourage conflagrations; and the more hazardous or more densely populated occupancies should not become so spread out as to present exiting difficulties.

A section is devoted to fire stopping. It emphasizes the importance of fire stopping, but does not describe what constitutes effective fire stopping. A similar situation has persisted to this day in most building codes and jurisdictions--guidelines are generally unavailable for what constitutes adequate fire stopping.

The protection of openings is dealt with briefly. A provision of fire protected spandrel panels at least 3' in height is a minimal facade protection feature. Some guidelines for prevention of radiation ignition due to windows are given, as are minimal requirements for fire doors and shutters. A lament was included that UL door testing up to that time was not sufficiently advanced, only one-hour tests having been performed.

It is important to note that no commentary is given as to why the particular numbers for the area and height limit tables were picked. No rational research, apart from that discussed in Section 10.2.2, appears to have been done in this area to this date. The most current study seems to be Woolson's poll of 1913.[86] He surveyed fire chiefs from 117 U.S. cities and distilled their personal recommendations into the following table.

	Recommended Maximum Stories in Height	Recommended Maximum Area Between Fire Walls (ft^2)
Brick and joist construction (not sprinklered)	3	6,000
Fireproof construction (not sprinklered)	5	10,000
Brick and joist construction (sprinklered)	5	13,000
Fireproof construction (sprinklered)	8	20,000

The NBS work in development of code endurance recommendations culminated in the report BMS 92, Fire-Resistance Classifications of Building Constructions, published in 1942. BMS 92 has remained to this date the most accessible thesis for building designers on the code approach to fire endurance. The report attempted to combine the existing code approaches with Ingberg's findings and provide both a guide to already used provisions and an incentive to the use of fuel load as a variable. In the latter endeavor it, regrettably, failed. The traditional material included a large compendium of fire endurance ratings and of roof test ratings and a summary of salient fire endurance provision in the building codes of six major cities.

The new work reported included the results of the NBS fuel load surveys, tables for determining the effective fuel load when combustibles are enclosed in metal containers, and rules for approximate thickness design of building components. Of greatest interest was the incorporation of Ingberg's compartment burn results to recommend endurance requirements. Four types of construction were identified:

I. Fireproof
II. Incombustible
III. Exterior-protected ("ordinary")
IV. Wood

For Types II through IV several sub-types were established which were governed by high individualistic criteria. The most unusual of these was the provision that the endurance of fire walls in Type II and III buildings be increased in the lower parts of the walls, and range from 2½ hours for fuel loads under 25 lb/ft^2 to 12 hours if greater than 250 lb/ft^2. The extra concern for the lower wall portions stemmed from Ingberg's desire to protect against smoldering debris.

The provisions for Type I buildings directly embodies the results shown in Table 2, applied in the following fashion:

SUBTYPE	FUEL LOAD (lb/ft^2)	ENDURANCE (hr)
I-A	Over 35	(see below)
I-B	35	4
I-C	30	3
I-D	20	2
I-E	15	1½
I-F	10	1

All the materials were to be non-combustible. The endurance for Type I-A was to be sufficient to withstand a complete burnout, otherwise one of three measures could be taken: (1) limit the height of the building to 50 feet, or 75 feet for warehouses, (2) provide sprinklers, (3) provide fire detectors and standpipes with hose.

The values given in the above endurance table applied to the structural frame, floors, roof, and fire walls (but the fire walls were required to have no less than 2 hr endurance). Corridor walls were to endure 1 hr, while stairway and shaft walls 1 hr or 2 hr. Other interior partitions could have 1 hr endurance or be unrated. The systematic variations in endurance required for different members were thus less than in most current codes, but nonetheless were not explicated.

4.1.2. UBC As Example

Basic Principles

The Uniform Building Code (1976 Edition) has been chosen for detailed consideration as typical of the model building codes. The other three U.S. model codes are similar in spirit although different in their particulars. The Canadian code is significantly different and in some respects more solidly founded on research results. A detailed study[87] by the Polytechnic Institute of Brooklyn (now the Polytechnic Institute of New York) provides comparisons of the five model codes. In addition, it considers the 1968 New York City Building Code, which was drafted by the same school. Its usefulness is limited in that the editions studied are now out of date and in that some of the analyses are spotty or technically lacking.

The basic operation of the code is founded on classification (as opposed to calculation). Three basic groups of variables are established.

<u>Occupancy</u>

A - Assembly
E - Educational
I - Institutional
H - Hazardous
B - Business
R - Residential
M - Miscellaneous

<u>Types of Construction</u>

I - non-combustible, fully fire resistive
II - non-combustible
III - combustible (protected)
IV - heavy timber
V - frame buildings

<u>Fire Zones</u>

1 - central business district
2 - other built up areas
3 - outlying areas

Each of the seven occupancy categories is further divided into as many as five sub-categories; several of the types of construction are also subdivided. Some manner of occupancy classification has always been used in building codes, the present set being merely the latest in historical evolution.

The evolution of types of construction is more specific. Originally codes required three basic types; fire-resistive, "ordinary," and wood frame. Heavy timber was soon added. In the 1940's the need became apparent for a category to include Quonset huts, Butler buildings and similar unprotected non-combustible structures. Fire-resistive categories were also eventually expanded to include several levels of fire resistiveness.

The concept of fire zones is a very old one, initially promulgated by the NBFU. It was reasoned that by creation of different fire zones and establishment of strictest requirements in Zone 1, the losses due to conflagrations in dense districts would be minimized.

The approach of using classifications has the advantage of being simple to apply and not requiring engineering capability. It has numerous drawbacks, among them the inability to evaluate the effectiveness of any single element, the proliferation of exceptions and modifications that it tends to breed, and the lack of cost effectiveness that can almost always be leveled against it. To evaluate the code in detail, it is necessary to outline its principal provisions for fire endurance.

A basic design using the code could proceed as follows: the designer determines the proposed occupancy, the fire zone, and the location on the property. He then takes the needed area and height of the building and looks in Table 5-C and Table 5-D to determine what is the minimum type of construction permitted for that area and height respectively. He then goes to Table 17-A to find the endurance requirements for the different assemblies involved. The basic endurance requirements are generally quite different for various assemblies. For instance, in Type I buildings the exterior walls must be of 4 hours endurance, the frame 3 hours, the floors 2 hours, and partitions only 1 hour. Almost all of these elements have provisions for numerous exceptions, however. These exceptions can be grouped into broad categories:

- -- exterior wall endurance, as a function of location on property
- -- protection of openings
- -- sprinkler tradeoff
- -- special exit and refuge requirements

Detailed Requirements

First, occupancies must be separated from each other. To that end Table 5-B is provided, giving the endurance requirements for occupancy separation (ranging from 0 to 4 hours). Different degrees of openness are permitted for the separations.

Separation Endurance	Wall Openings	Floor Openings
4 hr	none	none
3 hr	3 hr, length < 25% wall length	Use 2 hr shaft walls; shaft opening to have 1½ hr protection
2 hr	1½ hr	1½ hr
1 hr	1 hr	1 hr

In using Table 5-C to determine the allowed floor areas for a given type of construction the designer can consider several permitted increases.

-- for buildings in Fire Zone 3 the areas can be increased by 1/3

-- the effective area can be reduced by providing "area separation walls." These fire walls have to have 4 hr endurance in Type I, II-FR, III, and IV buildings (with 3 hr opening protection) and 2 hr endurance in others (with 1½ hr opening protection)

-- the area can be increased by up to 100% if the building is sufficiently far away from the lot line or the street. There are two reasons for this rule: fire fighting is easier if more access is available, and the exposure hazard to other buildings is presumed to be greater for larger floor areas. The latter argument is fallacious, but judging from the wording and the numbers used, was apparently considered more important.

-- large area increases are permitted if the building is sprinklered throughout, except in certain hazardous occupancies or when certain other tradeoffs are taken.

The maximum height from Table 5-D has only one major exception: a modest one-story increase is allowed for sprinklers.

The sprinkler trade-off allows one-hour fire endurance to be deleted when sprinklers are provided. A massive list of exceptions, including all buildings in Fire Zone 1, makes the trade-off of limited applicability.

Probably the most detailed and convoluted provisions are found in the area of the endurance of exterior walls and the treatment of openings in them. The basic requirements are contained in Table 17-A, where 0, 1, and 4 hour endurances are contemplated, depending on the type of construction. The exceptions now begin. For Type IV and V buildings Table 5-A is provided. In it a different endurance requirement is placed on exterior walls depending on the occupancy subcategory, the fire zone and the location on the property. In addition, 3/4 hour opening protection is prescribed in certain instances. Finally, each type of construction, except Type V, is given an additional list of exceptions in the chapter describing that type. These further exceptions are also based on occupancies, fire zones, and location on property. The whole methodology is an example of unsystematic, runaway patchwork legislation.

The individual chapters on occupancies contain other fire endurance provisions. In all except R, boiler rooms must be separated by one hour occupancy separation (2 hours for H occupancies). Minimum ventilation is prescribed for most occupancies with a glazed area of 1/8 of the floor area and half of it openable. The ventilation provision is viewed as a health rather than fire regulation. It is important for fire purposes because it sets certain ventilation minimums, even though not in a form uniquely suited for use in fire design.

Several requirements can be found which are pertinent to only one occupancy. Group I-1 occupancies (hospitals) must have each story subdivided into two refuge areas by a one-hour separation. In Group B-2 occupancies, specifically stores only, storage areas must be provided with a one-hour separation if in excess of 1000 ft^2 in unsprinklered buildings, or thrice that when partially sprinklered. Separation is not required if the building is fully sprinklered. In Group B-1, special provisions have been incorporated in 1973 for open parking garages. These provisions finally gave recognition to the fact that a parking garage in a non-combustible structure is one of the safest possible occupancies. Since repair, truck storage and gasoline station uses are excluded from these provisions, the only fuel load to be expected is that represented by the cars themselves. Based on the fact that tests have shown that an expected fire will not progressively spread nor lead to flashover, two special tables giving area and height limits have been established for these parking structures. They are less restrictive than any in Tables 5-C and 5-D. In Group R-3 occupancies (apartment houses) individual apartment non-bearing walls do not need to have any fire endurance.

A chapter is devoted to limitations with regards to fire zones. In Fire Zone 1 only those types of construction which provide at least one-hour of endurance, or else are of heavy timber, are permitted. There are two exceptions. Type II-N open parking garages and Type II-N small B and M occupancy buildings are permitted.

Just as for occupancies, each type of construction is discussed in detail in a separate chapter where numerous exceptions and special provisions are given. The most important restriction for Type I and II constructions is that they must be of non-combustible materials in addition to having the required endurance. Like most rules, this one carries an exception, permitting fire retarded wood to be used in certain partitions. A large list is given, as previously noted, of various exceptions for exterior wall endurance.

The most incredible provision is applicable to Type I and II-FR constructions housing Group A, B, or E occupancies. In these cases if the ceiling height is at least 25 feet, no fire endurance for the roof structure is required. The provision seems to have stemmed from somebody's conception that if a story is tall enough fire will not reach the ceiling.

Following the lead of New York City,[88,89] ICBO enacted in 1973 the so-called "high-rise package" of provisions governing Type I and II buildings when used as offices, hotels, and apartments (B-2, R-1 occupancies). These regulations contain several important endurance requirements. Foremost is a requirement for compartmentation. The building may be fully sprinklered, in which case compartmentation is not necessary. Otherwise, in order to provide areas of refuge, each story must be subdivided into at least two compartments. A section of the high-rise package introduces for the first time into the UBC a spandrel requirement. To reduce the likelihood of flame spread up the facade from floor to floor, either a 36 inch spandrel or a 30 inch eyebrow must be provided at the windows. This requirement was of long standing in most other codes but not in UBC. Finally, a requirement for some method of smoke venting is established. Venting is relevant to fire resistance because it can change the expected fire temperatures, as will be seen in Chapter 6.

Another instance where compartmentation is specifically required is in combustible attics. These must be subdivided to form spaces not greater than 3000 ft^2. The endurance of the wall is to be equal to ½ in. gypsum wallboard, 1 in. wood or 3/4 in. plywood. Along with other codes UBC used to have a provision for similarly subdividing large open spaces above fire-resistive hung ceilings. This requirement has now been dropped.

Other than the required openable windows and the vague requirements for limited smoke venting in the high-rise package, the only requirements for venting are for one-story industrial buildings. Those in occupancies B-2 and B-4, except offices and retail stores, must have roof venting for undivided areas over 50,000 ft^2. In H occupancies the requirement starts at 15,000 ft^2 area. The minimum areas and sizes of vents and their spacing is prescribed.

As might be expected, regulations for heavy timber buildings (Type IV-HT) are a prescriptive set of specifications, not much changed in the last hundred years.

The last major section devoted to endurance concerns corridor and exit endurance. A one-hour endurance for wall and ceiling is specified for all corridors, other than exterior balconies, with the following exclusions: corridors serving less than 30 occupants; one-story B-4 occupancies; and those corridors over 30 feet wide and having more than one exit. Doors in the fire-resistive corridors must be self-closing and have at least a 20-minute rating (but a hose stream test is not required). Enclosures around exit stairways must have an endurance of 2 hours in buildings over 4 stories and 1 hour otherwise. Doors are to have 1½ and 1 hour ratings, respectively.

Proposed UBC Area/Height Changes

The ISO Guide

The proposed revision[90] to UBC has been based on a 1974 manual published by ISO,[91] Guide for Determination of Required Fire Flow. The ISO understandably wants to know in their grading of municipal fire departments how much water may be required and if the fire department can supply that. Work of this nature has existed since the turn of the century. The NFPA handbook[247] gives some of the early rules. The conflagration potential is most often the worst in the densest downtown areas. Thus it was considered that if the downtown has adequate protection then other areas will likewise be sufficiently protected. The variable used to identify the water flow needs in these early rules was the population of the city. A weak variable it may have been, but better than none.

The new ISO guide represents a step beyond that. It uses total floor area of the largest building as the variable. To get a formula, the ISO staff first tried to correlate flows against area on the basis of available fire reports.[92] The process resulted in much scatter, so a more practical attack was used: the ISO staff examined grading reports from its field surveyors and correlated their recommended values against area. The fit was good; the circle is closed when it is realized that the field surveyors only have the ISO guidelines as a basis for making their recommendations.

The data were gathered only for "ordinary" construction, and the formula given is

$$F = 18\ C\ \sqrt{A} \qquad (4.1)$$

where F = flow (gpm)

A = total floor area (ft^2)

C = adjustment coefficient = 1.0

or, in metric units

$$F = 3.72\ C\ \sqrt{A} \quad (\ell/\mathrm{sec}) \qquad (4.2)$$

where A is in m^2.

To make the formula applicable to other types of construction the following rules were added, based apparently on educated guesswork only.

a) take C = 0.6 for fire-resistive construction; C = 0.8 for non-combustible; C = 0.9 for heavy timber; and C = 1.5 for frame.

b) for fire-resistive buildings consider only the area of the three largest consecutive floors (6 if vertical openings unprotected).

c) make reductions up to 75% for sprinklering.

d) increase or decrease according to hazard of occupancy, hazard of exposure, and shingle roofs.

e) require results to be within range of 500 to 12,000 gpm.

UBC Code Change Proposal

The concept of using the ISO flow formula for making height/area restrictions had its origins in a 1973 study[93] by the Sierra Group on the fire department of Davis, California. In making the evaluation the consultant decided to use the following approach: a) determine what water flows the fire department can apply with present men and equipment, b) survey the city buildings and assign a water requirement to each according to the ISO formula, c) identify those buildings which would require flows beyond the present capability, d) recommend either detector or sprinkler installation in those buildings, and e) suggest that the city, which uses the UBC, adopt changes to install this approach on a permanent basis.

It is noteworthy that this report, along with Ingberg (in BMS 92) and numerous others, have considered detectors to be something of a low-grade substitute for sprinklers. This concept is generally mistaken and should not be perpetuated. The only respect in which detectors and sprinklers might be viewed as interchangeable tools is in achieving the fire-safety goal of ensuring the safe movement of occupants. In the present case, however, area/height restrictions can only be reasonably considered to promote goals 3 and 4, namely, limiting property damage and enhancing firefighting potential. Thus, consideration of detectors is not pertinent.

The code change proposal that has been evolved[90] is intended to be quite general, not merely limited to one city. It follows the ISO formula with several differences. First, the flow requirement formula was reduced to take a low hazard occupancy as base and then was increased to consider the base as having some facade exposure problem. Taken together they represented a 25% flow increase. Next, the values of C were adjusted to reflect UBC classifications, as follows:

TYPE	C
I	0.60
II - FR	0.70
II - 1 hr	0.75
II - N	0.80
III - 1 hr	0.90
III - N	1.00
V - 1 hr	1.25
V - N	1.50

Finally, for some occupancies lesser area maximums were allowed. For occupancies H-1, 2, and 5, a factor of 0.36 was applied; for H-3 and 4, a factor of 0.46, and for B-1, 2, and 3, a factor of 0.56.

The greatest change in existing practice that is proposed is the discontinuance of unlimited areas generally permitted for Type I construction. For the designer who wants to exceed those areas it means that he can first specify sprinklers, which will allow him to treble the area. He may then provide 20 ft clear space on all sides, if he needs unlimited area.

Another provision taken directly from ISO is the recognition that in Types I and II-FR buildings floors are effective as compartmentation.

Thus the proposed change uses ISO's rule of counting the combined area of the three largest consecutive floors. No rationale is available for the choice of 3, however.

A new table of height limits is introduced. This has no precedent in ISO and its origin is unclear. The main new feature is to provide two sets of height limits, one if sprinklered and one if not. The maximum height contemplated in a Type I unsprinklered building is 75 feet, while the sprinklered limits are higher and are unlimited for Type I.

Two other changes are given. Fire limits, as such, are abolished. This is in keeping with the current thinking that they have outlived their usefulness. In their place Fire Flow Districts are established, which is simply a provision for legally recording different fire flow specifications for different parts of a city. Finally, exterior wall endurance requirements are slightly simplified and systematized, but rational principles, such as are contained in the Canadian code, are not introduced. The officials establishing the fire flow districts have a choice: usually the value of the flow specification is equal to the calculated capability of the fire department; for an ineffective one, a non-zero flow value can be set, representing not the extinguishing capacity but rather the maximum loss potential to be tolerated.

4.2. Insurance Ratings

An insurance company (except for so-called "preferred risk" carriers) will generally insure any property, however poor its firesafety design may be. In order to have the rates reflect the potential for loss, the insurance company needs a way of evaluating quantitatively the firesafety of each specific building, regardless of whether it is in full conformance to the code or not. Thus, of necessity the insurance industry must have a systematic methodology for evaluating the property loss related firesafety aspects of buildings. The firesafety designer, if prudent, may also examine the effect that various construction features will have on premium rates. For these reasons the insurance rating approach to fire endurance should also be considered.

There are two basic ways that premium rates are set for buildings--by use of class rates, or by an individual rating according to a rating schedule. Smaller occupancies with less complex buildings are generally given class rates. This means that an individual inspection of the property need not be made. Its premium rate is determined solely from its occupancy, size, general type of construction, and geographical location. Class rates are used mainly for residential buildings and for most small buildings except factories, fire-resistive buildings and sprinklered buildings. Other buildings are rated according to schedules.

Until 1971 rating of buildings was accomplished by numerous local fire rating bureaus, often on a state-wide basis. They published advisory rates for all cooperating insurance companies, which include most insurance carriers with the major exception of the Factory Mutual System, which operates its own rating bureau. In 1971 the local bureaus were merged into one nationwide Insurance Services Office. Prior to the merger each rating bureau had its own schedule, which commonly was a local adaptation of one of two systems, the Universal Mercantile System, or the Dean Analytic System. Rodda[94] has reviewed the general operation of rating bureaus, while the report by Atkiss[95] constitutes a very detailed, but unfortunately quite old, examination of a single rating bureau. In 1975 ISO[96] started to promulgate new schedules intended to be used nationwide. The main one is the Commercial Fire Rating Schedule[97] intended for all buildings except class rated ones, fully sprinklered buildings, and certain specialized categories of heavy industrial occupancies.

The CFRS focuses heavily on fire endurance and provides for the rating of a building according to the following groups of variables: building construction, including exposure hazards; occupancy hazard in the building; abnormal hazards or poor housekeeping; and types of fire-safety equipemnt. The most detailed task is the establishment of the occupancy classification. There are 71 major classifications used in the CFRS. Most are further divided into several sub-classes, each with a basic occupancy charge, a combustibility class and a contents susceptibility class.

The rating itself proceeds as follows: a schedule base of 50 points is set down, to it are added Basic Construction Charges, giving the Unmodified Basic Building Grade. This is multiplied by a modification and becomes the Basic Building Grade. To it are added the secondary Construction Charges and the Net Occupancy Charge, giving the Unexposed Building Grade. To it are added an Exposure Charge and a Communications Charge, giving the Exposed Building Grade. This is multiplied by a Protection Class Factor, producing the Gross Building Grade. Then the Internal Protection Credits are subtracted, giving the Final Building Grade. This is divided by 1000 and multiplied by a Building Conversion Factor. The result is the published Annual Building Rate. The published rate is further adjusted annually according to the applicable loss statistics of the past six years. This forms the ISO rate recommended to its participating companies, which do not necessarily always adopt it. A similar, somewhat less complex, procedure is also followed to obtain the rate for contents.

The three categories obtained for each occupancy can be viewed as follows: the Basic Occupancy Charge represents the variables comprising the chance for ignition and the potential loss if a fire occurs. The Combustibility Class represents some combination of fuel load and flame spread, while the Susceptibility Class refers to the potential for large damage to contents from a small fire and is only used in setting the contents rate.

From the viewpoint of fire resistance (excluding facade exposure problems) the primary constraints are the basic construction charges and the secondary construction charges. The primary classification in the CFRS is by Construction Class. The classes are basically as follows:

Class 6 - Fire-resistive, 2-hour endurance

Class 5 - Modified fire-resistive, 1-hour endurance

Class 4 - Masonry, with non-combustible or slow burning floors and roof

Class 3 - Non-combustible (non-combustible assemblies of less than 1-hour endurance; also slow burning construction)

Class 2 - Joisted masonry ("ordinary")

Class 1 - Frame

Ingberg's relationship of fuel load/severity/endurance is expressed in a curious way. The Unmodified Basic Building Grade, which is intended to evaluate the endurance of the structure is multiplied by a modification factor in obtaining the Basic Building Grade. This factor is determined by the Combustibility Class of the building and, for C-1 or C-2 Combustibility Classes ("non-combustible" and "limited combustibility") also by the combustibility of the structure itself.

TABLE 5

SUMMARY OF I S O DAMAGEABILITY CLASSES

Damageability Class	Frames	Floors	Walls
D-1	reinforced concrete ——— structural metal protected by: masonry concrete	monolithic concrete floors ⩾ 4" thick ——— concrete "joist" system	brick ——— reinforced concrete ——— solid block ——— hollow concrete block ⩾ 3 hours endurance ——— metal systems protected similarly as D-1 columns
D-2	structural metal protected by: plaster on metal lath ——— water-filled systems ——— pre-cast, pre-stressed beams listed by UL	as in D-1, but insufficiently thick ——— concrete floors on metal beams protected by plaster on metal lath ——— other pre-stressed and pre-cast units listed by UL	natural stone ——— insufficiently reinforced concrete ——— hollow concrete block ⩾ 2 hours endurance ——— metal systems protected similarly as D-2 columns
D-3	structural metal protected by: spray-on fire-proofing fiberglass batts gypsum wallboard intumescent coatings ——— pre-cast, pre-stressed beams, unlisted	concrete floors on metal beams protected by: spray-on fire-proofing fiberglass batts ——— other pre-stressed and pre-cast units, unlisted	adobe ——— clay tile ——— gypsum block ——— other masonry ——— metal systems protected similarly as D-3 columns
D-4	N.A.	metal joist systems protected by: spray-on fire-proofing fiberglass batts	N.A.

Further, the Net Occupancy Charge, intended to assess the hazards of different occupancies, is modified by an Occupancy Modification Factor. This latter factor, which is only applicable to Construction Class 3, 4, 5 and 6, provides for a reduction of charge depending on the Combustibility Class of the occupancy and, again, the combustibility of the structure itself.

The organization of the system of charges stems mainly from historical origins, while the categories established and their attendant charges are based primarily on engineering judgement. Loss experience statistics enter only into the Building Conversion Factor. The table for determining it considers three factors: the occupancy (lumped into rather large categories), the construction class, and whether the locality has a viable (Protection Classes 1-8) or ineffective or non-existent (Protection Classes 9, 10) fire department.

The Basic Construction Charges are noteworthy because they recognize two main factors: endurance and damageability. A building code cannot require that a building be readily restorable after a fire. The insurance rating can, however, penalize constructions apt to be costly to restore. The less damageable constructions tend to be heavier and costlier, so usually fire damage considerations alone will not determine the choice. ISO sees damageability as falling into four groups, summarized in Table 5. They are only applicable to non-combustible assemblies since ISO requires that for any member to be considered fire resistive it may not be combustible.

The Basic Construction charges include separate charges for walls and wall framing, for interior framing, and for floors and roofs. Assemblies which are not fire-resistive are grouped into several categories and are not rated according to their damageability; presumably total destruction is postulated.

The Secondary Construction charges evaluate the effects of shafts and vertical openings, area-height categorizations, roof combustibility, combustible attic spaces, combustible flooring or partitions, surface flame spread, exterior combustible devices, and general building dilapidation.

Four types of vertical opening (shaft wall) protection are established. The highest type provides for masonry walls or walls of 1-hour endurance. If the building is 4 or more stories high, then this requirement is raised to 2-hours. Doors are to be automatic or self-closing and rated at 1 or 1½ hours, respectively. For lower types of protection additional charges are applied, depending on the Combustibility Class of the contents. Taking into consideration that the schedule is not intended to evaluate life safety, the limited requirements on endurance make some sense. If there are no people and no fuel load in the shafts, then as far as containment is concerned fire has to pass through one rated wall and then back through another before it can continue spreading. The schedule seems to ignore two factors: firefighters should have tenable conditions in the stairways; also if structural collapse of the shaft occurs, the fire will become free to spread.

The area-height charge is levied on buildings except those having Combustibility Class C-1 contents in a building of Construction Class 3, 4, 5, or 6. A direct charge for height is made only for Construction Classes 1 and 2. For all classes height is penalized by adding a certain fraction of the area of other floors to the base area of the largest floor. The charges are expressed in a table relating effective area to construction class and combustibility class.

The roof charges are applicable only to un-rated coverings with one amazing exception: while an un-rated wood shake or shingle roof carries a charge of 10 or 20%, an air-supported structure or one with a framework supporting a fabric is charged a 200% levy. In the view of the schedule these structures are not distinguished from circus tents. The charges dealing with the various combustible portions of a building are assessed according to the percent of area that is covered with combustible or high flame spread material. These charges are heavier for the higher construction classes of buildings since their performance is considered to thereby be proportionately more compromised.

CHAPTER 5

INNOVATIVE APPROACHES

5.1. GSA Firesafety Systems Method

In 1972 the Public Buildings Service of the U.S. General Services Administration issued an "Interim Guide for Goal-Oriented Systems Approach to Building Firesafety."[98] Its second edition is now incorporated as a chapter in a draft GSA Handbook PBS P5920.9A -- Building Firesafety Criteria.[3] The work represented a decade of effort by Harold E. Nelson, former Director of the Accident and Fire Prevention Division of the GSA. The approach is noteworthy in two respects--it is the most inclusive and well developed systematic approach to building firesafety ever issued in the U.S., and it already has been put into use. Reports are available detailing its use for the new Federal Office Buildings in Seattle[99] and Atlanta.[100] Further, this method is now required by the GSA to be used for the design of all its buildings over 100,000 ft^2 floor area and five or more stories.

The GSA Handbook also details another, what might be called conventional, approach. The conventional approach is still being used for smaller structures. In basic philosophy it is similar to the UBC or the other U.S. model codes. Certain simplifications and rational improvements, nonetheless, have been introduced, but they will not be discussed here.

The following quotation (Reference 3, p. 230) establishes the guiding principle called upon:

> A basic premise through the entire system development is that there is no absolute state of firesafety. All activities and all structures involve a degree of risk to people, property, and operational continuity. The acceptable degree of risk is the controlling criterion. This criterion, which

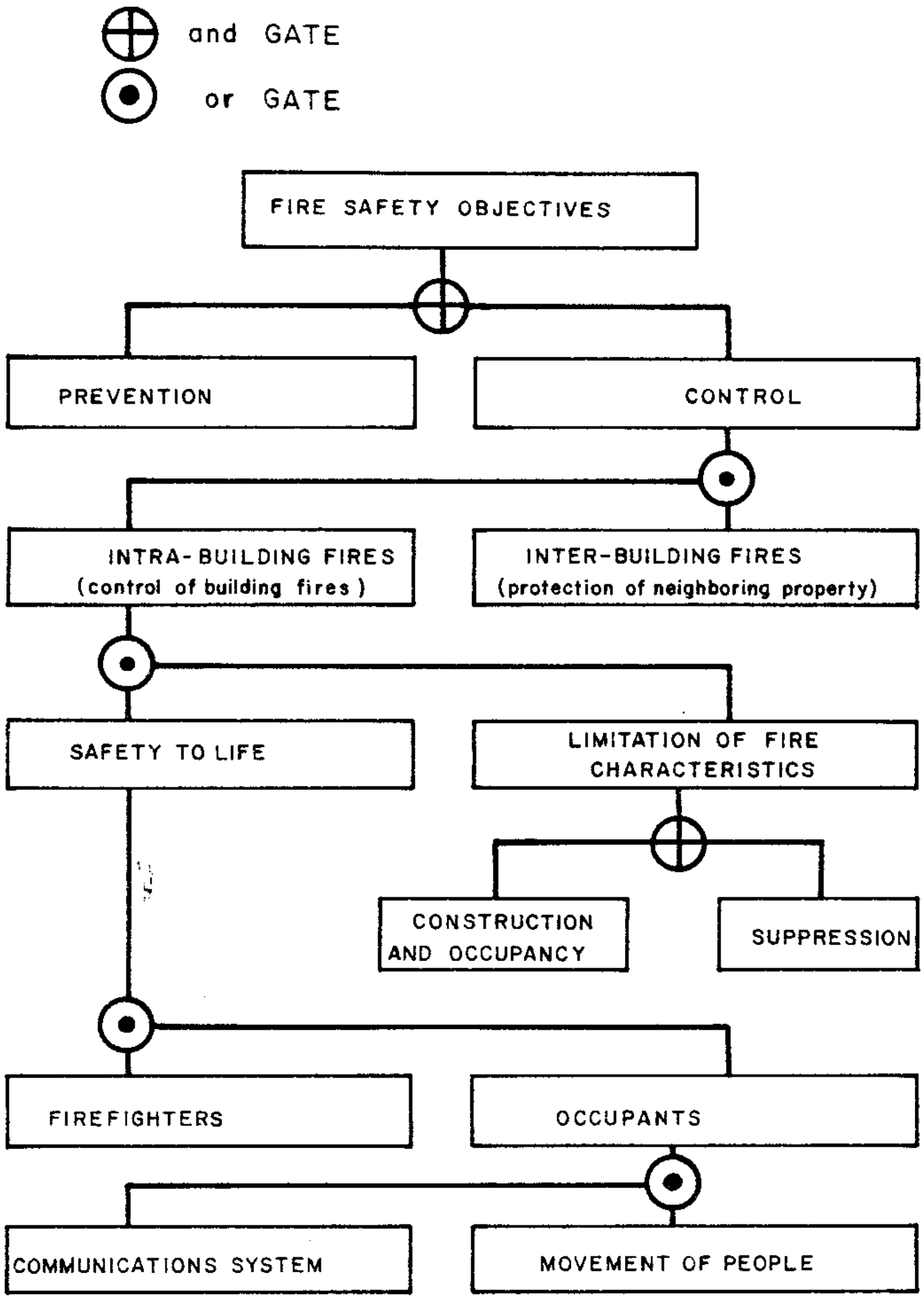


FIGURE 9 SKELETAL ELEMENTS OF THE GSA DECISION TREE

> is to be established by management, becomes the controlling parameter for the designer.

The approach is fundamentally different from a code approach. The heart of the approach is a decision tree. (See Figure 9.) It is a diagram which sets forth the firesafety goals and then gives all the possible ways that protection can be accomplished. The key here is completeness--the usefulness of the method stems from the fact that no available consideration is excluded. More alternatives are presented than will be used in a single building. To apply the method to a specific building, the designer observes that the paths through the tree branch in two ways, with "and" gates and with "or" gates. At an "and" intersection both pathways must be utilized, while at an "or" gate only one of several alternatives or, more commonly, a bit of each will be used.

The system is quantified by use of a stochastic variable. The variable can be expressed as

P(x) = probability that, given ignition, the fire will be stopped at or before it reaches size x.

Here x is taken as a space variable which increases in a pseudo-exponential fashion

1, 2, 3, 4, . . . n	Items
1, 2, 3, 4, . . . n	Work stations
1, 2, 3, 4, . . . n	Rooms
1, 2, 3, 4, . . . n	Floors
Whole building	

To make the method more applicable to general occupancies, Wilson and Fitzgerald[101] have replaced the first two categories by a continuous scale of area (m^2 or ft^2), up to full room involvement.

On a graph of P(x) as in Figure 10 two main curves are to be drawn, first, one representing the probability of success demanded by the owner, and the next, the curve showing the expected performance for a given

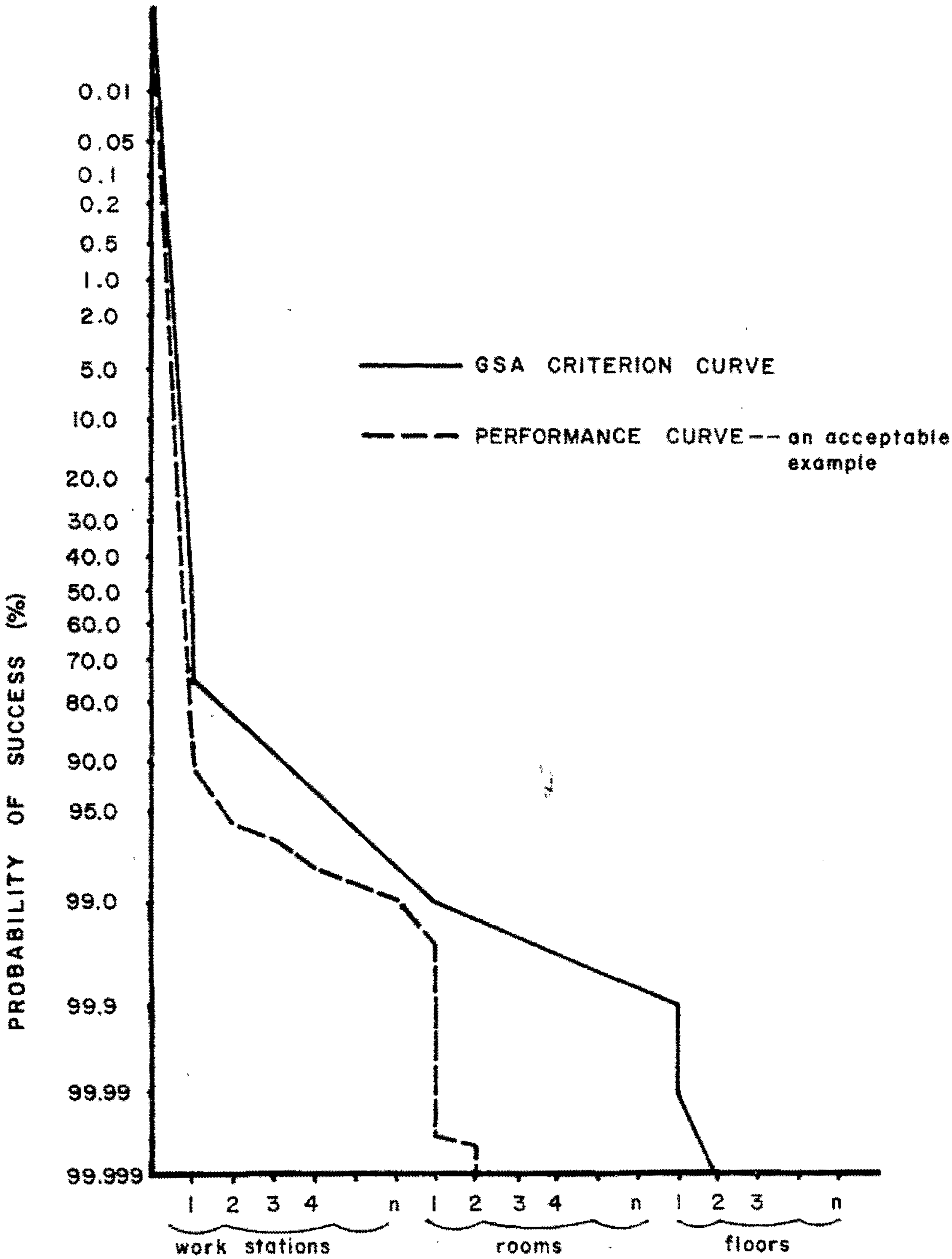


FIGURE 10 GSA FIRE SPREAD PROBABILITY DIAGRAM

design. The design is acceptable if the expected fire curve is everywhere below the criterion curve.

The Quantified Goals

According to this method, the owner must be able to translate his goals into a P(x) curve. Ideally this might be expressed in economic terms. Economic specification was discussed at a recent NFPA meeting where the question was put in terms of cost of rehabilitation and of lost rentals for a given period, as a function of fire size. A general procedure for quantification has not been achieved yet.

The GSA criteria for general operations which are shown in Figure 10, consist of success probabilities as follows:

50%	Prior to first work station
75%	At first work station
99%	At first room
99.5%	At third room
99.9%	Prior to first floor
99.99%	At first floor

and also

99.99% No ignition of adjacent structures.

For different owners of different buildings individual goal curves would have to be drawn. No more specific guidelines, especially economic ones, other than experience are given.

As can be seen from the definition of P(x) the quantified probability procedures only deal with spread of fires and effectiveness of extinguishment. They do not deal with the questions of reduction of ignition or of movement/refuge of persons. The entire area of prevention of unwanted ignition, although briefly treated in the Decision Tree (and somewhat more fully in a tree issued by the National Fire Protection Association[102]) is not covered in depth. It may be reasoned that any control or reliable improvement in ignition probability is too hard to achieve here. Thus all the curves start from the assumption that ignition probability is 1.0.

Safety of movement/refuge is treated in some detail but no systematic quantification is set down. A set of quantitative goals is given despite the fact that a quantitative methodology is not yet available for determining compliance.

Lifesafety goals for Normal Office Occupancies

1) Occupants exposed to fire environment are to be able to evacuate to a safe area within 90 seconds of alarm.
2) Approximately 15 seconds of the above can consist of travel towards the fire (dead end corridors).
3) An ultimate area of refuge is to be reached within 5 minutes of downward vertical travel or within 1 minute of upward travel.
4) The route from the initial safe area to the ultimate refuge is to be safeguarded against flame, high temperature, radiation, and atmospheres of 3% or greater contamination.
5) The ultimate refuge area is to be free from flame and intolerable temperature or radiation. It is also to have sufficient oxygen and no more than 1% contamination from fire atmosphere.

The major calculational effort is in the area of endurance and suppression. Since the scheme is to be used as a general engineered fire design, it covers both pre- and post-flashover stages. Throughout a building, there can, in the general case, be a succession of pre- and post-flashover stages. Ignition in a single room produces flame spread, eventually flashover is reached, then the containment elements are threatened, and if they fail the cycle repeats. Ignition occurs in the next room, fire grows, etc. A peculiarity of the GSA approach is that it treats only space as the primary variable. Except in one instance, time is not considered. In pre-flashover stages only the probability of extent of spread is considered. Values for the time to flashover, which is arguably the salient pre-flashover question, are not considered at all. It is only in the post-flashover stage that time is introduced, albeit in an ancillary fashion. Ingberg's concept of severity is used as the tool. Its role will be elucidated in the detailed analysis below.

Detailed Analysis

The success of building fire performance is judged in terms of three major elements:

1) Pre-flashover spread
2) Endurance at barriers
3) Post-flashover spread

In the diagram showing building performance on a P(x) plot the above elements can be identified as follows:

1) Pre-flashover spread (success in limiting thereof) represents the region from first item ignition to 1 room involvement.

2) Endurance is represented by vertical lines at 1 room, and similarly at 2 rooms, at 1 floor, etc. The length of the vertical line represents the probability increase due to the presence of the barrier.

3) Post-flashover spread includes all the area beyond 1 room except for the vertical lines at the barriers.

To construct the performance plot, a number of probability diagrams (using notation of Ref. 101) are constructed by the designer. Within the GSA organization suggested values for these curves are given. For other situations the designer must use available data and judgement to produce appropriate curves. The curves required are:

1) Pre-flashover spread

P(I) -- probability of self termination of fire. Several curves are given applicable to different fuel arrays.

P(A) -- probability of sprinkler extinguishment. Curves are dependent both on fuel array and on water delivery.

P(M) -- probability of manual extinguishment. This is taken ≈ 0 in pre-flashover stage.

P(L) -- the P(I) curve, as limited by P(A) and P(M).

2) Endurance at barriers. These curves, unlike all others give probability as a function of fire severity (in hours) not as a function of distance.

P(I')---probability of fire severity. Curves depend on fuel array.

P(M')-- probability of limiting severity by manual extinguishment.

P(A')-- taken as ≈ 0.

P(E) -- the P(I') curve as limited by P(A') and P(M').

P(TX)-- probability of endurance of wall X, according to thermal criteria.

P(DX)-- probability of endurance of wall X, according to stability criteria.

P(OX) -- probability of endurance of wall X, according to degree of openness.

Also similar curves for P(TF), P(DF), P(OF), and P(DFr) are given, where F = floor, Fr = frame.

3) Post flashover spread

P(M) -- probability of manual extinguishment. Two curves are given, one for interior attack, another for exterior.

P(A) -- taken as ≈ 0.

The main task is to calculate a complete P(L) curve, starting with ignition and ending with building failure. The calculations proceed as follows. In the pre-flashover stage, if there is no extinguishment, then values from the P(I) graph are used directly as the P(L) values. If automatic extinguishment is available, then at each point the effective value is obtained by taking $P(L)_x = P(I)_x + [1-P(I)_x] \cdot P(A)_x$. The last point thus calculated, $P(L)_g$, represents the probable success of avoiding flashing over the first room.

At the first barrier the added probability of success due to endurance must be calculated. If manual suppression is assumed available, then the severity curve P(I') must be adjusted for it. Defining P(E) as the expected severity with suppression effort,

$$P(E) = 1 - [1 - P(I')] \cdot [1 - P(M')]$$

To evaluate barrier success, the time variable must be integrated out. Thus P(TX/H), the probability of thermal success of wall X, given the expected severity distribution and the expected endurance distribution can be obtained:

$$P(TX/H) = \int_0^{\infty} P(TX) \frac{dP(E)}{dt} dt$$

Similarly values for thermal and stability success of floors and for stability success of walls, floors, and building frame are produced.

The post-flashover spread can now be calculated. The consequences of wall failure have to be defined. It is considered that if a wall fails structurally (stability), the probability is zero that the fire will stop short of flashing over the next room. When a wall fails thermally, however, this failure is taken as being a small ignition source. Thus the probability of no flashover in the next room is taken as $P(L)_g$, which assumes a spread history in the second room similar to that in the first room. If sprinklers are used, then their probability of success is assumed confined to less than first room flashover conditions. Thus barrier success values, P(TX/H), etc, do not take into account any increase due to sprinklering. Also, the $P(L)_g$ value used in the second and succeeding rooms is not the value used for the first room, but rather a value which assumes no extinguishment. Finally, if manual extinguishment is available, its effect is calculated in a manner similar to the automatic extinguishment procedure described above. It is to be noted that barrier openness is lumped together with stability. For larger size barrier openings the probability of success in preventing immediate next room involvement is smaller; but there is no provision of a gradually increasing, but finite, probability of flame spread through the next room, as a function of increasing openness.

5.2. Swedish Steel Design Manual

Research on rational methods for endurance design has been going on in Sweden for over a decade. A significant milepost was the publishing in 1974 (an English edition[103] was issued in 1976) of a practical design manual for engineered fire endurance design. The manual concerns itself only with steel structures, but a companion volume for concrete structures is in preparation. The objective of the Swedish manual is to enable a building designer, without the use of a computer, to calculate simultaneously both the expected fire and the response of the structure to it.

The initial part of the manual consists of a brief explanation of post-flashover fires for the designer and a recapitulation of the theory as originally presented by Magnusson and Thelandersson.[104,105] Additional information on fuel loads is presented, and finally sections on common methods of insulating steel and on critical temperature design are given.

From a design approach, the real interest is in the last part of the manual where the recommended approximate procedures for rational endurance design are given. The procedures are different for walls, which are treated as non-loadbearing slabs failing by thermal transmission, from those for floors and columns, where the critical temperature concept is used. For floors and columns, the basic methodology is as follows. Tables for suggested fuel load are given. The designer identifies his ventilation opening and wall materials, for which a list of thermophysical properties are also given. These variables would suffice to determine the room fire gas time-temperature curve. Instead of producing the time-temperature curve, the next step is immediately incorporated. The designer identifies the thickness and insulating properties of the steel protection and uses knowledge of the critical steel temperature to determine the endurance time.

Detailed Analysis

1) Expected Fire

The approach is similar to the purely deterministic option outlined in the present work (chapter 6) with some notable exceptions. Among these are:

a) The problem is made quasi-non-dimensional by dividing $A_v \sqrt{h_v}$ and the fuel load by A_w, the total area of the walls. This is perfectly satisfactory except that it forces the awkward description of fuel load in units of total wall surface area, rather than floor area, which is the functionally natural unit. As a result of the convenience of this quasi-non-dimensional formulation, fuel load data in Sweden has in recent years been reported mainly in total surface units.

b) Empirical heat release curves for wood fuel burns are used as input. No specific distinction is made between fuel and ventilation controlled phases in a fire.

c) When multiple openings are involved the sole recommendation is that simple averaging be used; as discussed in Section 6.1.3.

d) Only a single wall thickness of 20 cm was taken.

e) The curves used in calculating all subsequent tables were based on one set of thermophysical constants for a "standard" compartment. For use of other materials the method given entails multiplying both the fuel load and the opening factor by a multiplier, seven of which are listed. This procedure involves a hit-or-miss attempt to match curves to ones at unrelated conditions, and constitutes what is perhaps the least justified of the procedures.

2) Calculated Response

a) Beams and Columns

Two problems are involved--the determination of the critical temperature at which collapse will occur and the determination of the time that it will take to reach that temperature. The first problem is dealt with in some detail in the manual, but will not be elaborated here. The procedure given involves numerous graphs and appears to be rather complex for the amount of accuracy that can be expected from an approximate design method. It presumably reflects the fact that a detailed study of thermostructural considerations in steel structures has been going on at the Stålbyggnadsinstitutet for many years. This elaborate procedure is in sharp contrast to the failure temperature used in E-119, where only a single failure temperature of 593° C is judged adequate.

To determine the heat flow to the steel member, two procedures are listed, one for heavy bare members and another for those using various protective insulations. In both cases the steel is assumed to be at a uniform temperature(which implies infinite conductivity). For bare steel members the results--the highest steel temperature attained--are given in a table where the following input variables are used: fuel load, $A_v \sqrt{h_v}/A_w$, the member surface/volume ratio, and an effective emissivity to account for cases where not all member faces are exposed. Only a single table is needed, the methodology is very simple, and the accuracy, within the limits of the assumptions on the expected fire, is quite good. For insulated steel members the procedure perforce becomes more complex. Nine different insulating materials are considered; a table is included giving the conductivity for each as a function of temperature. Emissivities, densities and heat capacities are not used, but rather terms containing these variables are dropped from the equations. The main table for designing insulated members is then similar to the uninsulated ones except that instead of the effective emissivity variable a d/λ variable is used, where d = insulation thickness and λ = insulation conductivity. An iterative scheme is used to select a value of conductivity applicable to the average insulation temperature.

b) Floors/Ceilings

Floors are not treated except for consideration of suspended ceilings. Unlike for beams and columns, here no way is given of avoiding furnace testing. Instead an approximate method is offered in which results are first reported on a number of ceiling systems that were subjected to a fire test using a standard time-temperature curve. From interstitial thermocouple measurements and observation of collapse two items are determined: an effective d/λ and a T_c indicative of the collapse or other failure of the ceiling itself (as opposed to the floor deck or beams being protected). A table for using that test information is given which is similar to the beam/column tables. Fuel load, $A_v\sqrt{h_v}/A_w$, d/λ and the surface/volume ratio of the protected beam are the input variables. Values are obtained for both the ceiling interstitial temperature and the beam temperature. For a system to be satisfactory both have to fall below their respective critical temperatures.

c) Walls

Load-bearing walls are not treated. For non-bearing partitions a rudimentary design graph is provided. Five wall systems were tested and the temperature on the unexposed face measured. From the thermophysical properties that were then calculated and from the additional assumption that for gypsum wallboard T_c = 550° C, backface temperatures were calculated under different fuel and ventilation conditions. A thermal transmission criterion of 200° C on the unexposed face was established and from that the design graph was prepared. The graph plots fuel load on one axis and $A_v\sqrt{h_v}/A_w$ on the other. Curves for the five walls are presented; acceptable designs must lie below the appropriate curve.

3) Criteria

For walls only unexposed face temperature has been considered. For all other members only critical steel temperature, as an indication of collapse, was used. It is important to realize that with an approach in which the response is calculated, rather than furnace tested, these two criteria, plus backface radiation are the only ones readily possible. Thus the potential problems omitted from consideration are temperature rise for floors and collapse for walls. Other criteria, such as back face ignition or gas flow would demand a capacity for calculating non-homogeneous behavior which at present is not achievable.

CHAPTER 6

EXPECTED FIRE

6.1. Compartment Fire Theory

6.1.1. Research in Post-Flashover Fires

By 1922 fire testing had a well-entrenched methodology, but almost no background research beyond some crude burnouts was available. In that year Ingberg began a program of research into post-flashover fires that was to continue for some three decades. When Ingberg started his work he already had two well-established elements: the standard time-temperature curve and the philosophy of prescribing building regulations according to occupancy and type of construction. The above elements were becoming quite universally accepted--similar classifications and identical or very close time-temperature curves were being introduced in numerous other countries.

Ingberg sought to determine if the prevalent philosophy was correct. Burnout tests were conducted and it was determined that actual fire temperatures were often far different from the standard ones. Instead of giving up the concept of a standard curve, he developed, as discussed in Section 3.3, the equal-area concept of severity. The important fact to be noted here is that for the first time he identified fuel load, expressed as pounds of wood per square foot of floor area, as a physical variable--the only one--in the problem. Remarkable as it may now seem, prior to his work no quantitative comprehension of the effect of fuel loading was known. The next logical question was what determines the fuel load. This he took to be the occupancy of the building and he produced survey results to quantify the dependence. It bears remembering

(a) GENERAL VIEW OF BUILDING

(b) THESE SHUTTERS, TOGETHER WITH PIKES AND GUY WIRES WERE USED TO CONTROL VENTILATION

FIGURE 11 EXPERIMENTS CONDUCTED IN THE THIRD BURNOUT BUILDING AT THE NATIONAL BUREAU OF STANDARDS here that while these elementary results were already well publicized in 1942, they were never incorporated into the U.S. building codes.

Ingberg probably had an intuitive feeling for the importance of a second variable. His burnout test buildings had window openings which were covered by swinging shutters. During the course of his tests the shutters were adjusted to vary the ventilation. Figure 11 shows the use of these shutters in a burnout experiment. While Ingberg never quantified these concepts, it is apparent he had an inkling of both the importance of ventilation and of a possibility of "pessimization," a point which will be developed later.

As early as 1953 R. C. Corson[106] of Factory Mutual realized that a single standard time-temperature curve was not appropriate. He putatively proposed that four additional curves be established, but sufficient theory was not yet available for their calculation. The research needed was to come from Japan. In the early 1950's Fujita[107] and Kawagoe[108,109] started an extensive program of tests and began to evolve a theory. That work, which became available in English only in the late 1950's and early 1960's, led to the identification of two more variables: the ventilation and the wall thermal properties. Ventilation was provided by buoyancy flow through a window opening and was determined by window height and width. Wall thermal properties were conductivity, heat capacity, density, and emissivity. Whereas Ingberg had used the concept that an average gas temperature in the room was meaningful in a post-flashover fire, Fujita and Kawagoe made the assumption of a stirred reactor, that is, the "mixed" nature of the gas, central to their model. Their crucial contribution, which made it possible to identify the other variables came from the development of the heat (or more specifically, enthalpy) balance principle. The Japanese workers did not delve into the question of fuel release rates and did not calculate the temperatures past the peak, when release rates would control. Instead they used an empirical 7° C/min. or 10° C/min. rate of drop. Kawagoe also used and did not challenge Ingberg's equal-area hypothesis.

Ödeen[110] started, in 1963, the Swedish interest in post-flashover models. He independently produced heat balance calculations similar to Kawagoe's except that he quantified the effect of fuel release rates--which was a new variable, different from total fuel load--rather than ventilation. In more recent years theoretical modeling of post-flashover fires has been pursued with great vigor at the Lund Institute of Technology by Magnusson and Therlandersson.[104,105] Tuschiya[111] at NRC Canada has also made contributions.

6.1.2. Theoretical Model

The purpose of this section is to develop a model for post-flashover fire behavior that steers a middle course between two pitfalls. On one hand its purpose is intended to be practical; thus, the introduction of academic niceties that one cannot hope to detect in actual fires would be a waste of effort. On the other hand, the philosophy adopted is that wherever possible the model should account for all significant variables of fire behavior. If serious approximations or simplifications have to be made for design tractability, they should be made at the last possible moment, not in the initial assumptions. This approach stands in direct contrast to approaches pursued by Harmathy[112] and others, where drastic simplifications are made at the outset. It is this author's belief that such action renders a model much less general and less useful for cases where non-routine problems may be important to analyze.

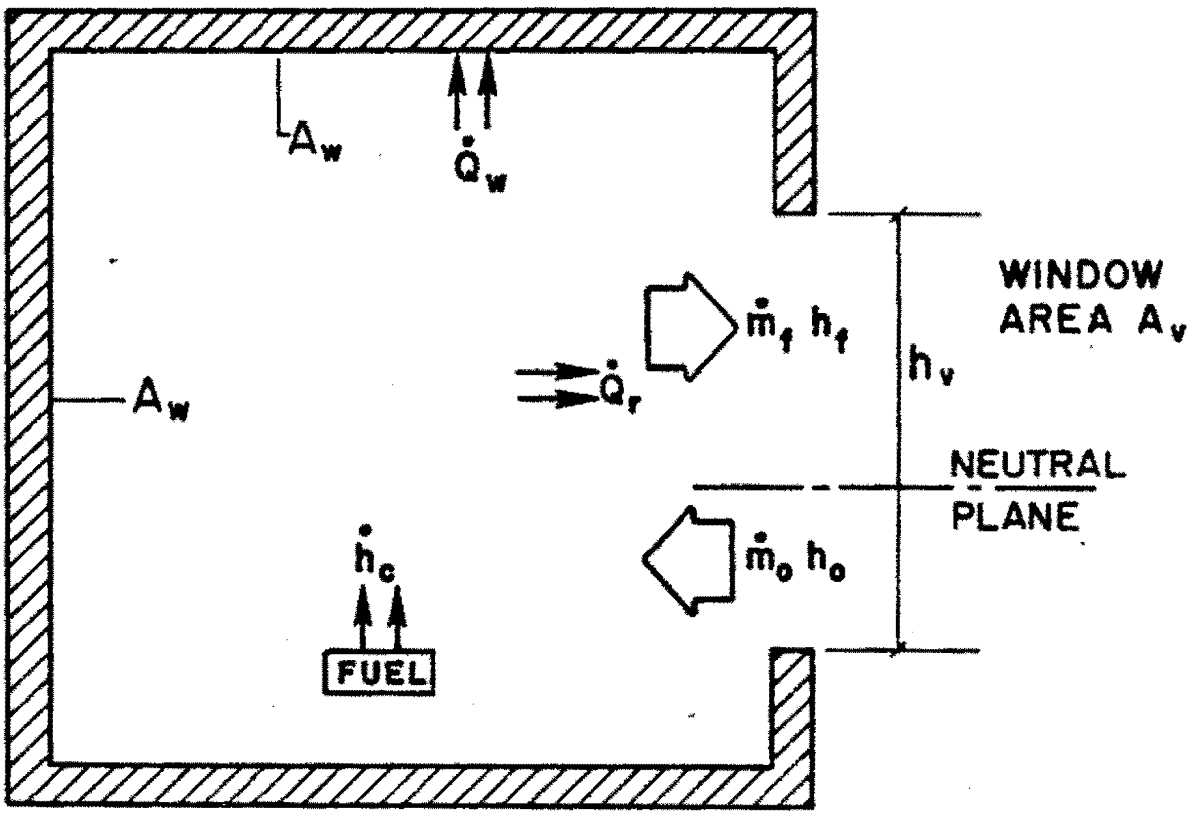


FIGURE 12 VERTICAL SECTION THROUGH COMPARTMENT AS USED IN THEORETICAL MODEL

Major Assumptions

The following assumptions may be considered important to the present model:

1) The system is taken to be a well-stirred reactor. There is sufficient mixing in the compartment to make the gas temperatures nearly uniform, except hear the floor and near the lower portion of the window. An example of the validity of this assumption is given in Figure 1b.

2) Burning is limited by mixing rather than by chemical kinetics. That is, the compartment while "well stirred" is not "perfectly stirred" which would imply that reaction rates are a limit to the combustion.

3) The air supply and gas outflow is through a single window in a vertical wall and is the result of natural convection. Forced convection could, of course, be treated even more easily; but it is hard to draw any general conclusions from that case since it depends so totally on the ventilation system design.

4) Walls are taken as portions of a homogeneous infinite slab. Non-homogeneous walls present trivial additional complication if all thermal properties are known.

5) Because fuel release rates are not well known, empirical values are used for wood, while a viable theory, but without realistic data, is suggested for general polymeric fuels.

Application of the First Law

The main equation to be written is the First Law of Thermodynamics, or as it is popularly known, the heat balance, for a system which is defined as being all the gas within the boundaries of the room. Let the room in question (Figure 12) have flashed over at t = 0 and consider the course of combustion. The chemical energy of fuel combustion is released and is released and is lost by several processes. A significant portion of heat leaves through the window. The net loss through the window is the enthalpy of the leaving gases minus the enthalpy of the inflow air. Another fraction of the energy is radiated out the window, while a portion of it goes to heating the walls, both by convection and by radiation. Finally, insignificant portions go into pressure work and viscous dissipation. This account of heat flows is the expression of the First Law, where the rate of increase of enthalpy of the system, $\Delta\dot{H}$, is equated with the heat added, $\delta\dot{q}$. Writing this balance for the whole volume of the room and dropping the pressure and dissipation terms the basic conservation equation results:

$$\dot{m}_o h_o - \dot{m}_f h_f - \delta\dot{q} = \frac{\partial}{\partial t}(\rho V h) \qquad (6.1)$$

and evaluating the enthalpies gives:

$$\dot{m}_o C_{po} T_o - \dot{m}_f C_{pf} T_f + \dot{h}_c - \delta\dot{q} = \frac{\partial}{\partial t}(\rho V h) \qquad (6.2)$$

where:

$\dot{m}$ = mass flow (kg/hr)

h = enthalpy (kcal/kg)

$\dot{h}_c$ = combustion enthalpy rate (kcal/hr)

ρ = density of gases (kg/m^3)

V = volume of room (m^3)

C_p = heat capacity (kcal/kg-°K)

and the subscripts denote:

o = ambient

f = fire gases

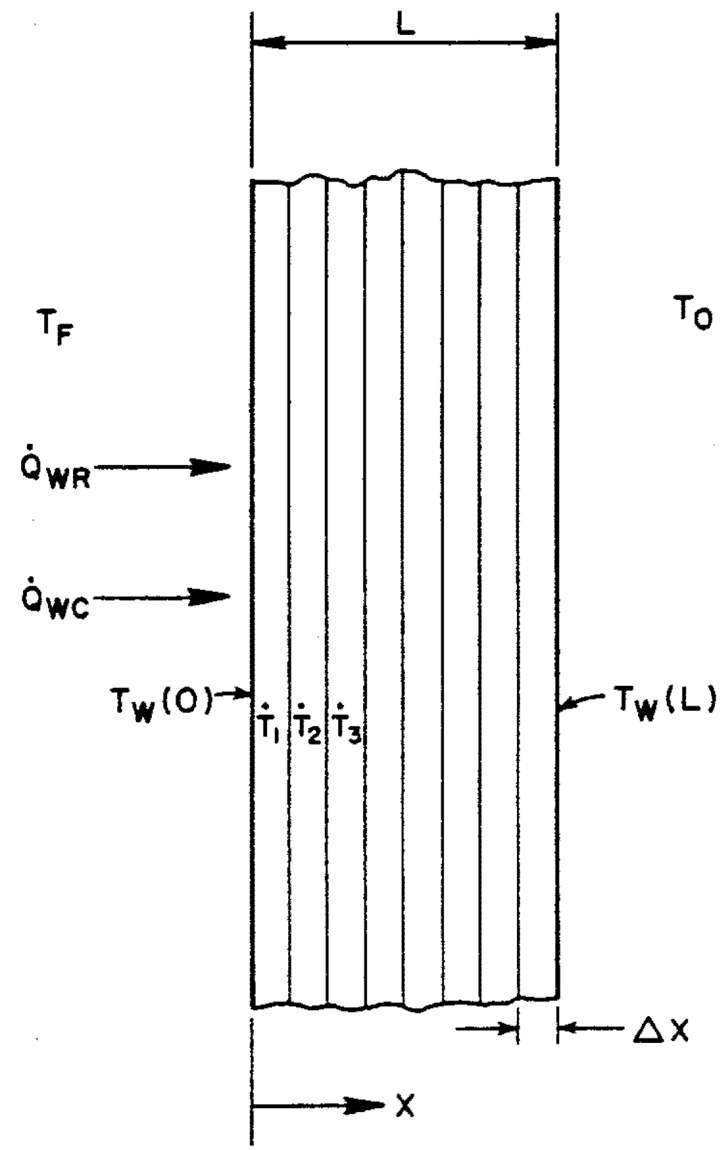


FIGURE 13 COMPARTMENT WALLS APPROXIMATED AS SECTION OF AN INFINITE SLAB

The $\delta\dot{q}$ loss term consists of:

$$\delta\dot{q} = \dot{Q}_w + \dot{Q}_R \qquad (6.3)$$

where:

$\dot{Q}_w$ = rate of heat transferred to the walls (radiated and convected)

$\dot{Q}_R$ = rate of heat radiated out the window

Finally we can observe that since the process is quasi-steady, the unsteady term $\rho V \frac{\partial h}{\partial t}$ will be very small and may be dropped.

These terms will be analyzed in greater detail in the succeeding section. The analysis will show that there are two unknowns--the gas temperature, T_f, and also the wall surface temperature, T_w. An additional equation is needed; this is the equation of heat conduction through the wall. Since the temperature variations along the surface of the walls are assumed small, the walls can be represented as a portion of an infinite slab, see Figure 13. A one-dimensional problem is to be solved for heat flow through this slab, where the fire gas temperature is the boundary condition on one side and ambient temperature is the boundary condition on the other. The equation to be solved is:

$$\rho C_p \frac{\partial T_w}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T_w}{\partial x}\right) + \dot{q}''' \qquad (6.4)$$

where:

$T_w(x) = T_w(x,t)$ is the wall temperature

T_f = gas temperature

T_o = ambient temperature

k = conductivity (kcal/hr-m-°K)

ρ = density of wall (kg/m^3)

C_p = heat capacity of wall (kcal/kg-°K)

$\dot{q}'''$ = heat generated (if any) within the wall $(kcal/hr\text{-}m^3)$

subject to initial conditions

$$T_w(x,0) = T_o$$

and to boundary conditions on the flame side (x = 0) of

$$-k \frac{\partial T_w}{\partial x} = h \left(T_f - T_x (0) \right) + \varepsilon\sigma \left(T_f^4 - T_w^4 (0) \right)$$

and on the unexposed side (x = L) of

$$-k \frac{\partial T_w}{\partial x} = h \left(T_w (L) - T_o \right) + \varepsilon\sigma \left(T_w^4 (L) - T_o^4 \right)$$

where:

h = convection coefficient $(kcal/hr\text{-}m^2\text{-}°K)$

ε = effective emissivity

σ = Stefan-Boltzman constant (kcal/hr-m -°K)

The first law and the heat conduction equations can then be solved together to yield T_f and the wall temperature profile $T_w(x)$.

The heat balance terms will be considered in detail later. At this point it is important to point out the role of $\dot{h}_c$, the rate of net exothermic enthalpy evolved from the combustion reaction rate. In general, $\dot{h}_c$ will be determined by one of two factors--either some step in the detailed kinetics of the reaction may be slow enough to be the governing factor, or else the rate is determined by the rate of supply of fuel and oxidizer. In normal compartment combustion, the rate of fuel or oxidizer supply is so slow compared with the reaction kinetics that the kinetics will not govern.

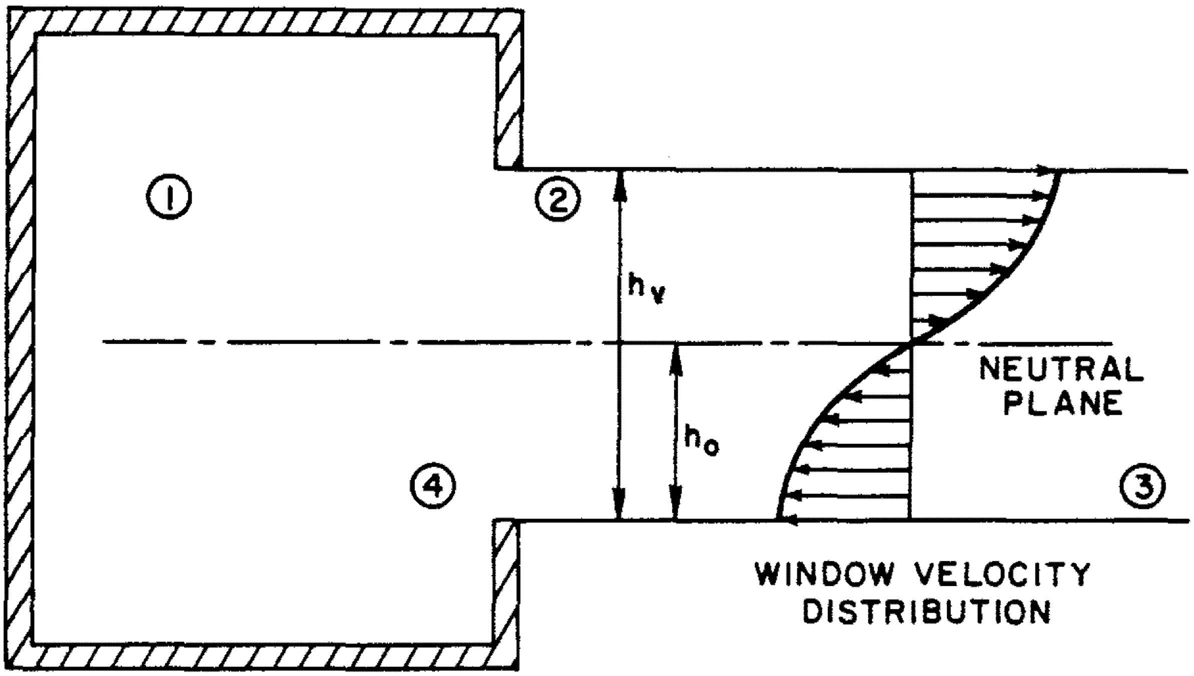
When the rates of supply govern, there can be two possibilities--either the rate of oxygen supply is limiting or the rate of fuel supply is limiting. In compartment combustion the former is termed *ventilation-controlled* burning, while the latter is *fuel-controlled*.

6.1.3. Details of the Model

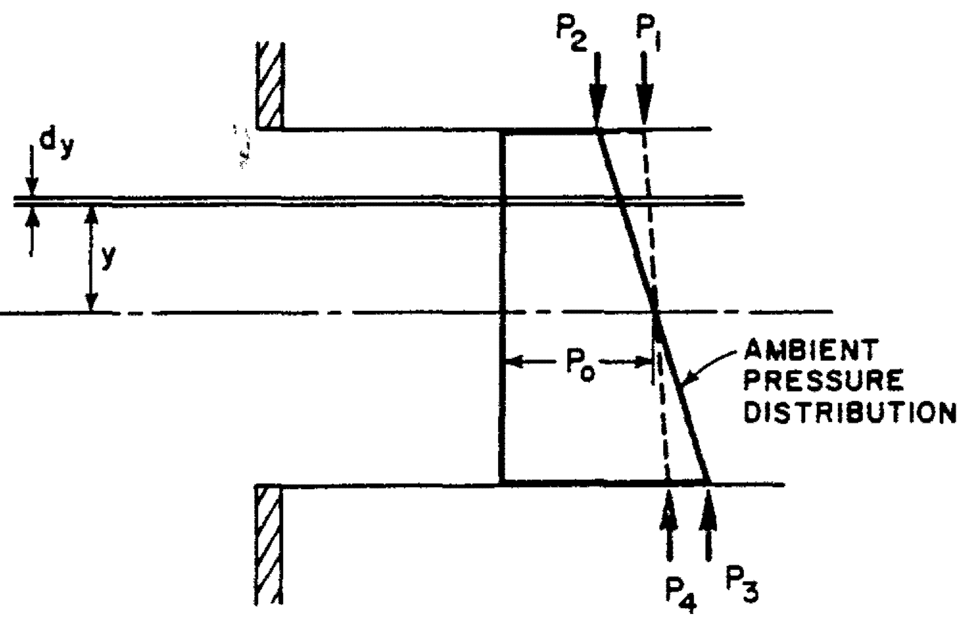
In this section the main terms comprising the heat balance equation will be examined.

A. Flow Through Compartment Windows

In the single uniform-temperature compartment model the flashed over compartment can be visualized as a stirred reservoir. Ambient air at temperature T_o enters and is immediately heated to the fire gas temperature T_f by the combustion reactions. The products then flow out at temperature T_f. The concepts necessary for the analysis of such flows between the atmosphere and an enclosed compartment were first studied by ventilation engineers for non-fire situations. Emswiller's work of 1926[113] is among the earliest analyses of window flows. More recently Brown and Solvason[114] reported on research at the NRC of Canada. Historically, the general area of buoyant flows in enclosed spaces can be traced back to Groume-Grjimailo's work[115] in Russia in 1911. The fire in effect acts as a pump with buoyancy providing the driving force. To calculate the rate of this flow, momentum conservation must be used.



(a) VERTICAL SECTION THROUGH ROOM SHOWING WINDOW FLOWS



(b) PRESSURE DISTRIBUTIONS

FIGURE 14 BUOYANCY DRIVEN WINDOW FLOWS

The situation to be described is shown in Figure 14a. In the simplest case where the same window opening is used to both take in air and discharge products, there will be a certain height at which there is zero flow. This is called the "neutral plane." Below this height will be inflow and above it outflow.

We wish to write the momentum equation along an assumed streamline at height y between point 1 well inside the compartment and point 2 just outside the window, Figure 14b. It must be first observed that the assumption of the compartment gas being at a uniform temperature has already been made. Since the gas is well stirred and does not have molecular weight variations, so the density is uniform. If the density is uniform, then the vertical pressure gradient must be linear.

In consequence, pressure at point 1 will have a distribution related to the density:

$$P_1 = P_o - \rho_1 gy \tag{6.5}$$

Whereas it can be shown that just outside the window there can be no difference between the issuing jet pressure and the ambient atmosphere pressure. Thus,

$$P_2 = P_o - \rho_o gy \tag{6.6}$$

where $\rho_o g$ is the ambient atmosphere pressure gradient. P_o is the same in both cases because we define $y = 0$ at precisely that point where $P_1 = P_2$.

Then we can write the momentum equation between 1 and 2:

$$\frac{P_1}{\rho_1} + \frac{V_1^2}{2} = \frac{P_2}{\rho_2} + \frac{V_2^2}{2} \tag{6.7}$$

where v_1 inside the room has zero directed velocity (although it may have local turbulence components). This gives

$$\frac{P_o - \rho_1 gy}{\rho_1} = \frac{P_o - \rho_o gy}{\rho_1} + \frac{v_2^2}{2}$$

where the gas density ρ_1 is the same at both positions since the temperature has not changed. Giving

$$v_2 = \sqrt{2gy\left(\frac{\rho_o}{\rho_1} - 1\right)}$$

Then using subscripts f and o this can be written as

$$v_f = \sqrt{2gy\left(\frac{\rho_o}{\rho_f} - 1\right)} \tag{6.8}$$

Similary, to obtain the air inflow velocity, consider point 3 far away from the window and point 4 just inside the window. Then

$$P_3 = P_o - \rho_o gy \tag{6.9}$$

$$P_4 = P_o - \rho_f gy \tag{6.10}$$

where the distances y are now negative. This gives

$$\frac{P_o - \rho_o gy}{\rho_o} = \frac{P_o - \rho_f gy}{\rho_o} + \frac{v_o^2}{2} \tag{6.11}$$

$$v_o = \sqrt{2gy\left(\frac{\rho_f}{\rho_o} - 1\right)} \tag{6.12}$$

Objections might be raised here that the flows do not necessarily move in straight horizontal lines along the path 1-2 and along 3-4. In observing fires one sees nonlinear flow paths. These depend on the specific local conditions; their detailed description would negate the goal of a model with general applicability. Also, it is to be noted that the flows beyond point 2 go into a plume. A description of this plume is not needed for compartment fire calculations. It would be of prime significance in considering facade exposures, which will not be treated here.

Experimentally, the differential pressures concerned are so small (in the order of 10-20 Pa) and the velocities so low (5-10 m/sec) that direct measurements of these quantitites were judged to give poor results and have, in consequence, rarely been taken. Kawagoe[109] reported a few typical measurements which bear out quite well the above theory. Improved instrumentation has since been developed and used in the Harvard experimental program.[116]

Using the velocity distributions proportional to the square root of the height, the following mass flows can be obtained:

Inflow: $$\dot{m}_{air} = C_d B_v \rho_o \int_{-h_o}^{0} v_o dy \qquad (6.13)$$

Outflow: $$\dot{m}_f = C_d B_v \rho_f \int_{0}^{h_f} v_f dy \qquad (6.14)$$

where:

$\dot{m}$ = mas flow (kg/hr)

C_d = discharge coefficient

B_v = window width (m)

and we can further specify that since the process takes place at a constant pressure of one atmosphere,

$$\rho = \frac{WP}{TR}$$

where:

W = molecular weight (kg/kg-mole)

R = universal gas constant

= 8.2056×10^{-5} atm-m^3/mole-°K

For inflow air, $W = 28.79$, while for the combustion products it of course depends on their composition. However, since more than 3/4 of the outflow will consist of nitrogen, a simplification if desired could be made by letting $W_f = W_o$. To find the height of the neutral plane, a flow balance must be performed. If no combustion were taking place (say, for a room heated with an electric heater) then simply $\dot{m}_f = \dot{m}_{air}$. However, pyrolysis of the fuel makes $\dot{m}_f > \dot{m}_{air}$.

To define the ratio of flows, write the overall chemical reaction for exact stoichiometry as:

$$1 \text{ kg fuel} + r \text{ kg air} \rightarrow (1 + r) \text{ kg products} \qquad (6.15)$$

where r is a constant for any given fuel and represents the amount of air needed to perfectly combust a unit mass of fuel. If the fuel and air are not present in that ratio, a factor ϕ can be introduced and will be discussed later.

$$1 \text{ kg fuel} + \frac{r}{\phi} \text{ kg air} \rightarrow \left(1 + \frac{r}{\phi}\right) \text{ kg products} \qquad (6.16)$$

Then

$$\frac{\dot{m}_f}{\dot{m}_{air}} = \frac{1 + \frac{r}{\phi}}{\frac{r}{\phi}} = 1 + \frac{\phi}{r} \tag{6.17}$$

and

$$\dot{m}_f = \frac{2}{3} C_d B_v (h_f)^{3/2} \ \rho_f \sqrt{2g\left(\frac{\rho_o}{\rho_f} - 1\right)} \tag{6.18}$$

$$\dot{m}_{air} = \frac{2}{3} C_d B_v (h_o)^{3/2} \ \rho_o \sqrt{2g\left(1 - \frac{\rho_f}{\rho_o}\right)} \tag{6.19}$$

Kawagoe empirically fitted his data to get values of C_d, which he found to range between 0.5 and 1.0 in his experiments. Prahl and Emmons[117] have found that $C_d = 0.68$ is a good choice.

If the total window height is h_v, then the fractional height of the neutral plane is

$$\frac{h_o}{h_v} = \frac{1}{1 + \left[\frac{\rho_o}{\rho_f}\left(1 + \frac{\phi}{r}\right)^2\right]^{1/3}} = \frac{1}{1 + \left[\frac{T_f}{T_o}\frac{W_o}{W_f}\left(1 + \frac{\phi}{r}\right)^2\right]^{1/3}} \tag{6.20}$$

The $\frac{h_o}{h_v}$ term is usually between 0.3 and 0.5. This is corroborated by the observation in fires that flames normally fill the upper half to 2/3 of the window. A different situation occurs if there is more than one opening in the compartment or if a window takes up essentially one whole wall. In the latter case, the reservoir created in the compartment is not well defined and the flow is much less than would be accounted for by using the actual area. Experimental data can best be correlated by using a C_d of about half the normal value for such cases.

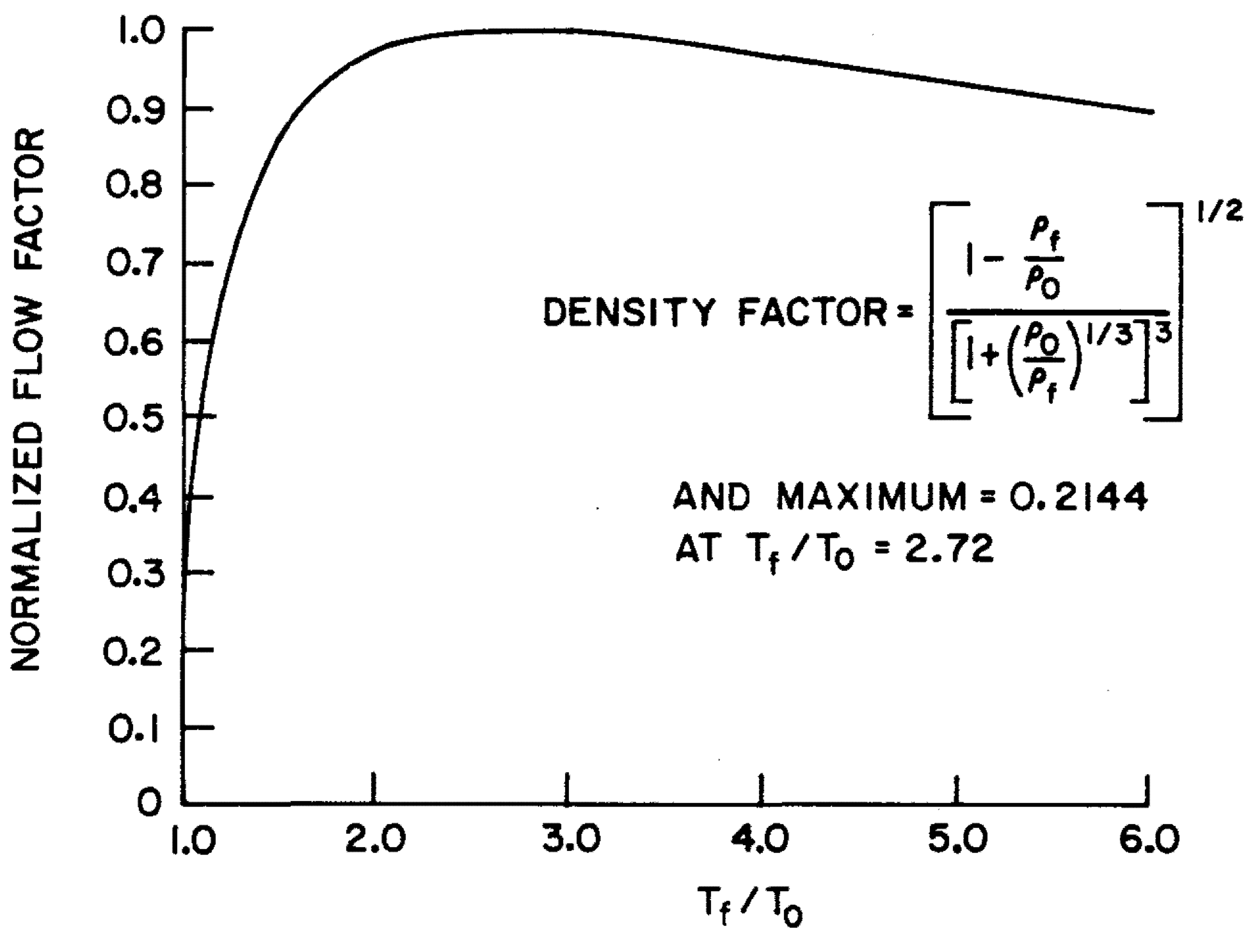


FIGURE 15 WINDOW FLOW DEPENDENCE ON GAS TEMERATURE, FOR $\frac{\phi}{r} \rightarrow 0$

In order to better understand the effects of the main variables, it is useful to consider some approximations. Assume equal mass inflow and outflow, that is let $\frac{\phi}{r} \to 0$. Then

$$\dot{m}_{air} = (A_v\sqrt{h_v})\,\frac{2}{3}\,C_d\,\sqrt{2g}\,\rho_o\left[\frac{1-\dfrac{\rho_f}{\rho_o}}{\left[1+\left(\dfrac{\rho_o}{\rho_f}\right)^{1/3}\right]^3}\right]^{1/2}$$

Furthermore, from Figure 15 it can be seen that the last factor can be approximated as 0.21. Taking ρ_o as 1.205 kg/m³ at 293° K and C_d as 0.7 we get

$$\dot{m}_{air} \approx 1880\ A_v\sqrt{h_v}\ \text{kg/hr} \tag{6.21}$$

Therefore, it can be seen that the variable group $A_v\sqrt{h_v}$ will be of prime importance in determining the air inflow.

The flow model presented above is the simplest that will give adequately accurate results. More complex approaches have recently been made available. Rockett[118] and Emmons[119] have considered the case where a vertical variation in compartment gas temperature is introduced. Since one more unknown is introduced, one more equation is needed. The equation needed comes from a detailed description of the spatial liberation and mixing of fuel. The additional data required would rarely be available in typical design instances, thus this refinement is not incorporated into the present work. Even more ambitious studies have recently been started to produce two or three dimensional flow and temperature mappings of both ordinary rooms[120] and more complex geometries as might be represented by corridors or stairwells.[121,122] While these models could be used for both pre-flashover and post-flashover study, the simple well-stirred assumption is generally so well satisfied after flashover that additional complexity would not be beneficial. A possible exception might be in the study of very large spaces, such as undivided factories. There the simple well-stirred approximation breaks down; however, many buildings of that type are designed with roof venting systems whose precise purpose is to *avoid* over-all flashover.

B. Ventilation Complications

The previous section treated the simplest, most common case of ventilation provided by one rectangular window in a vertical wall. This case presents no major complications beyond identifying the correct window area. In most compartment burns, and also in real fires, the window glass is observed to break out either shortly prior to or during flashover. Then, for post-flashover calculations, the window opening area becomes equal to the total glazed area; however, this does not happen in every case. Fires have been observed to completely burn out the contents of a room without breaking the windows. This probably occurs under the right combinations of limited leakage ventilation and a smoldering type ignition source. Under such conditions, temperatures are rather low. This deviant case does not present a serious problem since by assuming, through breakage of windows, flaming (rather than smoldering) conditions, a more severe and conservative condition is employed.

Roytman[69] considers that ordinary glass windows break out when the room gas temperature reaches approximately 300° C. Any such rule is very crude since the actual behavior is in fact bi-stable. If fire build-up is slow, high temperatures will not be reached, glass will tend not to break, and the fire will tend to go out for lack of air. Conversely, if build-up is fast, high temperatures will tend to break the window glass and this is likely to further promote the onset of flashover.

It may become increasingly more common to use window glazing that is more fire resistant than ordinary window glass. If wired glass is used then breakage will be much delayed, possibly depending on a pressure wave to finally cause breakage. It is also possible to use laminated glass or plastic glazing which is much more heat resistant, and under certain circumstances it might indeed to advantageous. Such a case would be if the window area is relatively small and the fuel load non-cellulosic. Then lower ventilation would decrease maximum temperatures while the customary difficulty of increased smoke production would not arise since generally only cellulosic fuels tend to produce more smoke at lower temperatures.

The next more complex case to be considered is that of multiple openings in a wall. These might be windows, or they might include doors that are either open or burned through. If the tops and bottoms of all the openings are at the same elevation, they are simply to be viewed as one equivalent large window where the area is the sum of all the areas. If the openings are at different heights, then two principles have to be observed:

a) the straight-line pressure distributions, as specified previously, are still valid, and

b) the mass flow equality

$$\frac{\dot{m}_f}{\dot{m}_{air}} = 1 + \frac{\phi}{r}$$

has to be maintained.

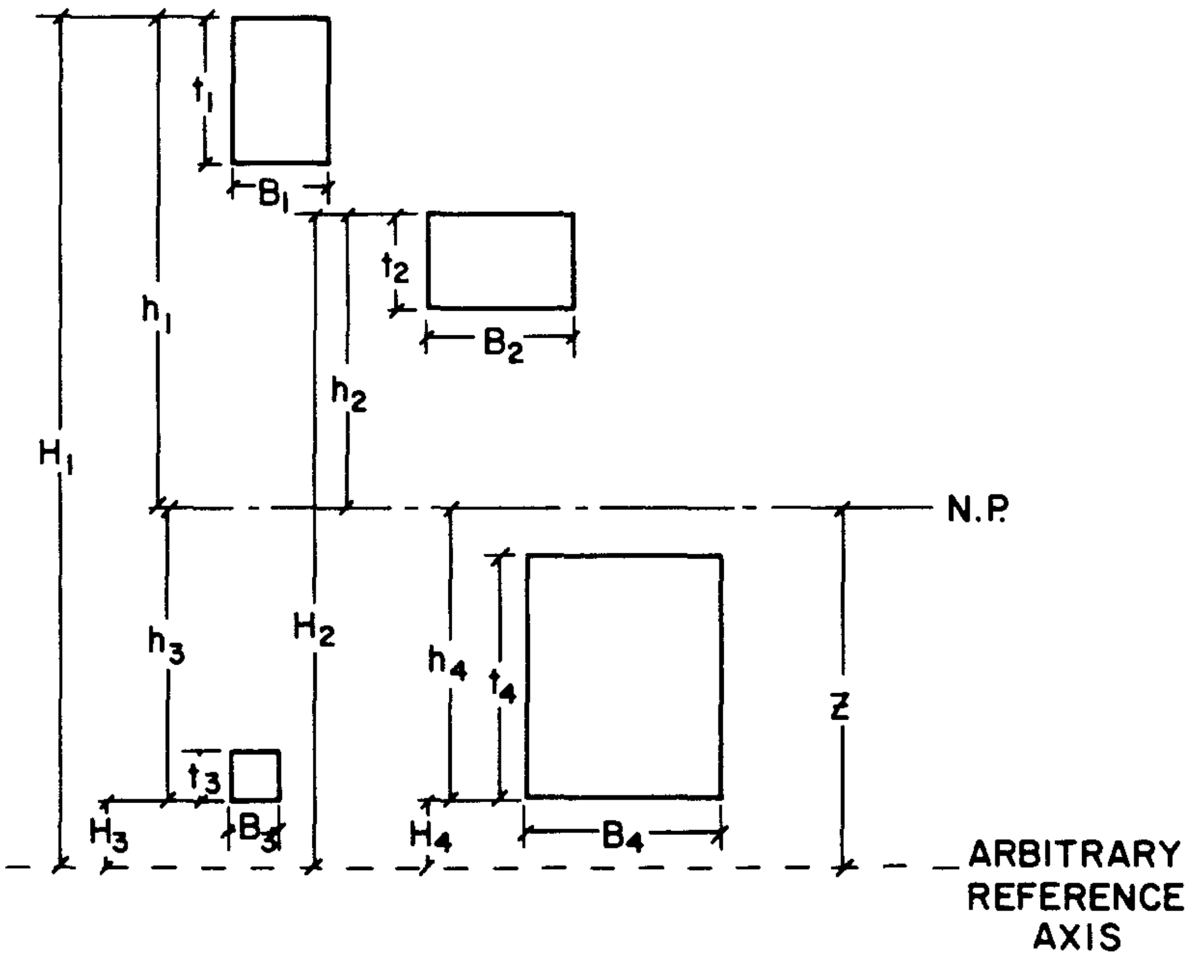


FIGURE 16 FLOW ANALYSIS FOR MULTIPLE WINDOWS

Thus, for multiple openings consider Figure 16. The flows become:

$$\dot{m}_f = \frac{2}{3} C_d \rho_f \sqrt{2g\left(\frac{\rho_o}{\rho_f} - 1\right)} \sum_i [(H_i - Z)^{3/2} - (H_i - Z - t_i)^{3/2}]\, B_i \quad (6.22)$$

$$\dot{m}_{air} = \frac{2}{3} C_d \rho_o \sqrt{2g\left(1 - \frac{\rho_f}{\rho_o}\right)} \sum_j [(Z - H_j)^{3/2} - (Z - H_j - t_j)^{3/2}]\, B_j \quad (6.23)$$

By substituting the values of m_{air} and m_f into the mass flow equation the height of the neutral plane, Z, can be found. Then, the problem is as before. Such elementary solutions based on inviscid flow have been more or less experimentally verified by Kawagoe and Brown and Solvason, but their applicability to highly unusual configurations has not been experimentally checked.

Magnusson and Thelandersson[104] suggest that as a rough rule for a number of similar windows without large vertical offset from one another, an equivalent opening factor can be defined:

$$(A\sqrt{h})_{equiv.} \approx \sum_k A_k \sqrt{h_k}$$

In case the openings are doors that gradually burn through, the flows and opening factors will have a time dependence. Numerically this situation presents only a slight additional complication.

Openings in horizontal surfaces (e.g., ceiling vents or skylights) must be considered a different case. When such an opening handles only a small fraction of the total compartment flows, Magnusson and Thelandersson suggest that it is reasonable to use the straight line pressure distributions and consider the vent as being all uniformly at the pressure found at the top of the room. For large vents a more exact analysis is needed. A heated column of lower density air stands above the roof of a vent effectively lowers the pressures and raises the neutral plane in a portion of the room below it. Roof venting theories are available[123,124] that give requisite principles for calculation.

Questions are sometimes asked about fire behavior under conditions of only leakage ventilation. If window openings are non-existent or do not break out and the only source of ventilation is, say, around door cracks, then a post-flashover fire may be considered to be precluded. Complete security is not assured, however, since with cellulosic and certain other fuels smoldering can proceed and the room can flash when a door is opened up. Numerical data on leakage flows have been collected by Sasaki and Wilson.[125] Leakage flows are primarily important because of their role in distributing smoke and gases from a fire through other parts of a building, a topic not included in the present work. Wakamatsu[126] gives a theory and algorithms for calculating these flows.

So far the above discussion has not treated quantitatively the lower limit for post-flashover fires. It is a known fact that if ventilation is sufficiently reduced, a post-flashover fire will not occur or be maintained. The theory as developed thus far and also in the ensuing sections ignores that fact and permits expected fire temperatures to be calculated which can be down to near ambient. Since the purpose of the present calculations for the expected fire is to produce design values which are close, but preferably conservative, there is little need for accurately determining very low temperatures. Theoretically the problem is of some interest and certain results are available. Gross and Robertson[127] noted that when the "ventilation factor" variable group $\frac{A_V\sqrt{h_V}}{A_W}$ dropped below about 0.008 $m^{1/2}$ the burning became unsteady and when it dropped below about 0.0035 sustained combustion did not occur.

To explain these results Thomas[128] tried to adapt the Semenov theory[129] of chemical kinetics rate-limited combustion. Using some order-of-magnitude estimations he proposes a lower combustion limit given by 0.003 $m^{1/2}$ for the ventilation factor.

Ventilation factors are clearly not the fundamental physical variable in determining reaction rates. A more directly usable approach of a slightly different sort has been taken by Jansson and Onnermark[130] in Sweden. They conducted a series of 24 burns with wood cribs in a compartment. Instead of trying to determine the lowest instance of sustained combustion they looked for a definitely flashed over situation, i.e., excluding cases where steady burning but no flashover resulted. Based on this criterion the flashed over fires all had a ventilation factor greater than 0.015 $m^{1/2}$. While necessary, it was not a sufficient condition. For ventilations exceeding that amount a certain minimum fuel delivery rate was also needed. The numerical value for it is closely associated with wood crib fires and is not fundamental. What was of more importance was Jansson and Onnermark's ability to identify a temperature criterion. In no case where the average gas temperature near the ceiling failed to exceed 500° C did flashover occur. Conversely, flashover was noted in all cases when the temperature surpassed 600° C.

C. Relevant Combustion Fundamentals

The problem at hand in post-flashover fires requires first and foremost a determination of the gas temperature within the compartment. This temperature, as mentioned above, is usually assumed to be uniform, that is, with no spatial variations. The basic problem is quite familiar to combustion engineers; a well-established methodology is

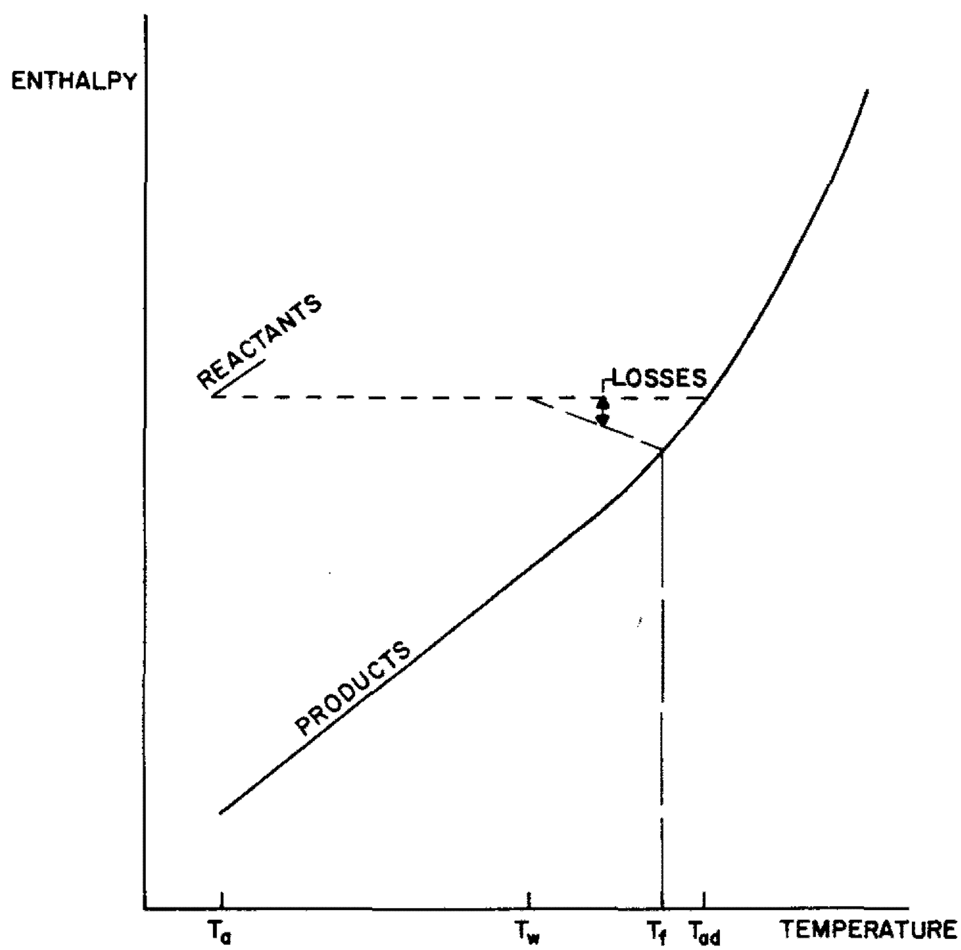


FIGURE 17 ENTHALPY-TEMPERATURE (LeCHATELIER) DIAGRAM

available which could profitably be used in the firesafety field.

Features of the combustion can be examined on the enthalpy temperature diagram, also called a "Le Chatelier" diagram, see Figure 17. The enthalpy h of the fuel-air mixture both before and after reaction is plotted as a function of temperature for several equivalence ratios ϕ, where

$$\phi = \frac{\left[\frac{\text{fuel}}{\text{air}}\right]}{\left[\frac{\text{fuel}}{\text{air}}\right]_{\text{stoichiometric}}}$$

and where air at atmospheric pressure is assumed to consist of 23% oxygen and 77% nitrogen by weight. This is the definition of the ϕ introduced earlier.

If the combustion takes place under adiabatic conditions, that is, with no heat loss, and if $\phi = 1.0$, that is, the exact amount of oxygen necessary for combustion is present, then the gas temperature achieved, T_{ad}, is known as the "adiabatic" flame temperature. The significance of the adiabatic flame temperature is that it is the highest temperature that can theoretically achieved with a given fuel and a given composition of air.

An "average" wood can be used as an illustrative example. From ultimate analysis of dry wood[131] the carbon, hydrogen, and oxygen content by weight can be determined as averaging:

C = 50%

H = 6%

O = 44%

This gives the following equations for stoichiometric ($\phi = 1.0$) complete combustion:

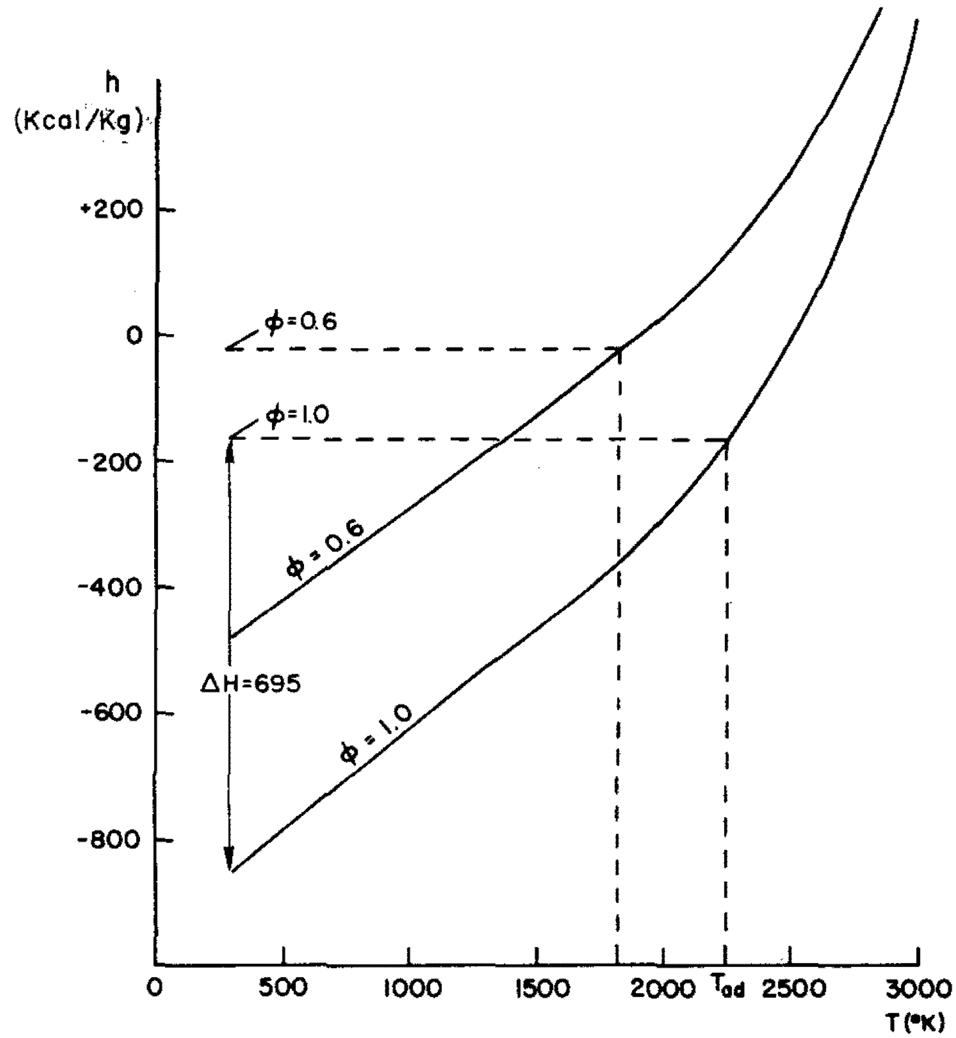


FIGURE 18 LeCHATELIER DIAGRAM FOR DRY WOOD COMBUSTION IN AIR

$$C_{0.32}\,H_{0.46}\,O_{0.22} + 0.32\,(O_2 + 3.77\,N_2) \rightarrow 0.32\,CO_2 + 0.23\,H_2O + 1.21\,N_2 \tag{6.24}$$

Examining, in Figure 18, the diagram for $\phi = 1.0$ in more detail a short line beginning with $h = -185$ at $T = 298$ K is shown. This line represents the enthalpy of the reactants. Its slope $\frac{\partial H}{\partial T}$ is by definition equal to C_p, the heat capacity. At stoichiometry the composition of the reactants is:

14.8% wood

85.2% air (by weight)

The average heat of reaction of wood can be taken as around -4700 kcal/kg. The heat of reaction of air is zero. Thus, the heat of reaction of the fuel-air mixture is $-4700 \times 0.148 = -695$ kcal/kg of mixture.

The lower curve for $\phi = 1.0$ represents the enthalpy of the products. The products, however, will not be solely CO_2, H_2O, and N_2 in actual combustion. At higher temperatures, dissociation into CO, O, NO, OH, H_2, etc., will occur with an attendant increase in the effective C_p. In addition, other species, such as CH_4 and solid carbon may be present.

The equilibrium concentration of the products can be calculated[132] from elementary thermodynamic properties. The complex equilibrium calculations do not, however, realistically predict the values for all the species involved since in some the reaction requires a long time to be completed, longer than the flow time of the products through the room. The equilibrium values are nonetheless a useful first approximation to the actual gas composition.

The heat of combustion represents the vertical distance on the enthalpy diagram between the reactants and products curve at 298° K and is equal to -695 kcal/kg in this case. In other words, the relationship exhibited is

$$h_{products} = h_{reactants} + \Delta H$$

when products have been cooled to the original temperature of the reactants. ΔH, the heat of reaction, has a negative sign. It is customary to define $\Delta H_c = -\Delta H$ as the calorific value or the heat of combustion; it is, therefore, a positive quantity.

The line joining the reactant and the product curves horizontally determines T_{ad} and is a straight line since it was assumed that the combustion takes place adiabatically. The reaction is not adiabatic, the line will bend down in proportion to the losses, see Figure 17. Suppose, for example, that the walls are not adiabatic, but rather isothermal, held at some temperature T_w. Let the heat transfer rate be represented by

$$\dot{Q} \propto h \quad (T_f - T_w)$$

Then the flame temperature will no longer be T_{ad}, but will be a lower value, T_f, located below the intersection of the combustion line with the products curve.

For room combustion, the factors that maximize the gas temperature need to be discussed. The effects on gas temperatures can best be visualized by considering the (fixed) volume of the room. The energy released is proportional to the mass rate of combustion of fuel times the calorific value. For pyrolyzing fuels burning in the fuel limited regime this can be expressed as

$$\dot{h}_c = \dot{m}_p \; (\Delta H_c b_p - \Delta H_p)$$

where:

$\dot{h}_c$ = heat of reaction released (kcal/hr)

$\dot{m}_p$ = rate of fuel pyrolysis (kg/hr)

ΔH_c = calorific value of fuel (kcal/kg)

b_p = incomplete mixing factor (ratio of fuel burned/fuel pyrolyzed)

ΔH_c = enthalpy of pyrolysis, positive if endothermic (kcal/kg)

The losses meanwhile are of two kinds: heat transfer at the boundaries and the enthalpy loss of heating excess gases. Heat transfer losses consist of convection at the walls and radiation to all the areas that can "view" the fire within the room; this will include the walls, the windows and many of the fuel surfaces. It may exclude the greater portion of the floor since the floor will tend to be shielded by the fuel (room furnishings). The excess gases which will absorb heat by being raised in temperature from near-ambient to the fire temperature can be of two kinds: they will be excess air drawn in through the window by convection when $\phi < 1.0$ or, if $\phi > 1.0$, they will be gasified fuel which is leaving unburnt because of the lack of sufficient oxygen. Since the volume flow of excess air can be very large (when the fuel is exhausted but the room not yet cooled down) while the production of unburnt pyrolysis gases is much more moderate, the losses due to this dilution effect can be much greater in the fuel controlled regime.

There are essentially two reasons that the highest possible compartment gas temperatures occur under stoichiometric burning. The first reason is that at $\phi = 1.0$ there is theoretically zero loss due to unneeded heating of excess air, and the farther ϕ drops below 1.0 the higher these losses become. The second reason is that at the stoichiometric point there are no unburned pyrolysis gases leaving and, therefore, all the chemical reaction energy is released inside the compartment. For ϕ values above 1.0 there is some loss of unburned fuel from the compartment. Thus from elementary combustion concepts it is clear that *the room temperatures will be the highest and the total heat transmitted the greatest if conditions are such that the combustion always takes place at stoichiometry.*

Stoichiometric burning is not possible in any real room; it will be approached most closely, however, at the point of switchover *between ventilation controlled and fuel controlled regimes.* The main cause for deviation from the ideal behavior is that mixing of the air and the gasified fuel is not done perfectly or instantaneously. The mixing involves large-scale turbulence, which would be extremely complex to attempt to describe, even numerically. Because we are not able to provide this description we lose a measure of the departure from predicted stoichiometric conditions.

As a hypothetical experiment, if fuel were burning at a constant rate within a room we could vary the window opening and measure the average outflow gas concentrations at the window plane. At a certain point we could find that not only were there both oxygen and fuel present at the window outflow, but that also the ratio of the two inside the room was in stoichiometric proportion. Yet, some of these gases would be unreacted because they never had a chance to interact in the flow pattern within the room. The factors affecting the degree of mixing are not well enough understood to be calculable. Currently the only way of accounting for this incomplete mixing is by an empirical correction. It might be presumed, however, that mixing would be greater in those geometries which permit more fully developed patterns of vortices. In practical terms, this may indicate greater mixing in rooms with small windows, and decreased mixing in configurations where the window extends all the way to the ceiling, or, in the limit, where one or more entire walls are absent. It is known that the plenum height (the distance between the top of the window and the ceiling) is a variable that should be considered, but no simple method of treatment is yet available.

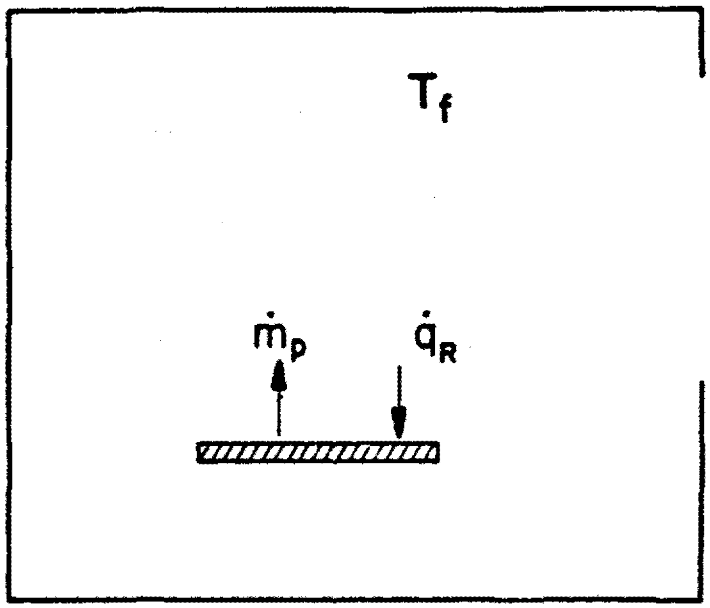
Combustion in burners, furnaces, and other appliances intended to promote efficient combustion takes place at temperatures reasonably close to the adiabatic flame temperature. In a burning room, however, we can measure temperatures which are quite low (only several hundred °C) but relatively uniform (perhaps with 10 to 30% variations). Such low temperatures, it might seem, would not be sufficient to sustain the chemical reactions necessary for combustion. The answer apparently lies in the presence of large-scale turbulence. It may be appropriate to visualize the volume of the room as consisting of a quiltwork of packets, some of which have high temperatures and are sustaining combustion reactions, while others are much cooler and do not have significant reactions occuring. The temperature measured even at a single thermocouple is not the high active temperature nor the low inactive one, but some value in between, depending on the particular flow situation. The detailed mechanism is not important for obtaining the heat balance but it would be important for predicting the behavior at very low temperatures, say below 400° C.

D. Combustion of Pyrolyzing Fuels

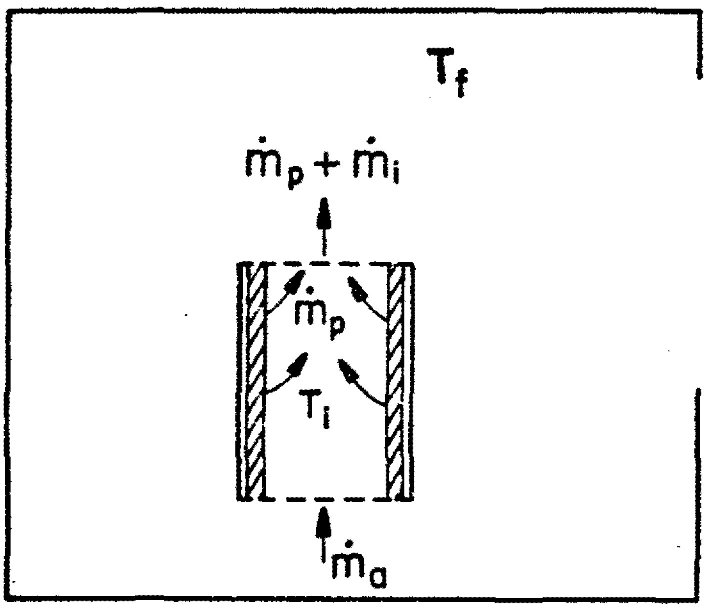
There are two basically different types of combustion reactions that can occur in a compartment fire. One is a solid state reaction at or below the fuel-air interface; the second is a gaseous reaction principally in the space above the fuel and within the compartment. If there is insufficient oxygen in the compartment, however, significant quantities of fuel, so-called "excess pyrolysates," may also burn outside the doors or windows of the compartment. This external spread mechanism is one of great practical importance; however, it is not within the scope of the present work. The present section will be primarily focused on the combustion reactions within the compartment and their relationship to the pyrolysis process which generates the gaseous fuels.

The solid state combustion reaction is generally exhibited by cellulosic fuels and a few man-made polymers such as neoprene. Although measurements are not available, solid state combustion is probably responsible for only a small portion of the heat generated in most fully developed compartment fires. The most significant effect of these surface oxidation reactions in compartment fires is to raise the fuel surface temperatures which can then aid in pyrolyzing combustible gases from the fuel. This interrelation of solid state and gaseous fuel production is not characteristic of simple thermoplastic fuels such as polystyrene, polyvinylchloride, or polyolefins, which do not exhibit the solid state combustion reaction. These materials soften and form liquid surface layers and essentially pyrolyze by a destructive distillation process.

The gaseous combustion reactions occur throughout the compartment and the assumption of a well-stirred reactor implies that they are relatively uniform. The actual generation of the gaseous fuel, however, is usually not uniform, but depends on the nature and geometry of the solid and liquid fuels in the compartment.



A) SINGLE STIRRED COMPARTMENT



B) COMPARTMENT WITH DIFFERENT STIRRED ZONE FOR FUEL PILE

FIGURE 19 TWO ELEMENTARY MODELS FOR FUEL PYROLYSIS IN FLASHED-OVER COMPARTMENTS

There is an infinite variety of fuel geometries that can be considered. To arrive at some useful models, one can envision two idealized cases. In the first case, schematically shown in Figure 19a, the fuel elements are sufficiently remote from one another so that they "view" surroundings, as established by the general spaces of the compartment, all at temperature T_f. In the second case, shown in Figure 19b, the fuel elements view a smaller stirred zone which does not represent the same conditions as do the remaining zones of the compartment. Thus there is, in effect, a compartment within a compartment.

In the single stirred compartment shown in Figure 19a the rate of fuel pyrolysis, $\dot{m}_p$, can be calculated for either purely radiative or purely convective heat transfer:

Radiative Heat Transfer:

$$\frac{\dot{m}_p}{A_f} = \frac{\dot{q}_{rad}}{\Delta H_p} \quad \text{kg/hr-m}^2 \qquad (6.26)$$

where:

A_f = fuel area (m^2)

ΔH_p = total enthalpy required to pyrolyze a solid fuel at its bulk inside temperature into gaseous fuel at temperature T_s

T_s = fuel surface temperature

and $\dot{q}_{rad}$ is proportional to $(T_f^4 - T_s^4)$ multiplied by some function containing the gas and fuel emissivities and the geometrical view factor.

Convective Heat Transfer (after Spalding[133,134]):

$$\frac{\dot{m}_p}{A_f} = \frac{h}{C_{pg}} \ln (1 + B) \quad \text{kg/hr-m}^2 \qquad (6.27)$$

where:

$$B = \frac{m_{O_2,\infty}\frac{\Delta H_c}{r_o} + C_{pg} \quad (T_\infty - T_s)}{\Delta H_p} \tag{6.28}$$

$m_{O_2,\infty}$ = mass fraction of oxygen in stirred compartment spaces

C_{pg} = heat capacity of the combustion gases

r_o = oxygen/fuel ratio = 0.23 r

and T_∞ and $m_{O_2,\infty}$ are the temperature and oxygen mass fraction, respectively, of the air flowing through or over the fuel pile.

The Spalding "B Number" is a dimensionless number which is strongly, but not entirely, a property of the fuel. It can be thought of as the ratio of the energy produced by the combustion of a given amount of fuel to the energy needed to liberate the same amount of fuel and heat it to the flame temperature. The $m_{O_2,\infty}$ and T_∞ terms are determined by factors other than the fuel itself. If they are fixed, then for simple liquid fuels the value of B can be relatively well defined, but it is more difficult to define for solid fuels, as will be discussed below.

The assumption of only convective heat transfer is one of the most important limitations of Spalding's theory. In a practical case both radiation and convection would normally have to be accounted for. Spalding's approach can still be used by letting the denominator of the B number expression become:

$$\left(\Delta H_p - \frac{\dot{q}_{rad}}{\dot{m}_p/A_f}\right)$$

And now the B number is strongly a function of the net radiated flux $\dot{q}_{rad}$ received and of T_s, which is also a function of $\dot{q}_{rad}$.

There have not been many experiments performed on burning isolated solid pieces of fuel in a flashed over compartment. The most common type of experiment involves burning the fuel in an infinite atmosphere with $T_\infty = 298°$ K. When a flashed over compartment surrounds a piece of fuel the mass fraction of oxygen $m_{O_2,\infty}$ will drop below its ambient value of 0.23 and act to lower B, while T_∞ will rise above T_o and act to raise B, and the presence of radiation, $\dot{q}_{rad}$, will also raise the value of B. In addition, any solid state combustion will act strongly to raise T_s, and therefore lower B and the pyrolysis rate. Thus there is a certain competition between the heterogeneous and the homogeneous (pyrolyzing) combustion. Furthermore, the net resulting burning rate tends to be less dependent on the value of T_∞ for those fuels which undergo solid state reactions.

The second model, schematically shown in Figure 19b, and involving a sub-compartment for the fuel, was originally developed for wood cribs by Block.[135] Kim, deRis and Kroesser[136] have also done work in this area. In its simplest conception, one can imagine that fuel lines the inside surface of open-ended ducts, there being no heat or mass transfer at the outside surface. This configuration can thus differ in two ways from th single stirred compartment: (1) the fuel now views a stirred temperature, T_i, which may be different from the T_f prevalent in the rest of the compartment; (2) the flow situation may be modified--if the duct is long and thin enough, pipe flow rather than boundary layer flow will result. The pipe flow case has been labeled as "densely packed fuel," while the boundary layer case as "sparsely packed."

The most obvious feature of this two-zone model is the spatial separation of most of the gaseous combustion of the fuel from the pyrolysis process. This means that for the two cases of either pure radiative or pure convective heat transfer the rate can be written:

Radiative Heat Transfer:

$$\frac{\dot{m}_p}{A_f} = \dot{q}_{\substack{rad \\ (local)}} \Big/ \Delta H_p \qquad kg/hr\text{-}m^2$$

where:

$$\dot{q}_{\substack{rad \\ (local)}} \propto (T_i^4 - T_s^4)$$

Convective Heat Transfer:

$$\frac{\dot{m}_p}{A_f} = \frac{h}{C_{pg}} \ln (1 + B) \qquad kg/hr\text{-}m^2$$

where h is now dependent on the density of the packing and B has to be redetermined. Even more importantly, however, the mass fraction of oxygen in the local fuel zone is subject to greater depletion by both the gaseous and solid state combustion reactions. This leads to a complex coupling of the rate of pyrolysis with the radiative feedback in the fuel zone and the oxygen supply. In either of the two models the rate of pyrolysis is considered to be the essential fuel variable for determining the compartment fire, and the heat released from solid state combustion, which has not yet been quantified is neglected.

The effect of varying fuel pyrolysis rates can be illustrated on a diagram of enthalpy versus time, such as that shown in Figure 20. Let us define a new term, $\dot{h}_p$, as the potential enthalpy of the gas pyrolyzed from the fuel bed. It is "potential" since it is the maximum fuel enthalpy release rate that would occur under ideal burning conditions. It can be defined as:

$$\dot{h}_p = \dot{m}_p \, \Delta H_c \quad \text{kcal/hr} \tag{6.29}$$

Then $\dot{h}_p$ becomes the main fuel variable. Also, let $\dot{h}_s$ be the rate of heat release for stoichiometric combustion,

$$\dot{h}_s = \dot{m}_{air} \, \frac{\Delta H_c}{r} \quad \text{kcal/hr} \tag{6.30}$$

Now, $\dot{h}_s$ will not vary much for different fuels burned in the same compartment since $\dot{m}_{air}$ is mostly a function of the window parameter, $A_v \sqrt{h_v}$ and the gas temperature and only very weakly dependent on fuel properties. Further, $\frac{\Delta H_c}{r}$, which is the combustion enthalpy developed per unit mass of air, is nearly independent of fuel type, as shown in the following table:

Fuel	ΔH_c (kcal/kg fuel)	$\frac{\Delta H_c}{r}$ (kcal/kg air)
wood	4,700	820
polyethylene	11,000	760
polystyrene	10,000	760
polyurethane	5,700	770
methane (gas)	13,000	775
benezene (liquid)	10,000	760

Finally, define $\dot{h}_c$ as the actual enthalpy release rate in a compartment. The actual enthalpy release rate in the compartment, $\dot{h}_c$, will be the *lesser* of $\dot{h}_s$ or $\dot{h}_p$, reduced by some factor, b_p, for incomplete mixing. Thus,

$$\dot{h}_c = \text{lesser of} \begin{cases} \dot{h}_p \, b_p \\ \dot{h}_s \, b_p \end{cases} \tag{6.31}$$

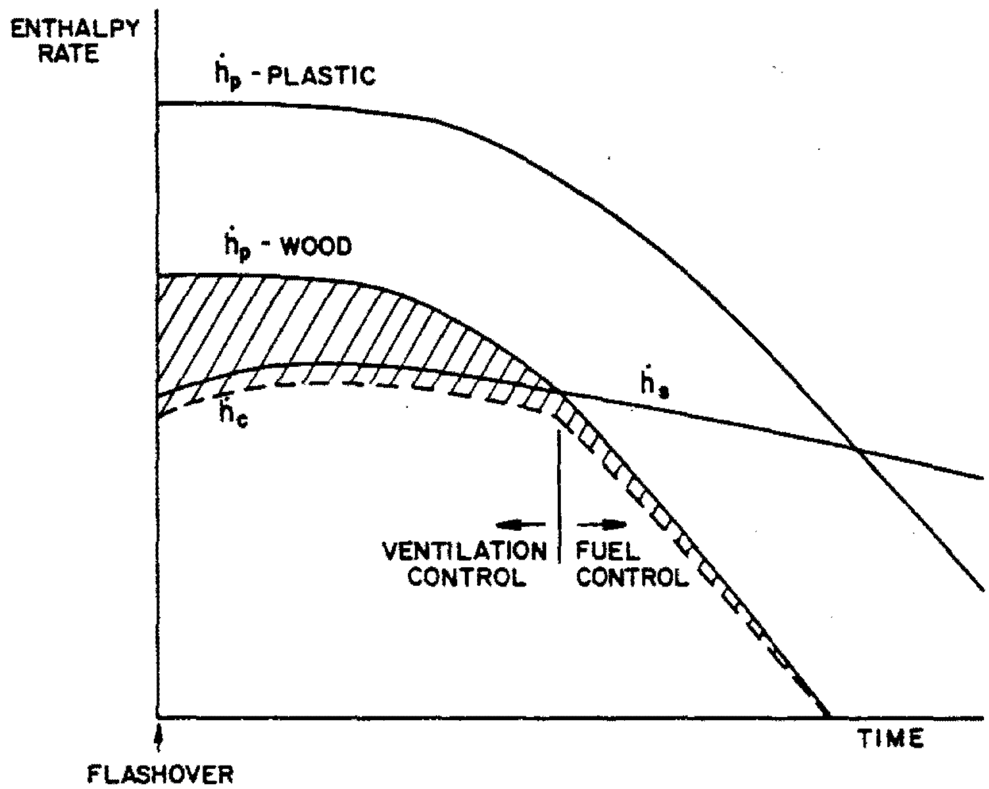


FIGURE 20 POSSIBLE ENTHALPY RATES IN A COMPARTMENT FIRE AS A FUNCTION OF TIME FOR TWO FUELS

If $\dot{h}_p > \dot{h}_s$, then there is more fuel being pyrolyzed within the compartment than can be burned *inside it*. The relative values of $\dot{h}_c$ and $\dot{h}_p$ for a "typical" compartment fire are shown in Figure 20 as a function of time. The difference $(\dot{h}_p - \dot{h}_c)$, shown hatched in Figure 20, consists of the excess pyrolysates released from the compartment. For fuels which pyrolyze easily, i.e., with a higher B number, this unburned fraction can be significant. It represents a salient hazard at facades, in corridors, and elsewhere outside the fire compartment, because it may cause continued combustion where it is discharged.

Figure 20 depicts a "typical" fire, which might start in ventilation control at flashover. The rate of pyrolysis eventually has to decrease, so somewhere the $\dot{h}_p$ curve will cross the $\dot{h}_s$ curve. At this point, by definition, the burning switches to fuel control. From then on the amount of fuel pyrolyzed is insufficient to use up all the oxygen and the combustion is fuel-lean.

It is significant to note that Kawagoe set his results down in a form which did not distinguish between $\dot{h}_p$, $\dot{h}_s$, and $\dot{h}_c$. Instead he used the fact that

$$\dot{m}_{air} \approx 1880 \quad A_v \sqrt{h_v} \qquad \text{kg/hr}$$

assumed $\frac{r}{\phi} = 5.7$ in dealing with wood fuel, and got

$$\dot{m}_p \approx 330 \quad A_v \sqrt{h_v} \qquad \text{kg/hr} \tag{6.32}$$

and

$$\dot{h}_c \approx (\Delta H_c) \quad 330 \quad A_v \sqrt{h_v} \qquad \text{kcal/hr} \tag{6.33}$$

Instead of taking $\Delta H_c \simeq 4700$ for wood fuel, he took $\Delta H_c = 2575$ kcal/kg, a figure much lower than the actual calorific value. This procedure was needed since his model could handle neither excess fuel nor excess oxidant. Thus, the fraction 2575/4700 was, in effect, an average correction factor to account for dilution. But since fire might first go from fuel-rich to quasi-stoichiometric and then to fuel-lean, a constant derating factor of this sort is highly approximate.

Some of the details of fuel pyrolysis should now be considered. Wood is still the most common fuel, thus it is somewhat surprising to realize that its decomposition and combustion behavior are both very complex and insufficiently well understood. Wood can pyrolyze[137] by two alternate competing pathways--dehydration and depolymerization. At lower temperatures, dehydration is preferred. It involves elimination of water molecules and a cross linking of cellulose chains. At higher temperatures depolymerization is preferred. This unzipping reaction produces primarily levoglucosan, a tarry substance which is released in aerosol form and rapidly decomposes further. These secondary products comprise a vast number of different species which are not readily isolated.

Thus, wood gets converted to various tar-related products in the gas phase and a solid charcoal matrix. The pyrolyzed gas-phase products burn homogeneously, while the charcoal can undergo heterogeneous surface oxidation. It is generally considered that except at low temperatures and low oxygen conditions the homogeneous reactions predominate. While numerically the enthalpy release rate due to heterogeneous reactions may be small, the effect of these reactions on the overall decomposition is not small. The surface reactions control the surface temperature, T_s, which in turn affects the pyrolysis rate. As a result, neither T_s nor B are constant for wood. Block[138] considered wood T_s as averaging

370° C in his natural convection (wood crib) experiments, while Holve[138] measured 1400° C in his forced jet flow experiments. For small free-burning specimens[142] T_s in the vicinity of 600-700° C is seen.

Other values needed in determining wood combustion rates are well characterized. The calorific value for wood can be taken as around 4700 kcal/kg. Ingberg[62] gave values for other cellulosic products. The total heat of pyrolysis (to heat up the bulk solid and to vaporize it) is approximately 710 kcal/kg for wood.[284] The majority of this value is presumably sensible heat since the latent heat of pyrolysis is only 48.4 kcal/kg.[139] The ΔH_p term could also be included in the overall compartment heat balance as a loss term; however, since it is small and since the fuel shields some compartment walls and prevents a corresponding heat loss there, it can safely be excluded.

A step in understanding the contribution of heterogeneous combustion has been made by the elucidation of charcoal combustion, charcoal being a fuel which shows only heterogeneous combustion. Evans[140] has been able to provide theoretical calculations and empirical measurements of $\dot{h}_p$ for charcoal burning. The equations for $\dot{h}_p$ are complex and not soluble in closed form. The results, as expected, show a strong dependence of T_s on the velocity of the air flowing past the fuel.

Synthetic polymer fuels, with a few exceptions, do not undergo surface reactions but burn solely by pyrolyzing. Under pure convective heat transfer conditions they could adequately be treated by using Spalding's B number concept. Since surface reactions are not present, the T_s is approximately constant and is near the boiling point. The presumption of constant T_s breaks down only under extremely high flow velocities and mass loss rates. For building fires the constant T_s assumption is well fulfilled.

TABLE 6

ESTIMATED PYROLYSIS RATES

MATERIAL	ρ (kg/m³)	ΔH_c (kcal/kg)	r_o	ΔH_p[a] (kcal/kg)	T_s[b] (°C)	CONVECTION[c]			RADIATION[d]	
						B	$\dot{m}_p''$ (Mcal/m²-hr)	v_p (mm/hr)	$\dot{m}_p''$ (Mcal/m²-hr)	v_p (mm/hr)
NYLON	1100	7620	2.34	220	700	1.45	320	38	3120	370
POLYPROPYLENE	900	11120	3.43	534	450	0.71	280	28	1870	190
POLYSTYRENE	1030	10090	3.08	502	500	0.74	260	25	1810	175
POLYETHYLENE	900	11120	3.43	622	390	0.63	255	25	1610	160
POLYMETHYL-METHACRYLATE	1180	6370	1.96	385	500	0.95	200	26	1490	200
POLYOXYMETHYLENE	1430	4045	1.07	720	595	0.55	85	14	500	90
WOOD	450	4700	1.37	710	370	0.59	106[e]	50[e]	106[e]	50[e]

(a) from references 284, 285

(b) estimated from references 135, 138, 286

(c) under conditions that:

$m_{O_2,\infty} = 0.10$

$T_\infty = 500°C$

$h/c_{pg} = 47$ kg/m²-hr, from reference 142

(d) under conditions that:

$\dot{q}_{rad} = 2.5$ cal/cm²-sec

$T_s \ll T_f$

(e) v_p measured value for 900°C, reference 147

No controlled large-scale post-flashover experiments have been reported for plastic fuels. Nevertheless, by extrapolating small-scale data some tentative observations can be made. Estimates are given in Table 6 for pyrolysis rates $\dot{h}_p''$ under two conditions--purely convective and purely radiative heating. The values assumed are by no means definitive, thus it is not intended that the results be used for design calculation. Yet even allowing for significant error, the markedly greater rates for plastic fuels are striking.

Available Results for Wood Combustion

Available studies of wood combustion basically fall into two categories: the burning of large panels in standard test furnaces, and the behavior of small specimens in an environment that is not flashed over. In both cases the oxygen fraction $m_{O_2,\infty}$ is usually closer to ambient than to realistic post-flashover conditions. Radiation is limited or negligible for the small specimens and quite significant in the test furnace case.

Results for large specimen burning have been given by Hall,[145] Schaffer,[146,147] and several authors in a symposium at Chalmers University.[281] In the tests reported, the specimens are thick enough that a nearly steady velocity of regression is established. Customarily termed "charring rate," this velocity has generally been measured only under conditions of exposure to the standard time-temperature curve. The most common value measured is

$$v_p \simeq 30 \text{ mm/hr} \qquad (6.34)$$

but in some cases approaches 50 mm/hr. Schaffer, further investigating the effect of wood moisture and density, found that both lowered the regression rate and could simultaneously be accounted for by taking the rate to be inversely proportional to the thermal conductivity. Schaffer was the only investigator to study the effect of furnace temperatures other than the standard curve. For three constant furnace temperatures he obtained the following rates:

T_t (°C)	v_p (mm/hr)
538	25
815	45
926	53

Wood fuel takes the form of large thick isolated surfaces only in rare cases. In practical cases the fuel may be small in thickness, small in area, or closely stacked together. In each case different expressions are needed. Small isolated specimens have been experimentally studied by numerous investigators.[141-144] The results obtained are not necessarily applicable to post-flashover fires. The main effects of small thickness, small area, and close packing are, nevertheless, understood. When a piece of fuel is thin enough that its centerline (or back face) can begin to measurably heat up in the course of burning its size has to be taken into account. Tamanini[282] measured burning rates of large thin wood panels in the ambient atmosphere. His results can be correlated by

$$v_p = 0.006\ D^{-0.6} \quad \text{mm/hr} \tag{6.35}$$

where D = panel thickness (m). This equation gives greater regression rates for thinner specimens and can be applied when $D \lesssim 0.05$ m.

For materials that are very large in only one dimension and smaller but still not thermally thin in the remaining two, a method by Ödeen[110] is available. For these shapes a constant rate of regression cannot be simply applied to all the surfaces because the corners would be "counted twice." If for some geometrical configuration

$$A = ar^{F-1}$$
$$V = \frac{a}{F} r^{F}$$

where:

A = burning area

V = remaining volume at time t

r = characteristic dimension

F = constant

then

$$\frac{A}{V} = \frac{F}{r}$$

and the rate of comsumption is

$$\dot{m}_p = v_p \rho A$$
$$= v_p \frac{M_o}{V_o} A = v_p M_o \frac{ar^{F-1}}{\frac{a}{F} r_o^{F}} = v_p \frac{M_o F}{r_o} \left(\frac{r}{r_o}\right)^{F-1}$$

$$\frac{\dot{m}_p}{M_o} = \frac{v_p}{\frac{D}{2}} F \left(\left[\frac{m}{M_o}\right]^{1/F} \right)^{F-1}$$

$$= \frac{v_p}{\frac{D}{2}} F \left(\frac{m}{M_o}\right)^{1-\frac{1}{F}} \tag{6.36}$$

where:

D = original thickness = $2r_o$

ρ = density

M_o = total mass before fire

m = total remaining mass at time t

F = configuration coefficient

Let $C = \frac{D}{2v_p}$ be the time it takes for m to go to zero. Then the differential equation describing the mass loss becomes:

$$\frac{\dot{m}_p}{M_o} = \frac{F}{C}\left(\frac{m}{M_o}\right)^{1-\frac{1}{F}} \tag{6.37}$$

It can be integrated directly to yield:

$$\frac{m}{M_o} = \left(1 - \frac{t}{c}\right)^F \quad \text{for the fuel amount}$$

and

$$\frac{\dot{m}_p}{M_o} = \frac{F}{C}\left(1 - \frac{t}{C}\right)^{F-1} \quad \text{for the mass loss rate} \tag{6.38}$$

For some configurations:

<u>Infinite Plane</u> (exposed on both sides)

$$F = 1 \qquad \frac{m}{M_o} = 1 - \frac{t}{C} \qquad \frac{\dot{m}_p}{M_o} = \frac{1}{C}$$

<u>Cylinder or Rectangular Stick</u>:

$$F = 2 \qquad \frac{m}{M_o} = \left(1 - \frac{t}{C}\right)^2 \qquad \frac{\dot{m}_p}{M_o} = \frac{2}{C}\left(1 - \frac{t}{C}\right)$$

Sphere or Cube:

$$F = 3 \qquad \frac{m}{M_o} = \left(1 - \frac{t}{C}\right)^3 \quad \frac{\dot{m}_p}{M_o} = \frac{3}{C}\left(1 - \frac{t}{C}\right)^2$$

Infinite Plane (exposed on one side only). For this special case:

$$\frac{m}{M_o} = 1 - \frac{t}{2C} \qquad \frac{\dot{m}_p}{M_o} = \frac{1}{2C}$$

Thus, according to the model, $\dot{m}_p$ is constant for an infinite plane, decreases linearly as a function of time for a long stick and decreases more sharply for higher values of F.

The next level of complexity to be considered is where the fuel is not thermally thick, in addition to being small in two of three dimensions. The most popular configuration for the study of this case is a geometrically regular cross-pile of square long sticks, known as a crib. Cribs have been used for more than 40 years as a standardized configuration for determining values of $\dot{m}_p$. Folke[148] reported experiments from the early 1930's of wood cribs burned in the ambient atmosphere. Gross[149] did a systematic study and first recognized that crib fires can be of two types. If the openings between the sticks are sufficiently large, then in this "sparsely packed regime" the crib behaves as if it almost consisted of isolated sticks, save for the complications introduced by radiation. If the sticks are close together, then in such a "densely packed regime" the rate of $\dot{m}_p$ is limited by the pipe flow condition and is less then it would be for widely separated sticks. Thomas[150] has reviewed most of the experimental work on cribs burned in the ambient atmosphere. Block[135] has studied the theory of pipe flow limited burning of cribs in the ambient atmosphere and provided correlations for wood cribs.

Taking the results obtained by Yamashika and Kurimoto[263] as indicative, the mass loss rate for sparsely packed wood cribs follows the form of Equation 6.37 and is

$$\frac{\dot{m}_p}{M_o} = \frac{0.027}{D^{1.6}} \left(\frac{m}{M_o}\right)^{1/2} \quad hr^{-1} \tag{6.39}$$

It is striking to note that the above equation can be expressed in terms of an equivalent regression rate,

$$v_p = 0.007\ D^{-0.6} \quad mm/hr \tag{6.40}$$

which is almost identical to the one derived for large panels.

The final stage of complexity involves spacing the sticks in a crib so closely together that the rate of pyrolysis becomes limited by the rate that gases can flow through the openings. The results for this case can be expressed in the form of a multiplier ψ to Equation 6.39.

$$\frac{\dot{m}_p}{M_o} = \frac{0.027}{D^{1.6}} \left(\frac{m}{M_o}\right)^{1/2} \psi$$

Expressions for ψ have been given by Gross,[149] Block,[135] Yamashika,[263] and others. Block has obtained an expression based on fluid mechanical considerations, thus his value should be preferable to the others which are only data correlations. An approximation to his rather complex expression can be taken as:

$$\psi = 490 \sqrt{hD} \left(\frac{S}{h}\right)^{3/2}$$

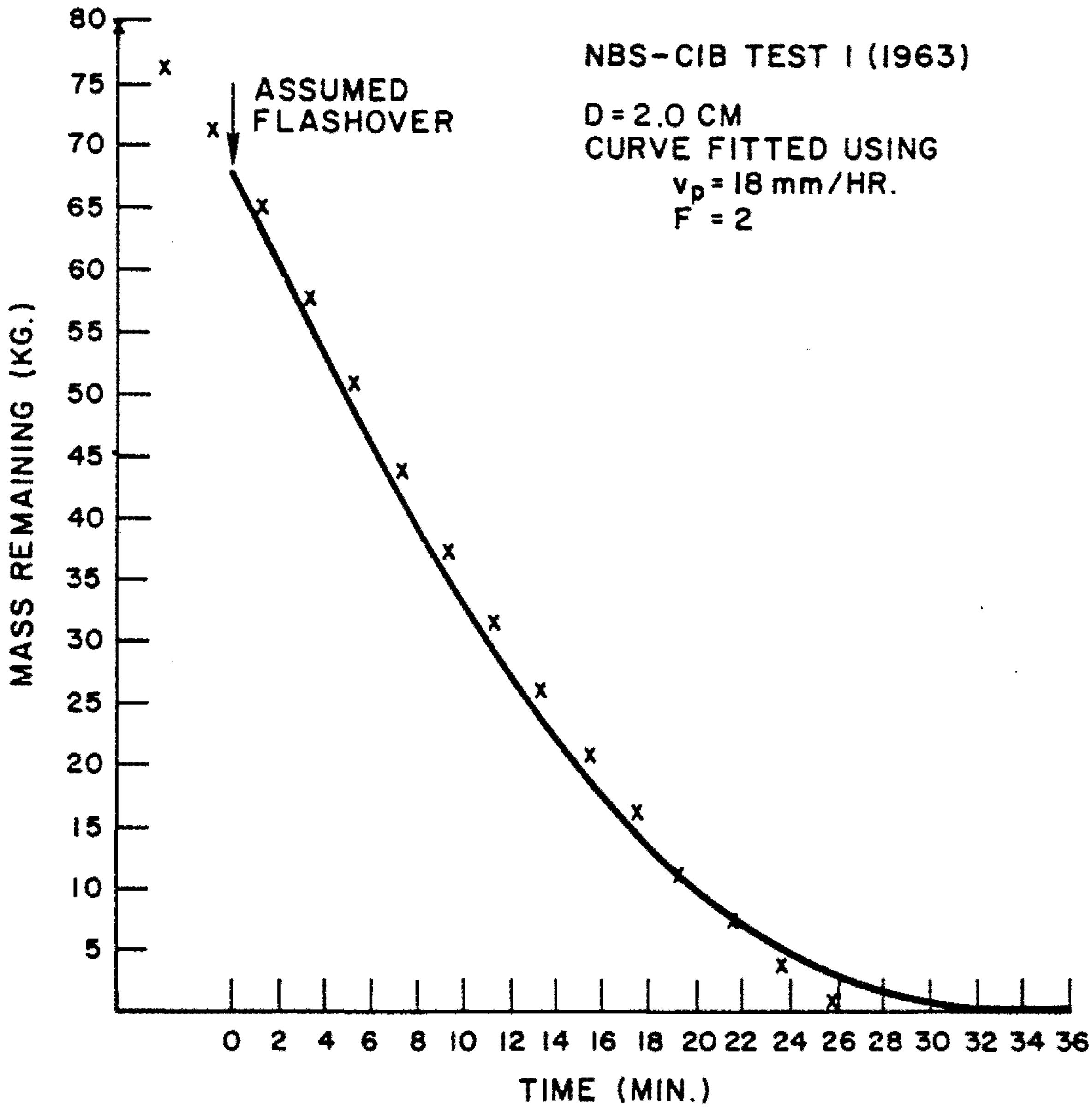


FIGURE 21 TYPICAL MEASURED FUEL LOSS RATES AND A CURVE FITTED USING ÖDEEN'S EQUATIONS

where S = clear spacing between sticks (m)

h = total height of crib (m)

The work on cribs burned in the open is not directly relevant to compartment fires since it represents boundary conditions of ambient values for temperatures and $m_{O_2,\infty}$ which are, by definition, not true after flashover. A more realistic assessment might be gained from burning cribs in flashed over compartments. The most thorough available work is that conducted under the leadership of the Conseil International du Bâtiment Commission W14 and summarized by Thomas and Heselden.[151] In that report the gas temperatures near the ceiling and near the floor, and weight loss of the wood cribs were reported along with a general description of the experiments. Figure 21 shows a comparison between wood crib data gathered by NBS in a compartment test of the CIB series and an expression of the form of Equation 6.39. Other post-flashover crib studies have been reported by Webster, et al,[152,153] Gross and Robertson,[127] Heselden, Smith and Theobald,[154] Magnusson and Thelandersson,[104] Nilsson,[155] and Arnault, Ehm, and Kruppa.[156] The above are only some of the most prominent studies. Practically every fire research laboratory in the world has at one time or another in the last two decades burned wood cribs in compartments.

The fire problem we wish to address is that in the home or office; it is not in the wood crib factory. While there is a certain satisfaction to be derived from being able to predict the pyrolysis behavior of a crib or other simple geometric configuration, for a model to be useful in design it has to represent actual fire conditions. It might be possible to formulate and solve the pyrolysis problem for a realistic load, which is an agglomerate of highly complex shapes. But this would not be fruitful since, in fact, the fuel load changes day to day. The desired model should be sensibly conservative and yet not complex. A fully operational one will require both detailed stochastic fuel load data and a more advanced model of fuel pyrolysis. The few studies on furniture in post flashover presently available[157,158] have not yielded generally applicable results.

In the meantime, Ödeen's approach for a crib theory can be used by judiciously assigning equivalent geometrical properties to the actual fuel to provide the required data. One can

a. identify the total fuel load per floor area,

b. estimate the average thickness of the fuel elements,

c. provide, if desired, any correction for dense packing.

In the following discussions and calculations the fuel loss terms will be based on Ödeen's work. The possible effects of non-cellulosic fuels will only be discussed qualitatively.

6.1.4. Numerical Solution for Fire Gas Temperature

A. The Heat Balance Equation

The gas flow terms and the $\dot{h}_c$ term have already been treated in the previous sections. The two terms remaining to be examined are $\dot{Q}_W$ and $\dot{Q}_R$. Looking at $\dot{Q}_W$, the wall loss term, it can be observed that the heat transfer to the walls occurs by two mechanisms: radiation and convection. Both mechanisms are extraordinarily complex. Siegel and Howell[159] set forth some of the intricacies involved in radiant energy transfer within compartments, while Ostrach[160] considers convective flows.

Both problems are not beyond the possibility of solution. Given unlimited computing capacity quite satisfactory inroads could be made.

However, we wish to work toward post-flashover approaches that are practical in addition to being theoretically acceptable, and unlimited computing capacity is not practical. The real question is how well can we do in roughly representing these process by only a few variables. At the moment, the problem is best approached by considering the walls of the room to be portions of an infinite plane. This gives the following expression:

$$\dot{Q}_w = A_w\left[\sigma\left(\frac{1}{\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_w} - 1}\right)\left(T_f^4 - T_w^4\right) + h(T_f - T_w)\right] \qquad (6.41)$$

where

ε_f = emissivity of fire gases

ε_w = emissivity of walls

T_w = wall surface temperature

h = convective coefficient

A_w = area of the walls

σ = Stefan-Boltzman constant

To get gas emissivity it is desirable to make the customary engineering approximation and treat the gas as grey. The gas emissivity can be broken down into two components. First, a certain contribution to emissivity, ε_{fb}, comes from band radiation of CO_2 and H_2O. For them the customary Hottel charts[161] can be used. Second, in fires a significant component of emissivity comes from soot. It can be expressed as

$$\varepsilon_{fs} = 1 - e^{-kx_F} \qquad (6.42)$$

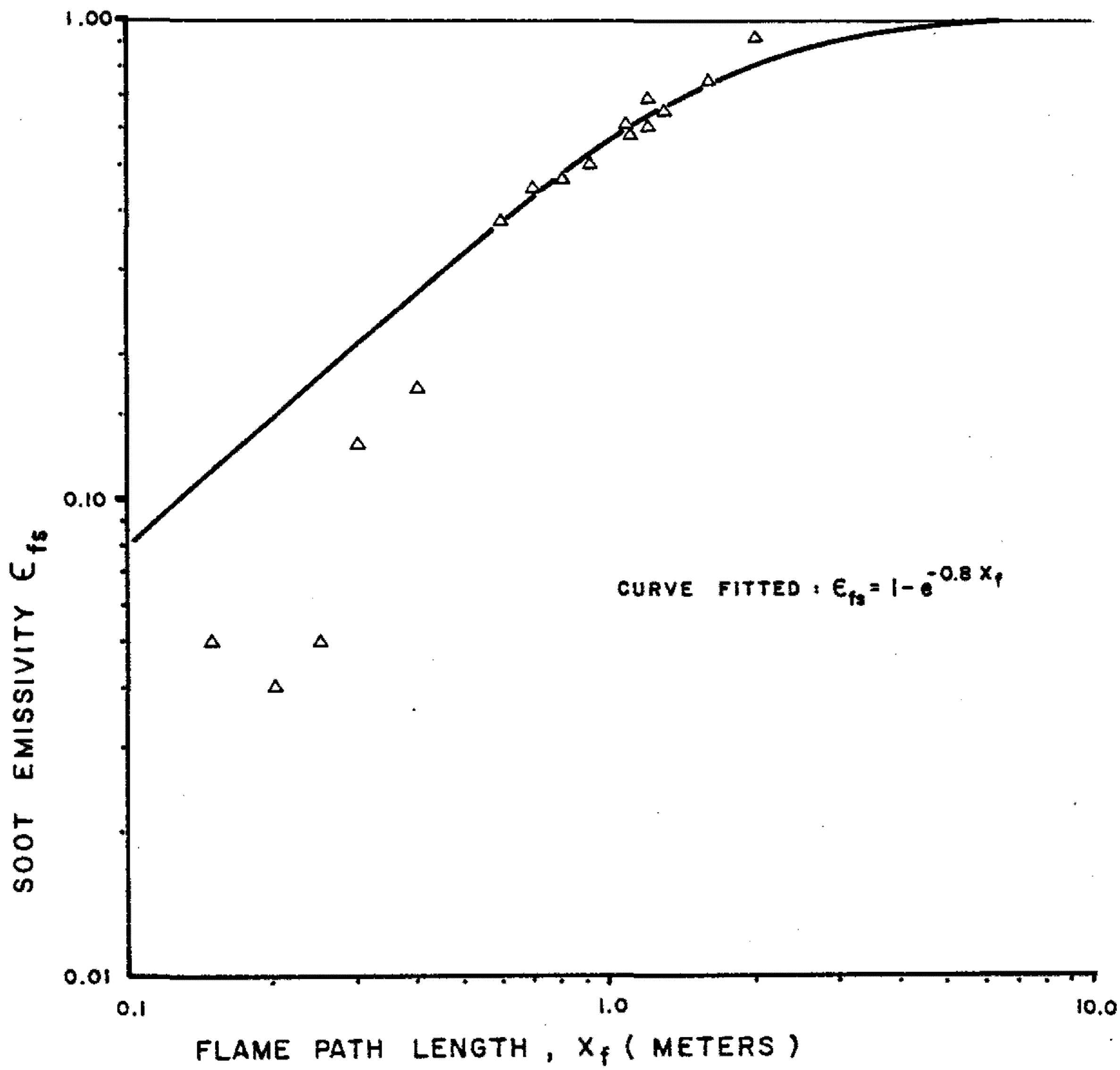


FIGURE 22 EMISSIVITY OF WOOD CRIB FLAMES

where x_f = flame thickness (m) and k is an absorption coefficient which depends mainly on the smokiness of the fuel. The total emissivity is obtained according to an equation developed by Yuen and Tien:[162]

$$\varepsilon_f = \varepsilon_{fs} + \left(1 - \varepsilon_{fs}\right) \varepsilon_{fb} \tag{6.43}$$

The k values are therefore needed for different fuels. Thus far the collection of these data have been meager, but the following values, albeit far from definitive, are available for diffusion flames.

Material	Investigator	k (m^{-1})
diesel oil	Sato[164]	0.43
polymethylmethacrylate	Yuen[162]	0.5
wood cribs	Hägglund[163]	0.8
assorted furniture	Fang[165]	1.13
polystyrene	Yuen[162]	1.2
city gas (46% H_2, 16% CH_4)	Sato[164]	1.5

Figure 22 illustrates how ε_{fs} varies with path length for wood fuel. For compartment sizes greater than 2-3 m the ε_{fs} and therefore ε_f is very close to 1.0. For slightly smaller sizes ε_{fs} dominates over ε_{fb}, while for values less than about 1 m it is desirable to take both into account, as indicated above. For full-size compartments, therefore, it is adequate to set $\varepsilon_f \simeq 0.9$, but for smaller models or for furnaces care must be exercised. The high absorption for city gas is striking and appears to be a particle size effect since Sato's values for diesel oil and city gas were taken for conditions of $\phi = 1.0$ and for both the volume fraction of soot was approximately 0.4×10^{-6}. Leaner mixtures produced somewhat less soot.

For convection the simplest expressions are the ones for turbulent flow of gases over cooled infinite vertical or horizontal plates. McAdams[166] gives them for horizontal surfaces as:

$$h = 1.31 \left(T_f - T_w\right)^{1/3} \quad \text{kcal/hr-m}^2\text{-°K} \qquad (6.44a)$$

and for vertical surfaces as:

$$h = 1.12 \left(T_f - T_w\right)^{1/3} \quad \text{kcal/hr-m}^2\text{-°K} \qquad (6.44b)$$

Further, the numerical coefficients in the above equations are themselves dependent on the thermal properties of the gas and thus are temperature dependent. Paulsen[167] gives a more detailed expression which takes into account this dependence. It appears, however, that under post-flashover conditions in fact the convective transfer is greater than the above equations would specify. The discrepancy can be attributed to the fact that combustion flows in a compartment are characterized by plumes, jets, and large-scale turbulence, whereas the above empirical equations come from measurements of undisturbed boundary layer flows. For forced flow turbulent jets measurements indicate that convective coefficients in excess of $h = 200$ kcal/hr-m²-°K can be found. The values are much less for low velocity natural convection but exact details cannot be specified without sacrificing the well-stirred reactor assumption.

The final term that is needed is $\dot{Q}_R$, the window radiation loss. Viewed from the outside world the window of the room can be thought of as representing a small aperture in a cavity. Such a cavity is intrinsically a black body when viewed from the outside, thus its emissivity is equal to 1.0. It is most convenient to set T_o equal to ambient temperature, even though at some times the window might be viewing a dark sky. Then:

$$\dot{Q}_R = A_V\sigma\left(T_f^4 - T_o^4\right) \tag{6.45}$$

where A_V = area of the window.

Now, combining all the above terms in the heat balance equation gives:

$$\dot{m}_{air}C_{po}T_o - \dot{m}_f C_{pf}T_f + \dot{h}_c = \dot{Q}_w + \dot{Q}_R \tag{6.46}$$

Evaluating all those except h_c and using the relation that:

$$m_{air} = \frac{2}{3} C_d \frac{W_o}{RT_o}\left(A_v\sqrt{h_v}\right)\left[2g \frac{1 - \frac{W_f T_o}{W_o T_f}}{\left[1 + \left(\frac{W_o T_f}{W_f T_o}\left[1 + \frac{\phi}{r}\right]^2\right)^{1/3}\right]^3}\right]^{1/2} \tag{6.47}$$

gives the desired final heat balance equation

$$m_{air}\left[C_{po}T_o - \left(1 + \frac{\phi}{r}\right)C_{pf}T_f\right] + h_c = A_W\,\sigma\left[\frac{T_f^4 - T_W^4}{\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_w} - 1}\right] \tag{6.48}$$

$$+ A_W\,h\left(T_f - T_W\right) + A_v\,\sigma\left(T_f^4 - T_o^4\right)$$

The above heat balance equation plus the wall conduction equation are then the two equations which must be solved.

B. Computer Calculations

Kawagoe[168] was the first to develop a computer program for calculating fire histories. He treated only the ventilation-controlled regime. After the end of the ventilation-controlled phase, he assumed that the gas temperature fell linearly back to the ambient. Magnusson and Thelandersson[104] have taken an essentially similar approach in that they only analyzed ventilation-controlled fires. They used an empirical curve of $\dot{h}_c$ which varies with time as an input parameter. Fedock[169] has also produced a program using Magnusson's model. Tsuchiya[170] was the first to analytically treat both regimes (although he did assume that fires perforce begin by being ventilation-controlled). His work represented the starting point for the current development.

They theory discussed above has been incorporated into a FORTRAN program by Babrauskas,[171] and is especially intended for design flexibility. Some additional aspects of the program COMPF that are not evident from the basic equations alone must now be examined.

The two equations which are to be simultaneously solved are the gas-phase heat balance and the heat conduction through the walls. Taking the latter first, we must solve

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \dot{q}''' \qquad (6.4)$$

where $\dot{q}'''$ can represent heat per unit time per unit volume that is being generated within the wall itself if it is combustible. For calculational purposes, transforming Equation 6.4 into finite-difference form, per unit area, gives

$$\dot{q}_{stored} = \dot{q}_{in} - \dot{q}_{out} + \dot{q}_{gen} \qquad (6.49)$$

for each thickness slice (see Figure 13). Then

$$\rho C_p \frac{T_{i,t+1} - T_{i,t}}{\Delta t} = \dot{q}_{in} - \dot{q}_{out} + \dot{q}''' \qquad (6.50)$$

The term $\dot{q}_{in}$ (and $\dot{q}_{out}$) can be treated in three different ways. It can be evaluated at the previous time step:

$$\dot{q}_{in} = -\left(\frac{k_{i-1} + k_i}{2}\right) \quad \frac{T_{i,t} - T_{i-1,t}}{\Delta t} \tag{6.51}$$

This method has been the most widely used thus far. It gives an explicit solution at each step in space and time. The explicit method has the unfortunate drawback that it can easily diverge. Chao[172] proves that the second law of thermodynamics is violated unless

$$\frac{k}{\rho C_p} \quad \frac{t}{(\Delta x)^2} < \frac{1}{2} \tag{6.52}$$

Another way is to evaluate the term at the current step:

$$\dot{q}_{in} = -\left(\frac{k_{i-1} + k_i}{2}\right) \frac{T_{i,t+1} - T_{i-1,\ t+1}}{\Delta x} \tag{6.53}$$

This requires a matrix solution at each time step since the temperatures are now only implicitly given. The implicit method is always convergent.

Finally, the term may be averaged over the prior and the current step:

$$\dot{q}_{in} = -\left(\frac{k_{i-1} + k_i}{2}\right) \frac{T_{i,t} + T_{i,t+1} - T_{i-1,t} - T_{i-1,t+1}}{2\Delta x} \tag{6.54}$$

This method, called the Crank-Nicolson method, gives the best convergence properties.[173] It also requires a matrix solution.

A slightly different condition is obtained at the wall boundaries. Considering the fire side, $\dot{q}_{in}$ has to be modified to account for the radiation and convection:

$$\dot{q}_{in} = \sigma\varepsilon\left(T_f^4 - T_w^4\right) + h\left(T_f - T_w\right)$$

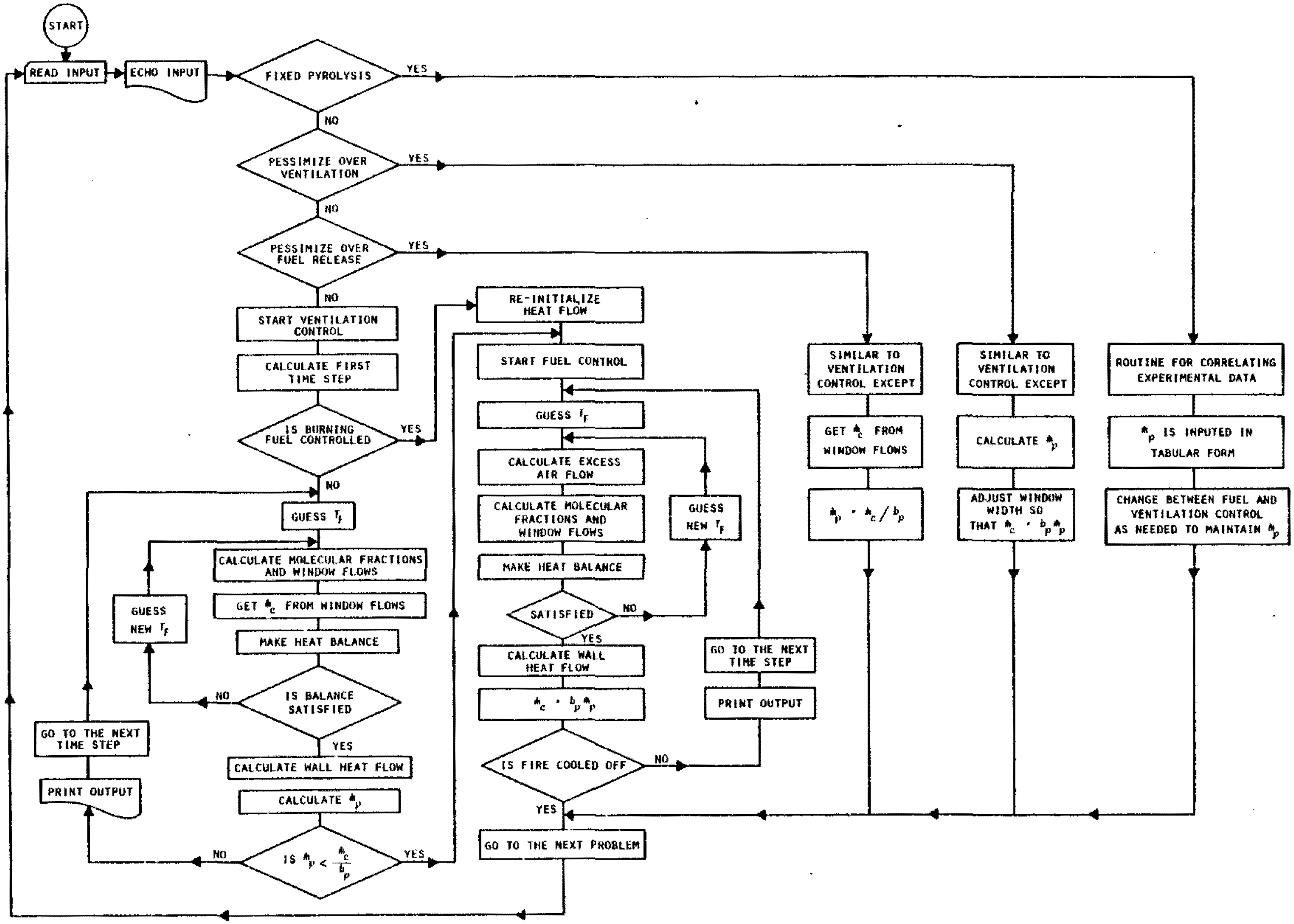


FIGURE 23 FLOW CHART FOR PROGRAM COMPF

Thus, we get a tridiagonal set of equations, the same in number as the count of wall slices, but with some nonlinear terms. Since reasonable matrix solution methods (e.g., Gauss-elimination) are available only for sets of simultaneous linear equations, the set should be linearized. This can be done by letting

$$\dot{q}_{in} = h' \left(T_f - T_w\right)$$

where:

$$h' = h + \sigma\varepsilon \left(T_f^3 + T_f^2\, T_w + T_f\, T_w^2 + T_w^3\right)$$

and all the temperatures in h' are already known. The solution requires several steps of iteration; but as will be shown below, since there is already an interation required at each time step the h' interation can also be done simultaneously. It has been found that since Δt can be significantly increased in the matrix methods, overall computation time savings usually result compared to the explicit method. The so-called unconditionally-stable variants of the explicit method are not, on the other hand, adequate since they cannot treat non-linear boundary conditions in a stable manner. Furthermore, the convergence criterion given above for the explicit methods would take an entirely different form at the boundaries.

The simplified conceptual flow chart of the entire program is shown in Figure 23. The operation is as follows: input consists of the description of the room and the fuel. Included is a provision for temperature-dependent wall thermophysical properties. The input is echoed and operating constants pre-set. Next, the mode of operation has to be fixed. There are four possible modes:

1. Deterministic time-temperature curve, with automatic selection of ventilation or fuel control.
2. Fixed ventilation and wall properties, with pessimization over the instanteous fuel release rate.
3. Fixed fuel pyrolysis behavior and wall properties with pessimization over the ventilation. This is done by keeping a constant window height but varying the width instantaneously to maximize the gas temperature. The window width can thus either increase and decrease with time, with the restriction that it not exceed a given maximum width.
4. A checking mode for using experimentally determined $\dot{m}_p$ values as a tabular input function of time.

The second and third modes of operation involve a process defined as "pessimization" which will be discussed later. Pessimization can be viewed as a mode of operation in which certain variables are not specified as input, but are rather adjusted to those values that will produce the worst fire. Thus, the process increases generality of the results by eliminating variables and represents a particularly useful mode of operation for designers to find a fire equal to or worse than that occurring under several design variable combinations.

All four of these routines are used in a similar manner and since they are similar in their basic principles, only the ventilation control calculations will be outlined. The wall temperature profile is initially set equal to ambient. A starting value for T_f at $t = 0$ is guessed. The initial pyrolysis rate is determined. The molecular fractions of the fixed gases can then be determined. It is assumed that all carbon goes

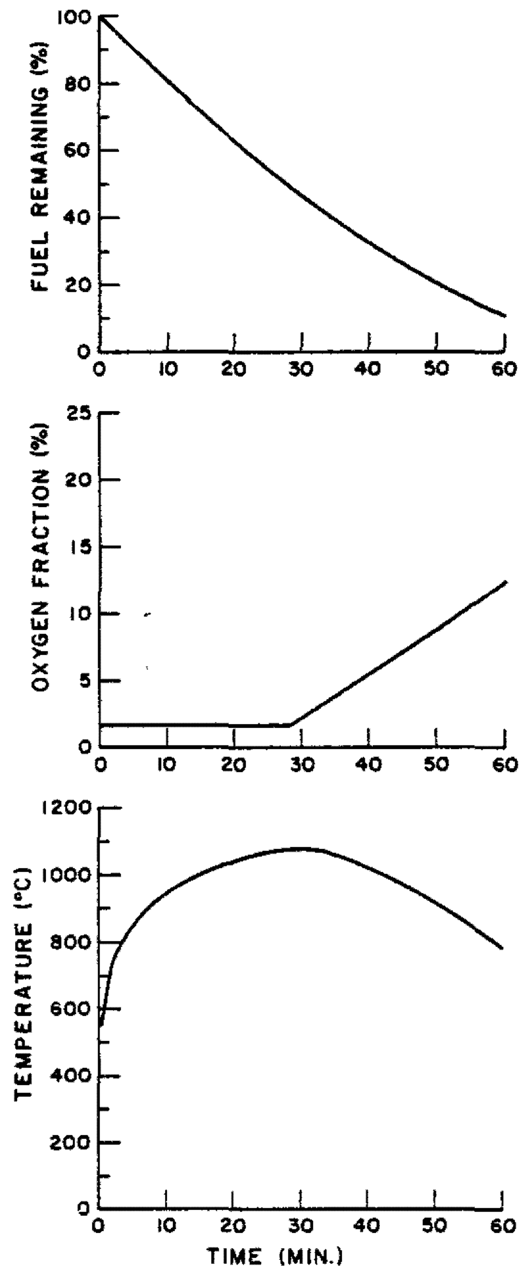


FIGURE 24 TYPICAL PREDICTED FIRE HISTORY

into CO_2 since the effect of CO on the heat balance is small and, furthermore, even complex equilibrium calculations will not give reliable CO fractions. From the calculated molecular weight and the known gas temperature, the window flows can be obtained. The heat balance is solved for T_f from the wall radiation term. If the solved and guessed values do not agree well enough, a new trial is made. After convergence is reached (beyond the initial few time steps, it normally takes about 2 to 5 iterations for 2° C accuracy), a new wall temperature distribution is obtained using the Crank-Nicolson method. A new value of $\dot{m}_p$ is calculated. If $\dot{m}_p < b_p \dot{m}_c$ a switch to fuel control is made. Printing, punching, and plotting are provided at specified intervals.

A typical calculated time-temperature curve is shown in Figure 24 as well as the oxygen mole fraction and the fuel remaining. The burning changes from ventilation to fuel controlled at 29 minutes, at which point the peak temperature is reached. Temperatures decrease after that while the oxygen level rises above the low value which was characteristic of ventilation control. Temperatures are lower in the ventilation control regime, prior to the switch-over peak, since the walls are still heating up. The excess pyrolysate effect on lowering the temperature is usually much smaller than that of the wall losses. After the peak, when burning is fuel limited, temperatures start dropping because excess air is flowing through the compartment.

C. Comparison with Experiment

The computer calculations described above generally compare well with experiments. It must first be realized that there is normally wide scatter of data in compartment burn experiments even under very closely

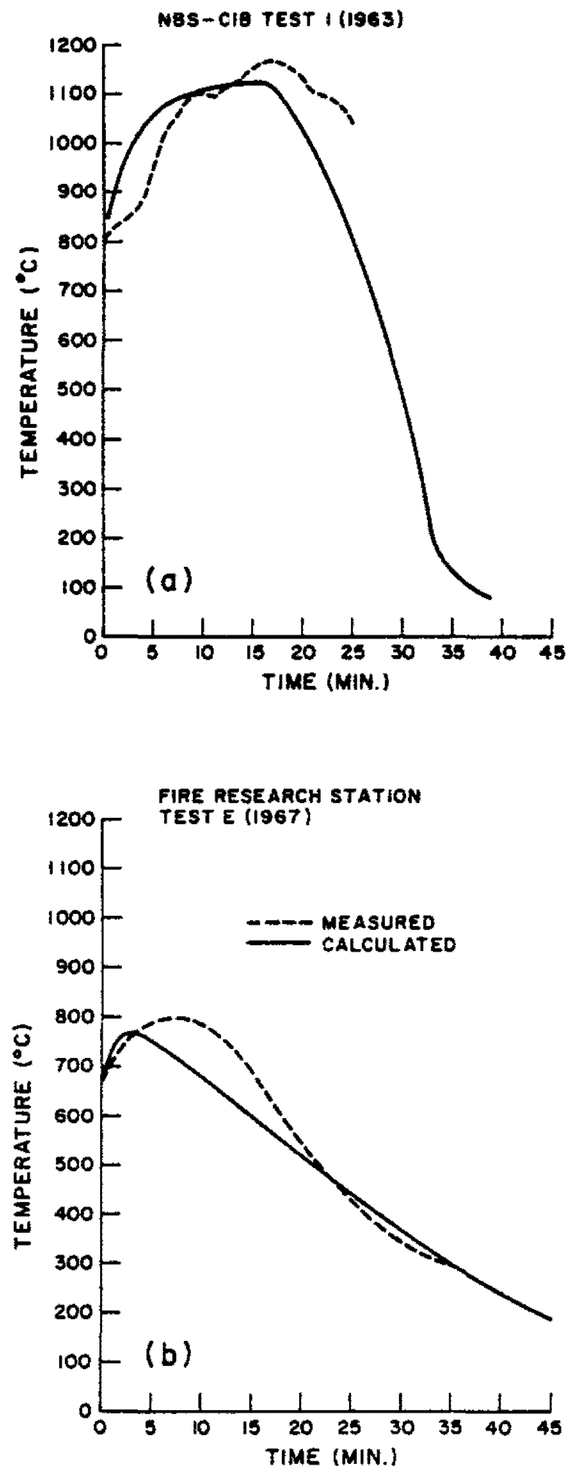


FIGURE 25 COMPARISON OF THEORY WITH EXPERIMENTS FOR A SMALL SCALE AND LARGE SCALE FIRE

controlled laboratory conditions. Using realistic fuel loads the scatter becomes much greater. Thus agreement better than perhaps 20% would be illusory or coincidental.

Figure 25 illustrates predicted versus measured gas temperatures in the upper portion of two compartments. Figure 25a shows the results for a wood crib burned in a 1 m high asbestos millboard compartment by the National Bureau of Standards.[174] Figure 25b shows the results for a wood crib burned in a 3 m high insulating plaster compartment by the Fire Research Station.[175] The fuel loss rates for the NBS test are shown in Figure 21, where it can be seen that an expression of the type used by Ödeen can provide a good empirical fit.

In developing the computer program the results of a number of compartment burn experiments were compared to those predicted by the program and the agreement illustrated in Figures 21 and 25 is typical. It is regrettable that at the present time no useful data are available for other than wood fuel. For wood crib burns one of the best instrumented series is that conducted by Croce[176] at Factory Mutual Research Corporation. A comparison of his data with the predictions generated by program COMPF is given in Appendix C.

D. Effect of Major Variables

One of the most useful applications for the computer model is to perform a number of simulations and examine the influence of the various choices open to the designer. First, however, it is necessary to illustrate the effects of varying some of the major variables that are not strictly at the designer's disposal.

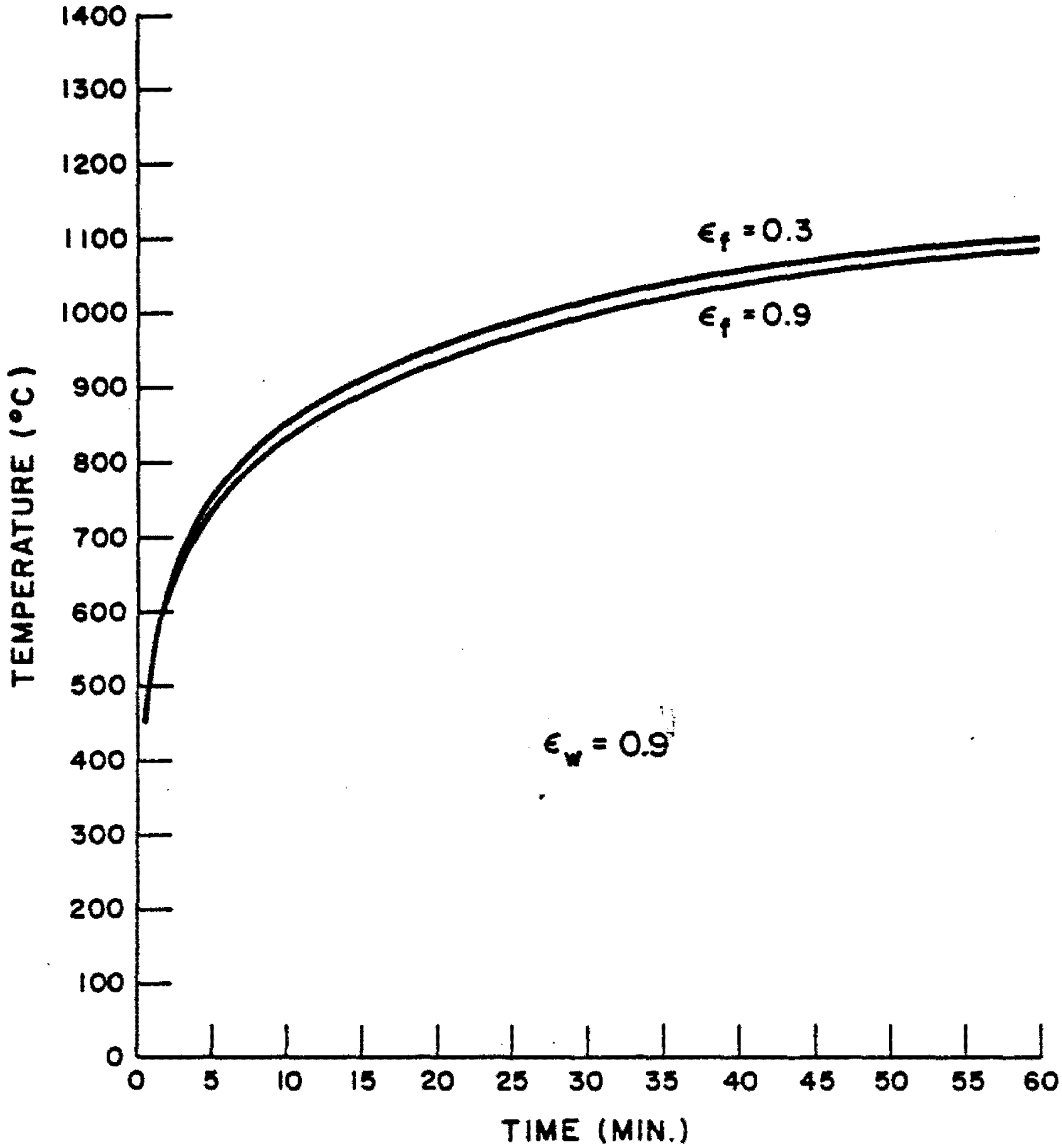


FIGURE 26 EFFECT ON GAS TEMPERATURE OF VARYING FLAME EMISSIVITY

1. Scale Effect: If the window height is kept constant while the window area and wall area are both scaled by a given factor, the time-temperature curve is unchanged. This is strictly true only if the fuel load per total A_w, rather than per floor area, is kept constant. This is the reason why in some countries, notably Sweden, fuel load data has been collected on a basis of total room wall, rather than floor area. Under most practicaly scale variations, however, the ratio of the floor to the total areas will not change significantly. Thus, in general, the scale effect is minor.

2. Window Radiation: First, consider a case where all the walls of the compartment are adiabatic. Then, window radiation is the only source of losses, i.e., the reason why temperatures are not equal to the adiabatic flame temperature. If, in addition, the fuel is forced to burn at the quasi-stoichiometric condition, the temperatures are then constant over time. The gas temperature will usually be around 1200-1400° C. This value depends on the fuel composition and on the window height, h_v, but *not* on the window area. Doubling the window width will double both the radiation losses and the combustion rate; therefore, the temperatures will be unchanged.

3. Emissivities and Convective Coefficient: The effect of ε_f and ε_w can be considered simultaneously since they enter into the equations symmetrically. If the gas temperature curve were to be prescribed and ε_f varied over a large range, then there would be significant differences in the heat flow through the wall. If, however, the gas temperature is obtained from solving the heat balance equation, then the effects are minimal, as illustrated in Figure 26. The wall heat flows show similarly slight variations; decreased ε_f gives higher T_f, and the radiation to the wall tends to remain constant, which accounts for

the minimal variations in the latter case. The effects of varying the convective coefficient h are smaller and take place mainly at lower temperatures. On the other hand, since the ambient air temperature is prescribed, variations in h and ε_w at the unexposed face have a significant effect on wall temperatures in the vicinity of the rear face.

4. Wall Losses: The wall heat flow equation does not have any simple analytical solution. Certain approximations are revealing and useful for understanding this aspect of compartment fires; several groups of physical parameters can be identified that are dominant in the early, middle and later portions of a compartment fire.

a. At the early stages of a fire, just after flashover, the fire will start heating a cold wall. If we consider the initial heating of a thick slab by the convection, then

$$\frac{T_w(0) - T_\infty}{T_f - T_\infty} = 1 - e^{Bi^2 Fo} \ \text{erfc} \ (Bi\sqrt{Fo}) \tag{6.55}$$

where:

$$Fo = \frac{k}{\rho C_p} \ \frac{t}{L^2} = \text{Fourier number}$$

$$Bi = \frac{hL}{k} = \text{Biot number}$$

and L is the slab thickness, which in fact cancels from the $Bi\sqrt{Fo}$ group. If $t \simeq 0$, then $Fo \ll 1$, and

$$\frac{T_w(0) - T_\infty}{T_f - T_\infty} \simeq \frac{Bi\sqrt{Fo}}{\pi} = \frac{h}{\pi}\sqrt{\frac{t}{k\rho C_p}} \tag{6.56}$$

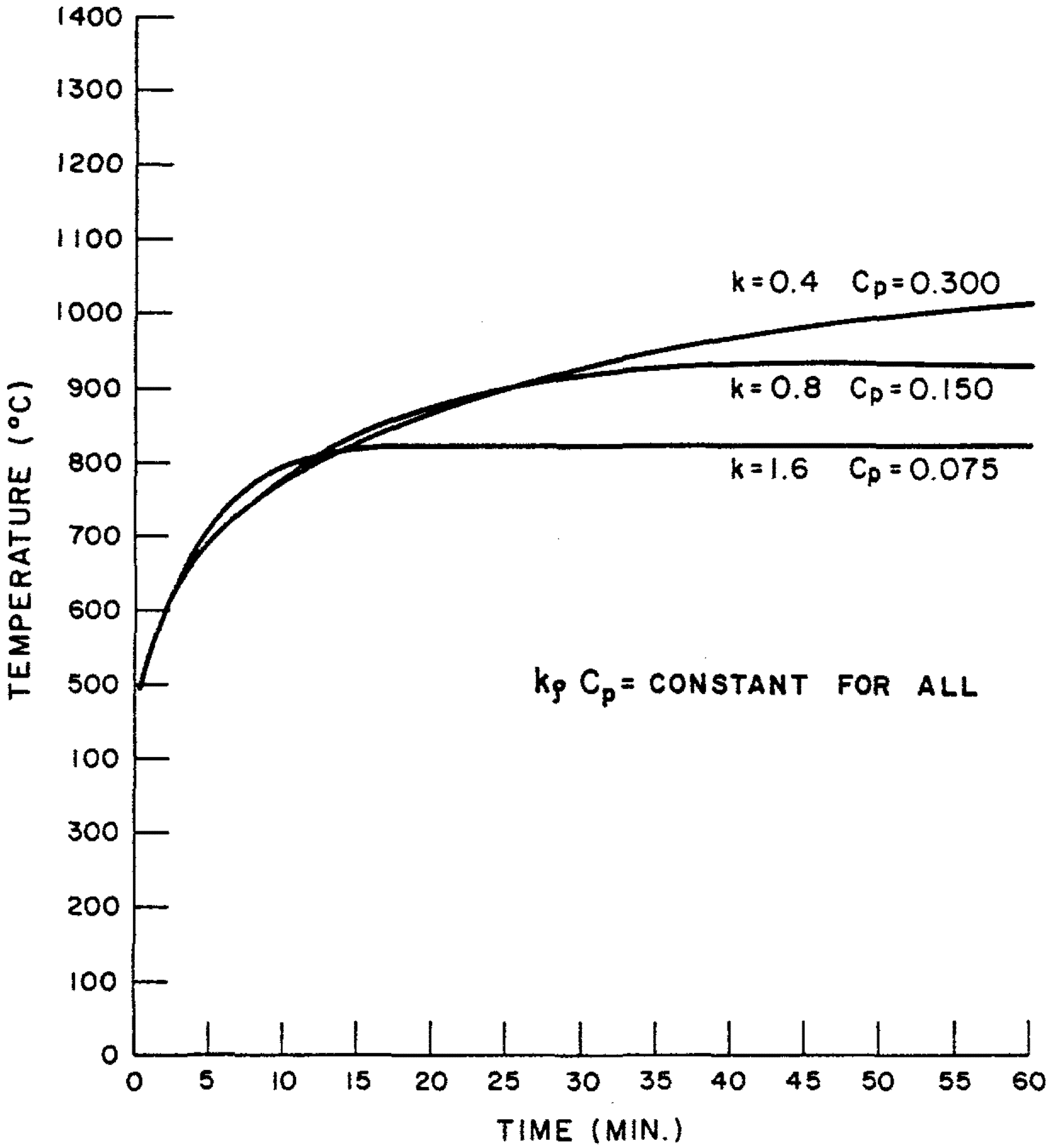


FIGURE 27 EFFECT ON GAS TEMPERATURE OF VARYING WALL k AND C_p

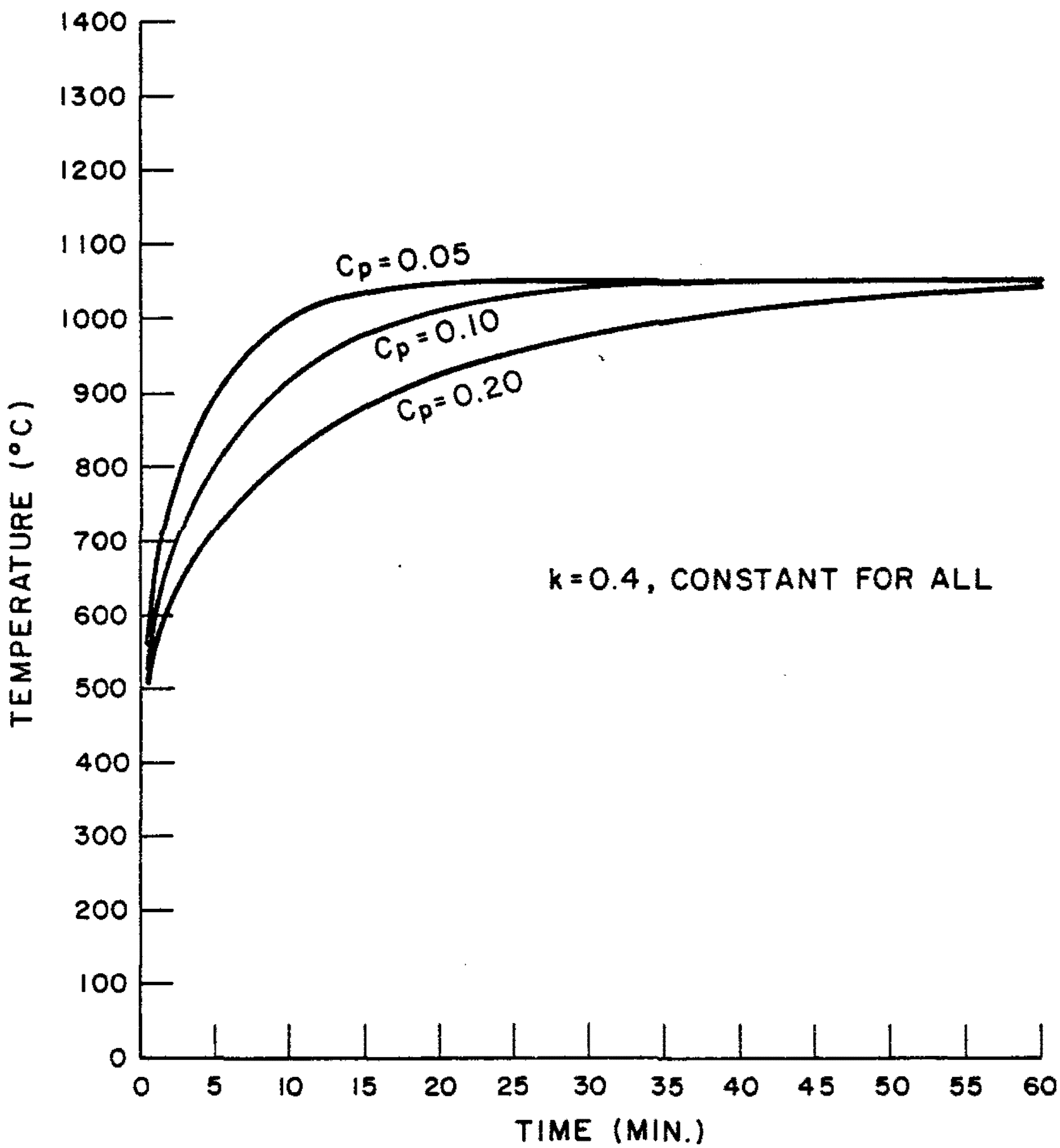


FIGURE 28 EFFECT ON GAS TEMPERATURE OF VARYING WALL C_p

Therefore, the variable of importance at the beginning of a fire is the group $k\rho C_p$, which has been termed the "thermal inertia." Initially, the wall temperature at the exposed face rises in inverse proportion to the square root of the thermal inertia. Lowering either k or ρC_p will increase the heating of the front of the wall, which will result in decreased wall losses and higher gas temperatures. This is illustrated in Figure 27 where three possible time-temperature curves are shown with different values of conductivity, k, and heat capacity, C_p, but constant $k\rho C_p$. Note that they diverge after the first fifteen minutes, with the low conductivity walls producing a 200° C higher gas temperature at 60 minutes.

b. At the later stages of a compartment fire, the bounding walls play an entirely different role. Consider the wall temperatures in a final steady state distribution (a steady wall temperature distribution will, of course, not be reached if fuel is exhausted rapidly). Then the time-varying terms drop out, and

$$\frac{T_w(0) - T_\infty}{T_f - T_\infty} = 1 - \frac{1}{1 + \frac{h_f L}{k} + \frac{h_f}{h_\infty}} \tag{6.57}$$

As expected, value of the heat capacity ceases to be important. This is illustrated in Figure 28, where the curves approach the same final temperature although the heat capacities of the walls vary by a factor of four. Conversely, the effect of varying thermal conductivity

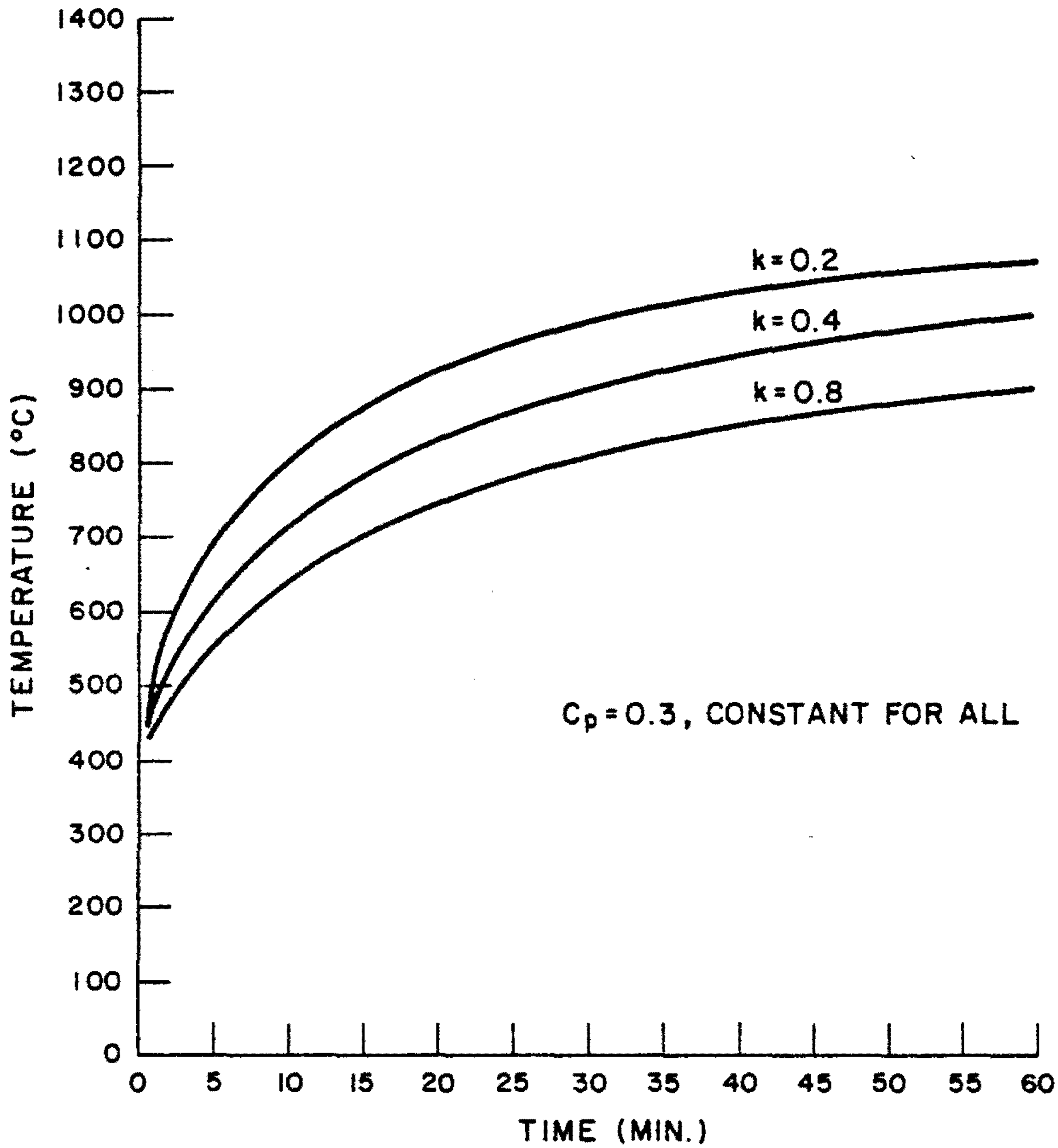


FIGURE 29 EFFECT ON GAS TEMERATURE OF VARYING WALL k

can be seen in Figure 29.

c. In the most general case, neither soon after flashover nor at steady state, no simplification is possible. The governing groups of variables include both the Fourier number and the Biot number, but they are not--as in case (a)--combined in such a manner as to permit simplification. For heat transfer by convection only, with constant properties and constant h, standard solutions[177] are available and can be plotted as so-called Heisler charts.

All of these considerations are brought together in Figure 30 where the governing wall properties are shown schematically for the early, middle and late periods of a compartment fire. As noted above this does not take into account any temperature decreases due to depletion of fuel. Wall thermal properties potentially could be varied by the designer, but other factors such as cost and aesthetics usually outweight the thermal performance in actual design decisions.

The effects of several major groups of variables have now been outlined in addition to the basic $\dot{h}_c$ and $\dot{m}_{air}$ dependences shown earlier in Figure 20. In the next section the effects of ventilation and fuel load will be explored in the context of design utilization of the expected fire model.

6.2. Design Fires

6.2.1. Deterministic Design

A straightforward application of the principles given above can be used to calculate a deterministic fire time-temperature curve. By deterministic is meant that all the required variables are known and are

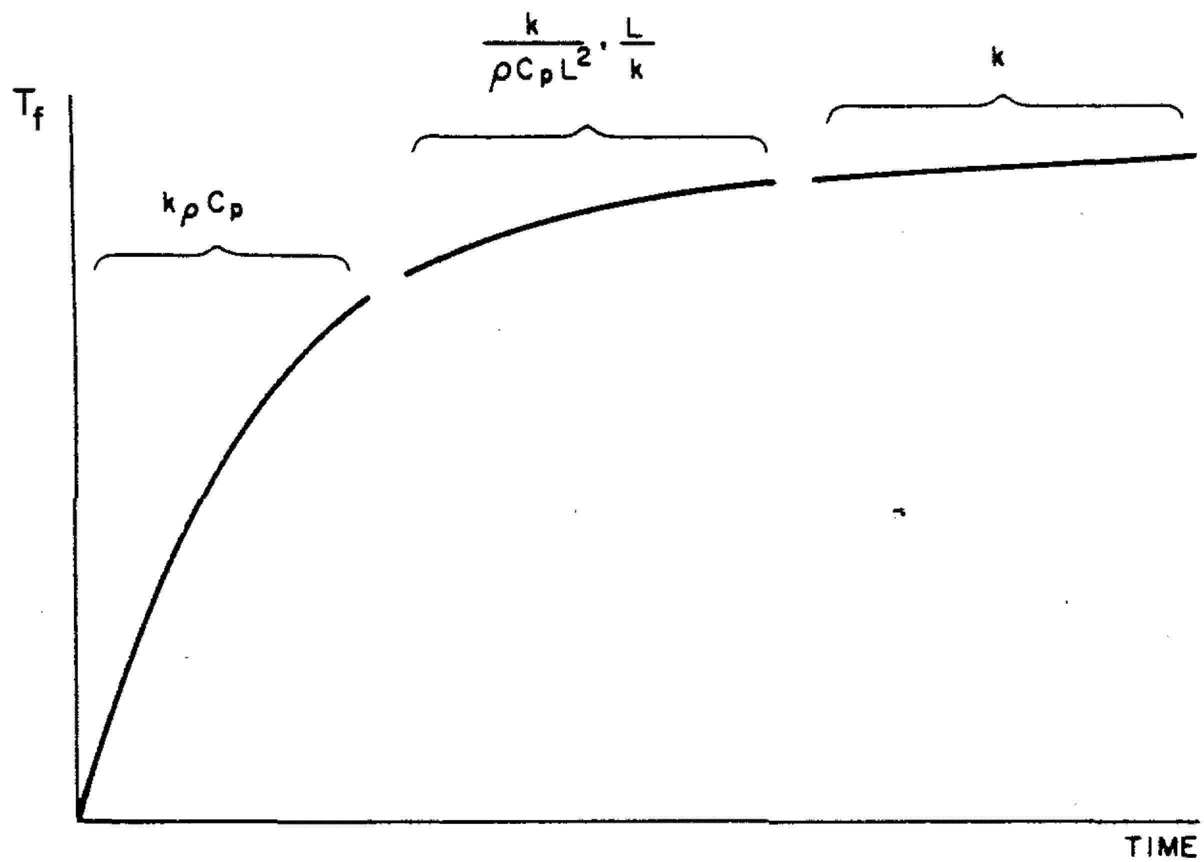


FIGURE 30 GROUPS OF GOVERNING WALL THERMAL VARIABLES

specified. This is an easy curve to calculate and it is quite satisfactory for certain applications, most notably for mass-produced buildings. A case history where the deterministic approach was useful is given in Appendix D.

Difficulties arise when fires in non-standardized spaces are considered or when some required data are missing. In other words, the deterministic approach lacks generality.

Ingberg attempted to introduce generality by inventing the equal area severity concept. This particular concept has been demonstrated to be faulty (section 3.3). Yet it can also be seen that it would be difficult to establish any valid substitute severity concept. The difficulty lies in the coupling of the fire and the material of the barrier. Different classes of materials react in different ways to fire and any rule which focuses only on the fire and ignores the material cannot have general validity.

Normally, the purely deterministic approach can be considered too cumbersome. If a certain assembly is intended to be useable in a variety of design compartments, each with a different time-temperature curve, then in the deterministic procedure the assembly would have to be fire tested a large number of times. To require multiple fire tests of the same assembly is usually economically precluded.

Five alternatives can be seen:

1. Parametrized variable space and a small number of curves.
2. A "pessimization" procedure to reduce the dimensionality of the variable space.
3. A critical temperature approach.
4. Stochastically based designs.
5. Various rules-of-thumb.

The five alternatives are not mutually exclusive and can be intercombined.

6.2.2. Parametrized Design

The simplest method is a parametrized solution. Suppose the designer is willing to accept a design or test fire that is not exactly right but deviates from his actual expected fire by no more than a certain known amount. He then no longer needs an infinity of curves to cover all possible time-temperature courses. By accepting only a small number of curves he will introduce greater uncertainty into his results, but by picking a number significantly greater than one, he will still gain in accuracy, as compared to Ingberg's approach. Four curves might represent a reasonable compromise.

The method in itself is not especially elegant. It becomes more appealing when combined with other approaches. In Section 6.3 an illustration is carried through showing how curves can be obtained that are parametrized over the fuel load and pessimized over the ventilation. The result is an approximate, but technically sound, derivation of the kind of set of curves that Corson[106] was seeking.

6.2.3. Pessimized Design

Since the problem at hand stems from the dimensionality of the problem being greater than desired, a simple and appealing solution can be used to reduce correctly that dimensionality. A method called "pessimization" is offered as a suitable tool. Pessimization is taken to mean a process of reducing the number of variables by continually adjusting one or more to give the most conservative results. Pessimization is analogous, but inverse to, optimization. In optimization the

TABLE 7

PESSIMIZATION ALTERNATIVES

VARIABLES SPECIFIED				
FUEL LOAD	VENTILATION	WALL THERMAL PROPERTIES	FIRE DURATION	TEMPERATURE
---	---	---	Infinite	T_{ad}
YES	---	---	Finite	T_{ad}
---	YES	---	Infinite	T_{ad}
---	---	YES	Infinite	Curve, Very Close to T_{ad}
YES	YES	---	Finite	Usually, Less Than T_{ad}
YES	---	YES	Finite	Curve, Variable
---	YES	YES	Infinite	Curve, Variable
YES	YES	YES	Finite	Curve, Variable (Deterministic)

designer takes the loading as given and varies the structure. In pessimization he takes the structure as given and varies the loading (i.e., fire). Pessimization is not the same as a worst-case approach. In a worst-case approach all the controlling problem variables are adjusted for the worst value. On the other hand, in pessimization, only certain problem variables are adjusted. Limits are placed on the range of the pessimized variables to correspond to expected design limits. The design range for any variable is usually smaller than the total physically possible range.

By a judicious selection of pessimization variables the designer can purge significant dimensions from his problem and thus obtain significant generality at only a moderate cost increment. Figure 31 illustrates, schematically, this effect for ventilation as a pessimized variable. It shows the desirability of pessimizing over variables which do not have a monotonic influence on the design cost, but rather have a shallow maximum.

Consider the three main groups of controlling variables: fuel, ventilation, and wall properties, Table 7. If the problem is pessimized over all of them, then the expected fire is at the adiabatic flame temperature, T_{ad}, and is of infinite duration. This pessimization over <u>all</u> problem variables is indeed the same as the worst-case approach and is of little usefulness. More realistically, one of the variables could be specified and pessimization carried out over the other two. The results are not much more useful. It appears that the most useful approach is to specify two variables and pessimize over the remaining one. It is desirable to specify the wall properties for two reasons: (a) in practical building design there is normally less variation in wall losses than in fuel or window sizes; thus one curve can attain more generality; and (b) if the wall losses are not specified, the temperatures can, near the

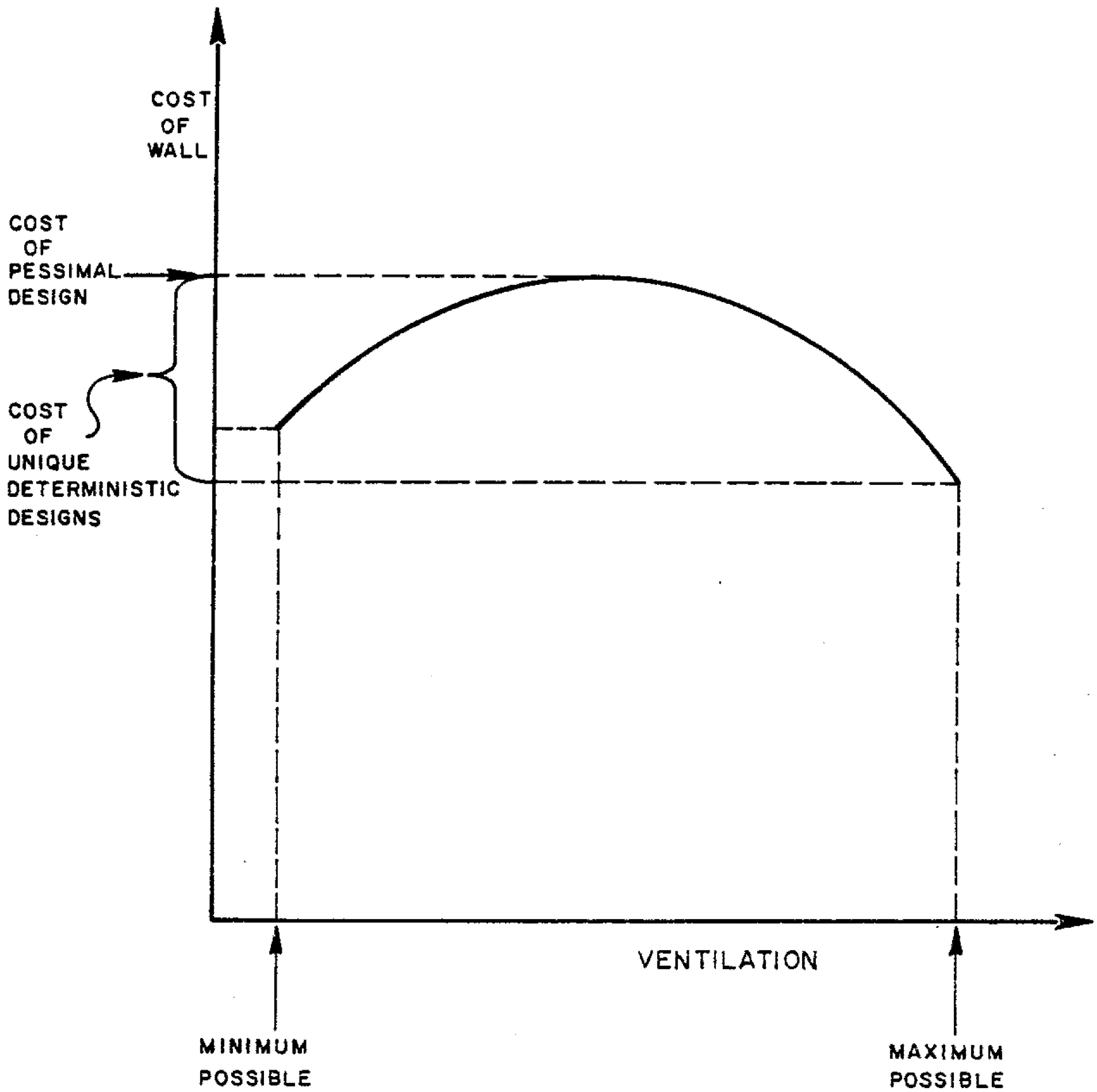


FIGURE 31 EFFECT ON WALL COST OF PESSIMISING VENTILATION

stoichiometric condition, approach very high, near T_{ad}, values. There does not appear to be any *a priori* reason for choosing between specifying fuel or ventilation, whilst pessimizing over the other, but it will become obvious that pessimization over ventilation is more useful.

By following a pessimization process, as outlined above and implemented in the computer program COMPF, a simplified description of the post-flashover fire process is obtained. It is different from most prior methods in that it is not based on assumptions which deny physics as Ingberg's do, nor does it rely on overly simplified approximation. Instead it is based on first obtaining a sufficiently accurate model of the compartment fire and only then making rational design generalizations.

Figures 32 and 33 give examples of the effect of pessimization over fuel load and ventilation, respectively. The effects of varying the wood fuel load and of pessimizing over it are shown in Figure 32. In this illustration the temperatures increase with increasing fuel load. For large loads, especially of easily pyrolyzing polymer fuels, a point would also be reached where increasing fuel load decreases the temperatures. This cannot currently be illustrated because data for $\dot{h}_p$ and the C_p of the excess pyrolysates are not yet available.

Similarly, the effects of changing window width are shown in Figure 33. Here it can be readily seen that either over-ventilating *or* under-ventilating will act to lower temperatures. For the deterministic curves, an intermediate value (4% in this example) gives the results closest to pessimal. This knowledge has significant fire-fighting implications. In Figure 34 are shown two fires; in each case the window width was doubled at 20 minutes. The base fire in Figure 34a was fuel-limited. Breaking out more windows cuts down on intensity. In Figure 34b, however, a fire which was ventilation-limited, as is especially

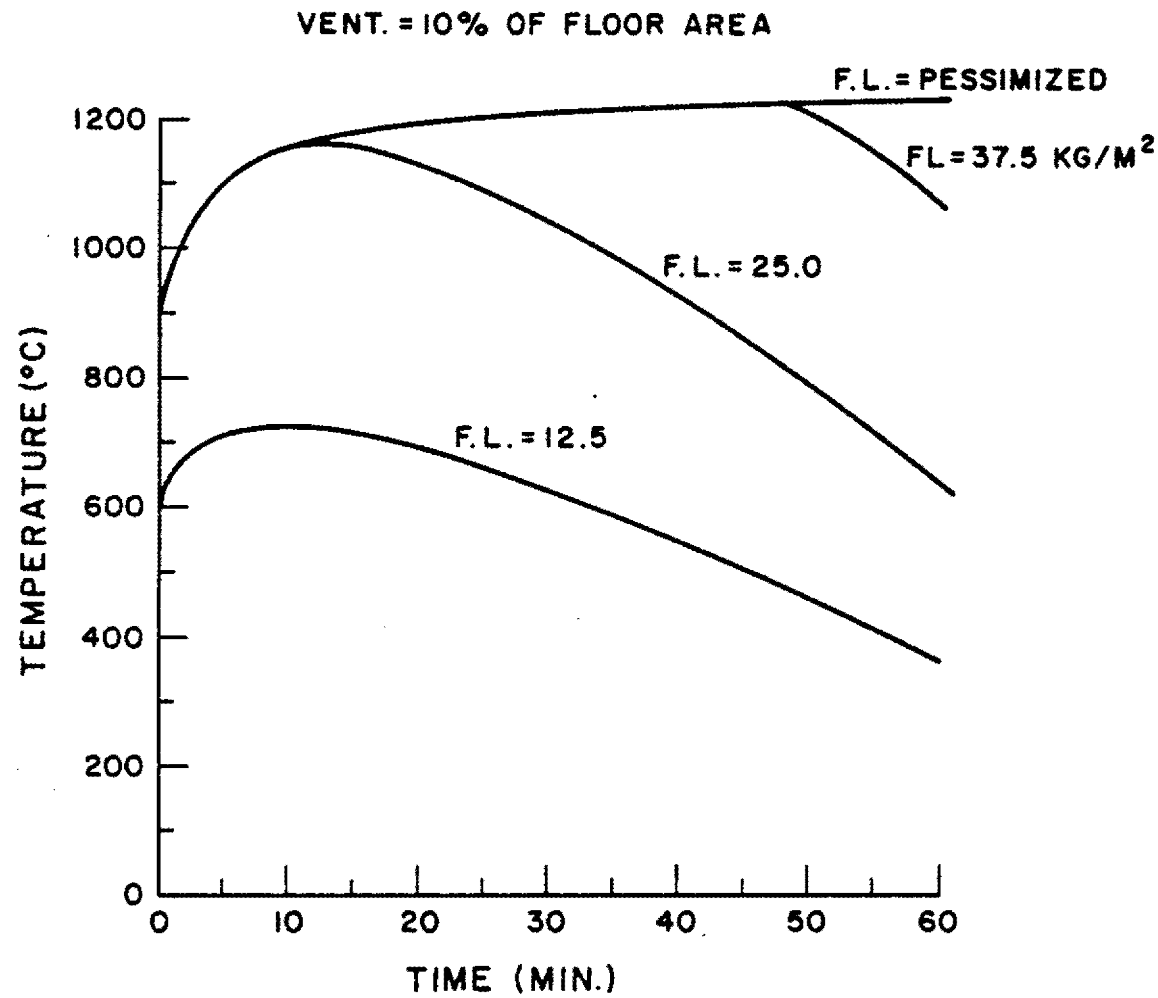


FIGURE 32 EFFECT OF VARYING FUEL LOAD FOR A GIVEN VENTILATION

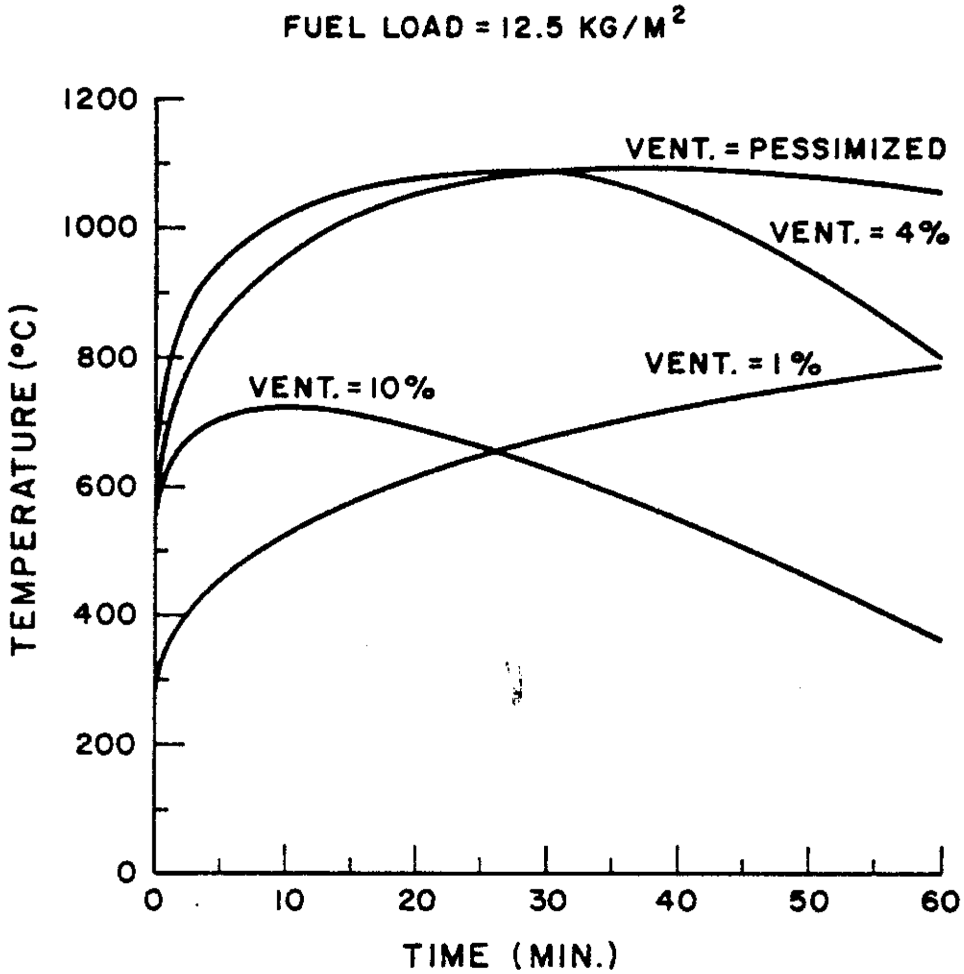


FIGURE 33 EFFECT OF VARYING VENTILATION FOR A GIVEN FUEL LOAD

likely for high fuel loads or high B-number fuels, showed a significant increase in temperature when ventilation was increased. Such increased ventilation can be highly disturbing if unexpected. Furthermore, most polymeric fuels will not show, as does wood, any decrease in smoke production with higher ventilation.

From the viewpoint of pessimization it can now be surmised that Ingberg did have some notion of the importance of ventilation in a compartment fire. In his tests he varied the shutter openings on the test building window (Figure 11). He must have used some visual clues or tried to detect from thermocouple output the pessimal position for the shutters. He even appreciated the quantitative significance of the shutter openings enough to keep a log of their settings; no formal use, however, was made of this information.

6.2.4. Critical Temperature Design

Ingberg's hope of testing assemblies under one set of conditions and then using the resulting information for diverse designs need not be completely denied. It is possible to do that if one is willing to use a response which is partly calculational, partly experimental and to use rules which are material-dependent. One procedure of this kind can be termed "critical temperature" design. It can only be used where a critical temperature can be associated with failure criteria. Thus it is not applicable to determining, say, gas flow through cracks as a failure mechanism. The basic scheme involves obtaining a calculated assembly response to a predicted fire. The predicted fire can be on a deterministic, parametrized, or pessimized approach. Material properties, both relating to heat conduction and to T_c, meanwhile, are determined from a standardized test or specific materials tests.

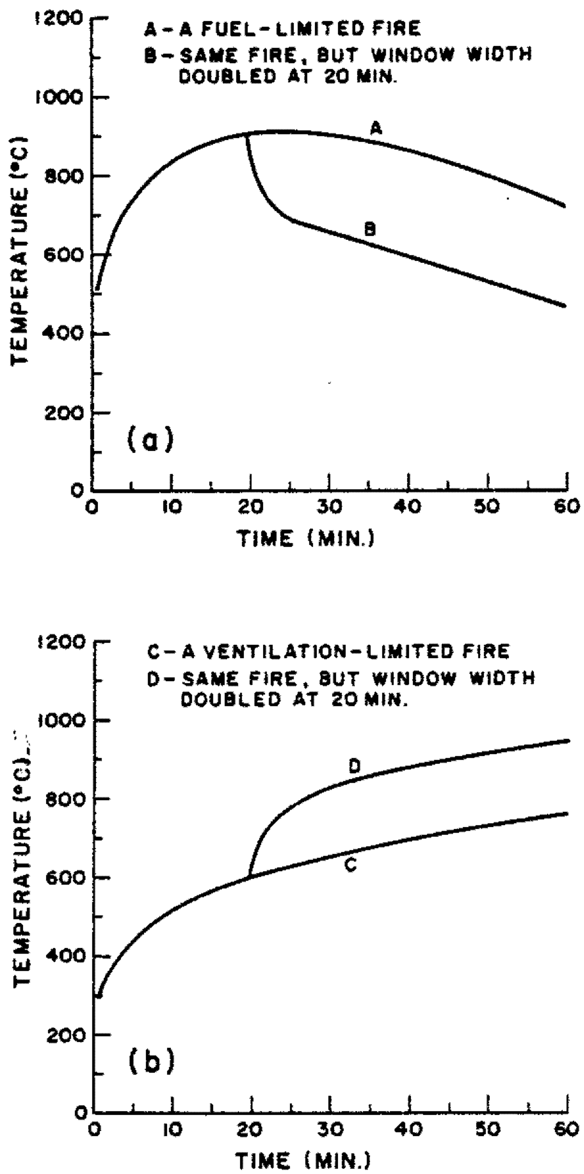


FIGURE 34 TWO POSSIBLE RESULTS WHEN THE VENTILATION IS DOUBLED 20 MINUTES AFTER FLASHOVER

Critical temperatures designs will be discussed in more detail in Chapters 7 and 8.

6.2.5. Purely Stochastic Design

A final alternative is for a purely stochastic design. It involves determining what is the probability associated with obtaining every conceivable intensity of fire in a given compartment. The fuel load is obviously a stochastic variable over time even in one given compartment. Although less striking so, ventilation and wall properties also have some variation associated with them. Thus even a single supposedly well described compartment has not just one deterministically set fire but a whole range of different ones.

In design usage the purely stochastic model would be subject to the same shortcomings of lack of generality as the deterministic design outlined above, since only a single compartment is treated. Thus there is no gain in flexibility; there is, however, a gain in accuracy. Nelson has adopted such a philosophy in the GSA system approach.[3] The method becomes tenable only if the dimensionality of the problem is strongly limited. For that reason Nelson was forced into using Ingberg's hypothesis, adopting severity as the single stochastic variable describing the fire. A fundamental advantage of the method is that it focuses on the stochastic nature of the component's response. It acknowledges that the reliability of the component is a critical variable and establishes a numerical procedure. Component reliability is further discussed in Section 7.4.

Coward[178] has recently made preliminary studies with a similar method, but with two differences. The population for which the stochastic variables were used was a general one, in her case "office occupancies," rather than one specific design room. And, second, she used not Ingberg's relationship between fuel load and severity, but rather the one evolved by Law.[179] Use of Law's relationship is, as noted below, subject to similar criticism as is Ingberg's. The use of large, unrestricted groups as the study population represents the other extreme to Nelson's use of a single specific design room. A choice anywhere in between these two is also possible. The trade-off here is a customary one: the more generally applicable the design, the less economical it tends to become.

Magnusson[180] has investigated the theoretical concepts used in applying stochastic methods to fire endurance. His work is especially valuable for focusing on the response problem. A fully stochastic method will involve treatment not only of the fire but of the structure and of its response. His work, in effect, represents an attempt to introduce a stochastic basis to the Swedish teel design manual, which is based on critical temperature considerations. The GSA method uses, on the other hand, a stochastic version of the conventional furnace test approach, although with the added feature of reliability considerations. Certain comments applicable to the GSA method (see Chapter 10) are also applicable to the stochastic critical temperature approach. Foremost among these is that they suffer from a lack of data. It can be presumed that the usefulness of stochastic designs will increase in future years if ways can be found to collect the data needed for them.

6.2.6. Rule-of-Thumb Design

The five above ways for producing a design fire share the common characteristics of being fully based on the theoretical model developed in Section 6.1. Other ways that acknowledge the existence of some of the controlling variables but do not use them in a rigorous fashion have been propounded in recent years for establishing design fires. They are basically analogous to Ingberg's fuel load/fire severity relationship except that they incorporate some further variables in addition to the fuel load. They suffer from the same drawbacks as applicable to Ingberg's severity hypothesis. As a result they cannot be recommended except as crude estimating aids. The two most widely known of the newer rules are the one due to Law and the one in German standard DIN 18230.

Law[179] proposed a rule whereby the equivalent fire duration is

$$t = k \frac{F}{\sqrt{A_V/A_W}} \quad \text{min}$$

where F = fuel load (kg wood/m^2 total surface area) and k is an empirical constant in the vicinity of 1.0 min-m^2/kg. The rule, in effect, accepts Ingberg's severity hypothesis, but adds window area, in addition to fuel load, as a controlling variable for determining the severity. The wall thermal properties are ignored and so is the window height. Recognizing ventilation area adds a certain refinement, but all the drawbacks of Ingberg's severity hypothesis still remain.

Another common basis for creating rules-of-thumb could be termed a "factor method." In a rule of that kind a list of known variables is enumerated; the effect of the variables is not treated rigorously but is simply obtained by assigning an additive or multiplicative factor to each variable. The German standard DIN 18230,[181] which is intended as a model building code provision is an example of that kind of rule. The required endurance under DIN 18230 is a function of an effective fuel load, where the effect fuel load is defined as the actual fuel load multipled by a set of adjustment factors. Factors are specified for fuel thickness and special hazards, fire department effectiveness, compartment area and accessibility, the number of stories, and the ventilation. The latter, for instance, is treated quite roughly: three levels of ventilation are established, A_v/A_{floor} less than 0.04, between 0.04 and 0.08, and greater than 0.08. A factor rule of this kind might be appropriate in cases where trends are known but no theory is available. For compartment fires a theory does exist, so little reason can be seen for accepting such crude rules, especially ones where not even the proper variable groups (e.g., $A_v\sqrt{h_v}$) are preserved.

6.3. Building Design Data

6.3.1. Fuel Properties

Concerted data collection programs in any field become viable only when a theory exists to point out what should be collected. Thus in characterizing building fires, where for many years fuel load was the only known variable, it is understandable that fuel load data were the only ones collected. The early NBS work is not no longer relevant since the types of furnishings used have changed radically over the last several decades. Fuel loading, and all other fire variables, vary according to geography, social custom, affluence, and other similar factors. At the moment, however, so few studies anywhere are available that it is necessary to consider all the creditable current surveys.

Office Buildings

The most useful data are those collected by Culver[68] in the recent NBS survey. Some 2226 rooms in 23 buildings were surveyed in detail for furnishing fuel load, for window sizes, and in less detail for wall properties and fuel content. Another ambitious survey has been that of

TABLE 8

FUEL LOAD VALUES

(in kg wood equivalent/m² floor area)

OFFICES

Cumulative Probability	U.S.A. (Culver)	W. Germany (CECM)	Sweden (Berggren, Erikson)	Holland (Witteveen)	England (Baldwin)
25%	20	25	24	5	5
50%	35	43	28	10	20
80%	50	60	38	24	32
99%	100	130	70	46	110

RESIDENCES

	Sweden (Nilsson)
25%	37
50%	40
80%	45
99%	53

OTHERS

Sweden

	Schools (Forsberg, Thor)	Hotels (Forsberg, Thor)	Hospitals (Magnusson, Pettersson)
25%	17	15	30
50%	22	18	33
80%	26	22	35
99%	43	34	71

the Convention Européene de la Construction Metallique.[182] They have conducted a study of 500 rooms in 10 West German office buildings. The data were segregated into two categories, movable contents and fixed contents, including the fuel of finish and structural materials and built-in furniture. Other recent studies available include those by Baldwin in Britain, Berggren and Erikson in Sweden, and Witteveen in Holland. Baldwin[183] surveyed 65 rooms in two buildings and reported some preliminary findings. Berggren and Erikson[184] surveyed 104 rooms in 12 modern office buildings. They obtained data for furnishings only, not for finish and structural materials and also made note of window sizes. Witteveen[185] conducted a similar study of furnishings in 270 Dutch office building rooms.

Residences

The major NBS residential fuel load study has not yet been finished. The best current results are those of Nilsson.[186] He surveyed 295 rooms (bedrooms and living rooms) in modern Swedish apartment houses. A study on hotel rooms was done by Forsberg and Thor.[187] The furnishings in 60 guest rooms in the vicinity of Stockholm were examined.

Other Occupancies

Forsberg and Thor also surveyed school buildings. Thirty rooms each from lower, middle and high schools were surveyed. Magnusson and Pettersson[188] studied hospitals in Sweden. The fuel load of furnishings and finish material in 268 hospital rooms was reported.

Values Used as Typical

The fuel loading results discussed in the previous section are summarized in Table 8. Values have been converted to units of kg wood equivalent/m^2 floor area in those cases where they were originally reported in different units. In some cases values have also been rounded, interpolated, or averaged. Only a limited number of cumulative frequency values should be considered. Witteveen[189] has proposed that the 80% fuel load value be considered as suitable for design. His rule has also been accepted by Forsberg and Thor.[272] In addition to the 80% value several other points have been tabulated: the median, 50%; the 25% value, as typical for low fuel loadings, and the 99% value, as indicative of extremely heavy loadings.

The values quoted in Table 8 are not all strictly comparable since the different investigators treated interior finish and structure fuel loads in different ways. Except in residential buildings, the fuel content in finish and structure is typically low. Culver, for instance, found that in private office buildings finish materials (which are included in his totals) averaged 9.3 kg/m^2, with a standard deviation of 1.9. In residential buildings no good data for finish materials are available, although it will clearly be much higher than in offices. For the structural component fuel load an estimate can be made that in a typical wood frame house about 30 kg/m^2 in each story are represented by wood framing and floors.

Unburnt Fuel

When wood cribs are burned in compartments there is no fuel-remaining problem. Something in the order of 5% of the crib weight may remain unburnt, comprised mostly of ash. With real furnishings the situation is different. Ingberg[64] was the first to study fuel remaining after fires. In connection with his records protection work he developed the following table. The values below are multipliers by which the actual fuel load protected by steel containers is to be multiplied to obtain an effective fuel load.

TYPE OF STEEL CONTAINER	PART OF COMBUSTIBLE IN CONTAINERS		
	Less Than 1/2	1/2 to 3/4	More Than 3/4
Backed and partitioned shelving	0.75	0.75	0.75
Shelving with doors and transfer cases	0.60	0.50	0.25
Filing cabinets and desks	0.40	0.20	0.10
Safes and cabinets or $\geq$ 1 hr fire resistance rating	0	0	0

No substantiating data were ever published to explain the origin of these figures. The reason why the burned fraction of a given load should, in some cases but not all, vary with whether additional unprotected combustible load is present is quite unclear. Be that as it may, Ingberg's table has remained the only source of this information until recent years.

In the 1970's the Centre Technique Industriel de la Construction Metallique started a program to obtain newer data. Their work[158] first noted that in general office occupancies paper represented an average of 82% of the fuel load, ranging from 27% in conference rooms to 92% in libraries. Thus the burning behavior of paper should properly be accounted for. A series of ten burns was conducted with a fuel load consisting mostly of wooden office furniture and papers. The unburnt fuel remaining was evaluated and amounted to 5-23% of the furniture and 36-55% of the papers. The values were influenced by packing densities but not by window ventilation.

The next step in the CTICM program is the determination of the effective calorific value of paper and its combustion in metal containers. The results available[190] are not definitive but indicate that under smoldering conditions the effective calorific value may be significantly reduced from its free-burning value. It is not clear, however, whether in this work the $\dot{h}_p$ and $\dot{h}_c$ distinction was adequately observed.

Fuel Properties Other Than Fuel Load

In addition to the fuel load, the effective fuel thickness and packing density must be known if a complete calculation is to be done. No survey data are known for these variables. The packing density is not important if sparsely packed fuel arrangements are considered. Since the sparsely packed configuration gives higher $\dot{h}_p$ values, in the absence of other information it can be assumed that the fuel is sparsely packed. The results will be conservative except in cases where large unburnt pyrolysate fractions are present.

Fuel thickness can, to some extent, be visually estimated. For stacks of paper the effective thickness is equal to sheet thickness only if the papers exfoliate while burning. Otherwise, the effective thickness is much greater than single sheet thickness, but less than stack thickness, due to leaf separation.

6.3.2. Ventilation Properties

Ventilation properties have been collected in some of the above-mentioned surveys, although not in depth. The Swedish surveyors collected information on the ventilation factor $\frac{A_v\sqrt{h_v}}{A_w}$ and found the following ranges:

Offices	0.09 to 0.22	$(m^{\frac{1}{2}})$
Apartments	0.025 to 0.053	
Schools	0.07 to 0.11	
Hotels	0.06 to 0.09	

Culver gives office data but does not give complete distributions. For general offices in private buildings he quotes the median ventilation factor as 0.10 $m^{1/2}$ and the median A_V/A_W as 0.178. These values imply a median window height of only 0.33 m, which does not seem possible.

The lower limit for ventilation is a no-window condition. A plausible upper limit, however, can be estimated. Consider squarish rooms. Then one entire wall, if absent, (which is a practical upper limit for well-stirred compartments) is about 0.18 of the total area not counting floors. In an office, window height will rarely exceed 2.0 m for a floor height of 3.0 m , while in an apartment assume 1.5 m out of 2.5 m total height. This gives upper limits for the ventilation factor of 0.17 for offices and 0.13 for apartments.

6.3.3. Wall Properties

Even though their exact values are somewhat less crucial than fuel and ventilation properties, the wall thermophysical properties should still be known at least approximately in order not to introduce avoidable error into the time-temperature curves. The lack of knowledge of these values for common building materials is quite astounding, especially since values are often known for quite exotic substances. There is no particular incentive for manufacturers to study them except for materials specifically designated as insulations. There are also no government efforts in the U.S. to collect them.

Wall surfaces can be comprised of a vast array of materials. In new construction, however, the single most common material is gypsum wallboard. To study typical cases it is appropriate to pick wallboard walls, unless more specific information is available. An exception would be crawl spaces in residential dwellings, for which it is known

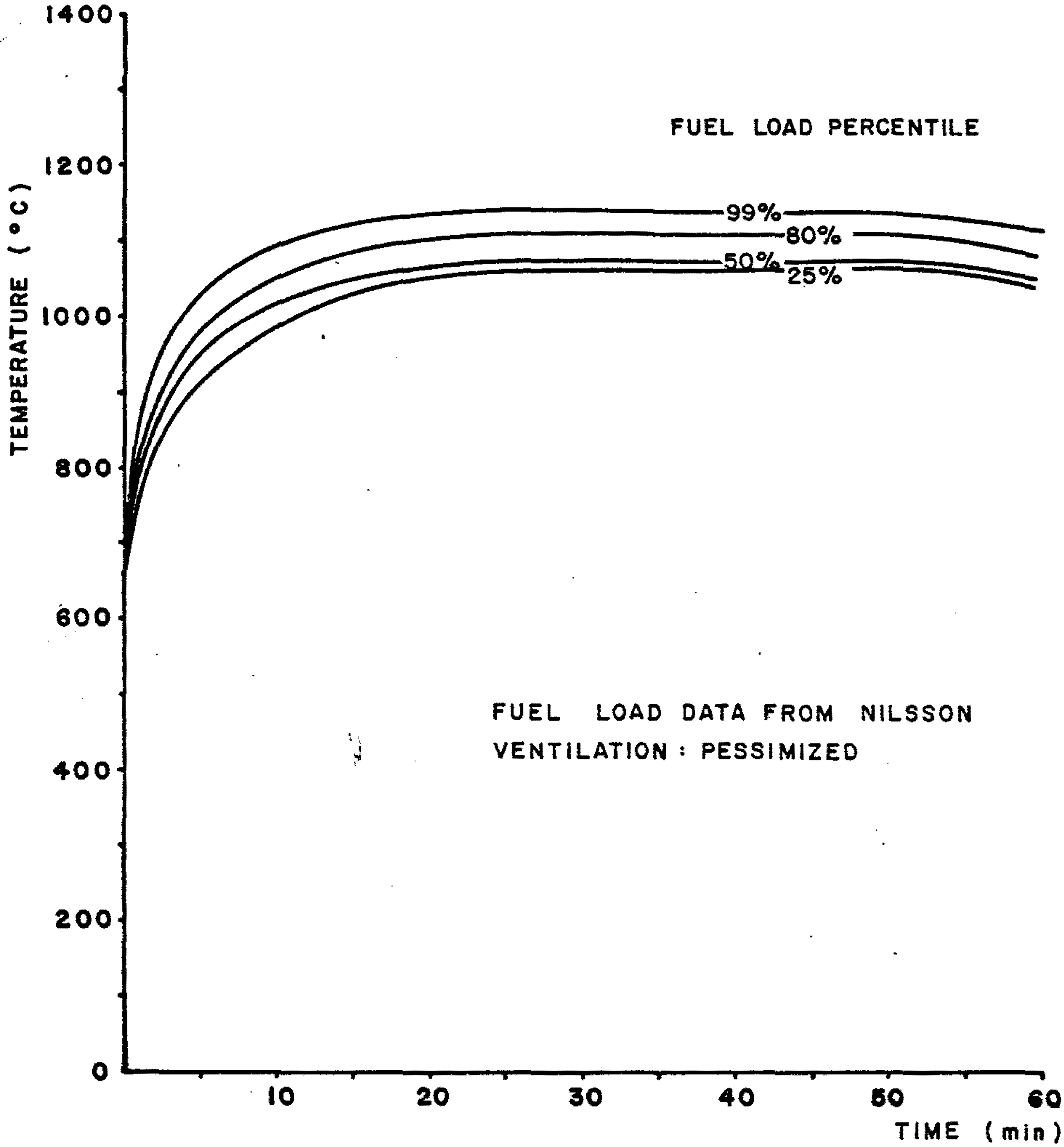


FIGURE 35 PREDICTED FIRES IN RESIDENCES

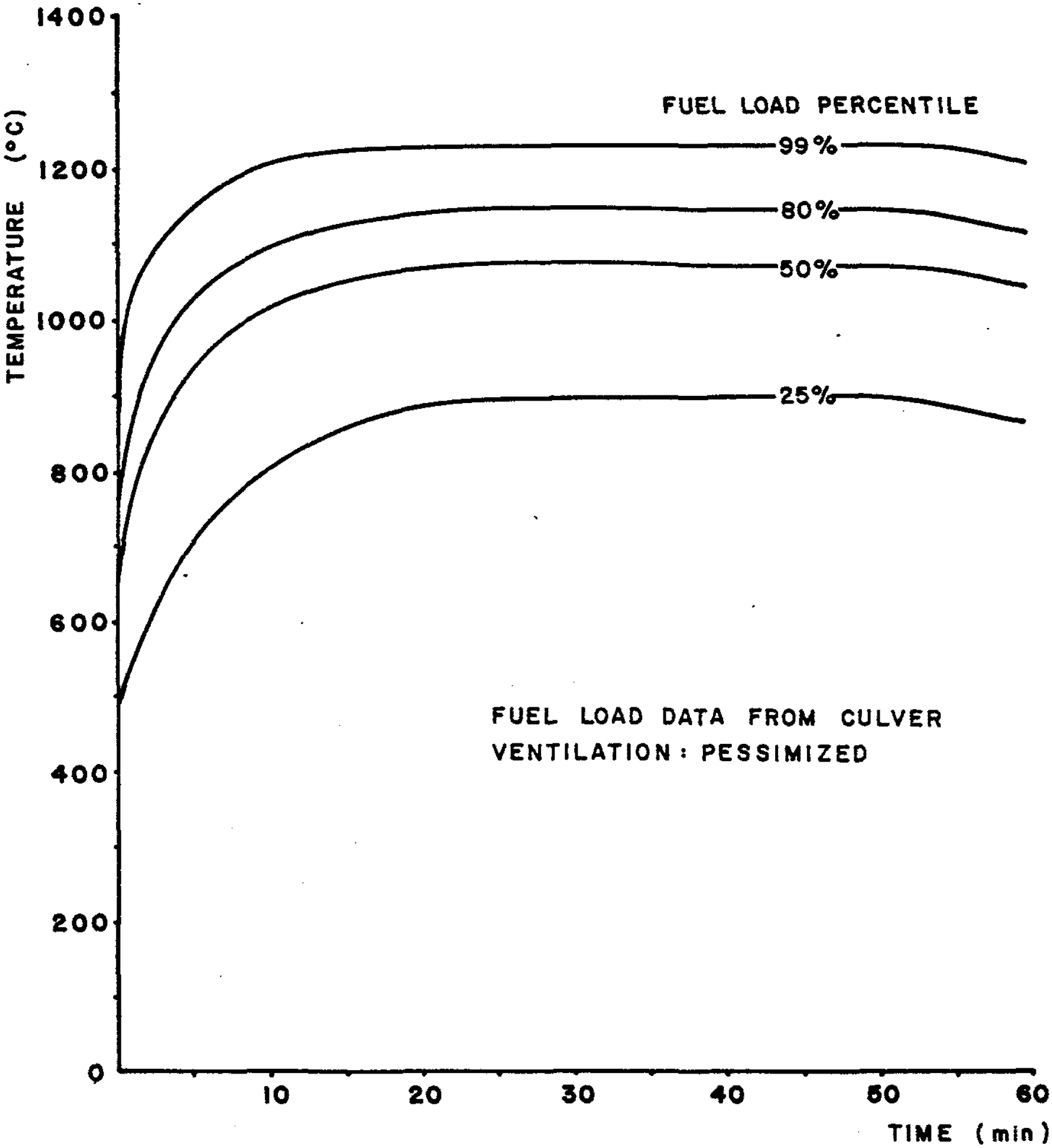


FIGURE 36 PREDICTED FIRES IN OFFICES

that wood is the predominant material. Fortunately, the thermophysical properties for gypsum wallboard have been reported. Castle[191] and Pettersson, Magnusson and Thor[103] have reported similar values.

6.3.4. Examples

From the above considerations time-temperature curves have been calculated for typical office and residential occupancies. Culver's fuel load values were used for offices and Nilsson's for residences. Pessimized ventilation was used, with the upper limits set to the values indicated in Section 6.3.2. Gypsum wallboard surfaces were assumed. The results are shown in Figures 35 and 36. The calculations for residences do not indicate much difference between various fuel load percentiles because Nilsson's data showed very little spread of values. To what extent his results would apply to American residences cannot be judged. For offices the values for the top three curves are significantly higher than temperatures in the ASTM standard. Less stringent conditions would result if the designer can better limit either the ventilation maximum or minimum. It might be noted that in all these examples the fuel is exhausted very shortly after 1 hour. Thus while the temperatures may be higher that the ASTM curve, the duration nowhere nearly approaches the 4 hour endurances which are the greatest currently required by the UBC. It must be emphasized that the office values include only general spaces and not libraries or file rooms.

6.4. Furnace Test Requirements

6.4.1. Modeling Assumptions

The practical reason for constructing the expected fire model is to use it as a basis for calculating or for physically measuring the effects of fire on building elements. Problems associated with mathematical procedures are discussed in Chapter 10. In this section some requirements will be outlined if physical testing is to be done.

A fundamental hypothesis must first be postulated: *A test fire imposed upon a specimen must either duplicate the predicted expected fire as closely as possible, or else deliberate variations must be rationally justified.* It might seem that a similar hypothesis should also be made about the test specimen. If that were done, it would result in excluding all tests except total building burnouts. Burnouts are usually economically precluded. At the other extreme there is a valid need for small-scale tests on simplified specimens. Their requirements will not be considered here. Instead, attention will be focused on medium-scale specimens of building components, similar in size to the minimum requirements in effect in Standard E-119. Requirements for these specimens are the most stringent since, unlike small-size specimens, they are expected to be structurally representative and, unlike burnout specimens, they must fit in a standard furnace.

6.4.2. Modeling of the Fire

Fire requirements will first be examined. The fire can be described by its temperatures, velocities, gas composition, radiant and convected flux, pressures, and other quantities. Of these parameters the minimum truly needed should be selected. It is evident that gas velocities have an effect only insofar as they determine the convective flux. Thus they will not be separately studied. Gas composition has no effect on non-combustible specimens. It has some effect for combustible ones. The gas temperatures and fluxes are intimately related and will be examined together. The pressures constitute an important and separate issue and will be treated first.

A. Pressures

The question is: what are the pressures in a natural compartment fire? To determine the maximum positive pressure it is seen from Equation 6.10 and Figure 14 that the height above the neutral plane and the gas density must be known. Consider a room height of 3 m. Since the window will generally be slightly higher than halfway up the wall and the neutral plane can be expected to fall about halfway, or at 1.5 m of the room wall next to the window. The pressure distributions in the model were only calculated at the window. Inside the room, away from the window, the neutral plane height will vary; its exact location depends on fuel arrangement and pyrolysis rates. Since worse smoke flow conditions result from a lower neutral plane, consider its height as 2 m below the ceiling. Pick a rough approximation of $\rho_f/\rho_o \approx 1/3$. Then the positive pressure at the ceiling level, with respect to ambient pressure at the same level, is

$$\Delta p = \rho_o \left(1 - \frac{\rho_f}{\rho_o}\right) gy$$

$$= 17 \quad \text{Pa}$$

According to the same reasoning a negative pressure, numerically about 1/2 the above value, would be expected at the floor level.

The test furnace pressures are not important for lineal barriers (beams, columns). Nor are they important for planar elements if the possibility of any cracks or apertures is precluded and pressure stability is assured. These conditions can rarely be assumed. The most obvious case where careful control of pressures is needed is for doors. It is necessary to be able to determine if the door is an effective barrier to flame and smoke spread. This cannot be done unless there is a controlled positive pressure over the same regions of the test specimen as expected in the compartment fire. Crack heating is another effect that is also especially noticeable for doors but may be important for other assemblies. If the furnace pressure is positive, the cracks, such as the one between the door top and the jamb are heated. Conversely, if the pressure is negative, the cracks are cooled. For a door, the flow direction can affect warpage and, if the door is combustible, control its edge burning.

Pressure stability is a factor mainly for tile ceilings. It is not unusual for ceiling tiles in a grid ceiling to be so weakly held down that they could be lifted out by fire pressure alone. The furnace pressure in a floor furnace should be at least positive enough to simulate the conditions of a natural ventilation fire. If there is a possibility of greater positive pressures due to mechanical ventilation, then those conditions should also be taken into account.

The control of a furnace to produce requisite pressures is not difficult. In a natural draft wall furnace the pressure distribution is intrinsically similar to the compartment fire. The gradient of the distribution is determined by the density and therefore temperature of the gases. The neutral plane height, however, is under the control of the operator and can be set by use of dampers. In any forced draft furnace (which includes most floor furnaces) the neutral plane height is determined by blower settings.

The ASTM E-119 Standard is silent on the question of furnace pressure, while the E-152 standard for doors specifies, incredibly enough, to "maintain the pressure in the furnace chamber as nearly equal to the atmospheric pressure as possible." Most U.S. test laboratories traditionally run all fire tests with negative pressures over most of the specimen. The only reason, other than tradition, for this practice, it seems, is to avoid smoke infiltration into the laboratory.

The ISO international recommended standard[192] prescribes a positive pressure of 15 ± 5 Pa at the ceiling level for assemblies other than doors, while for doors[193] it is only required that the pressure should be positive over the upper 2/3 of the door. The German standard DIN 4102[194] requires 10 ± 5 Pa at the top of a door and zero at the bottom.

It must be recommended strongly that for any specimens, save lineal ones, positive furnace pressures should be maintained. For wall and other vertical assemblies an appropriate neutral plane height must first be fixed. For most furnaces of straightforward design once the neutral plane height and the temperature are fixed, the numerical values of the pressure distribution become determined. Except for assemblies subject to pressure instability the exact magnitudes are not important provided they are of the right sign and the values are adequately measured.

B. Temperatures: Emissivities

Temperature measurement in fire test furnaces has been an area of long-standing controversy in recent years. The controversy has been generated by the valid observation that some current practices raise the question of the validity and interlaboratory reproducibility of test data. The controversies persist for numerous reasons: the economic incentive to retain one's current practices; the interests of some manufacturing groups that any special advantages their products are given under present practices not be terminated; the lack of good instrumentation; the fact that no conclusive round-robin interlaboratory tests have been conducted;

and finally the fact that research in certain areas, especially radiation, has until very recently been lacking. Some of the above problems have also occurred in other areas of test control but they have been most noticeable in the area of temperature control.

One can consider in what way the furnace is likely to be different from the actual fire compartment in its heat transfer characteristics. The main way is in depth. A full-size room will probably be at least 3 m on a side. From Figure 22 it can be seen that this is enough to assure $\varepsilon_f > 0.9$, allowing one to take $\varepsilon_f \approx 1.0$. If a furnace has at least that depth and is fueled by wood, then it can be assumed that there also $\varepsilon_f \approx 1.0$. Furnaces nowadays are fueled by gas or oil. Despite data[162] to the contrary, it is commonly assumed that the emissivity for oil is lower than for wood and even more so for natural gas. Reliable measurements are not yet available. However, van Keulen[195] did not find any systematic differences in a comparison study between heat fluxes in gas and oil fire wall furnaces.

The depth of furnaces has never been standardized. For reasons of emissivity alone it would seem desirable to make them as deep as possible. In actuality there are other reasons, such as high cost and fuel wastage, that discourage use of large depths. Keough[196] has found in a sampling of 21 laboratories that the depths of floor furnaces, ranged from 0.7 to 4.0 m and averaged near 1.5 m, while for wall furnaces it was 0.3 to 2.4 m and averaging near 0.7 m. This means that for wall furnaces one might expect an effect due to $\varepsilon_f \neq 1.0$.

A related effect that needs to be considered is furnace wall temperatures. If the furnace is infinitely deep and $\varepsilon_f \approx 1.0$ then the specimen does not "see" the far furnace wall. Consider a case, as in Figure 46, where the thickness x_f is not large. Then the temperature and emissivity of the furnace wall has an effect on the heat flux to the specimen. The effects of gas emissivity and of furnace wall condition are best treated simultaneously. Calculations are given in Appendix F.

One might also suppose that because of differing geometries the difference in convective fluxes would need to be accounted for. It has been fairly conclusively established by Williamson and Buchanan,[197] Kanury and Holve,[198] and others (although note may be made of a report[199] in which the opposite conclusion was reached on a basis of the subtractive balance) that the convective portion of the wall heat flux ranges from immeasurably small to some 11 percent of the total. Therefore no great errors will be introduced in the over-all results even if a significant deviation in the convective furnace flux were registered.

It can readily be seen that it is the total heat flux entering the wall that controls its temperature distribution not just the gas temperature. The question might then be asked--why not control a furnace by controlling the heat flux rather than the gas temperature? The answers are multi-faceted and not simple. First, one can note that for the radiative component the heat flux entering the wall can be divided into two portions: one which is incident upon the wall, $\dot{q}_{inc}$, and one which is reflected, $\dot{q}_{ref}$. The incident flux is that which would be measured by a black calorimeter with a surface temperature $T_w << T_f$ and is

$$\dot{q}_{inc} = \sigma \varepsilon_f T_f \tag{6.58}$$

The reflected portion is then

$$\dot{q}_{ref} = \left(1 - \varepsilon_f\right) \dot{q}_{inc} + \frac{1}{\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_w} - 1} \sigma T_w^4 \tag{6.59}$$

The net flux is the incident flux minus the reflected flux. The next question is which flux, the incident or the net, should be controlled.

To control the net flux would have the same effect as modeling exactly both the gas emissivity and the temperature of the real fire. Both could be different in the test furnace, but the combined effect would be the same. To control the incident flux would mean something quite different. Consider two walls, a good insulator and a poor one. In a fire the poor insulator will have much less reflected flux and a higher net flux for the same incident flux. The incident flux will be somewhat lower, however, because the greater losses will cause a lower gas temperature. If the incident heat flux is the quantity fixed then the poor insulator would be penalized slightly, unless the time-temperature (and therefore heat flux) curve used had been calculated by properly taking into account the effect of wall losses on gas temperature.

The practicality of these measuring methods becomes the real issue. First, it must be realized that there is no simple way of controlling the net flux. To do this would require a calorimeter simulating the wall surface temperature and emissivity, an impractical undertaking. On the other hand, to measure the incident flux using standard calorimeters is possible. The obstacle is the following: while calorimeter measurements can be done on an experimental basis, to do so for routine testing is not practical. There are at least three reasons.

1. Cost. The cost of a calorimeter is over 20 times that of a thermocouple assembly.

2. Reliability. The current standard Gardon-foil calorimeters, despite their simplicity, are subject to unpredictable failures.

3. Precision. The available calorimeters easily drift out of calibration and give low output, high noise signals.

Thus it appears that despite the seeming attractiveness of a heat flux based furnace control it cannot be recommended.

Another heat flux method has sometimes been suggested--control of the fuel input to the test furnace. The primary objection here is that it is a very indirect method. Any variation of furnace heat losses would affect the results. Such variations, which cannot be eliminated, depend on variables such as damper and burner settings. The theoretical advantage of this control principle would be automatic compensation for wall losses. The flow of fuel would be calibrated for an adiabatic specimen. Actual wall losses would then lower the furnace temperature in a manner similar to wall losses in a compartment fire, thus eliminating the need to treat wall thermal properties as a problem variable. Combustible specimens would be treated in a way which, while seeming more encompassing, would in fact be less appropriate. The enthalpy available from a combustible specimen should properly be considered as part of the $\dot{h}_p$ term for the fuel load. Time-temperature curves appropriate for the added fuel should then be used for furnace testing. If a constant-furnace-fuel mode is used instead, an overly severe testing will be done on those combustible assemblies intended for limited ventilation compartments.

With methods based on heat flux control discarded, two things must still be done. The numerical effect of the gas emissivity and furnace wall material must be evaluated and an operational procedure suggested. The former is taken up in Appendix F, where it is shown that in the U.C. Berkeley wall furnace a typical value of 65 percent of the theoretical heat flux is realized.

It is most noteworthy that the E_i value is, to within the accuracy of the measurement, independent of both time and gas temperature. The fact that it is independent of time indicates the validity of treating furnace thermocouples more as effective heat flux, rather than local gas temperature, measuring devices. This independence explains why test results obtained in furnaces with radically different lining materials are quite similar and do not require the sort of compensation that Paulsen[167] has proposed. A furnace lining with a low $k\rho C_p$ is desirable, nonetheless, because it tends to make temperatures more uniform, but, in fact, the lining effect on the results is small. It is further apparent that specially designed (aspirated) thermocouples, to measure only the local gas temperature, would not be at all desirable. A suggested improvement would be to locate thermocouples as is done presently, close to the sample, but with radiative shields to make them view only the gas and the furnace wall but not be influenced by the specimen. A possible thermocouple of this type is shown in Figure 46.

The fact that the E_i value does not depend much on temperature has a propitious implication for control. Ideally one would wish to use the E_n value to raise the gas temperature in order to compensate for the fact that $\varepsilon_f \neq 1.0$. Since the E_n is not measurable and also depends on specimen emissivity, it may be sufficient to make the correction by use of measured E_i values. Thus, a first approximation to a corrected operating procedure can be made by operating at an indicated temperature T_t

$$T_t = \frac{1}{E_i^{1/4}} T_f \tag{6.60}$$

C. Temperatures: Time Characteristics

A thermocouple, if it is of finite mass, does not respond instantaneously, but rather takes some time to approach its final reading. Deviations from the expected value can be termed "response time" error, and are proportional to $\frac{\partial T}{\partial t}$. This, of course, is not the only source of error. Another group of errors consists of all steady-state errors. Some of these are treated in Appendix F.

The errors due to response time have been known for a long time but have been ignored. When furnace tests ranged in duration from 1 to 4 hours it was possible to ignore these errors; when using the standard time-temperature curve they are large only near the start of the test and become negligible at about 20 minutes. Now, however, when tests as short as 1/6 hour are required,[200] it becomes important to consider response time errors.

The details are treated in Appendix G. From there it is seen that the effect is considerable and should definitely not be ignored. Since a bare thermocouple has a short lifetime (for 20-gage [0.183 mm] Type K thermocouples experience shows that one in nine fails at 45 minutes when subjected to a constant temperature of 900° C) and the current thermocouples prescribed in Standard E-119 are shown to be excessively slow, it is appropriate to select some longer lasting but fairly fast responding ones. The experience at U.C. Berkeley with 1/4-inch [6.35 mm] O.D. thermocouples which contain an 18-gage [1.016 mm] element swaged in MgO and grounded to the case has been satisfactory.

Calculated time-temperature curves are always obtained under the assumption that there is no delay in temperature measurement. To use curves so obtained and then conduct furnace tests with slow responding thermocouples is inappropriate and results in greater exposure than desired.

Fast-responding thermocouples can also improve furnace control. It is hard to control a device accurately if information about its status arrives after a significant time delay. Even for conducting tests under the current E-119 standard, faster-responding thermocouples can be used to good advantage. The procedure, as evolved in the U.C. Berkeley test facility, is as follows. From calibration tests a curve is obtained for the readings of the fast thermocouples under the condition that the ASTM thermocouples are following the standard curve exactly. In testing a specimen, then, the fast thermocouples are used to follow the special calibration curve. By doing so, it has been found that it is possible to reduce the deviations from the standard curve to negligible values.

Any test curve, such as that prescribed in the E-119 standard, which is based on gas temperature measurement by slow-responding thermocouples, is objectionable for one additional reason. Calculations of component behavior can only be readily accomplished if furnace temperatures are known at any given time without a response time error. If theoretical heat flow calculations have to be compared with data taken from slow response thermocouples, a correction must be provided to give an estimate of actual instantaneous temperatures. Use of the correction term introduces error that can easily be avoided by better measurement technique.

6.4.3. Modeling of the Assembly

The bounding surfaces of the compartment were modeled in Figure 13 as simply segments of an infinite plane. That type of model is adequate for determining the fire time-temperature curve. Additional care must be exercised, however, in characterizing the test specimen whose response is to be determined. Even radically simplified models of the wall heat flow can be adequate for determining the expected fire, but more detailed considerations of the specimen geometry are needed to physically or mathematically model its behavior under fire. In this section only factors important in furnace testing will be considered; other points, of primary import in mathematical response calculation, will be taken up in Chapter 9.

The following factors, at the very least, can be identified as being potential pitfalls in modeling: specimen size, loading conditions, joint and edge effects, moisture content, and workmanship.

1) Specimen size. The expected fire theory was constructed without reference to compartment size. While it was admitted that there can be certain small size-related effects, they were not considered precisely because a fire history which is size-independent is much more useful than one that is not.

Failures, under my criteria, can qualitatively be considered of two types: average and point failures. If failure of some component by a given criterion is based on an average value over its area being exceeded, then specimen size is not important. But supposing the failure occurs only over a small area, then the probability of it being noted is proportional to both the density of the detecting instruments (detectors/ specimen area) and the specimen area. If the "detector" coverage is complete, as in the observation of flame-through then the total probability of failure is proportional to specimen area.

In current U.S. practice the minimum specimen sizes are specified in the E-119 standard. The actual test specimens generally exceed this minimum by only a small amount, thus in all test furnaces they may be taken as being similarly sized. The deviations come from the building use conditions. Logically, there should be a pro-rating rule for decreasing the endurance time with increasing surface area when failure is of a point nature. The problem deserves further, specifically stochastic, study.

In some cases the specimens tested in a standard furnace are very nearly full size. Firewalls for use in apartment building, for instance, when tested in a height of 2.7 m, correspond very closely to the prevalent height in actual construction. The length may vary but the structural behavior of walls is usually independent of length, provided the length is great enough to avoid edge effects and to encompass several modular units, if the wall has identifiable modules.

Major deviations of specimen size from actual size occur for two reasons: cost, which is the primary factor in limiting furnace size, and the fact that many assemblies do not come in any standardized size in actual construction. The question then occurs, what are the difficulties in testing components at a reduced scale? Thermally there is little problem, provided that edge effects are minimized and that point failures are properly accounted for. Structurally, however, there are some major obstacles.

The unfortunate fact is that most structural behavior does not depend linearly on the length or area of a member, but rather depends in a manner which often is not predictable or else not capable of completely scaling. For instance, by reducing the length of a beam it is not possible to maintain the same ratio of shearing stresses to bending stresses. Shear stresses are proportional to beam length, while bending stresses are proportional to $(\text{length})^2$. The only practical non-computational solution is to determine whether shear or bending failure can be expected in real life and load the test member accordingly. The desirable solution has gradually been incorporated into the E-119 method by introducing critical temperature concepts. Currently in E-119 they are only given for steel. The measured temperature is independent of length, and any dependence of the critical temperature on component scale can be calculated analytically.

In other situations a worst case approach has traditionally been taken. Fireproofing for steel columns is normally tested on some small section, often W10x49, which has a high surface area to weight ratio since the time for heating to a given temperature, a high conductivity material, such as steel, protected by a low conductivity insulation varies approximately as

$$t \propto \frac{\rho V C_p}{A} \quad \frac{L}{k}$$

where ρV, C_p, and A are the weight per unit length, heat capacity, and surface area of the steel, and L and k are the thickness and conductivity of the insulation, respectively. Larger members, which have lower $A/\rho V$ ratios will then be adequately protected when the same fireproofing is applied to them.

2) Loading conditions. As indicated above, scale can have a significant effect on loading conditions. The arguments given indicated that there is much to be said for obtaining only temperature distributions for unloaded members and then calculating, rather than measuring their structural response. To be able to do the calculations (see Chapter 9) some loaded tests are needed to determine the T_c values, especially when buckling failure is involved. These preliminary loaded tests do not, of course, have to simulate actual load conditions.

In recent years probably the single most controversial area of fire testing has centered on end restraint in floor specimens. Discussions culminated in a symposium on restraint[201] and the adoption of rather vague rules on restraint in the 1973 edition of E-119. The subject was controversial because until very recently methods were not available for analyzing whole structure behavior which would be sufficiently accurate to determine restraint values. The methods, which will be further considered in Chapter 9 are now becoming available and should obviate future uncertainty about expected loadings.

3) Joints and edge effects. A furnace test should ideally model actual structure joints and inhomogeneities and, conversely, not introduce any boundary conditions (edge effects) different from those in the design building. The first requirement has almost never been met. Tests of beam-column joints are perhaps unnecessary since the joints experience small temperature rises due to additional heat sinking. Wall-ceiling joints, however, can be expected to be points of weakness, especially in regard to transmitting gases. Since only a very few furnaces have been built to accommodate such joints, no body of knowledge is available.

Edge effects are hard to treat because they represent essentially unlimited sources of error. Ingberg[202] discussed the matter in a general way in 1949. The problem is usually of greatest importance in small-scale testing, where edge effects can contribute significant error due to the small size of the specimen. Often preliminary heat flow results obtained from small-scale furnace tests are de-rated by some empirical factor, introduced to compensate basically for edge cooling.

Even in a standard size E-119 test specimen there may be noticeable edge effects. An example can serve to point out difficulties to be guarded against. In a wall specimen the regions close to the sides of the frame will stay cooler than the rest of the specimen because of the shielding action by the relatively massive frame. If studs are so spaced as to fall close to the frame side, these end studs will remain cooler than the others. If the wall loading consists of a single rigid beam across the entire wall, a disproportionately large share of the load may be held up by the cooler end studs. To avoid unjustifiedly favorable results for wall tests conducted[203] in the course of Operation Breakthrough loading beams split in the middle were mandated. Bridging behavior is thereby avoided and an indication of failure is possible even though reserve capacity is still available from the cooler end studs.

4) Moisture Content. The E-119 standard specifies that 50% relative humidity be the standard condition for curing of a specimen. The air humidity is important for some materials, most notably wood and concrete, containing free moisture. Free moisture is the water that is held in a specimen which is in dynamic equilibrium with the moisture of the surroundings. Bound water, important for gypsum materials, is by contrast chemically attached and does not vary with the humidity of the surroundings.

The actual humidity in a building will depend on local conditions and may not at all be close to 50%. Thus, under actual use conditions the endurance may be different than measured or calculated. Rules-of-thumb[204] are available for making endurance corrections, if desired.

5) Workmanship. Field-erected specimens will, as a rule, be built to higher standards when intended for furnace testing than for actual use. Invectives against the practice can, and have been made, but to little avail. The consequences become serious only when the effect of workmanship has a drastic impact on endurance. To date the major problem has appeared with membrane protection tile ceilings. The issue is explored further in Section 7.4. Another practice of concern has been the punching of holes in fire barriers for pipes, ducts, and similar services. As indicated in Chapter 7, the seriousness of the concern should depend on both the area of opening and the criteria used (whether ignition or toxic gas flow).

CHAPTER 7

STRUCTURE

7.1. Role of Knowledge of the Structure

The viewpoint traditionally associated with the fire endurance testing of barriers is that the structure is a black box. The test standards have, generally speaking, been carefully worded in order to be equally applicable to any conceivable material or assembly techniques. Building codes have usually adopted the same attitude. Some exceptions can be noted. The separation of assemblies into combustible and non-combustible ones and the placing of restrictions on the use of combustible assemblies is an outstanding, although not well founded, exception. The introduction of the T_c based criteria into the E-119 standard is another. Finally, there is a list in most codes of what might be called quality control provisions. Certain barriers, for example membrane-protected ceilings or sprayed on fireproofing, known or suspected to be often improperly erected are regulated in more detail.

Within traditional approaches, the damageability concept of the ISO provides the one clear instance in which it is admitted that not all x-hour components are equivalent.

7.2. Division Into Materials/Components/Structure

Because of the traditional unwillingness to admit that components that test out the same in a standard fire test will not in fact behave identically under all conditions, the understanding of the structure has not been systematized. Some concepts can, however, be developed here to clarify matters. A definition of terms will first be given.

Materials are the basic building blocks. They are the simplest elements into which the structure can be broken down and include all the raw building materials: steel, concrete, timber, gypsum wallboard, nails, and so forth.

Components are assemblies of materials, built into their final form. Components include walls, floor-ceiling assemblies, columns, doors, and frames, prefabricated plumbing cores, and so forth. Geometry and orientation are important for components, whereas these properties are not needed to define the material. A barrier consists of one or more components.

The structure is the building itself. For the purposes of analysis and testing, however, it may also include large representative areas of a building. For instance, an entire story, or an area bounded by occupancy separations, or one of several bays of a building may all be considered as a "structure" for some structural design or testing purposes.

Tests can be categorized according to whether they test materials, components or structures. Examples of material tests include methods for determining:

calorific value
potential heat[205]
thermal expansion coefficient
melting and boiling points
thermophysical properties:
  conductivity, heat capacity, and emissivity

Examples of component tests include:

fire endurance (E-119)
flame spread (E-84)[206]

Esamples of structure tests include:

tests for smoke flow through a building[207,208]
burnout tests

It must be observed that flame spread tests are properly not material tests, but rather component tests. The effects of size, orientation, thickness, and edges are often crucial for describing flame spread. These are all variables which do not describe bulk properties of the material, but rather are identifiable only when a component is described. Thus it is well known that the performance of certain materials in an E-84 tunnel test varies radically with the substrate used. Similarly, in carpet tests results depend on the type of backing pad used.

By definition, a burnout test includes all tests for determining the fire resistance in a total structure.

7.3. Critical Temperature Concept

Two primary factors are important in producing a good fire resistive barrier--a low thermal transmission and a high critical temperature T_c. The thermal transmission is governed by the three thermophysical properties discussed in the previous chapter, conductivity, volumetric heat capacity (ρC_p), and emissivity. The critical temperature concept will be discussed in some detail here. We shall define T_c as follows:

T_c = a temperature at which a material or a component collapses or undergoes a disintegrative change.

Physical disintegration is associated with a material and is usually easy to detect. Examples include charring of wood, calcining of gypsum, or melting of aluminum. The temperature may be a precise single temperature, as in the case of the melting of a pure element, or it may cover a broader range, as in the case of softening of thermoplastics. When a physical disintegration occurs it is assumed that the material retains only negligible mechanical strength. In many, but not all cases it will also fall off or otherwise lose its stability.

The second type of critical temperature pertains to a specific combination of material and component. A simplified example is a beam that is designed with a safety factor of 1.5 against collapse. If the beam is uniformly heated to a temperature at which the material strength is reduced to 1/1.5 of its unheated value, the beam will collapse. In this situation both the properties of the material and the way the component is designed are of importance.

The load-bearing behavior that is considered is not limited to the primary loading force. For example, in a steel stud wall where gypsum wallboard is attached with spring clips the spring clips are load carrying members also, not just the studs. Their failure will result in the fall-off of the wallboard.

Fortunately for the designer, many common materials show a slight strength degradation up to a certain temperature region and then a rapid decrease beyond that. In these cases the exact safety factor used is not consequential since it will not affect T_c significantly. For instance, using a safety factor of 1.5 for the ultimate strength of mild structural steel gives a $T_c \approx 470°$ C and a factor of 2.0 gives $T_c \approx 540°C$.

Conceptually, examples of critical temperature behavior might be noted as follows:

MATERIAL	T_c
metals (load bearing)	temperature at which the safety factor < 1.0
metals (negligible load)	melting point
wood	charring temperature
concrete; brick	varies, generally not reached in fire
gypsum	calcining temperature
synthetic polymers	softening temperature (thermoplastics);[209] charring temperature (thermosets)

Using available data, a rough tabulation of typical values can be made

MATERIAL	T_c
steel, mild	550° C; load release, if tensile safety factor ≃ 2.0
aluminum, pure	1500° C: melting
aluminum, alloys	150 - 200° C: load release
	560 - 600° C: melting
concrete (compression)	400 - 600° C: crushing
wood	320° C
gypsum	95 - 200° C
thermoplastics[210]	
ABS	170 - 245° C: deflection temperature at 66 psi
nylon	374° C
polycarbonate	240 - 290° C
polyethylene	100 - 190° C
polypropylene	185 - 250° C
polystyrene	180 - 240° C
polyvinyl fluoride	270 - 300° C

Considerations of the critical temperature concept make it evident why endurance test and design methods that were satisfactory fifty years ago are no longer adequate. The type of materials and components in general use have changed significantly. Fifty years ago in any structure requiring a definite fire endurance, the walls, floors, beams, and columns tended to be of heavy steel, concrete, or masonry. A major advance in building design since then has been the lowering of the structure's dead weight and the use of new, lighter materials. By reducing the thickness of a member, its heat transmission, and possibly other properties, are made worse. More accurate assessment is then needed to determine if an adequate safety reserve still remains. Furthermore, new building materials often have lower T_c and lower reliability, a point which will be taken up below.

7.4. Reliability

Deeply entrenched in the conventional view of fire endurance is the assumption that reliability is perfect. That is to say, a wall that is tested to have an endurance rating of two hours will not fail at 119 minutes. Most testing engineers and some design professionals realize that this is not true. To counteract that view of perfection requires some quantitative techniques of evaluation.

The concept of reliability is well established in some other technical disciplines. There is, for instance, an accepted methodology for rating the cycles or hours of operation that electronic components will endure; also, a technique for augmenting measured automotive engine emissions values by a factor derived from long-term testing. Each

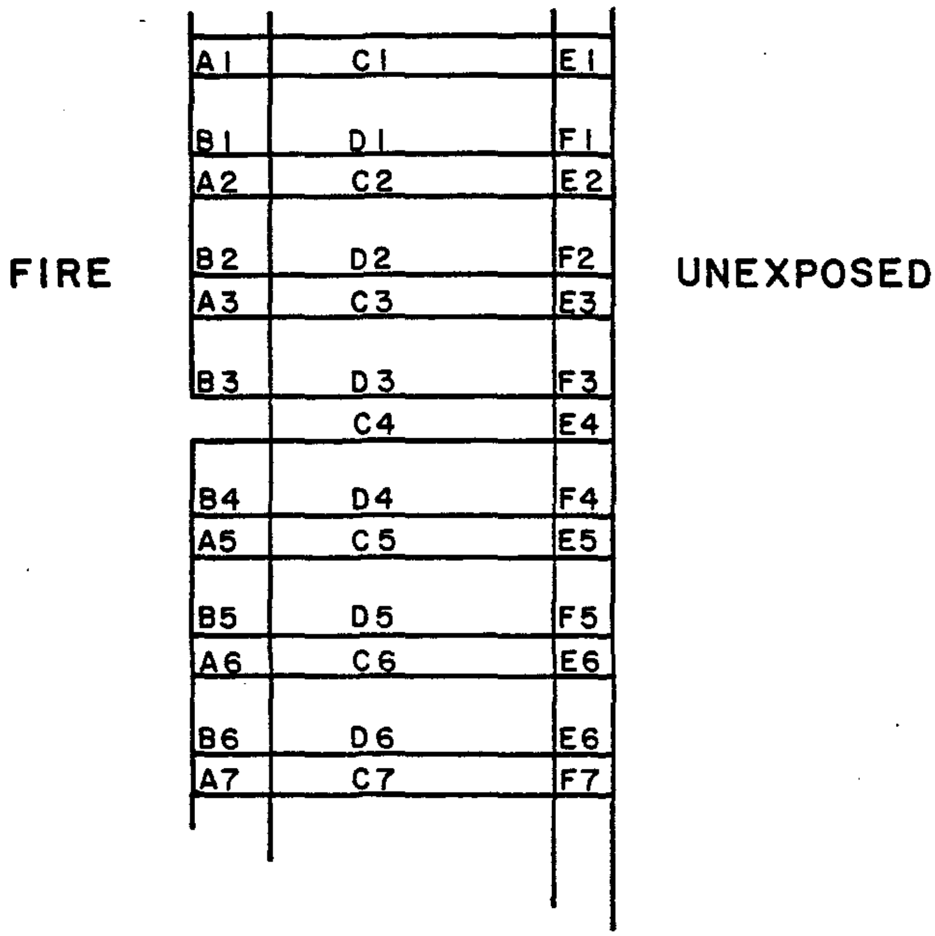


FIGURE 37 VERTICAL SECTION THROUGH A WALL

method of this kind presumes that it is not adequate to simply test one specimen under one condition and have any genuine credence in the test data.

By its very nature it is apparent that reliability cannot be determined without multiple testing, but that testing need not be done on an entire component. It is not absolutely necessary but it is most instructive to introduce the idea of discretization. Only a limited amount of useful, affordable data can be gathered by treating a component as a black box. Much greater insight can be obtained by realizing that, almost without exception, a building component is physically not homogeneous but is made up of modules. Even as simple an assembly as a concrete masonry wall contains modules of concrete block and of mortar, and often also reinforcing steel and grout. A gypsum wallboard wall consists of at least four types of modules: wallboard, studs, fasteners, and joint sealant.

Modules can be arranged in an infinite multiplicity of geometries, but there is a way of organizing the study of these arrangements. Consider a simple example--a non-loadbearing wall. The wall is assumed to be a planar component, having repetitive parallel lines of symmetry in two perpendicular directions, but no required symmetry in the third, thickness, direction. Consider that the main failure path is in the thickness direction. Two types of failures will be examined: disintegration and temperature rise. That is, a module can fall off, melt away, char or otherwise lose its integrity, or it can undergo a higher than desired temperature rise. Figure 37 gives a schematic illustration where one module has disintegrated. The failure criteria will be applied only to the modules on the unexposed side, i.e., E_1, E_2, F_1, F_2,

A FAILURE = DISINTEGRATION

B FAILURE = $T_w(L) \gg T_{ignition}$

C FAILURE = $T_w(L) \gtrsim T_{ignition}$

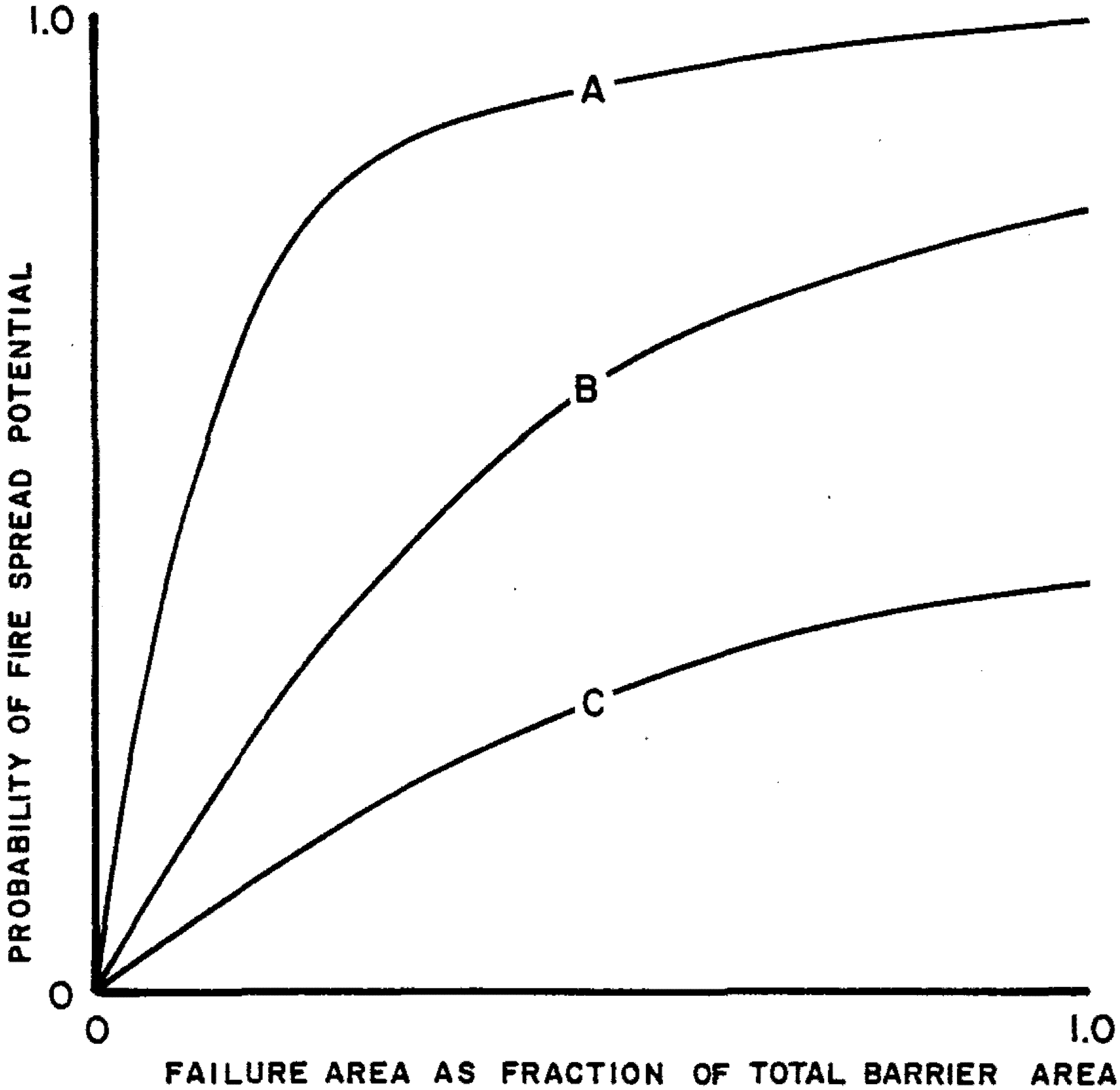


FIGURE 38 RELATIONSHIP BETWEEN BARRIER FAILURE AREA AND FIRE SPREAD POTENTIAL

etc. These must disintegrate or overheat for failure to occur. Their time to failure, however, is influenced by the failure of other modules.

The area of failure is a critical factor. Unfortunately as of now it cannot be fully quantified, although certain observations can be made. Consider the simple goal of protecting combustibles in the space on the unexposed side of a barrier from igniting. The problem is complex but some simple observations can be made.

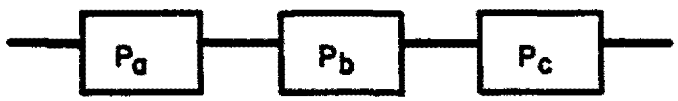
1) A hole or an area of high temperature on the unexposed side of the barrier will ignite combustibles only if it is sufficiently large. An infinitesimally small area of failure brings only an infinitesimal chance of ignition.

2) An absence of an entire wall between two rooms will cause simultaneous flashover in both. This is the well-stirred reactor hypothesis.

3) It is evident that the probability of fire spread beyond the barrier is proportional in some way to the area of the failure and also to the nature of the fuel in the adjoining room.

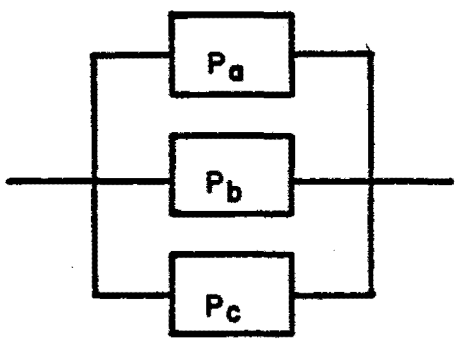
4) A fully probabilistic model would take into account the particular nature of the adjoining room combustibles. At present, some simplified criterion must be adopted, as discussed in Chapter 8.

Lacking a better basis, a simple example can be constructed by assuming that the probability of fire spread beyond a barrier is linearly proportional to the area of barrier failure, when failure is disintegration or temperatures greatly in excess of expected ignition levels. The actual shape of the curves might be more as indicated in Figure 38.



$$P_\Sigma = P_a \cdot P_b \cdot P_c \cdot \ \ldots$$

(a) SERIES CONNECTED ELEMENTS



$$\overline{P_\Sigma} = \overline{P_a} \cdot \overline{P_b} \cdot \overline{P_c} \cdot \ \ldots$$

(b) PARALLEL CONNECTED ELEMENTS

FIGURE 39 SERIES AND PARALLEL CONNECTION

Each module of a barrier can be described not only by its area but also by its relation to adjoining elements. An element can be connected to adjoining elements in series or in parallel. Figure 39 shows the two possibilities. The connection is <u>functional</u>, rather than literal. Elements are understood to be connected in series if the failure of any of them brings the failure of all. Let P_a = probability of success of module a, then the total probability is

$$P_{\Sigma} = P_a \cdot P_b \cdot P_c \cdot \ldots \tag{7.1}$$

Conversely, elements are connected in parallel if the full success of one alone is enough to ensure the combined success. Letting $\overline{P} = (1-P)$, the total probability for parallel elements is

$$\overline{P}_{\Sigma} = \overline{P}_a \cdot \overline{P}_b \cdot \overline{P}_c \cdot \ldots \tag{7.2}$$

The failure of modules of a wall is somewhat complicated because the probability of success for each module is a function of temperature, while temperatures are a function of both time and location within the wall. It can be seen that the critical temperature is properly a stochastic variable (Figure 40), and its value depends on the level of certainty specified to be required. Existing data are rarely available on a stochastic basis; usually only a typical range of values is available.

At this point it can be seen that even though the problem has been greatly simplified, two probabilistic quantities have to be treated:

--probability of fire spread, as a function of area of barrier failure

--probability of module failure, as a function of temperature (T_c).

An understanding of failure mechanisms can be reached more easily if a viewpoint is considered where the T_c is used only deterministically. Consider the wall in Figure 37. The failure determination goes in the following steps, once the T_c for each material is known.

1) At each time step calculate the temperature distribution.

2) Examine each module to see if its T_c has been exceeded.

3) If it has, consider as disintegrated both that module and all the ones which are series-related to it.

4) If no module of the unexposed face (E and F in example has surpassed its T_c, advance to next time and go to step 1.

5) If an unexposed face module has surpassed its T_c, consider its area as having failed.

6) Advance to next time.

In the example of Figure 37 if C_4 fails first, and if A_4 is in series with it, then A_4 must be considered as having also become ineffective. In the same example if the structural configuration is different, so that all of A_i to A_n and B_i to B_n are series-related to it, then they will all become ineffective. An immediate failure will not occur, but in the next time step much higher temperatures will be recorded. Conversely, another arrangement can be imagined whereby for A_4 to fail not only C_4 but also D_3 and D_4 have to fail. Then C_4, D_3, and D_4 are in parallel path, as far as their effect on A_4 is concerned.

What emerges from the example is that the failure geometry is not isotropic. Disintegration of C's or D's will cause direct disintegration of related A's or B's, but the converse is not true. Thus for each module a separate chain must be constructed.

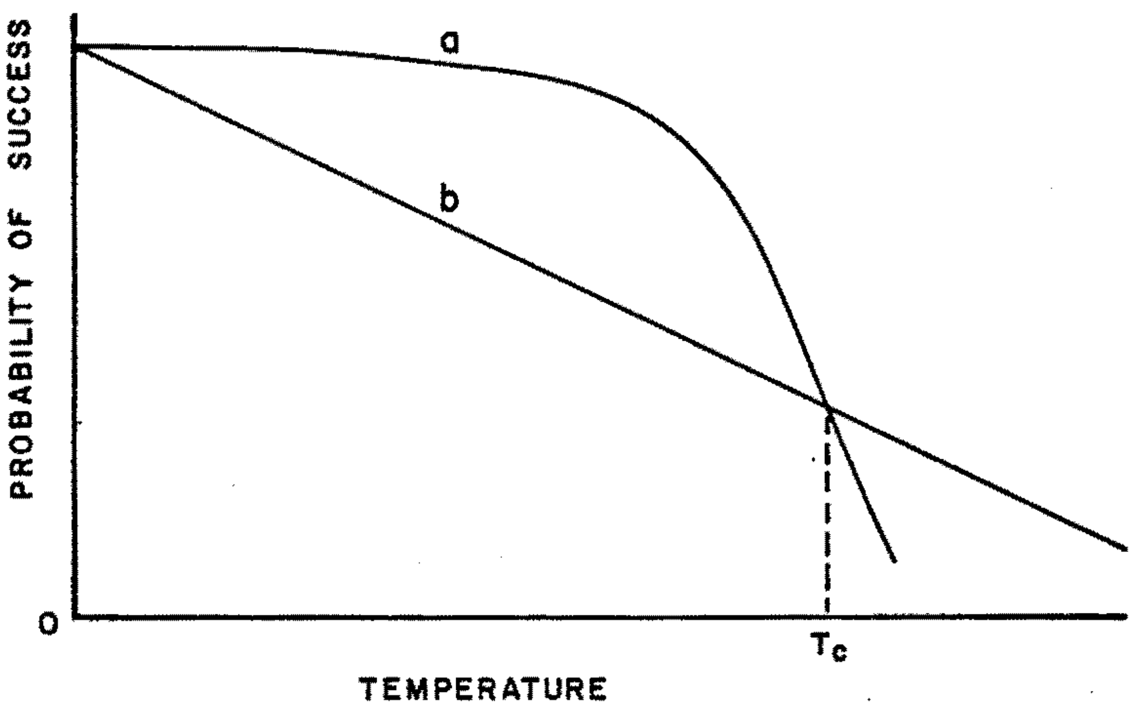


FIGURE 40 STOCHASTIC NATURE OF T_c

Viewed stochastically, the go/no-go failures of each module at T_c are simply changed to a temperature-dependent probability. The calculations are complicated but the concept is not.

Realistic examples can now be considered. Confidence is often placed in the fire endurance performance of a reinforced concrete floor, yet a similar confidence is not justified[211] for a floor assembly using lightweight bar joists protected by a ceiling comprised of lay-in tile on a T-bar grid. Why should that be, in view of the fact that both can achieve the same E-119 furnace test rating? The lack of confidence will not be dispelled even if the exposing fire and the criteria are made as realistic as now possible.

The reason for the lack of confidence can be ascribed to two factors:

--components which have a significant probability of failure at a low T_c, even though the mediam T_c is quite high, e.g., components with behavior as in curve b, rather than a, in Figure 40.

--conditions which make extensive series-related failures possible, especially if dependent on wide-variation components, as above.

Returning to the comparison examples, consider the elements in a concrete floor. Let a single tension reinforcing bar be of poor quality and fail at a very low T_c. Some local spalling might result but a large area will not be affected. On the other hand, let a single joint in a T-bar grid ceiling be incorrectly screwed together so as to restrain a connection that is intended to slide upon expanding. It is quite likely that not only will the member so screwed down buckle at a very low T_c, but also that it will allow several tiles to collapse.

Once the tiles have fallen out, the temperatures in the space below the bar joists will rise rapidly and total collapse may follow shortly.

The above practical and theoretical considerations suffice to indicate that the reliability of the structure is a factor of decided importance. The connection between critical temperature and reliability concepts can lead to an approach incorporating both simultaneously. For this to become feasible several steps must be taken. A useable catalog of T_c data must be established. Then a quantification of the relationships of Figure 38 is needed. Guidelines for determining the series and parallel connection of elements in actual components are needed. Also, the criteria must be expressed in terms of probabilities.

It is worth noting that a related approach is encompassed in the GSA manual.[3] Probability of success curves are used there for different barriers, as a function of (Ingberg's) severity. A one-hour rated concrete masonry wall is given a 0.3% probability of structural failure prior to one hour of test, while a similarly rated steel floor deck assembly is assessed at 4.0%.

CHAPTER 8

CRITERIA

8.1. Existing E-119 Criteria

Appendix H gives a summary history of the criteria, as included in ASTM E-119, its predecessor standards, and the parallel door standards. The provisions can be grouped into several broad areas.

A. Stability

The simplest consideration of stability is that a load-bearing member should withstand its normal design load under fire without collapse. This requirement has been applied to floors, walls, columns, and beams ever since their testing was provided for. Taking directly from the New York City standard, the earliest edition specified 150 psf as a mandated floor load because of related code provisions for structural design. A specific value was abolished in the 1918 edition. A deflection limit was prescribed for floors in 1907-8 in an apparent attempt to exclude insubstantial constructions. It was not related to deflection as a measure of impending collapse, a concept which was never espoused in the ASTM standard.

The standard, again going back to New York City provisions, contained during 1909-1918, criteria for walls that they "must not warp or bulge, or disintegrate under the action of the fire or water to such an extent as to be unsafe." The motivation was similar to the deflection requirements for floors in trying to eliminate flimsy constructions. A vestige of that philosophy continues to this day--test laboratories usually record floor and wall deflections, even though no failure criteria based on deflection are given in E-119.

As pointed out in Chapter 3, the hose stream test has been one of the mainstays of fire testing since its beginning. It is now retained only for walls and doors. Hose stream requirements for floors were dropped after 1953 because of the difficulty in obtaining uniformity, the destructiveness to furnaces, and the fact that floors very rarely failed on account of hose stream criteria; while for columns hose stream requirements were never present except for a brief mention in the 1918 edition. Prior to 1918 the hose stream test was to be conducted on the same specimen as that subjected to the full furnace exposure. In 1918 the section was changed to permit the hose stream test to be done on a second specimen which had been tested for only 3/4 of the desired endurance period. The requirement was further limited by stating that the hose stream exposure was not to exceed 1 hour; nor was it needed for specimens with endurance of 1/2 hour or less. The numbers were changed in 1926 to reduce the hose stream exposure to 1/2 the endurance rating of less than 1 hour. In this form the hose stream provisions are still in effect for walls. No reason was given for the changes.

A curious re-loading requirement was in effect for floors from 1907 to 1953 and is still in effect for loadbearing walls: after the hose stream test the specimen is to be reloaded to a higher superimposed load, equal, since 1926, to 2 times the test load. Historically the requirement goes back to New York City floor test procedure; no other explanation has been offered.

Starting in 1947 the critical temperature concept was introduced as a permitted alternative, first for columns, later for beams and floors. It can be presumed that the reason the same concept was never incorporated for walls is that, in its current version, it is only applicable to steel structures (or concrete with steel reinforcement, where steel temperature is presumed governing). Wall failures will more often than not be due to critical temperatures in materials other than steel. Even where failure is due to steel T_c first being reached, in a wall of lightgage elements failure will probably be due to buckling and thus occur at a much lower T_c than the values used in E-119 for floors, beams, and columns, which are based on simple yield strength degradation.

B. Thermal Transmission

The earliest requirement for floors and walls as thermal barriers was simply that they not pass flame or fire. In 1926 the requirement was somewhat quantified, by specifying the criterion as whether cotton waste, applied to the unexposed face, will ignite.

Unexposed face temperature measurement was first specified in 1918 for walls and in 1926 for floors. The measurement was not incorporated earlier because a reproducible measuring technique had not been developed. Ingberg described these early measurements as follows:[212]

> "[at Columbia University] the temperatures on the unexposed surface were measured at the middle of each panel with a thermometer whose bulb was in contact with the panel, the stem of the thermometer and the wall area around it being covered by an empty cigar box with the open side against the panel. In tests conducted after 1910 the cigar box was replaced by a 2 by 4 by 4 inch asbestos pad. The thermometer was inserted through an inclined hole in the pad and had its bulb in contact with the unexposed side of the panel."

A pad is used under the thermocouples for three reasons: 1) it is intended to simulate the conditions of combustible goods stacked directly against a wall or floor. 2) A true surface thermocouple can in some instances be hard to properly mount; it is easier to retain one interstitially. 3) A thermocouple protected by a pad is less sensitive to convective currents at the back face than a surface mounted one. Thermally a padded thermocouple represents conditions fairly close to adiabatic at the wall surface, at least up to temperature levels of the kind specified in the standard. The padded temperatures are always higher than the surface temperatures; when padded temperatures reach 150° C surface temperatures are only in the vicinity of 110° C.

Initially, in the 1918 edition, a value of 149° C was picked for the thermal criterion. In 1926 the specification was changed to a 139° C rise, measured with respect to ambient room temperature. The change was in line with considerations of heat flow equations, where $(T_w(x) - T_\infty)$ is the governing variable, and served to not penalize tests conducted in warm climates. Also in 1926 a provision was made to limit the maximum single point rise, in addition to the average rise. A value of 30% higher, 181° C was chosen. The single point rise is intended to eliminate components which tend to develop localized hot spots.

The 1918 criterion apparently stemmed from a study done in 1915 at the Forest Products Laboratory, in Madison.[213] Samples of nine species of wood, each 3.2 by 3.2 by 10.2 cm in size were tested in a constant temperature tube furnace for up to 40 minutes. At that maximum time the piloted ignition temperatures ranged from 157 to 195° C.

The piloted ignition values given would naturally give rise to 150° C as an ignition criterion. Matson, Dufour and Breen[214] have summarized much of the later literature. It is evident that for unpiloted ignition, which is certainly the one to be considered, since prevention of any flame is precisely the avowed object, the temperatures are significantly higher. Graf,[215] in particular, reports quite extensive tests on even smaller specimens (7 to 13 g) but under unpiloted conditions. The ignition temperatures are almost all in the range of 231 to 264° C justifying instead a 250° C criterion.

C. Completeness

Completeness means the absence of openings penetrating an assembly and is applicable only to planar barriers. The property of completeness has two aspects--to avoid spread of flame and to avoid propagation of toxic combustion products. (Lineal barriers, by contrast, have only a function of supporting load.) Lack of completeness can be produced in different ways. Cracks can open up in an assembly while it is being tested or while in a real fire. Or, it may be designed to contain openings already in it. Call the former "tested openings" and the latter "untested openings." A test standard, such as E-119, deals only with tested openings. Restrictions on tested openings can be placed directly based on their size. This is the approach taken in the door test standard where limits on size of openings and on edge warpage are set up. Or, openings may be regulated according to their effect. The actual transmission of flame is restricted by the cotton waste criterion and was already included under thermal transmission above. The gas spread potential is not currently limited or restricted in the ASTM standards. Only the 1907-9 editions of the test standard contained a criterion for floors and walls; they were not to pass smoke. Untested openings are currently regulated, but in a non-quantitative manner, by other sections of the UBC. Section 4305 contains a general admonition for enclosing openings, while Section 301 further requires that the building plans indicate what protective measures were taken.

8.2. Rational Bases for Criteria

The criteria for fire endurance should stem from the firesafety goals. The goals relevant here are:

(a) reduce probably property damage, potential for conflagration, and operation losses

(b) provide for safety of occupants in case of fire

(c) provide for safe and successful firefighting.

The means for using fire endurance to promote the three goals are not separate. Each goal requires a curtailment of flame spread, while the latter two goals also require a curtailment of smoke spread and a limit on temperatures and heat fluxes. It might also be considered that the function of fire endurance is to prevent falling objects as a source of injury. An extreme case can be envisioned where a portion of the back face of some assembly falls off much earlier than it actually transmits flames. Such failure is rather unlikely, and it will be assumed to not occur prior to the failure of fire spread curtailment.

8.2.1. Curtailment of Flame Spread

Fire spread in a building is influenced by the structural geometry. Three factors must be considered. The physical spread of fire through the geometry must be limited. The geometry must not be changed by fire in a deleterious manner. The building may be designed to induce a desirable change in geometry. For example, thermoplastic skylights can be used which will melt out and ventilate in case of fire, detector-operated fire-rated movable partitions or more commonly fire doors may be employed, or even collapsing ceilings may be used to smother a fire. These active methods will not be discussed in detail herein. What is then desired is that a barrier not disappear and that it not transmit flame, heat, or combustible gases in quantity sufficient to propagate the fire. To be useful the above statement has to be made quantitative and more specific. A subdivision into stability and thermal transmission areas can be made.

A. Stability

i) Representativeness of Varying Loadings

Measurement of an element's resistance to collapse, i.e., its stability, would seem to be simple. In an actual building it is normally obvious whether an element has collapsed or not. In a test furnace or in a numerical simulation several difficulties arise. If the test specimen is not full size of if the connections or mountings are different from those of the modeled element, as they all perforce will be in any standardized test, then collapse may not come at the same time. End restraint modeling is recognized to encounter this problem. End restraint, which is normally considered only for floors can be thought of as loading orthogonal to the main direction in which the service load is applied. Walls present a somewhat different loading problem. The service load here is applied parallel to the member surface, so an orthogonal loading is one perpendicular to its surface and arises, not from restraint against thermal expansion but from random loads. Unlike in a floor, in a wall the service stresses are compressive; the imposition of bending stresses from perpendicular loads will not induce beneficial "prestressing" as with floors, but rather decrease the performance. The orthogonal loads can be expected to come from any number of sources: objects falling, load shifting, or even a hose stream played against it.

In a wall or a column, unlike a floor, it is possible also to have restraint in the direction of the service load. The effect has not been studied for walls. For columns the effect can be visualized by comparing a column near the bottom of a multi-story building to one at the top. No thermal restraint will be noted if the structure is heated uniformly. If, however, only a portion near the column is heated, then the column at the top will pick up much less additional load than the one at the bottom. The subject of restraint is complex and ill-understood, yet important, since it is known that it can have up to a several-fold effect on endurance. Restraint can rationally be taken into account by calculating the whole-structure response. If that is done, then special criteria are not needed to account for it. Currently the best recommendations is that if significant restraint effects are expected, a whole-structure analysis, as discussed in Section 9.2.2, be performed to calculate the stresses and deflections.

ii) Point of Collapse

With many materials and assemblies the point of actual collapse is not clear. Floors especially can deflect far beyond reasonable bounds for some time before the unit actually falls down. The E-119 standard is silent on the question of what constitutes reasonable deflection. In an attempt to answer this question Ryan and Robertson[216] proposed that the following two criteria, based roughly on elastic deflection theory, be used for floors and beams:

Deflection

$$\frac{y}{L} \leq \frac{1}{800}\,\frac{L}{d} \qquad (8.1)$$

Rate of Deflection

$$\frac{dy/dt}{L} \leq \frac{1}{500}\,\frac{L}{d} \quad \mathrm{hr}^{-1} \qquad (8.2)$$

where y = deflection

L = span length

d = specimen depth

The above relations have been adopted, often with some modification, in many parts of the world but not in the U.S. A definite numerical criterion for transversely loaded members should also be adopted in the U.S.

Walls and other parallel loaded members collapse by crushing or, more commonly, by buckling. In either case the time elapsed from incipient failure to total failure is normally quite small. For that reason no similar criterion has been proposed. Indeed, the recording of wall deflections, as currently practices could well be abandoned.

iii) Orthogonal Loading and Hose Stream Testing

In the U.S. the importance of orthogonal loading for walls is known only from the hose stream requirement still in effect. Hose stream testing in the last century was initially applied to all components. It served two functions. Foremost was to exclude those materials (mainly cast and wrought iron and certain types of terra cotta) which shattered when hit by water in a building fire. A brittle collapse of this nature is undesirable; its possibility had to be investigated as long as building materials were commonly available which might collapse by shattering. Current building materials do not shatter under hose streams, thereby obviating the need for continued hose stream testing. The second function of the hose stream test was to ascertain whether components were not so flimsy as to fail when orthogonal loading was added. This test objective remains valid for walls. It is not relevant for floors since here hose stream loading is in the same direction as the service loading and is but a small additional increment.

The hose stream test is still also applied to doors. Here an additional stability requirement (beyond staying in place) can be justified on the grounds that it might exclude excessively flimsy components, but by itself this is not a sufficient reason since no falling objects or shifting loads could normally be imposed on doors. Thus no hose stream or similar requirement should be contemplated.

For walls it is desirable to maintain a horizontal loading requirement in order to exclude components of poor reliability. This objective can, and should, be reached by means that are more precisely controllable than a hose stream, and also that represent more clearly a calculable horizontal loading condition.

The basic hose stream force was measured by Ingberg[217] who determined that with 30 psi water pressure, under E-119 conditions the measured force against a test panel was 257 N, quite close to the value calculable from flow formulas. The area on which the stream impinges is approximately 56.7 cm^2, giving an average static stress of 45.3 Pa.

An average stress value is not truly meaningful, however, unless failure arises from the flexural or buckling deflection of a large segment of the test assembly. Walls do not fail in this manner in the hose stream test. The E-119 criteria as currently written prohibits any hose stream penetration of the assembly. Most walls tested, especially those using gypsum wallboard, if they fail the hose stream, they fail by puncturing, not by starting to collapse. The failure usually starts at a crack and propagates from there, much as in fracture or tearing failures. An improved horizontal load test could consist of two possibilities--either a pendulum impact test after the specimen is removed from the furnace (as is done in Germany),[194] or a constant orthogonal loading applied throughout the test.

The orthogonal loading can be applied in two different ways. For loadbearing walls the simplest is an eccentric application of the vertical loads. This will cause bending stresses like those produced by transverse loads, except for being invariant over the height of the assembly. The second possibility is to apply transverse loads directly to the back face of the specimen by means of a loading frame. The area over which the loads are applied should be significantly greater than the diameter of a water jet, to ensure that any collapse occurs from bending rather than from punching shear or local crack propagation. The direct loading scheme is more cumbersome for loadbearing assemblies and there is little to recommend it over the eccentric axial load scheme.

For walls which are not designed as loadbearing members the situation is more difficult. In the E-119 standard such walls are not truly treated as non-loadbearing not only because a hose stream test is prescribed, but also because it is specified that the wall should be tested fully restrained against thrust in its furnace mounting frame. It might be more reasonable to require that these walls instead of being tested restrained should rather withstand a small vertical load, applied with a large enough eccentricity to given appropriate bending stresses.

A trial recommended value for the bending moment could be arrived as follows, if it is desired to maintain the same stress as currently. Assume that the hose stream force of 257 N acts as a point load halfway up a 2.75 m high wall. Assume also that it acts on one stud or other vertical load-carrying module, and that these are spaced on the average 0.406 m (16 inches) apart. Then the desired bending moment is

$$M = 865 \text{ (n-m, per m wall length)}$$

The unreasonableness of the present criterion is evident from the fact that manufacturers will often produce a wall which is perfectly adequate for normal service conditions and then wish to get a fire resistance rating on it. In some instances such walls have, on a developmental basis, been given a hose stream test which they failed, <u>without the assembly having first been exposed to fire</u>. This is clearly tantamount to imposing a higher safety factor requirement on the structural strength of a member when under fire than when not, which is the opposite of accepted structural design philosophy. The identical objection can be offered to the double liveload reloading requirement. The hose stream test can be replaced with a better procedure, as suggested. The reloading requirement should be abolished.

B. Thermal Transmission

A column or a beam can fail only in stability since there is no other way it can act as a barrier except by continuing to support load. A wall, floor, door, or other planar element is intended both to be sufficiently stable and to effectively stop fire spread beyond its location. Failure to do so can be called thermal transmission. Thermal transmission can occur in four different ways:

i) Openness

Spread of fire through direct flame spread can occur if the barrier has apertures through which flame or combustible gases can pass. The amount of direct flame or gases passed is proportional to the area of the aperture and to the square root of the pressure difference across it. To reduce the potential for fire spread through openings they must either be made small or a negative pressure differential must be imposed. Pressure differentials depend on building geometry and the ventilation system, which might be designed to minimize the effect of openess. But pressure control has not yet been developed to a sufficient extent that it could be considered reliable.

Means for gas transmission measurement are suggested in Section 8.2.2 which, if adopted, would also serve for determining the contribution of openness to flame spread potential since similar measurements are required for both. Cotton waste testing can be used for supplemental indication, on specimen areas not otherwise instrumented. To make either method useful it is of paramount importance that a proper pressure distribution be used. In addition, to make the cotton waste test useful the furnace burners should be run in a diffusion rather than pre-mixed mode, in order to avoid a large excess of air.

The present E-119 standard does not have a quantitative openness criterion. The cotton waste test serves qualitatively as partly a direct flaming indicator, partly as a conduction ignition hot spot indicator (see below) and partly as a flame flow detector. Its usefulness for flame flow studies is minimal since it is not quantitative. Because fire tests are customarily made under negative pressure differentials, the use of cotton waste as an opening indicator is precluded and cotton waste testing is useful only for detecting back face smoldering.

ii) Direct Flaming

If the barrier is combustible, then its back face can catch fire. Any significant flaming clearly constitutes a failure. How to define "significant" is not completely obvious. At an instrumented part of the specimen it is hard to imagine failure by direct flaming unless failure by openness, conduction ignition, or radiation has already occurred. But since thermocouples or gas flow apparatus cannot cover the whole back face, direct flaming failure may be observed before these other failures. Cotton waste is currently used to detect direct flaming, but since it will ignite very soon after being subjected to a small flame, direct observation may be just as adequate.

iii) Conduction Ignition

If the back face of a barrier becomes hot enough, any combustible materials which are placed in direct contact with it can ignite. To obtain failure by this mechanism combustibles must be piled in contact with the barrier. Codes require that combustibles not be piled against fire doors; thus the criterion is inapplicable to them. Combustibles are also not piled against the exterior of buildings. Roofs do not normally hold combustibles except for any combustible material in the roofing itself, which is normally hard to ignite in those buildings where fire endurance is specified. Floors, however, may be fully covered with carpets. Up to the present time work has not been done to define the ignitability potential of carpets exposed to a post-flashover fire from below.

Conduction ignition through barriers can be limited either by management of the combustibles or by limitation of back face heating. In practice both are needed, management because some materials ignite at very low temperatures, and limitation of back face heating to provide some protection against spread of fire during accidental or temporary storage.

The current E-119 criterion of 139° C for average rise was derived in 1926 from the 1918 limit of 149° C by subtracting an average 10° C ambient to yield the rise value. It has remained unchanged ever since. In 1924 Ingberg established[218] two separate ignition criteria: 150° C (actual, not rise) for hazardous materials such as matches and nitrocellulose and 250° C for "ordinary combustible materials of vegetable or animal fibers" and for wood structural members. Walls tested by NBS were then given two ratings, one for each limit. The E-119 standard never reflected this distinction. Some three decades later[60] Ingberg again explored ignition temperatures. In tests of brick walls he placed boxes containing cotton and others containing excelsior against the back faces of walls. The behavior of both was similar--no ignition below about 204° C, some smoking at 204-232° C and usually ignition at 232-260° C. That such high temperatures were required for these finely divided, and therefore highly ignitable, specimens which were heated for 1½ to 12 hours, is one further indication that limits in the 150° C area are grossly conservative.

From systematic studies[219,220] it is known that time of heating and size of sample are both of prime importance in determining ignition, but the effect of these variables is usually not taken into account in designing ignition tests. Consequently, results of different investigations are hard to compare, and requirements tend to be set from the lowest quoted temperature.

It has been asserted that conservativeness is appropriate because the temperature limits are only measured until the end of the test. After the furnace is shut off in a standard E-119 test, the back face temperature continues to rise. Ingberg found[60] that if the furnace was shut off when the back face of a solid brick wall reached approximately 150° C, the temperature rose on the average for an additional 80° C. For hollow masonry or for dry wall constructions, the majority of walls today, the post-test rise is much less. Some data taken at the University of California indicate that a 20-30° C increment is more likely.

The concern with post-test rise in this case is spurious. No known real fire behaves like the E-119 furnace test, where the gas is abruptly shut off to end the test. Any natural fire dies down quite slowly. As a result it is unusual to see any backface temperature increases (or load failures) once the fire temperatures have died down. The problem would thus not be important if the test time-temperature curve were to model reality better. In other instances where a definite time limit for criteria should be prescribed (see Section 8.2.3) post-test concern is again obviated.

As discussed above, it is reasonable to presume that in the typical case combustible materials stored in an adjoining room will, at least insofar as walls are concerned, be located somewhat removed from the barrier and tend to ignite by radiation rather than conduction. Thus it can be suggested that the present conduction ignition criteria for walls might better be replaced by radiation ignition criteria. The question of carpet ignition on floors is one area where conduction ignition is important and needs to be explored.

iv) Radiation Ignition

To establish a radiation criterion a means of measurement has to be adopted and allowable levels have to be established. The measurement can be by a radiometer. Conventional radiometers are difficult to use, however, since they have low output and high uncertainty. Instead, it may be possible to use a water calorimeter. In such an arrangement a large flat tank of water would be placed some distance away from the unexposed surface. The water would be stirred and its temperature measured. It might also prove possible to correlate backface temperatures with backface radiant fluxes. In that case, thermocouple instrumentation similar to that now used for the conduction ignition criterion could be used, except that different failure values would have to be established.

Much further work is needed before a criterion of this type can become feasible. Existing data[221] have mostly been gathered for high-flux rates, short times, and simple geometries. To produce viable criteria investigations would be required of ignition under end-use conditions. A room with a common arrangement of furniture bordering on the unexposed face of a test barrier would be an appropriate configuration.

8.2.2. Additional Life Safety Needs

The criteria considered so far have a bearing not only on property safety but also on life safety. Some additional requirements must be considered that are specific only to life safety. The two salient ones are air quality and the thermal environment. For both of these criteria two separate populations must be considered--building occupants, and firefighters. Two sub-groups of occupants can be pertinent--occupants to be protected while escaping and occupants to be protected while remaining in the building throughout the course of the fire. While all three categories need to have their air quality and thermal environment controlled, it does not follow that the same values for the criteria apply to all three.

A. Air Quality

An adequate atmosphere requires the delivery of sufficient oxygen, a suitable removal of occupant-generated carbon dioxide, and a freedom from harmful amounts of contaminants. The first two requirements are related to ventilation design and only the last is a concern for fire endurance. What must be ensured is that the rate of introduction of contaminants is sufficiently low for a given ventilation system; thus some knowledge of ventilation is required here also.

Detailed consideration of gas flow criteria is presented in Appendix J. It is shown there that to establish gas flow criteria the following data are needed:

1) concentrations of toxic species in a fire
2) human tolerance for the different species
3) ventilation of the inhabited compartment
4) information on the completeness of the barriers.

The first three points are far removed from the main consideration here, the design and testing of barriers, and will not be taken up. The completeness of a barrier, however, can be tested in a furnace test. The objective is to obtain a graph for each planar barrier of the crack area, A_c, as a function of time. A proposal is made in Appendix J of a possible apparatus for gathering these data. Once this information is known the evaluation of a barrier can be accomplished if all the other points listed above are also known.

B. Thermal Environment

The environment to which the people protected by barriers are subjected must not be so hot as to cause panic or injury while in place or while escaping. Possible sources of heat are a flow of hot gases through barrier openings and the heating of the backface of the barriers. Heating through gas flow may not need to be considered since a concomitant transport of toxic species is likely to be an earlier threat. Barrier heating, on the other hand, presents a problem similar to that discussed

8.2.3. Time Duration

Conventional design philosophy implicitly postulates that all criteria must be fulfilled for the whole time it takes a fire to burn itself out. Two exceptions are given in the E-119 standard. Loadbearing walls must withstand a double live load reloading after they have cooled down from the hose stream; in addition, the hose stream test itself is not of the same duration as the rating period. The second exception is for restrained floors where the critical temperature requirement is applicable for a time which may be shorter than the rating period. There is no clear reason for either of these two specific provisions.

Some failures can be expected after a fire is burned out. Thermal transmission failures, as indicated above, may occur but are unlikely. Structural stability failure is more probable. If a calculated whole-structure response, as discussed in Section 9.2.2 is used, then these failures are easily determined. No other response methods, except burnout tests, can presently be used to predict them.

The question of time duration for criteria, however, is a serious one and should be taken up. At this point the reason for making distinctions between safety of property, of confined occupants, of escaping occupants, and of firefighters can be seen. For property safety goals it is simplest to specify that the endurance should be sufficient to withstand the expected fire. But this endurance time is not the only possible one. If long duration fires are expected, it may be impractical to provide a commensurate endurance. If a stochastic design is employed, numerous possibilities are opened up. Combined reliance on barrier endurance and automatic extinguishment can lead the designer to for radiation ignition. There is a fundamental difference in this case between the problem of escaping occupants and the problem of occupants in refuge areas. In the case of escaping persons, the time of exposure is short and direct radiation from the barrier is the governing variable. For confined occupants, on the other hand, whose time of exposure can be quite long, body equilibrium with much less elevated temperatures can be detrimental.

It is not the purpose of the present work to assign numerical values to human tolerance. It will simply be noted that Dinman[222] and Parker and West[223] indicate that radiant fluxes of 0.6 cal/cm -sec (corresponding to a black body temperature of 185° C) constitute a pain threshold. Below this value radiant exposures, even if prolonged, do not cause pain. For higher fluxes Kerslake[224] gives a relationship for maximum tolerable radiator temperature that varies inversely with exposed time. Criteria for confined occupants require, as with gas flow, knowledge of the ventilating conditions. Procedures for calculation are given by Pefley, Bell, and Shiamoto[225] and Jansson.[226] Their examples indicate that even for surface temperatures much lower than 185° C intolerable conditions can result with long exposures and low ventilations.

For confined occupants, because ventilation largely controls both gas flow and temperature rise, it is more useful to design the ventilation to suit the barrier, rather than conversely. The crack size and unexposed face temperatures of the barrier cannot be subject to a limit in themselves, but rather should be used as input values in the design of ventilation.

select a design fire which is much shorter than an unextinguished fire.

Sometimes it may be uneconomic to provide any property safety beyond that which is assured by life safety requirements. This viewpoint has been taken in the Minimum Property Standards,[200] where for one and two family residences endurance times are prescribed that in many cases are clearly less than the fire can be expected to last, but are judged sufficient for occupant escape. Under all circumstances it is desirable to provide a sufficient endurance time to assure the occupants reaching safety. This is a minimum.

If occupants are confined, then post-fire habitability must be considered, this constitutes one of those few cases where explicit post-fire evaluation must be provided. A complete time-temperature history of the unexposed face of the barrier in response to a calculated fire contains all the needed information about the fire, therefore, no additional arbitrary time limits need to be set; the response calculation must merely be continued until an ambient steady state is re-established.

Firefighters are the third group whose safety must be provided for. Their situation is different from the occupants' in several regards. First, to some extent firefighters can choose whether or not to enter a building. Thus stability throughout a burnout does not necessarily need to be ensured, provided that collapse does not occur precipitously and unexpected. Second, the thermal environment needs to be controlled only where and when firefighting efforts are applied. Thus, if any interior attack is contemplated safety in stairways should be assured but not necessarily safety in all other areas. Finally, the air quality requirements can recognize that protective breathing apparatus can be used, given the understanding that its use impedes fire fighting efforts.

Thus it is seen that in general it is not appropriate to assign a single time to all endurance criteria. The criteria, instead, should be grouped according to the goals, and separate levels of protection and duration times should be applied, as needed, for each goal.

8.3. Use of Criteria in Design

For any criterion to be meaningful, it must depend only on quantitatively determinable variables. The determination can be of two different kinds: measurements in a furnace test, and calculations by numerical methods. All of the criteria discussed in the previous section can be measured. Not all, however, can be determined in numerical simulation, at least as yet.

Structural stability for service loads can be determined numerically. A hose stream test response cannot be numerically calculated, because of the localized nature of the failure. Substitute criteria for orthogonal loading could be treated in a calculated response if the loadings are not impactive and are applied over large areas. This is the main reason for adopting an improved orthogonal loading criterion. Openness and direct flaming cannot be expected to be numerically calculable. Back face temperatures and heat fluxes can easily be calculated. Gas flow behavior, which is related to openness, similarly cannot be calculated.

CHAPTER 9

RESPONSE

9.1. Classification of Response Methods

It has generally been considered that fire endurance response can be divided into two categories: physical determination by furnace testing and numerical assessment by calculation. Prior to the introduction of computer techniques, the examples of methods for determining response were limited. Furnace testing, "thickness design," and greatly simplified heat flow calculation techniques were the only common ones. Even the latter, because of its poor results, could not be used except for rough estimating. The choice of reliable methods is now greater and a different classification is appropriate. The hierarchy of materials, components, and structure was developed in Chapter 7. On that basis it becomes desirable to classify response methods according to the highest level of modeling they employ. Thus those methods which are based on structure response potentially include the effect of all important aspects of structure behavior; those based on component response do not fully treat joints, restraint forces, and similar problems related to the interconnection of components; while those based on material response take into account only the behavior of a single material.

9.2. Methods Based on Structure Response

9.2.1. Burnout Tests

The ultimate test of a building's fire resistance is a burnout. As with any other full-size destructive proof test, the cost is high, satisfactory instrumentation and test control are difficult, and the results are of uncertain benefit. In a more philosophical sense, if any branch of technology often needs full-size destructive tests, it can surmised that the technology itself is primitive.

Nowadays component testing is usually done in a laboratory furnace while structure (burnout) testing is performed on a building in the field. This distinction was not always clear. The early testing of assemblies for fire resistance in the U.S. (mainly in the period 1896-1910) often consisted of building an ad hoc room which was neither a standardized furnace nor did it not accurately model all the components of an actual structure.

Burnout tests performed to determine the fire resistance of walls, floors, and other elements have rarely been conducted in a quantitative manner. The main reason for conducting burnout tests has usually been to evaluate phenomenologically the fire performance of some new or previously untested type of structure. Since the high cost of a burnout test prohibits its use on a routine basis, it is appropriate that burnout tests be used primarily to explore qualitatively the weak points of different building systems. Early burnout tests (typical examples are in References 227 and 228) were often conducted by manufacturers of various patented building systems. However, unless supervised by a reputable engineer their results were not considered credible. Later there are records of burnout tests being performed on buildings ranging from steel garage buildings[229,230,231] to plastic air supported structures,[232,233] not excluding mundane brick and wood joist buildings.[234] A bibliography by the Joint Fire Research Organization[235] tabulates 30 burnout tests that have been described in the published literature in a ten year period alone.

Because of the publicity aspects often dominant in building burnout tests there has never been a standard test method promulgated in the U.S. In France a standard test method,[236] however, is available. This test is required of modular pre-fabricated housing units which do not utilize a conventional structural system.

A standard method for burnout tests may not be fruitful since there is, in fact, not much to standardize. The structure, ventilation, and fuel load must be as in actual use. A major problem, that arises when a building has more than one room, is where to set the fire. Ideally, one would want to know the effect of making every single room the compartment of origin and recording the fire's progress from there. Practically, it is rare that more than one test would be feasible. The experimental plan is then open to reproach as not having given the most severe fire condition, or even a typical one.

9.2.2. Calculational Methods

Burnout testing is not cheap. It is not quick. It is not easy, nor is it convenient. Furthermore, in recent years calculational methods of determining whole structure response have advanced to such an extent that very often they can make burnout testing unnecessary. The main limitation is in criteria. Failures under some criteria, for instance gas flow, cannot yet be successfully calculated. However, if it can be presumed from prior similar experience that failure in a given instance will occur under one of the criteria which can be modeled, then a calculational approach is greatly to be preferred. No universal rules can be given that would obviate the need for engineering judgement in making this determination. It is usually true that calculated responses can be used for all lineal barriers and for those planar barriers where the failure is not of a localized, point nature. Prior experience is yet the only guide for determining the latter condition. Additional important considerations are that all the thermophysical and mechanical properties of the materials used must be known, and that a workable structural behavior model has to be available. Efforts so far have been directed mainly to characterizing the properties of steel and concrete, the two most common structural materials for larger buildings. A model for the behavior of joints and connections is not always available. This may require supplementary component or burnout testing in some instances to determine such failures.

Even with computer methods it is costly to model an entire large building. If a building consists of many repeating bays or units, it is sufficient to only model several adjacent units; thus a "whole structure" model does not, in fact, necessarily require that it be modeled in its entirety.

In practice, analysis can proceed as follows:

1) Determine the expected fire, using one of the techniques given in Chapter 6.

2) Calculate the temperature distribution which would result in the members.

3) Knowing the temperature history, calculate the stress distributions and deflections.

4) If any critical temperatures are reached prior to failure, correct for any re-arrangement of the geometry. Then recalculate steps (2) and (3).

Steps (2) to (4) will not be considered in detail here since adequate procedures are already available. General heat flow programs suitable for accomplishing step (2) have been developed by Becker, Bizri and Bresler,[237] and Polivka and Wilson.[238] Structural routines to perform step (3) have been developed by Becker and Bresler[239] for reinforced concrete frames, by Nizamuddin and Bresler[240] for concrete slabs, by Svensson and Bresler[241] for prestressed concrete elements, and by Chiapetta and Salmon[242] for steel and composite frames.

Since these techniques are so new, examples of analysis and design are scarce. One of the most interesting cases has been the computer analysis[243] of the Military Personnel Records Center fire which took place in July 1973. More general discussions[244,245] of the various programs have also been published.

9.3. Methods Based on Component Response

A more inclusive model is appropriate only when a less inclusive one is insufficient. In many circumstances a whole structure model would not give more accuracy than a model of an isolated component. No rigid rules can be set as to whether a whole structure model is required or whether a simpler component model will suffice. In general terms, loadbearing members may be inadequately analyzed by stopping at the component level, but for non-loadbearing barriers this should suffice.

9.3.1. Furnace Testing Using Ingberg's Hypothesis

This is the status quo approach. The fallacies inherent in the use of a standard time-temperature curve have already been pointed out in Section 3.3. The main advantages of the method are that it is well established and that no engineering judgement or understanding is required. Design and analysis costs can be saved by dispensing with professional help. A feeble set of advantages, indeed.

If some minimal additional instrumentation were added, however, useful data could even be gathered from the standard tests. It should be required that thermocouples be placed at all interfaces between two materials in a component. These temperatures can be recorded and published and used for two purposes. From correlations of temperatures with visual observations or with load variations a catalog of T_c values could be established. Also, if furnace temperature measurement is properly done with fast-responding thermocouples, the readings from these interstitial thermocouples could be used to verify, by trial computation, the thermophysical properties of the different materials.

Thus, even by rejecting the conventional standard time-temperature curve methodology it is seen that data useful for other, more rational methods could be gathered in the course of such tests, if these tests are continued.

9.3.2. Testing According to Calculated Fires

The simplest application of the expected fire theory developed in Chapter 6 is to use a rationally calculated curve to govern the temperatures in a furnace test. This alternative is most appropriate for new or novel components where the mode of failure is unknown and a catalog of T_c values is unavailable. This method is also necessary when failure is expected to be under those conditions that are not amenable to a critical temperature analysis. The details of the required considerations for the expected fire, the structure, and the criteria have been given in the previous chapters.

9.3.3. Critical Temperature Design

Critical temperature design is based partly on calculation and partly on testing. The basic tool is a computer program for heat flow calculation. A one-dimensional simulation may be sufficient for walls, while two- or three-dimensional calculations may be needed for floors and lineal elements. Testing is needed for three reasons:

1) To verify the mode of failure,

2) To determine thermophysical properties of materials, and

3) To obtain T_c values.

It is hard to prescribe completely general rules to cover point (1). Sufficient experience with identical or similar components must be available to the designer to determine, first, that the failure is expected to be under those criteria that can be treated by critical temperature design, and second, that assemblies have been investigated sufficiently to know that the relevant T_c values have been collected. Once this is done, the thermophysical properties and T_c values can be determined in several ways. It may be convenient to test small specimens, or the required data may be gathered in the course of traditional standard furnace testing.

The procedure to be followed in design has been suggested in Section 7.4. The design fire is first determined. Then a heat flow analysis is performed and modules reaching their T_c are progressively removed. The process is continued until failure is recorded.

It can be expected that if this method obtains currency, various design aids will be prepared to simplify the heat flow analysis. An example already existing is the T_c procedure for steel structures given in the Swedish manual.[103]

9.4. Methods Based on Material Response

Of all the physical testing methods the simplest and cheapest are those that can be used in small scale. Since it is not possible, in general, to accurately model the structural behavior in a small scale, the usefulness of small furnace tests is limited to two applications:

1) Testing of homogeneous, or almost homogeneous specimens, where only failure due to heat transmission is considered, and

2) Generating data for critical temperature design use.

The latter is a straightforward application. The former can indeed be considered to be only a furnace test procedure. In practice for fairly homogeneous components the procedure has usually been combined with rule-of-thumb calculation procedures known as "thickness design." Thickness design rules usually take the form of

$$t_e = RL^n$$

where t_e = endurance time, for exposure to a "standard" fire.

R = constant depending on material thermal properties

L = thickness

n = exponent, usually between 1 and 2.

Since R is only known from experiments, it is often more convenient to express the rule as:

$$\frac{t_e}{t_{eo}} = \left(\frac{L}{L_o}\right)^n$$

Where the subscript o denotes some experimentally known endurance. Ingberg's rule in BMS 92 gives n as = 1.7. Neisel[246] gives a more complicated expression; but the basic trend follows $n = 1.5$. Generally, it can be shown from elementary heat transfer considerations[198] that for thermally thick walls Fourier number constancy gives

$$t_e \propto \frac{\rho c_p}{k} L^2$$

while for thin walls or walls of high conductivity, or walls where the heat of dehydration is the main source of protection (e.g., gypsum)

$$t_e \propto \rho c_p L$$

or

$$t_e \propto f \Delta H_{vap} L$$

where f = moisture fraction

ΔH_{vap} = latent heat

Since thickness design is so simple to use, attempts have occasionally been made to apply it to more complex situations, i.e., either where failure other than from thermal transmission is expected, or for components with several materials. The method then becomes totally empirical and applicable only to "standard," not to realistic, fires.

Current day building codes do not explicitly condone thickness design. Yet it is widely used, usually somewhat as follows: A building designer wants to use certain materials where the code requires a two-hour fire wall. A similar system as the designer intends to use is listed by some agency as giving a one-hour endurance when used in certain thickness and a four-hour classification for greater thickness. To estimate the thickness for a desired two-hour endurance, which is not listed, he interpolates between the two listings. Many building officials will accept such a design.

CHAPTER 10

EVALUATION OF EXISTING DESIGN METHODOLOGIES

10.1. Analysis of Effectiveness

There are many possible ways in which the effectiveness of a fire-safety design system could be evaluated. These include:

1. Total impact on fire losses and casualties.
2. Cost effectiveness in control of losses.
3. Quantitative correspondence to known physical or human fire factors; also absence of self-contradiction.

Secondary items for consideration may involve:

a. formulation in quantitative terms, not readily open to varied interpretations

b. general ease of comprehension, ease of use, and freedom from tendencies for error in use

c. suitability for evaluation of safety of non-conforming designs or of modifications.

In the ensuing sections each of the established design methodologies will be examined and evaluated from the viewpoints listed above in regards to their fire endurance provisions.

10.2. UBC Analysis

To analyze the UBC in these terms it is useful to see first what it attempts to do in the area of endurance and then to evaluate the success of that attempt.

1. What impact does the UBC have on fire losses and casualties? A controlled experiment to determine this point is certainly not

possible. The only thing one can do would be to assume that the effectiveness of the UBC is similar to the other U.S. codes and compare U.S. statistics with foreign ones. This has often been done[247] and shows the U.S. to be worse off than any other industrialized country. These statistics can be misleading, since social factors and data gathering procedures may have as large an influence on the results as building practices. Some relevant U.S. statistics are given below:

Losses for 1974	Percent of Building Fires	Percent of Total Dollar Value of Fire Losses	Percent of Total Fire Deaths
Dwellings			
Oregon[248]	54	33	44
California[249]	68	--	39
U.S.[250]	52	25	57
Other Residential Occupancies			
Oregon	14	16	26
California	--	--	24
U.S.	19	15	--

From these emerges the fact that the total impact of fire endurance standards on the nation's fire deaths--although not necessarily dollar losses--is likely to be limited. Roughly half the fire deaths occur in dwellings. Building codes make little provision for endurance in dwellings. To provide meaningful endurance would require dividing up a dwelling into compartments. This solution is unrealistic; the preference for open, undivided spaces is too strong. Garages and utility rooms are about the only spaces where it is feasible to provide compartmentation without causing serious inconveniences. In the future, if detector-operated doors become more common and less expensive they might offer a means for permitting significant fire endurance to be designed into dwellings. In view of the required open nature of the barriers, currently about the only effective aspect of fire endurance that can systematically be provided is structural stability. If it is agreed that the time for stability can, for economic reasons, be set only to the time required for occupant escape, then the need for designed endurance in dwellings of current construction types becomes minimal. In most current dwellings intrinsic endurance of walls and floors is sufficient to permit escape from any expected fire. Appendix D brings out the fact that in the area where the intrinsic endurance may be the least--over a crawl space--the expected fire is also comparably minimal.

The question of loss impact should then perhaps be narrowed. One might ask, for instance, about the impact of various endurance methodologies on buildings other than dwellings. No statistics comparing the different methodologies are available on that basis.

2. What is the cost effectiveness of a building code? This question is even harder to answer than the previous one, since detailed cost accounting data are required. Costs for a given feature can normally be evaluated quite readily but the effectiveness in reducing losses can rarely be calculated. Certain inroads can be made, however. If a feature can be shown to be opposed to known physical or behavioral

TABLE 9

ANALYSIS OF REASONS CITED BY I C B O
CODE CHANGES COMMITTEE FOR ADOPTING CHANGES

(From the recommended changes to the 1976 UCB, as given in Reference 251)

Class of Reason (All code provisions, not limited to firesafety)	Percent of Total Reasons
Provide flexibility or ease of enforcement for building official	2
Eliminate provisions of dubious legality	1
Editorial clarifications; increase ease of use	22
Adopt national standards or measures at uniformity	13
Correct inconsistencies among different codes of same governing body	5
Close unintended loopholes	1
Correct technical inconsistencies or omissions within code	12
Needed for public safety/welfare--no other documentation	12
Need (or lack) shown in technical or statistical study	14*
Need (or lack) shown from practical or field experience--not otherwise documented	5*
Recognize new materials or methods	4
Recognize accepted practice	4*
Increase safety factors--no other reason given	1
Relax requirements--no other reason given	1
Drop requirements that seem unjustified	4

* This category infrequent for firesafety provisions.

laws, then its effectiveness can be assumed negligible. This point will be taken up below. Or if two different features are judged to offer similar effectiveness, then they can be evaluated on the basis of cost alone. It is especially striking that the administrative and regulatory bodies charged with code formulation have almost never taken any interest in cost-effectiveness. Table 9 lists the major categories into which reasons for recent changes in the UBC can be grouped. Cost effectiveness is not given as a reason for any of the changes.

3. Is the code in reasonable conformity to physical and behavioral reality and is it self-consistent? Here enough data are available and the UBC will be analyzed from that viewpoint in the following section. It can be noted that reasons for changes as a result of quantitative research are fairly common only for the structural design sections of the code. In all other sections, including firesafety, they are infrequent.

a) Considering next the secondary factors, it can be asked--is the code formulated in quantitative, unambiguous terms? The answer here is a strong yes. One of the main advantages of a conventional classificatory code is its relative unambiguousness. The designer is freed from requirements to think or to understand theory. All he is asked to do is to apply code provisions. Even the choices available are limited. It is only in recent years that a few provisions such as the sprinkler tradeoff and the high rise package have been added which do give some real choices to the designer.

b) Is the code easy to use and straightforward? This question is of some substantive importance since an approach that is confused and convoluted in its presentation is not likely to have sprung from a clear understanding of the theoretical basis. The converse, of course, is not true--a clear prescription does not necessarily indicate an adequate understanding of the underlying principles. The UBC is generally clear and easy to apply, but there are some salient exceptions.

As an example, the organization of the chapters on Occupancies and on Types is redundant and inefficient. The most glaring example, however, is of the provisions governing exterior walls. There are two aspects to the problems of facade protection against radiant ignition--"opposed ignition," the prevention of ignition of the facades of buildings facing the one being designed, and "self-ignition," the prevention of story-to-story spread of fire via the facade along the building under design. [Note that there is no problem converse to the first one, i.e., one should not need to protect the building under design from an opposing facade fire. To be safely and conservatively designed, the opposing building had to be designed so that it would not ignite the most sensitive item, which might be drapery fabric, located at the lot line of the building under design.] The first problem requires knowing primarily the window area and the distance from the lot line. Also needed are the size of the fire plume and the effective flame temperature. From these an effective radiant flux can be calculated; the technical basis for doing this is available in the literature. The Canadian code[80] has incorporated simple rules based on these considerations. The UBC, however, has a large, confusing set of rules, tables, and exceptions, all of which bear no relation to the simple physics of the problem. The self-ignition problem is more complex and is not seriously addressed by UBC or most other codes. Again, some good approximations are available and methods of protection are known. The best methods are balconies or "eyebrows." A simpler provision is for a fire-resistive, rather than glass, spandrel. The high-rise package includes such a provision but permits spandrels of probably insufficient height. A useful spandrel would approach a story in height.

c) Can the code adequately evaluate the fire safety of non-conforming design, alternates or variants? Here lies the greatest difference between a systems approach and a conventional code approach. A code such as the UBC provides a purely go/no-go framework. Designs are either acceptable or not and no quantitative scales for evaluation exist. This inflexibility is one of the reasons that innovations are difficult to introduce into the code. A method or material cannot be simply accepted on the assessment of its firesafety; it either has to be fully equivalent to one already existing in the code or else a new set of go/no-go rules must be formulated.

10.2.1. General Technical Analysis

The UBC incorporates standards E-119 and E-152 to govern the fire testing conditions. A technical analysis of these standards has already been given in the previous chapters. In the current section the remaining major firesafety design provisions related to endurance will be examined. The code system of classification for requiring fire endurance has two places where the variables controlling the expected fire could be considered. The Occupancy classification could reflect the contents fuel load while the type of construction could reflect the fuel load of the structure. If changes to this effect were incorporated the code would be up to date as of 1928, when Ingberg published his findings on fuel load as a fire variable.

The basic problem is that the present definitions of occupancies do not reflect fuel load differences. Two occupancies are vaguely defined by their fuel load: B-4 occupancies consist of low fuel load industrial uses, while H occupancies are intended to cover especially hazardous occupancies. Even in the latter occupancy the fuel load/occupancy relationship is tenuous since in three of the H occupancy sub-groups the uses involve mainly explosion, rather than high fuel load, hazards. Repair garages and airplane hangars constitute the remaining two sub-groups and are especially poorly classified, since they have both a low fuel load and a good fire experience.

It could be argued that the reason that the occupancy classifications are poorly descriptive of fuel load is because they have to do double duty--treat both endurance and exit provisions. An inspection of UBC Chapter 33 reveals, however, the the present occupancies are as inappropriate for regulating exits as they are for specifying endurance. While it is not within the scope of the current work to focus on exit requirements, it would not be hard to demonstrate that the occupancy classifications, as applied to exits, suffer from two ails: the requirements are often either duplicated for different occupancies or, when restricted, appear restricted for no valid reason. If exit requirements do, in fact, require a classification by occupancy, the reasonable approach would be to construct a separate set of occupancy designations for this purpose, one that does reflect relevant differences. ISO has recognized a similar possibility by having separate combustibility and susceptiblity scale values for each occupancy.

The types of construction are solely an historical artifact. In the last century one could distinguish four basic types of buildings:

frame, ordinary, heavy timber, and fire-resistive. It was natural to use these types as classifications. Later non-combustible unprotected buildings came into vogue, exemplified by Butler buildings, Quonset huts, and the like. A new category was established for them. Finally, in view of the increasing importance of fire-resistive construction, most codes have split that category into two, roughly those with about 4-hour resistance ratings and those with about 2-hour ratings.

Complexities and fallacies are introduced into the code to a large extent because an unrealistic division is made between combustible and non-combustible structures. It is the total fuel which is of importance in determining the expected fire and it includes contributions from both contents and structure. The current requirements in the code are reflected mainly in the height/area tables. Thus Type II (non-combustible) and Type III (combustible, ordinary) have the same limits imposed, while Type V (frame) is more restricted, a differentiation which appears to have no justification.

As described earlier, the only known study on justifications for height/area limitations was Woolson's survey of 1913. Reasons adduced for establishing height/area limits (e.g., BMS 92[64]) included the desire to limit losses to an "acceptable" value and a desire to make escape possible. Ingberg also considered[64] that heights should be limited to ensure that a collapsing building would not fall on neighboring property. This peculiar viewpoint ignores the complexity of the pre-collapse fire effects and has not been seriously considered by others. The relation of height and area to effectiveness of fighting a fire, although the most suasive of the possible reasons, has usually not been explicitly considered. A change to the UBC has been proposed[90] which would make height/area limitations a direct function of extinguishing capacity. The proposed change, because of its significant impact on traditional code philosophy is discussed in detail below. The acceptable loss reason is vacuous since it has never been quantified in connection with any U.S. building codes. The only demonstrated relation of compartment <u>size</u> to escape is in the area of flame spread, not fire endurance. With materials of extreme flame spread potential, as exemplified by unprotected foam plastics, the size of compartments must be limited if the fuel cannot be protected because otherwise flame spread may outrun fleeing occupants.

The UBC may be considered as offering the designer a certain choice between compartmentation and increased endurance requirements. The effect of the code on this choice can be examined. Take single-story buildings as an example. Three levels of functional subdivision can be identified:

(a) Basically undivided buildings (but may include minor divided areas). These will mainly include industrial occupancies and some storage facilities.

(b) Buildings divided into a few large compartments. This category may include factory/office combinations, assembly and recreational buildings, and retail shops.

(c) Buildings subdivided into a large number of similar compartments. Typically these will be hotels, apartment buildings, classroom buildings, hospitals, and some office buildings.

In category (a) consider what happens when the owner's need for total area exceeds that permitted for the cheapest construction (Type II-N, III-N, IV, or V-N). His choice, according to the code, is then to either provide for compartmentation or to specify a more resistive Type of Construction. To take the compartmentation option he would have to provide walls of either 2 hour, or in the case of the higher Types, 4 hour rating. Constructing one or more partitions of even the 2 hour rating solely for fire protection, when no functional requirement exists, is a costly undertaking. Looking at the option of upgrading the Type, instead, consider that the building is of Type I. Then the permitted area is unlimited. The costs can be quite reasonable. The floor will probably be a slab-on-grade. Thus its fire resistance is not an issue. It is not possible to generalize about the exterior walls, since their requirements are so much dependent upon the building location. There are no interior partitions in this alternative design. Thus only column and roof resistance need be considered. The columns would need to be provided with 3 hour rating and the roof with 2 hour.

To take a specific example, consider that a building of B occupancy with an area of 36,000 ft^2 is to be built in Fire Zone 1 or 2. The compartmentation option would involve dividing the space into at least four compartments for a 15 ft ceiling height. This would entail about 5700 ft^2 of 2 hour partition, as compared to the main expense of providing 36,000 ft^2 of ceiling protection. Assume, very roughly, that the cost per square foot for erecting the partition is 4 times the cost of hanging ceiling protection. Then the costs of the compartmentation option are somewhat less, but not by much. Because in this application functional requirements would be somewhat hampered by compartmentation and since the cost incentives given by the code for this option are slight, this option would normally not be taken. The example, then suggests that buildings fall into category (a) primarily because of functional considerations, with little effect from code mandated endurance costs.

Single-story buildings in category (c), on the other hand, incur almost negligible endurance related costs. Take a motel as typical in that category. For functional reasons there has to be adequate sound isolations between units, and conversely, there is not much need for significant openings or penetrations. Thus, for functional reasons alone, the construction could consist of stud walls with 1/2 inch gypsum board on each side. If the gypsum board is of Type X and appropriate joint detailing is followed, the assembly can qualify for a one hour endurance. To have these walls function as area separations, they would have to be raised to 2 hour endurance. A design using an additional 1/2 inch layer of gypsum board could readily qualify.

Looking at the other extreme, high-rise buildings, they are perforce required to be of Type I construction. Since floors must have a 2 hour rating, effective vertical compartmentation will be present. No incentives are provided for any fire walls to establish horizontal compartmentation. Specific requirements extend only to endurance for corridor and stairshaft walls and to provisions for dividing walls in the high-rise package.

It is signally unrealistic that the code officially recognizes only horizontal but not vertical compartmentation. Curiously, vertical compartmentation is admitted for "occupancy separation," but not for decreasing the effective area within a single occupancy. A floor, especially if it is protected other than by grid ceiling, will for structural stability requirements alone tend to be at least, and probably more substantial than wall constructions. Furthermore, penetrations in floors will consist of poke-thru and chases, which are much smaller than the doors in fire walls. Thus while floor openings may be more numerous, they are also smaller and easier to protect.

Technically speaking, by far the most faulty provision in the entire code is the exemption of buildings in certain classes with tall ceilings from fire endurance requirements for roof/ceiling assemblies. Not only is it contrary to the prime assumption of post-flashover fires, that the compartment is stirred, but it contradicts a simple understanding of buoyancy. Hot gases move upwards. Practical experience is also ignored by that provision. One of the most dramatic large loss fires in recent years was the McCormick Place fire[252] of 1967 where the magnitude of the loss was largely ascribable to the failure to provide reasonable fire endurance in the roof of a tall-ceilinged building.

Degree of Openness

The important question of holes or potential holes (e.g., doors) in fire-rated assemblies is very poorly and inconsistently treated in the code. For example, the following requirements are given:

Wall Fire Rating	Opening Protection
4 hr	Occupancy Separation: Openings not allowed. Area Separation: 3 hr, plus size limit. [Shafts + Exits: 4 hr walls never required]
3 hr	Occupancy Separation: 3 hr, plus size limit. [Area Separation: 3 hr walls never required] [Shafts + Exits: 3 hr walls never required]
2 hr	Occupancy Separation: 1½ hr Area Separation: 1½ hr, plus size limit Shafts + Exits: 1½ hr.
1 hr	Occupancy Separation: 1 hr [Area Separation: 1 hr walls never required] Shafts + Exits: 1 hr

There is no methodology evident from the above list. As has earlier been observed, a hole or an area of diminished endurance in a wall will lessen its probability of stopping the effects of fire according to its size. Neither the size of the door nor the relation of its fire resistance to the wall fire resistance are treated consistently.

Shafts are a serious problem in particular because they affect the pressure distributions and smoke flow within a building. The detailed arrangement of HVAC systems under fire conditions is a large subject in itself and outside the scope of the present work. One issue regarding flame spread must be raised, however. Shafts can hold mostly non-combustible contents, such as metal ducts and pipes. Or they can contain material of significant flame spread and fuel release potential, such as plastic telephone cables. It is obvious that these two types of shafts should not, as they now are, be treated identically. Shafts with combustibles should to some extent be treated as compartments, that is, their required resistance should be determined by the more severe possible fire--in the shaft or in the adjoining compartment.

The applicable criteria must be considered carefully--a shaft without any combustibles inside need not require protection against ignition inside. On the other hand, a shaft is likely to be an avenue of smoke spread, so its gas transmission properties must be controlled.

The code does not do much better in the area of firestopping. (Firestopping is protection applied to any openings or gaps in construction except those governed by specific requirements for shafts, doors, windows, or dampers.) The code has detailed prescriptive specifications for firestopping in wood frame construction. Otherwise only vague admonitions are offered in Sections 301 and 4305. A sense of perspective needs to be maintained with regards to firestopping. Isolated small openings will only cause a negligible decrease in the probability of limiting a fire. Small openings become a serious fire hazard when either consecutive vertical failures can occur, creating a flue effect, or when progressive horizontal failure can occur. Small openings may also be serious contributors to toxic gas flow into refuge areas or escape routes. Thus, in all constructions except wood frame either prescriptive rules or a method of performance evaluations or testing should be adopted to give guidance to the designer where he presently has none.

The conclusion emerges that fire endurance requirements for walls, floors, and other large components are treated inconsistently in the UBC and are not consonant with known principles governing post-flashover fires. What is worse, the requirements are not even based on thorough or controlled field study. In one of the major recent code changes, the high-rise package, the approach taken was truly remarkable for its lack of technical considerations. The New York City report[89] outlining the desired provisions for the package was based on an investigation of two fires and on no technical, economic, or statistical analysis whatsoever. A later report[253] praises the adopted provisions while simultaneously offering statistics demonstrating the superior fire record of the very same type of building that was to be subject to the numerous additional requirements.

10.2.2. Analysis of Area and Height Limits

For a given set of fire controlling variables the expected fire will be of the same duration and intensity regardless of the area of the compartment. Thus, it can be asked whether there is any reason to consider the areas of the compartments involved. Compartmentation can only be indirectly related to life safety. It can be useful for limiting the maximum economic fire loss, but this consideration should not properly be a building code requirement. The appropriate goals to be considered are two: safe and effective fire fighting and prevention of conflagrations.

First consider buildings for which no fire endurance has been specifically provided. A fire in such non-resistive building should not lead to a conflagration. Several factors are important in determining this assurance--the separation of buildings and their facade ignition potential, the possibility of significant brand generation, the firefighting resources, and finally, the size of the initial fire. The building having been assumed as non-fire-resistive, the fire size is the total size of the structure.

It is clear that a relation should exist between the maximum building size and the firefighting capability. In some cases where concern is solely for the prevention of a conflagration, no building size restriction would be needed if the building were sufficiently removed from any other buildings or flammable vegetation. In general, however, it is reasonable to posit that the building fire should not exceed the firefighting capacity.

Consider an uncompartmented building where all the load-bearing members are designed to fully withstand a total burnout. If, in addition, there is no brand generation and the facade problem is appropriately solved, then there is ideally no need for area limits and no need for firefighting capacity. Put in these terms, the situation is tenable but foolish. Society has generally taken steps to discourage foolish risks on part of its citizens even when the matters are seemingly only of private interest.

Furthermore, in the usual case there is a facade protection problem. A valid reason for setting area limits with the expectation of controlling a fire before burnout is to keep the facade problem manageable. If a potential for fire spread via facade ignition exists, then whether or not the original fire can be controlled can make a significant difference in whether curtailing facade spread becomes feasible.

If this viewpoint is accepted, then it becomes reasonable to limit the fire compartments in such a way as to make reasonably sure that the fire could be controlled and extinguished either by automatic sprinklers or fire department action or both. The role of time has to clearly be understood in this case. Sprinklers, if appropriately designed, will activate and control a fire significantly before flashover. A fire department cannot, however, except in fortuitous circumstances, be presumed to arrive and control a fire prior to flashover. Thus the fire it will face must be assumed to be the total flashover of the most difficult compartment. If arson needs to be considered then possibly more than one compartment must simultaneously be presumed alight; protection against such an occurrence, however, may hot be economical.

The above argument is in addition to, rather than a replacement for, compartmentation. It is possible to have compartmentation without extinguishing capability--large compartments, in excess of extinguishing capacity. Conversely, area limits set by extinguishment capability are possible without compartmentation--a small structure with no fire barriers.

The pivotal question becomes how to relate building features to extinguishment capacity. In order to have an accurate relationship it is clear that both the fuel load and the manner of extinguishment would have to be accurately quantified and the relationship experimentally determined. This has not been done, although various limited studies are available. Among the earliest was a 1947 Danish study[254] by Adeler with small experimental wood crib fires. Adeler identified the time from start of fire to first application of water as having primary importance and gave the formula for required water flow as

$$F = 0.00014\ tA \qquad (\ell/\text{sec})$$

where t = time from start of fire until water was applied (min)

A = floor area (m^2)

Subject to an upper limit for fires attacked late of

$$F = kA \qquad (\ell/\text{sec})$$

where k is 0.03 to 0.08. This upper limit was derived from actual, rather than test, fires. In the 1950's Royer and Nelson[255] used Adeler's formulas and found them to be faulty when fog nozzles, rather than solid streams, are used in extinguishment. They proposed that

$$F \approx 0.02\ V_r \qquad (\ell/\text{sec})$$

where V_r = volume of room (m^3)

If we take an average room height of 3m, then Roher and Nelson's value in fact falls within Adeler's upper limit range. A few other studies of small room extinguishment have been made at the Illinois Institute of Technology by Maatman[256] and Salzberg.[257]

Besides ISO, statistical approaches based on data for the extinguishment of factual fires have also been taken by Thomas,[258] Baldwin,[259] and Labes.[260] None of these workers have differentiated between types of construction, but it is reasonable to assume that their studies are most closely applicable to the "ordinary" type. Thomas' data for large fires gave results expressed in terms of streams required for extinguishment. Baldwin has assumed that the average delivery rate per stream was 10 ℓ/sec, giving

$$F = 3.3\sqrt{A} \qquad (\ell/\text{sec})$$

Labes' results from 134 fires were fitted by Baldwin to give

$$F = 1.24\ A^{0.664}$$

a figure not too dissimilar tin the range of 100-1000 m^2 fire areas. It is especially remarkable how closely Thomas' value compares to the ISO formula. By contrast, Royer and Nelson's formula gives a value smaller by a factor of 5 for 100 m^2 fires, suggesting that the ISO formula may be less reliable for small fires.

Labes also presented additional data on extinguishment of experimental fires, showing that the delivery rate requirements averaged 1/4 the value given by his formula for actual fires. The conclusion here is that experimental approaches or semi-theoretical ones -- such as used by Kida[261] and Ivanov[262] -- are not sufficient since they only determine a lower bound to the water requirement. It might additionally be noted that Thomas and Labes also gave formulas for time of control of fire. These are again roughly proportional to $\sqrt{A}$; thus the total water required to control a fire, being the product of the rate and the time, is dependent on $A^{1.0}$, as one would expect.

10.2.3. Evaluation of the Proposed UBC Change

Woolson's study of fire chiefs' opinion was exactly that--just a survey without any technical data. Yet U.S. codes have until this date incorporated similar tables based on committee action without any research. The first significant exception has been the proposed changes to the 1976 UBC.

The question of area/height limits hinges on the following postulate: that building codes should require measures facilitating the successful extinguishment of a fire in a compartment prior to its total burnout. While it is not clear that this is an appropriate legislative posture, it cannot be disproven, either. Given that, it becomes appropriate to examine the effect of the particular proposed scheme. Problems of ignition of neighboring property are somewhat connected with this issue; no substantive changes have been included, thus they will not be re-examined.

The criteria and the question of time must first be considered. To a large extent area limitations are only applicable to property safety. Some ancillary life safety issues are involved such as the safety of firefighters or passersby, but in the main, success in extinguishing of post-flashover fires is a property safety concern. Thus for fire-fighting purposes only two types of building designs need be considered: those with fire resistance (on the basis of the criteria of Section 8.2.1) sufficient to withstand the expected fire, and those with lesser or negligible resistance. The area that must be extinguished then, is the area of the largest compartment in the first type and the total structure in the second. The ISO use, by comparison, of a 3-floor design compartment in fire-resistive buidings seems based on some probability of facade failure, but is unsubstantiated.

Once the area of fire to be extinguished is determined the water delivery requirements must be assigned, and if they are insufficient either the area must be decreased or the delivery capacity increased. The methodology adopted by ISO and by UBC attempts to do this, but on a fairly undifferentiated approach. As seen from the previous section, the reason for the crude approach is that a satisfactory theory is not yet available. Thus, while a better alternative cannot immediately be suggested, certain shortcomings can be identified.

A better theory would probably account for three groups of variables: fuel type, fuel amount, and fire temperatures. The ISO approach, by comparison, uses only two empirical factors. The C factor is varied for Type of Construction; flow requirements are also adjusted for Occupancy Group, according to the established UBC categories. The distinction between buildings with combustible framing and those without could be treated in a comprehensive way by considering the fuel type and amount represented by the structure.

The Fire Flow District concept could potentially provide the appropriate way for treating firefighting difficulties. Windowless buildings, sites with difficult access and similar problems are usually handled on an ad hoc basis. These factors could all be subsumed into one regulation by providing de-rating of water flow capability according to the expected local water delivery difficulties.

The allowable tripling of area for automatic sprinklers raises an interesting question. Deterministically it would seem unjustified. After all, a fire is either put out by sprinklers, in which case no area limit is needed, or else it fully flashes over and requires just as much water to put it out as in an unsprinklered building. Yet probabilistically the provision is qualitatively reasonable. What should most preferably be used as a criterion is the probability of success of not producing a burnout of more than a specified area. Sprinklers increase that probability, thus an increased area, which diminishes the probability, can be provided. To decide quantitatively if the factor should be 3 or something else would require the knowledge of two pieces of data: the probability of success of a fire burning out of its own accord, as a function of area; and the corresponding probability of success when sprinklers are included. Appropriate data are not presently available.

The evaluation of the proposed heights table is also difficult. The basic principles are three:

1) There is a definite upper limit to how high a fire can be fought from the exterior. Ingberg suggested in BMS 92 that it is in the range of 50-100 feet. The value depends on the capabilities of a specific fire department and its equipment but this range is appropriate for most urban fire services.

2) Fires can safely and successfully be fought from the inside only in fire-resistive buildings.

3) Whether fighting from the outside or the inside, the higher the fire is in a building the harder it is to fight.

From these principles several desirable rules can be deduced.

a) If uncontrolled burnouts are to be prevented, buildings over 50-100 feet must be capable of resisting a burnout.

b) The allowable area per compartment in fire-resistive buildings should be reduced in the higher stories of a structure.

c) In an un-resistive building the less total area should be allowed the more stories there are.

d) The above requirements have nothing to do with occupant movement potential, and thus must not be confused with exit provisions.

Finally, another rule can be seen--

e) Buildings prone to explosion hazard or to difficult to extinguish flammable liquid or metal fires should preferably be of a single story.

The above rules contrast with the UBC requirements in several ways. The Table 5-D, which has allowable story numbers of 1, 2, 3, 4, 5, 12 and unlimited, appears to be capricious. One-story limits are appropriate for hazardous industrial occupancies, as stated above. The UBC definition of uses included in that category is not suitable, however. Similarly as with area limitations, varying allowed heights according to Types of Construction has little justification. A basic limit of 5-10 stories should be set for buildings which cannot resist a burnout.

For Type I buildings there are currently no height limits. The proposed UBC change would establish a 75 feet limit unless sprinklers are provided. The 75 feet limit essentially denies the effectiveness of interior firefighting in fire-resistive buildings and thus seems overly conservative. The loss experience of American high-rise buildings without sprinklers has been very good; a general tightening up is not warranted.

Most contrary to desired rationale is the UBC provision for multi-story building areas. As currently written, the total area allowed for all multi-story buildings, whether fire-resistive or not, is double that allowed for a single story building. For fire resistive buildings, as has already been pointed out, each compartment should be limited individually, a total limit is not justified. For non-resistive buildings, the opposite to the UBC rule is desired--if the number of stories is raised, for a given water flow capacity, not only should the total allowed area not be increased, but it should be decreased since those portions on the upper stories are harder to extinguish.

The occupancy classifications for the purpose of limiting heights should be only two: a) normal, and b) explosion hazard or extra flammable liquid or metal hazard. Especially inappropriate are the special requirements relating to assembly occupancies. These occupancies have low to moderate fuel conditions and no unusual firefighting difficulties. Their only differences should be in carefully controlled exit provisions, and height limits are a property loss control, not an occupant movement tool.

10.3. Insurance Rating Analysis

The CFRS does, as intended, provide a quantitative way of evaluating fire endurance designs. Yet it is founded on essentially identical assumptions and historical development to those of the UBC. One major difference from the UBC is the establishment of a vast number of occupancies. The extra categories may be useful in reflecting the relative incident of ignition and the possibility for pre-flashover fire spread. For post-flashover design they are not demonstrably more useful than the ones in the UBC.

The major advance represented in the CRFS is the concept of damageability. It is not a substitute for the kind of fundamental focus on reliability that was shown to be needed in Chapter 7. Yet it is important in that it at least recognizes the problem of damageability and attempts to categorize existing types of products.

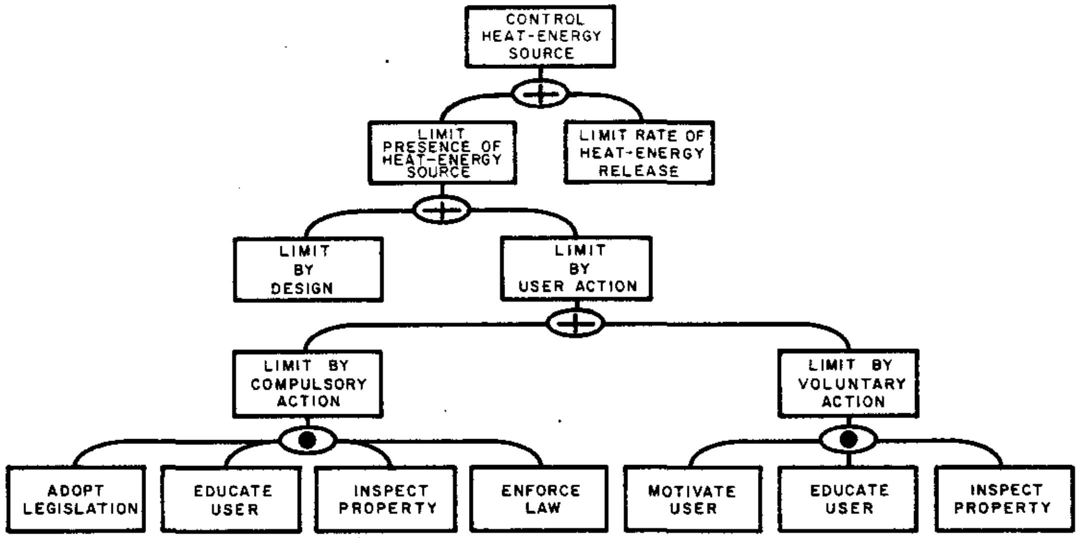
10.4. GSA Systems Method Analysis

Since it has not yet been widely used, it is impossible to evaluate the GSA method on its total impact or on its cost effectiveness. It is reasonable to surmise that, when properly used, its cost effectiveness should be high, since the main reason for its development was to eliminate waste by designing only those firesafety features which are considered to be effective in each specific instance. An evaluation of self-consistency and physical bases will be considered below.

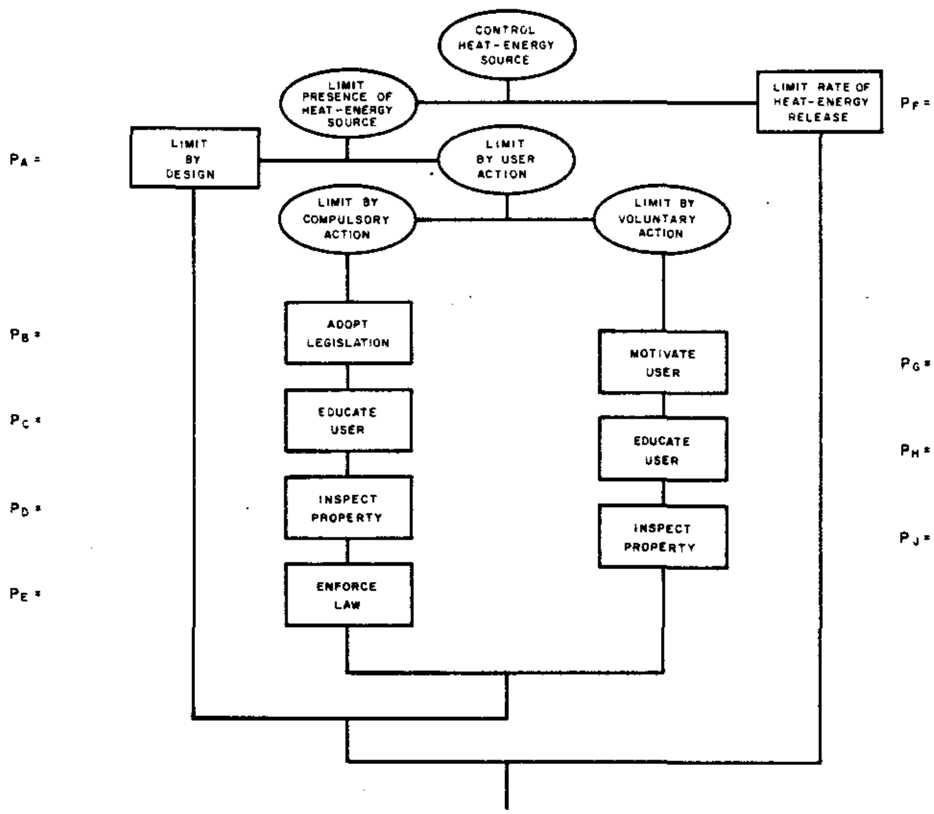
Examining the first and second of the secondary factors, it is seen that the GSA method is in an ambiguous position. The framework is definitely both quantitative and set up with the intent of being easy, or at least methodical, in use. But there are no well-substantiated numbers for most of its calculations. The designer has, to a large extent, to use educated guesses instead of compiled data. Thus critical elements of designer experience and goodwill are inserted. The designer must have a "feel" for the fire situation far beyond that required under traditional codes. The element of goodwill is also important since it would be hard to conclusively prove that any assumption is wrong. The difficulty could be mitigated by mandating certain assumptions, but the more this is done the less the system would be responsive to individual requirements, and it would then tend to defeat the goal of reflecting physical reality.

It is on the final point, the possibility for comparing designs, that the method truly excels. This is not unexpected, since the GSA methodology is the only one considered here that encompasses most of the total building firesafety analysis on a single basis. In two areas--smoke spread and human movement--the unification is less useful since they are covered sketchily.

Technically, the GSA systems approach has two separate innovative aspects which should be discussed individually. First is the use of a decision tree to systematically delineate all the firesafety goals and attendant means. There is no question but that using a decision tree is of significant benefit in organizing the work of the designer and ensuring that all needed aspects are considered. Two criteria for a successful tree can be seen. It should include all the needed firesafety provisions, and there should be a clear flow, with a minimum of redundancy. The skeletal GSA tree shown in Figure 9 gives only the



(a) PORTION OF **NFPA** DECISION TREE.



$$P_{\substack{TOTAL\\ENERGY}} = 1 - \overline{P}_A \cdot \overline{P}_F \cdot (1 - P_B P_C P_D P_E) \cdot (1 - P_G P_H P_J)$$

(b) QUANTITATIVE RELIABILITY DIAGRAM FOR SAME PORTION.

FIGURE 41 QUANTIFICATION OF DECISION TREE

goals and main means. A detailed tree, as given in references 3 and 98 includes a veritable flood of items to be considered.

A detailed consideration of that tree here is not appropriate. It is a document which can continually change and evolve and thereby improve the efficiency of design planning. It does not have a direct impact on endurance calculations except insofar as it points out, by comparison, the lack of purposiveness in a code approach. The tree in reference 3 is adequately inclusive but lacks clarity because of significant redundancies. The tree issued by a systems design committee of the NFPA[102] strikes a somewhat better balance between clarity and inclusiveness.

The other major innovation of the GSA approach is the use of a probabilistic approach for firesafety design. The GSA method is not the only, nor is it the first in attempting to do so. Numerous other approaches[180,264,265,266] are available in the literature. The uniqueness of the GSA approach lies in the fact that it is one of the few that have been implemented for practical design. Firesafety is an eminently practical science; proposed methods are of little interest unless they can be implemented by the designer.

It is first possible to realize that the use of a decision tree and the probabilistic approach need not be disparate. They can be combined by making the tree quantitative, i.e., by making them into a reliability tree. Figure 41 illustrates how this can be done for a segment of the NFPA tree. The fundamental possibility that has to be exploited is changing the digital nature, which uses "and" and "or" gates into an analog topology, where each element can assume a probability of anywhere from 0.0 to 1.0. An analog basis can be established which is the same as given in Equations 7.1 and 7.2 for determining component reliability. In addition to a proper series and parallel organization another distinction has to be established. In the NFPA decision tree usually only the bottom item of any string has a quantitative probability attached. The remaining items are simply identifiers that provide a title for a string but do not require numerical evaluation. They can be placed in circles to distinguish from the quantitative elements, which are in squares.

Pre-flashover Spread

In the GSA method, the probabilistic scheme has three segments: pre-flashover spread, fire endurance, and post-flashover spread. The first is outside the scope of the current work to consider in detail. The main observation here is that there is no provision for manual occupant pre-flashover extinguishment. The P(M) curve provides for no firefighting effort prior to flashover. Data have recently been collected at the University of California on occupant (taken to include also any other non-professionals) firefighting. Two surveys have been conducted. Berkeley residents, mostly occupants of low-rise private dwellings and small apartment houses were surveyed in 1974[267] and residents of high-rise apartments buildings in San Francisco were surveyed in 1975.[268] The results are as follows:

EXTINGUISHMENT
PERCENT OF INCIDENTS REPORTED IN SURVEYS

	Berkeley	San Francisco
By occupants	75	62
By fire department	19	30
None, fire self-terminated	6	8

The occupant extinguishment success is higher in the Berkeley survey because of both demographic factors (lower median age and higher education) and greater availability of extinguishment means for low-rise occupants (e.g., garden hoses are available, burning objects can be carried from the premises).

Extinguishment by occupants can only be considered successful prior to flashover. Thus the above successes have to be attributed to less-than-room-size fires, and it is then seen that far from being negligible, the success by occupant firefighting is much greater, about ten times, than success due to self termination.

Aside from extinguishing efforts, questions of fuel effects on pre-flashover spread are important. The P(I) curves presented are recognizely very rough. Work is at present being conducted at several institutions (NBS and the Illinois Institute of Technology) to develop a more sophisticated pre-flashover methodology. It is expected to involve detailed numerical modeling of fuel, geometry, and other factors, and will also include a time element. When available, this new procedure could take the place of the existing GSA curves.

Fire Endurance

In considering endurance probabilities, the crucial drawback is the dependence on Ingberg's equal-area hypothesis. Neither does the method currently include consideration of ventilation and wall thermal properties. A more complete array of P(I') curves could be provided to include the two additional groups of variables. What is not easy to accomplish in the present format is to replace the severity hypothesis. A revised approach improving this area might be feasible. Time-temperature curves, such as the ones shown in Figures 35 and 36, can be obtained for fixed wall properties, pessimized ventilation, and differing probable values of fuel load. Then this resulting curve could be used directly as input into a T_c calculation. To establish a fully probabilistic basis, all the elements of a heat flow calculation would have to be given probability distributions. This includes three areas:

1. Thermal properties and material thickness
2. T_c values
3. Criteria, if based on a physical determinant, such as avoidance of ignition of combustibles or load carrying limits.

It is simplest to consider a scheme in which only the T_c is given the full probabilistic treatment. A resulting barrier success probability, after integrating out all the variables, could be expressed as

P = probability of never reaching T_c, given expected variation in the fire and in the failure T_c's.

Post-flashover Spread

The conventional design methods do not explicitly consider the possibility of post-flashover spread, since barrier failure is assumed to be precluded. Even so, by carefully examining the details, it is clear that the possibility of post-flashover spread is vaguely acknowledged. What other reason could one think of for the UBC requirement that Type I buildings have 2 hr floor endurance but 3 hr frame endurance were it not the desire to somehow mitigate the effects of a potential floor failure? An eminently positive contribution of the GSA approach is to quantify the possibility of post-flashover spread.

A practical difficulty with the GSA method is dimensionality. The post-flashover spread problem, assuming a multi-story, multi-compartment building, is a three-dimensional one. To treat a stochastic problem of three-dimensional spread paths is a difficult calculational task. The GSA method shrinks the model to one dimension, the sequence being--item ignition--work stations 1 to n--rooms 1 to n--floors 1 to n--whole building. Precluded entirely from the simplified sequence is, for instance consideration of a sequence where the fire races up a shaft through several stories, then slowly spreads out on the individual stories. Such a sequence occurred in several recent New York City high-rise fires.[269,270] An additional complication is evident when the possibility of compartments that are not identical is considered. Even in seemingly repetitive structures, such as hotels or office buildings, enough different types of compartments might be found to negate the interchangeability assumption.

The objective here, similarly as in the case of fire severity, is to reduce the dimensionality of the problem. A simple, yet correct, procedure may be possible; the way of finding it is not evident at the present.

General Features

Considered overall, the GSA systems approach is the most rational and most complete of the design methods in existence. It, unfortunately, is the weakest in the area of endurance. Thus while the integration of pre-flashover spread and post-flashover endurance is illuminating and logical, the incorporation of Ingberg's severity hypothesis seriously limits the numerical usefulness. As is true in quite a few cases, the method is flexible enough to accommodate a better endurance procedure, when such a procedure becomes available which is probabilistically correct and yet simple.

More generally, an argument of self-consistency can be considered. The present systems method is not fully probabilistic in two important aspects. The first item ignition is not considered probabilistically. The criterion curve is drawn, therefore, on the probability of termination success, given initial unwanted ignition. A full probabilistic treatment would, on the other hand, give the building overall success probability, including the effect of potential ignitions. The owner, after all, wants to know the complete estimate of firesafety in this building, not just the chances once a fire is started. Taking a common ignition source, electrical troubles, as an example, the present system would not differentiate between a building with a poor electrical installation and prone to recurring ignitions, from one with a competent installation.

A second non-probabilistic aspect of the method lies in its choice of the P(I) curve. It is presumed that the room representing the worst flame spread conditions should be used as the ignition room. In fact, the whole range of existing rooms, assuming they are not all identical, should be considered, avoiding the use of a pre-selected worst case path.

Crucial to the assessment of the GSA method is the availability of numerical data. First is the question of generating the criterion curve. No aid is offered in the selection of that curve, other than supplying one for GSA use. To construct it rationally would require evaluation of three main areas: property loss potential, operation loss potential, and life loss potential.

For the first two a conventional cost/benefit analysis can be made and some examples are available in the literature. Note that it is much easier to construct a specific criterion on the basis of cost/benefit analysis then it is to evaluate, say, a code approach in terms of a cost/benefit analysis. If only a single building needs to be considered, then the data for the analysis may be more readily obtainable. To determine the general usefulness of a code approach on this basis would require, on the other hand, a survey analysis of all the buildings governed by that code.

To evaluate life loss potential is much harder. The oldest approach had been to simply estimate[271] the lost earning capacity or some other monetary equivalent of a victim. This view is now discredited since it is clear that decisions in society are not made on that basis. A more realistic basis may be to replace "life loss potential" by "freedom from fear," viewing as most important not the actual effect of any resulting deaths but rather the individual or collective subjective evaluation of exposure danger. A similar factor has long been recognized by structural designers. Long bridges and tall buildings are often designed to limit deflections not only enough to prevent physical failures, but to levels low enough to not give users feelings of endangerment, however unjustified such fears would be on physical grounds. To a certain extent values for life safety limits can be taken as corresponding to the risk that people are adjudged to be willing to take at the present time. But fears tend to vary greatly with time and place and are subject to being inflamed by news reports. Also, to the degree that the risk acceptance varies with physically irrelevant factors, it becomes incompatible with a system designed precisely to evaluate buildings on a physical basis.

Data availability for generating the performance curve is the second broad area for concern. Fire performance data have scarcely ever been gathered on a probabilistic basis. The various curves given in the GSA handbook represent educated guesses which are based on meager deterministic data and generous interpretation. Even in the few cases where requisite probabilities have been tabulated, for instance, by Baldwin[272] for the success probabilities for self-termination of fire prior to the second item involvement, the variables are usually not in the right form for direct use. Baldwin's data, for example, are differentiated according to occupancy rather than fuel types. Some reasons for the particular curves chosen by GSA have been published in the proceedings of a GSA conference.[273] No special testing was done, however. Cost is the main factor to be considered for any testing efforts. The difference between fire testing a wall on a go/no-go basis and obtaining a distribution of success probabilities is vast in cost if numerous samples of an entire wall were tested. Thus multiple specimens have normally only been tested in situations where testing costs are relatively low, for instance fabric flammability. It can then be said in general that applicable test results are scarce because most have been gathered deterministically, rather than probabilistically; analyses of actual fires, on the other hand, have usually not been feasible in terms of those specific variables required for the model. The method of component design utilizing critical temperature and module reliability concepts could be introduced for improved treatment of endurance and post-flashover fire spread.

10.5. Swedish Steel Design Manual Analysis

The Swedish procedures constitute the first published method that combines both calculation of the expected fire, based on a theory similar to that given in Chapter 6, and prediction of response, based on critical temperature concepts. Thus the Swedish procedure is restricted by some of the same limitations that are applicable to any critical temperature based design: it cannot be used to evaluate certain criteria. The expected fire model (see Chapter 5) has been simplified in certain ways. Simplification was partly motivated by the desire to make a computer unnecessary for design. In consequence, some more unusual fire histories, not provided for in the charts, cannot be treated.

The main limitation of the method is in the kind of structures it undertakes to treat. Only structures whose loadbearing members are of steel are treated. That is satisfactory; however, the assumption also is made that the T_c of the steel will govern the failure. Thus the method does not explore the kind of possibilities for reliability assessment given in Chapter 7. The method would probably be adequate to predict performance for heavy weight components, especially beams and columns.

A section for membrane-protected ceilings and one for walls are given. These sections constitute the only provisions for dealing with components having multiple elements with low T_c. The walls are not treated generally, only a few specific designs being treated and design aids developed for them. The ceilings are treated by introducing one additional T_c, to characterize the hanger system. The procedure developed is interesting but is not fully realistic, since in a membrane protected ceiling numerous failure modes are possible and should all be evaluated. These modes can include not only the failure of the hanger system, but also such matters as the finite probability that hold-down clips may be omitted.

At the moment the Swedish Steel Design Manual Method can be judged the best component level response method for steel beams and columns. When used for these members in instances where a component method is judged adequate the only major limitation of the method is its slight simplification of compartment fire theory. Indeed, one aspect is even approached in a detail excessive for design purposes. The T_c determination for steel components is based on extended calculations which affect the endurance but slightly. For using the method with other types of components discretion is needed to judge whether or not it is likely to cover the expected failure mechanism.

The most encouraging fact about the method is that it has actually been adopted for building code use. Thus there is now at least one example of an officially recognized endurance design method that is rationally based and that incorporates a realistic understanding of compartment fires.

10.6 Comparative Merits

The considerations developed in Chapters 6 through 9 represent an improvement over any of the existing methodologies. No independent new methodology was developed there; instead the procedures outlined there could be used to technically advance one or more of the existing methodologies. Summarizing the comparisons of the existing methodologies the following main points can be seen.

a) The UBC represents an approach least in accord with the principles developed in the present work. Its least sound aspect, the height/area limits, may soon be significantly improved. The main advantage is the minimal design effort that is required under this method.

b) The ISO procedures are quite similar to the UBC, but are established for evaluation, rather than design purposes. It is an improvement over UBC in that it recognizes the need for reliability analysis.

c) The GSA method has the same drawbacks as the two traditional methods insofar as it is based on the equal-area hypothesis. But it is much more consistent, treats fuel load in a better way, and recognizes the stochastic nature of fire. It is more difficult to use at the present, but is likely to become less so with increasing designer education and data accumulation.

d) The Swedish steel manual method is most closely in accord with theoretical principles. Its ease of use is similar to the GSA method.

CHAPTER 11

CONCLUSIONS AND RECOMMENDATIONS

11.1. Areas Needing Further Research

Few of the topics dealt with in the present work have already been investigated fully. Realizing that, it becomes appropriate to identify those areas where lack of knowledge is currently placing the most serious impediments to effective design for endurance. The whole area of compartment fires is rich in unexplored behavior; fortunately in many instances this lack of knowledge has but slight implication for design purposes, or else is relevant only under unusual circumstances. Certain other gaps in knowledge may have significant impact on the ability to produce reliable practical designs for endurance. These can be enumerated.

1) A quantitative description of flashover in large undivided spaces.

2) The composition and specific heat of the excess pyrolysates of various fuels. This is especially important for fires where a large excess pyrolysate fraction is expected.

3) Gas flows in compartments when one entire wall is absent.

4) The effect of window location, in the vertical direction, on flows.

5) A method for determining pyrolysis rates of non-cellulosic fuels in post-flashover environments.

6) Non-cellulosic furniture combustion properties in post-flashover fires.

7) Better data on emissivities, especially for fuels used in test furnaces.

8) Performance data for furnace thermocouples which are shielded against the specimen, but not against the furnace walls.

9) Experimental verification of reliability-oriented critical temperature design.

10) Radiant ignition values and comparisons with conduction ignition temperatures.

11) Experimental comparisons between hose stream failures and failures under other orthogonal loadings.

12) Ways for calculating required time duration for criteria.

11.2. Major Findings

The following constitute the salient observations, conclusions and recommendations, as developed in the preceding chapters.

1) Clear firesafety goals need to be established before design means are considered.

2) Non-negligible fire endurance is needed only after flashover.

3) The current standard for fire testing reflects adequately the knowledge of compartment fires of 1918 but incorporates few of the later findings.

4) S.H. Ingberg's hypothesis of equal-area severity is contrary to know behavior of materials and should be dropped from usage.

5) The U.S. model building codes have not incorporated Ingberg's 1928 findings nor any major research results in the area of fire endurance since then.

6) The current building code philosophy mandates large expenditures for fire endurance but discourages rational design methods for it.

7) A building code philosophy should be adopted which encourages engineered designs and penalizes undifferentiated ones.

8) The stirred reactor assumption for compartment fires is realistic and is required to make the problem tractable.

9) In addition to total fuel load, the following variables are important in determining the expected fire. *Fuel:* size, spacing, pyrolysis rates. *Ventilation:* window height and area. *Wall properties:* conductivity, volumetric heat capacity, emissivity.

10) The deterministic compartment fire theory yields calculated fire histories which compare closely with available experimental data.

11) A more general way of design, termed "pessimized," can be useful.

12) Other rational methods for determining design fires that represent an improvement over the UBC include parametrized curves, the critical temperature approach, and stochastic designs.

13) Realistic furnace pressures should be used in test furnaces.

14) For gas emissivities $\neq 1.0$, a test furnace, when controlled by use of thermocouple-measured temperatures, provides a less severe exposure than the calculated fire. Control by use of calorimeters is impractical but an adjusted operating temperature curve can be used.

15) Slow-responding thermocouples, as mandated by the current test standard, make difficult both furnace control and the analysis of results. Fast-responding thermocouples are practical and should be used instead.

16) Whenever possible, loadbearing components should be designed using critical temperature concepts, rather than being tested loaded.

17) The instrumenting, recording, and publishing of interstitial temperatures should be required even for conventional endurance tests, in order to establish a data base of critical temperatures and to verify thermophysical properties of materials.

18) Quantitative reliability concepts can be introduced into critical temperature design to account for presently known but unquantified poor field experiences with certain types of barriers.

19) The re-loading requirement in wall tests should be eliminated.

20) The back face temperature rise criteria should be re-investigated; protection needs for combustible goods, escaping occupants, confined occupants, and firefighters should be distinguished.

21) Hose stream test requirements should be replaced by a more readily quantifiable orthogonal loading for walls and discontinued for doors.

22) A gas flow measurement technique should be adopted.

23) The method for providing area limits based on the ISO flow formula is an advance over current UBC procedures. The concomitant height limits are not a significant improvement.

24) The analysis methodology represented by the insurance rating schedule represents a slight improvement over the UBC.

25) The GSA systems method offers a comprehensive framework for firesafety analysis of buildings but does not incorporate current knowledge of expected compartment fires.

26) The Swedish steel design manual offers a viable and adequate method generally consonant with theory but applicable to only certain simple structures.

APPENDIX A

FIRE TEST CHRONOLOGY

Type	Institution	Place	First Started	Temperature Curve
floor	Hyatt	London	1877	Not known
column	Technische Hochschule	München	1884	Surface temperature controlled instead
column	Möller and Lühmann	Hamburg	1887	Surface temperature controlled instead
floor	Andrews, Jaques & Rantoul	Denver	1890	Average ≈ 800° C for 24 hours
floor	Johnson & Flad	St. Louis	1891	Average ≈ 815° C for 6½ hours
wall	Königlichen Technischen Versuchsanstalten	Charlottenburg	1891	Average ≈ 1000° C for 1 hour
column	Municipal Committee	Hamburg	1892	Maximum of 1200° - 1400° C, up to 7 hours
column	Building Department	Vienna	1893	Surface temperature controlled instead
floor	Bureau of Buildings	New York	1896	Average ≈ 1093° C for 4 hours (lowered to 926° C in 1902)
column	Continental Iron Works	Brooklyn	1896	Not standardized
floor, wall, door	BFPC	London	1899	Used BFPC standard
window	Bureau of Buildings	New York	1901	Not known
wall	Bureau of Buildings	New York	1901	926° C at 30 min., then constant until 1 hour
column	Bureau of Buildings	New York	1902	Average ≈ 926° C for 4 hours
floor, wall, door, window	Columbia University	Brooklyn	1902	Same as New York City
door, window	Underwriters' Labs	Chicago	1903	Not known
column	National Fireproofing	Chicago	1904	Average 800-1000° C for 3 hours
wall	U.S.G.S.	Chicago	1907	Two hours, similar to ASTM E-119
wall	Underwriters' Labs	Chicago	1909?	Not known
floor	Underwriters' Labs	Chicago	1912?	Not known
column	UL, et al	Chicago	1917	ASTM E-119

APPENDIX B

EXTRACT FROM THE NEW YORK BUILDING LAW OF 1899
(As Given in Reference 279)

The following were the main provisions governing the fire testing of floors:

> "Such tests shall be made by constructing within inclosure walls a platform consisting of four rolled steel beams, 10 inches deep, weighing each 25 pounds per lineal foot and placed 4 feet between centers, and connected by transverse tie-rods, and with a clear span of 14 feet for the two interior beams and with the two outer beams supported on the side walls throughout their length, and with both a filling between the said beams, and a fireproof protection of the exposed parts of the beams of the system to be tested, constructed as in actual practice, with the quality of material ordinarily used in that system and the ceiling plastered below, as in a finished job; such filling between the two interior beams being loaded with a distributed load of 150 pounds per square foot of its area and all carried by such filling; and subjecting the platform so constructed to the continuous heat of a wood fire below, averaging not less than 1,700 degrees Fahrenheit for not less than four hours, during which time the platform shall have remained in such condition that no flame will have passed throughh the platform or any part of the same, and that no part of the load shall have fallen through, and that the beams shall have been protected from heat to the extent that after applying to the underside of the platform at the end of the heat test a stream of water directed against the bottom of the platform and discharged through a 1-1/8 inch nozzle under 60 pounds pressure for five minutes, and after flooding the top of the platform with water under low pressure, and then again applying the stream of water through the nozzle under the 60 pounds pressure to the bottom of the platform for five minutes, and after a total of load of 600 pounds per square foot uniformly distributed over the middle bay shall have been applied and removed, after the platform shall have cooled, the maximum deflection of the interior beams shall not exceed 2-1/2 inches."

APPENDIX C

RESULTS OF COMPARISONS WITH EXPERIMENT

One of the most suitable test series of compartment burns for comparison with theory has been the one recently completed at Factory Mutual Research Corporation.[176] Wood cribs in three different size enclosures were tested. The gas temperatures were taken as the average of readings at 1/2 and 3/4 the height of the compartment.

Compartment descriptions are given in Table 10. Wall material was as follows:

Compartment	Size H/W/D (m)	Material	Thickness (m)	Density (kg/m^3)
Small	0.610/0.610/0.914	Johns-Manville Cerefelt	0.010	224
Intermediate	1.220/1.220/2.230	Johns-Manville Marinite	0.013	368
Large	2.438/2.438/3.658	gypsum wallboard	0.016	792

Material thermophysical properties were as given by manufacturer or by Castle.[191] Wood fuel consisted of oven-dried sugar pine sticks, of sizes and weights as given in Table 10. Crib packing was such that cribs burned as "sparsely packed." Results of comparison of measured temperatures with predicted ones (but using measured mass loss data) are given in Figure 42. The agreement is seen to be adequate.

TABLE 10

DESCRIPTION OF TEST CONDITIONS

Test	Compartment Size	A_v (m^2)	h_v (m)	Crib Mass (kg)	Stick Thickness (mm)
273	S	0.0743	0.061	0.947	15.9
274	S	0.0743	0.061	0.596	15.9
261	S	0.0372	0.061	0.947	15.9
262	S	0.0372	0.061	0.586	15.9
146	S	0.1486	0.122	0.781	15.9
148	S	0.1486	0.122	0.545	15.9
72	I	0.2973	0.244	6.847	22.2
74	I	0.2973	0.244	4.565	22.2
119	L	0.5946	0.244	51.89	31.8
100	L	1.2139	0.488	50.12	31.8

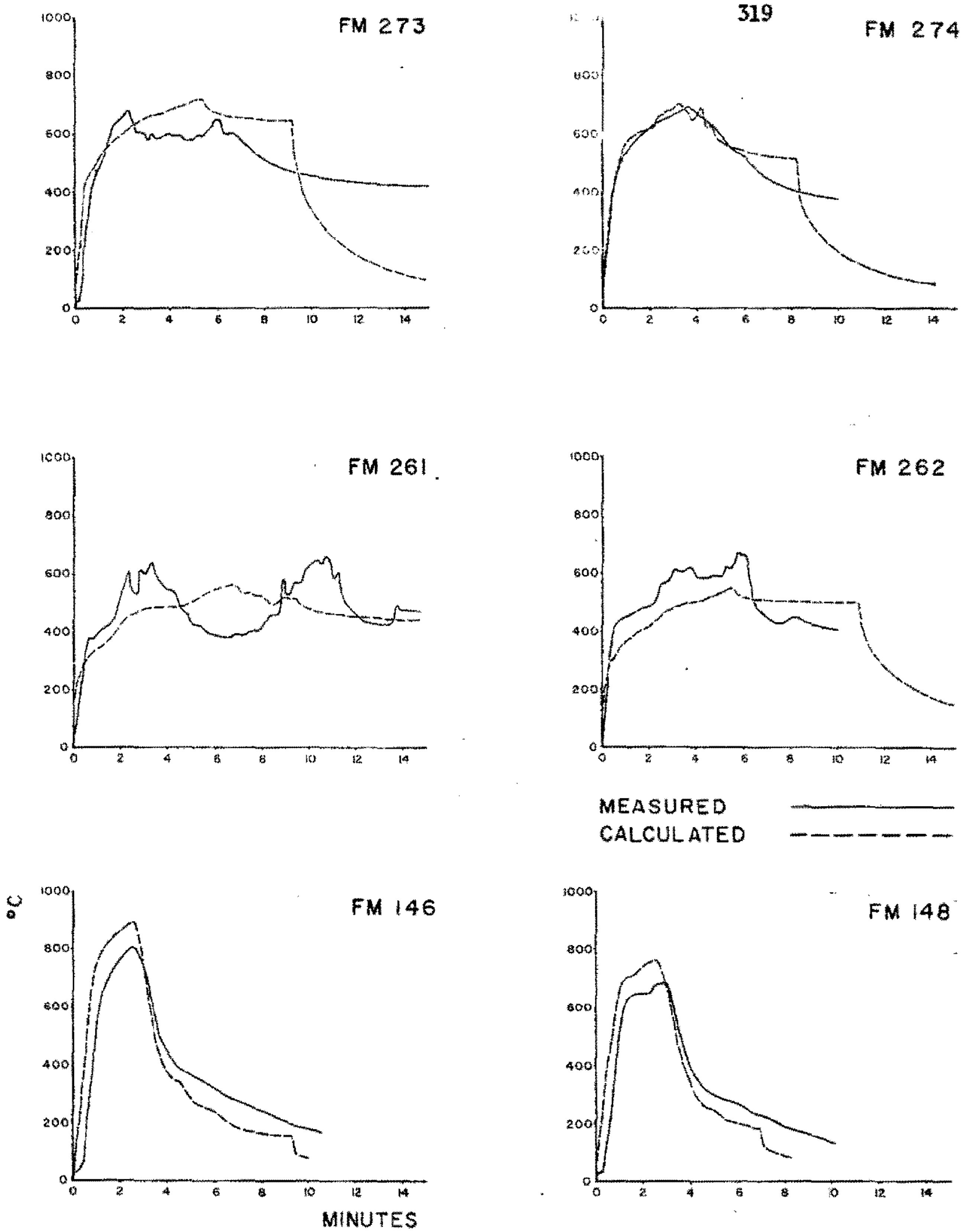


FIGURE 42 COMPARISONS WITH FMRC EXPERIMENTS

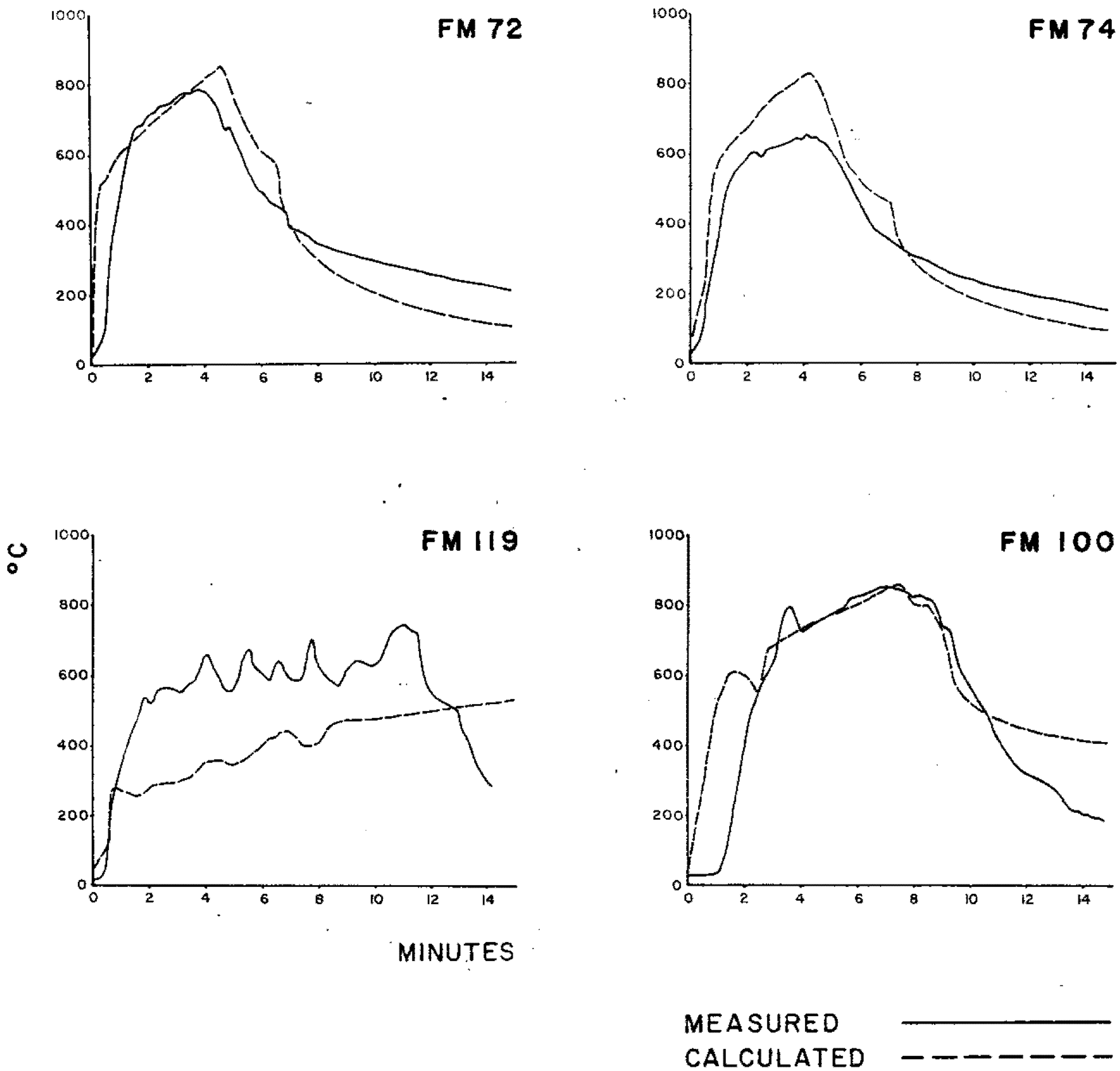


FIGURE 42 -- CONTINUED

APPENDIX D

CASE HISTORY--DETERMINISTIC APPROACH

One of the common practices in large portions of the United States is to build single family detached houses with an unoccupied space under the lowest habitable floor. This space is called a "crawl space" since it is usually not much over 0.5 m high. A crawl space can occupy the entire area under a house and often will be completely undivided and may be over 100 m^2 in area. In the early 1970's the United States Department of Housing and Urban Development, through its "Operation Breakthrough Guide Criteria" and later the FHA Minimum Property Standards (MPS),[200] sought to require a 10 minute fire endurance rating for all floors over a crawl space. This would mean that the floor systems would have to be subjected to a standard ASTM E-119 fire test which follows the time-temperature curve shown in Figure 7. Several fire tests were conducted on metal and plastic floor system alternatives to the common wood joist system and they all failed at less than 10 minutes. To determine if the use of the standard curve had been realistic the COMPF program was used to estimate the time-temperature curves that would be expected in these spaces.

The FHA-MPS[200] requires a minimum area of ventilation opening in crawl spaces of 1/150 of the floor area when the earth is exposed. If a vapor barrier is spread over the entire ground area the minimum ventilation required is reduced to 1/1500 of the floor area. The possible fuel load in a typical crawl space is severely limited by the restricted height of the area and the general practice of providing only limited access. A simple deterministic approach generated the time-temperature

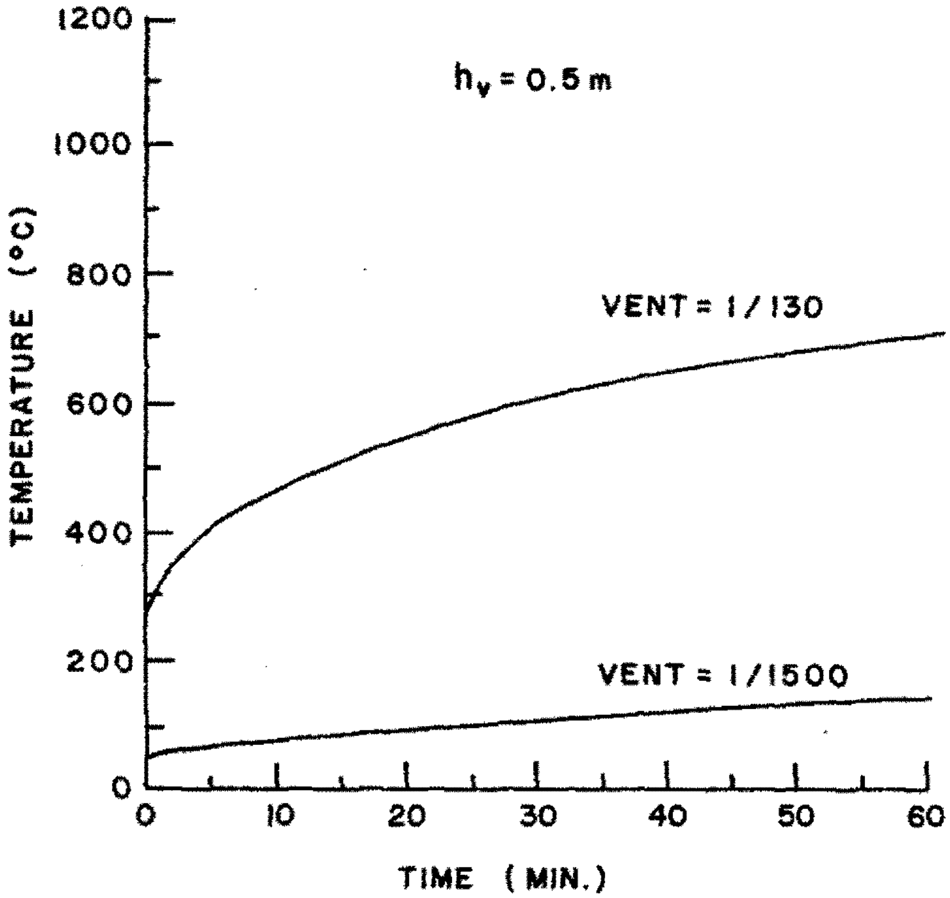


FIGURE 43 PREDICTED FIRE TEMPERATURES IN FHA-MPS DESIGN CRAWL SPACES, WITH TWO VALUES OF VENTILATION

curves in Figure 43. It is evident that for the 1/150 ventilation the fire would be of low intensity substantially below the level of the ASTM E-119. For the 1/1500 ventilation it would appear that a fully involved fire is essentially precluded since temperatures of 400-500 C are normally needed to sustain a fully involved fire.

As a result of this analysis, the fire endurance requirements for crawl spaces were dropped[287] from the FHA-MPS. The designer, however, should use some caution with either the 1/150 or 1/1500 ventilation in a crawl space. A scenario may need to be considered where a limited, pre-flashover source, such as heating furnace, allows a fire to burn through the ceiling, vent itself, and thereby greatly increase its burning rate.

APPENDIX E

UNIVERSITY OF CALIFORNIA WALL TEST FURNACE FACILITY

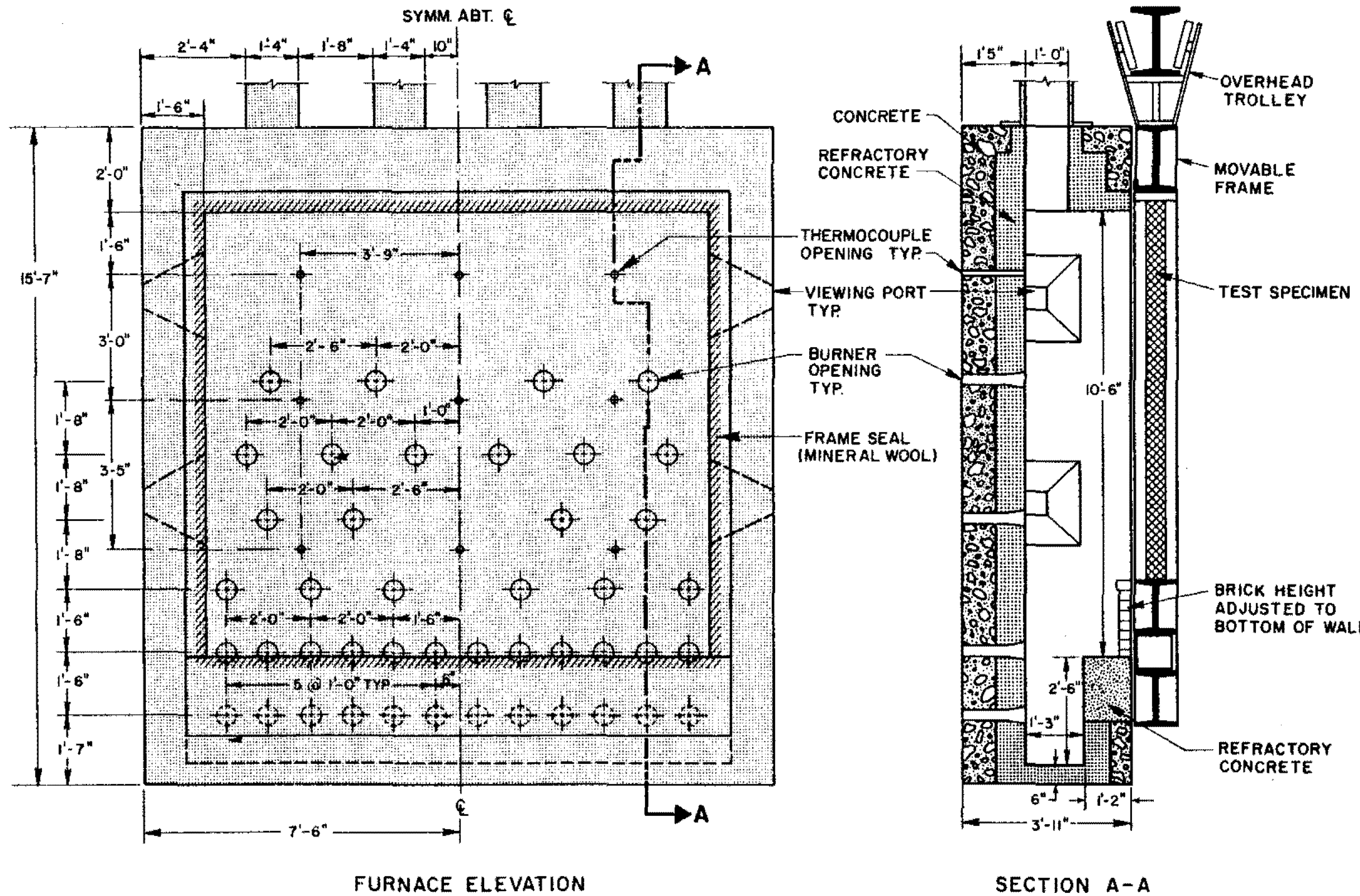
The test furnace is a natural draft (updraft) wall furnace fired by 44 natural gas burners. (See Figures 44 and 45.) Furnace lining consists of a cast refractory with $\rho = 1470$ kg/m^3 and an estimated value of 0.39 kcal/m^2-hr$^{1/2}$-°C for the product $\sqrt{k\rho C_p}$ at a temperature of 700° C.

Burners: Model S-5 manufactured by Ransome Gas Industries, San Leandro, California. These burners have a diffusion grid for spreading the flame and a venturi for entraining air into the gas stream. The venturi has an adjustable shutter plate; by fully closing this plate it is possible not to pre-mix any air into the gas stream. The burners are mounted in the furnace wall with a gap around them. Thus, additional air is pulled in from around the burners.

Stacks: There are 4 stacks, each 7 m tall. The draft is adjusted by manually opening or closing dampers which are located at the top of each.

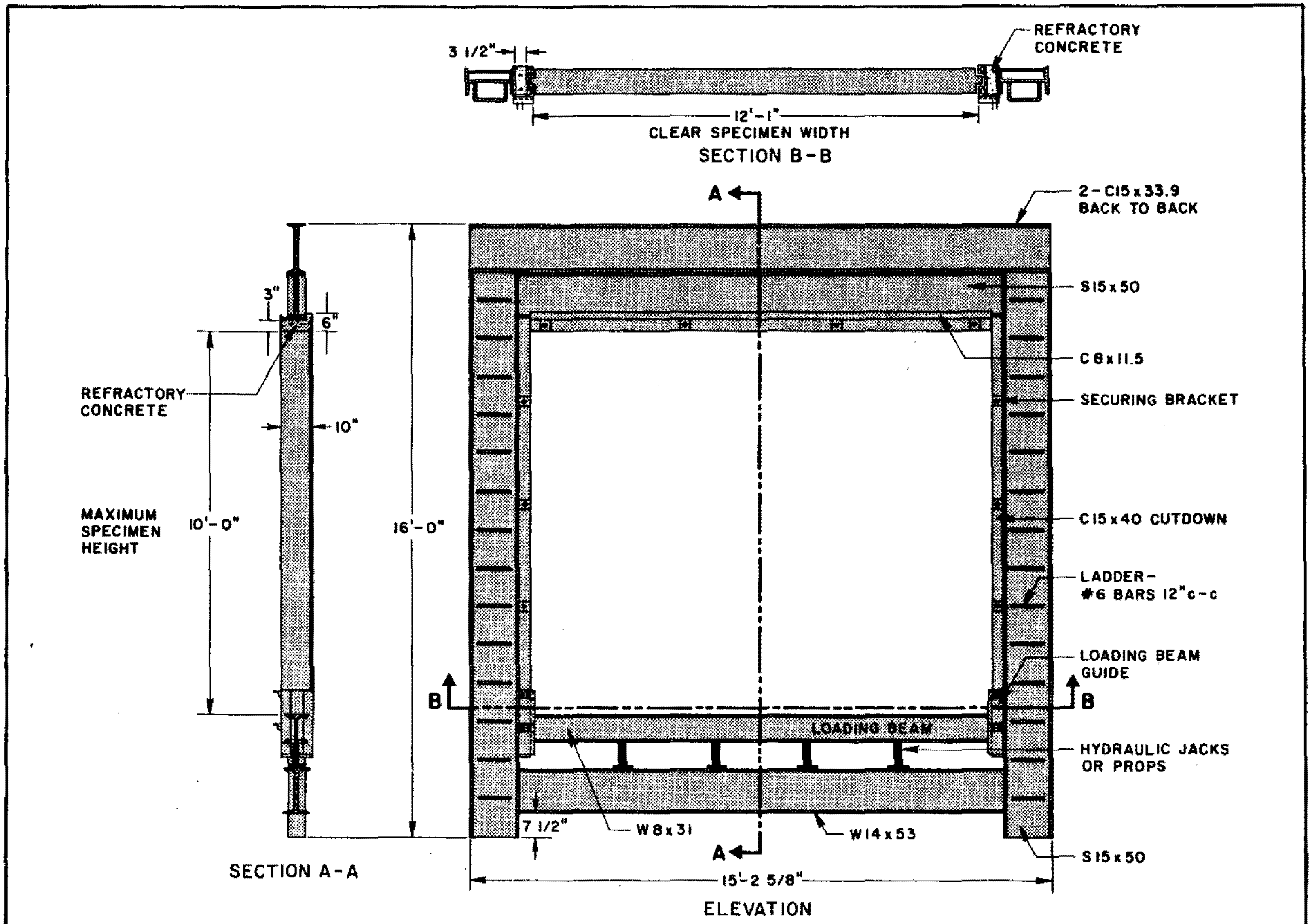
Gas Supply: Natural gas supplied by the Pacific Gas and Electric Company is used as fuel. The pressure is regulated to 50 Pa and fed through a 2 inch main. The gas consists of over 90% methane and has a calorific value of approximately 9.1 Mcal/m^3.

Pressure Measurements: A Validyne variable reluctance transducer is connected to a scanner switch, enabling up to 8 pressure ports to be sampled. Pressure tubes consist of Inconel 600 tubing (OD = 0.64 cm, ID = 0.46 cm). The readings are converted to digital form by a Validyne demodulator and inputted to the data acquisition system.



UNIVERSITY OF CALIFORNIA, BERKELEY	WALL TEST FURNACE – E119 & E152 TESTS	DWG RFS75-2

FIGURE 44



UNIVERSITY OF CALIFORNIA, BERKELEY	FURNACE DOOR ASSEMBLY - FOR ASTM E119 & E152 FIRE TESTS	DWG RFS75-3

FIGURE 45

Specimen Mounting: Wall specimens are erected in one of three similar movable frames. They are secured at the top by steel brackets and by an adjustable beam resting on screw jacks at the bottom. The edges of the frame exposed to furnace fire are covered with 7.5 cm of refractory concrete. Joints and edges of the wall specimen are plastered with vermiculite plaster. The frame is rolled into place on an overhead trolley and clamped with four anchorages against a ceramic fiber rope sealing gasket.

Data Acquisition System: All of the electrical measurements are logged on a digital data acquisition system. The system is based on a Digitrend Doric 210 Scanner and has the following capabilities

-- 100 channels of input data

-- Maximum scanning speed ≈ 2 channels/second

-- Output in millivolts, or directly in °C for Chromel-Alumel thermocouples

-- Real time averaging for furnace thermocouples

-- Panel display and punched paper tape output

Thermocouples: The furnace is provided with three sets of nine thermocouples each for measuring the gas temperatures:

-- Slow: These are the standard thermocuples prescribed by ASTM Standard E-119 for following the time temperature curve. At the UCB Lab they consist of 8-gage (3.26 mm) Chromel-Alumel elements. The elements are enclosed in, and grounded to, a protective metal tube. This tube is standard weight schedule 40 half-inch pipe (OD = 2.13 cm, ID = 1.58 cm) made from Inconel 600.

-- Fast: These are 0.64 cm OD Inconel tubes which are packed with MgO refractory and contain a grounded 18-gage (1.02 mm) thermocouple junction.

-- Bare: These are 20-gage (0.81 mm) Chromel-Alumel wire thermocouples supported through porcelain insulators.

APPENDIX F

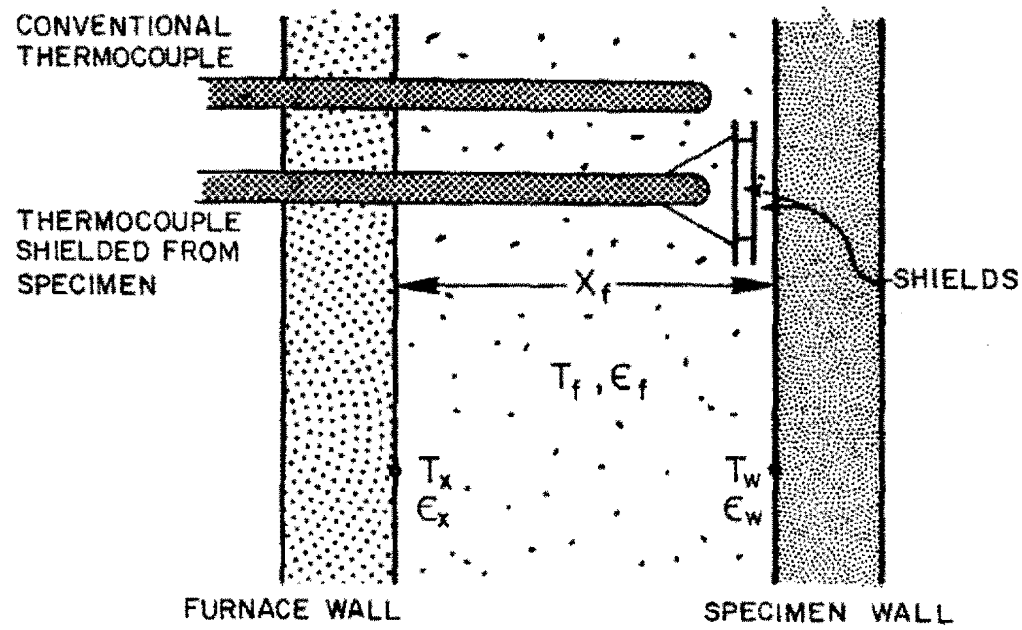
RADIATIVE HEAT TRANSFER IN A FURNACE

Assume that the furnace gases are all at a uniform temperature T_f, the exposed surface of the component being tested is at temperature T_w, and the remaining furnace walls are at temperature T_x. Further, following Williamson and Buchanan's[197] determination that in the furnace described in Appendix E the convective heat flux is negligible compared to the radiative, only transfer by radiation will be treated. An electric resistor circuit can then be drawn, as shown in Figure 46. Here the voltages represent σT^4, the current represents q_{net}, and the resistor values are indicated. The parallel plane wall geometry is of most interest. In that case, the areas are equal, $A_w = A_x$, and the view factors, F, are all equal to 1.0. Then

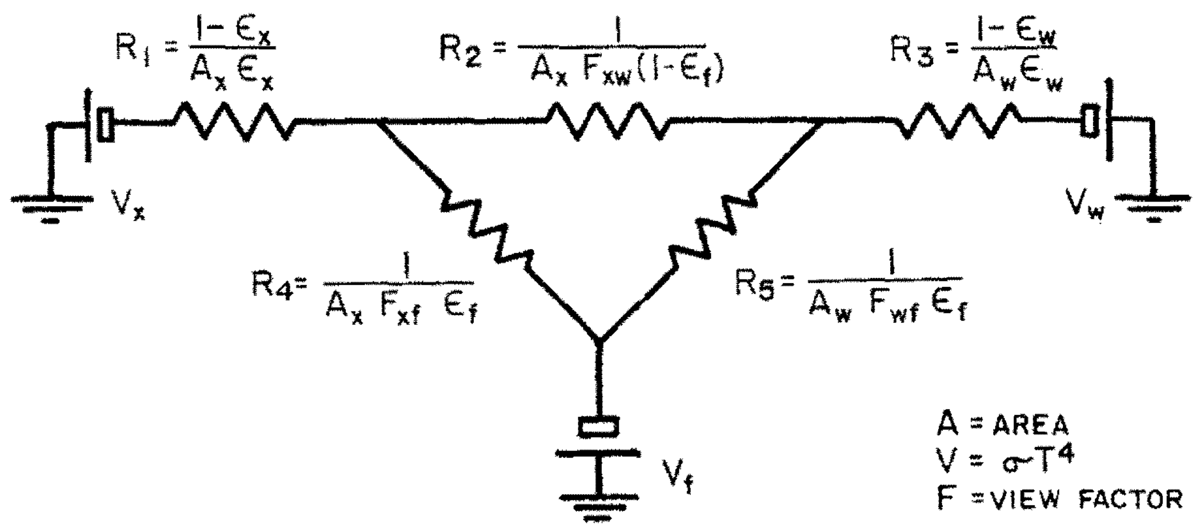
$$q_{w\text{-furnace}} = \sigma \frac{\varepsilon_w \left[\dfrac{\varepsilon_f + \varepsilon_x - \varepsilon_f \varepsilon_x}{\varepsilon_f (1 - \varepsilon_f) \varepsilon_x} + \dfrac{A_w (1 - \varepsilon_x)}{A_x \varepsilon_x} \right] (T_f^4 - T_w^4) - \dfrac{\varepsilon_w}{\varepsilon_f} (T_f^4 - T_x^4)}{\dfrac{\varepsilon_f + \varepsilon_x \quad \varepsilon_f \varepsilon_x}{\varepsilon_f (1 - \varepsilon_f) \varepsilon_x} \left[1 + \dfrac{A_w}{A_x} \quad (1 - \varepsilon_f)(1 - \varepsilon_x) \; \dfrac{\varepsilon_f + \varepsilon_w - \varepsilon_f \varepsilon_w}{\varepsilon_f + \varepsilon_x - \varepsilon_f \varepsilon_x} \right]} \tag{F.1}$$

This represents the actual heat input to the test component while in the test furnace if temperatures are so controlled that the furnace T_f is the same as for the room fire. In the actual room fire, on the other hand,

$$q_{w\text{-room}} = \sigma \frac{1}{\dfrac{1}{\varepsilon_f} + \dfrac{1}{\varepsilon_w} - 1} (T_f^4 - T_w^4) \tag{F.2}$$



(a) VERTICAL SECTION THROUGH FURNACE



(b) RESISTOR NETWORK

FIGURE 46 RADIATIVE HEAT TRANSFER IN A FURNACE

The error in the furnace test, due to the fact that $\varepsilon_f < 1.0$, might be represented by the ratio of these two heat flux expressions.

Example A

Select, as an example, indicative values for the room fire as

$T_f = 900°$ C

$T_w = 750°$ C

$\varepsilon_f = 1.0$

$\varepsilon_w = 0.8$

and for the furnace environment as

$T_f = 900°$ C

$T_w = 750°$ C

$T_x = 800°$ C

$\varepsilon_f = 0.4$

$\varepsilon_w = 0.8$

$\varepsilon_x = 0.8$

The ratio of the net heat flux realized in the test furnace to that expected from an actual fire can be represented as:

$$E_n = \frac{q_{w\text{-furnace}}}{q_{w\text{-room}}} \tag{F.3}$$

The above example gives

$$E_n = 0.59$$

This is nowhere nearly as far off as the ratio of the two ε_f values (0.4/1.0).

Example B

Such favorable behavior is dependent on the furnace wall heating up faster than the test component. Furnace linings are normally made of insulating refractory material, whereas the fire-resistive component being tested will usually have greater density and conductivity and will be slower to raise its surface temperature. If this is not the case, take $T_w = T_x = 750°$ C in the above example. Then the heat flux ratio

$$E_n = 0.45$$

and is still higher than 0.4.

In actual fact the furnace thermocouples do not measure T_f. The thermocouple reading, T_t, consists of contributions from both the gas and the furnace wall temperatures, and--as a complication which to the first approximation can be ignored--the specimen temperatures. Further, assume that there is not convective or conductive losses for the thermocouple. Then its reading can be determined by using Equation F.1, setting $q = 0$ and $\frac{A_w}{A_x} = 0$. This gives

$$0 = \varepsilon_t \,(T_f^4 - T_t^4) - \frac{\varepsilon_x \varepsilon_t \,(1 - \varepsilon_f)}{\varepsilon_f + \varepsilon_x - \varepsilon_f \varepsilon_x} (T_f^4 - T_x^4)$$

where t subscript signifies thermocouple.

Thus to properly evaluate the ratio E_n, in the expression for $q_{w\text{-furnace}}$ the T_f value is not the same as in the room fire, but is equal to T_t, which can be approximated from the above expression.

Example C

Keeping everything the same as in Example A and using an indicated T_t = 900° C, solve for T_f. This gives

$$T_f = \left[\frac{\varepsilon_f + \varepsilon_x - \varepsilon_f \varepsilon_x}{\varepsilon_f} T_f^4 - \frac{\varepsilon_x (1 - \varepsilon_f)}{\varepsilon_f} T_x^4 \right]^{1/4}$$

$$T_f = 994° \text{ C}$$

Inserting $T_{f\text{-furnace}}$ = 994° C in Equation F.1 and keeping $T_{f\text{-room}}$ = 900° C in Equation F.2, and also letting T_w = 844° C, and T_x = 894° C in Equation F.1, one gets the more correct expression for E_n

$$E_n = 0.76,$$

a value which is quite different from the 0.59 calculated on the assumption that the thermocouples measure the gas temperature.

Example D

Similarly, modifying the values of Example B to equal $T_{f\text{-furnace}}$ = 994° C, and $T_w = T_x$ = 844° C, one gets

$$E_n = 0.58$$

The calculated expressions above have been generated on the assumption that there is no convective or conductive heat transfer to the thermocouple. If there are conductive losses (i.e., heat flow down the stem) the T_f will be greater than calculated for any given T_t. Conversely, if there is a convective transfer and if the gases in the area are at the same temperature as the average T_f, then the T_f

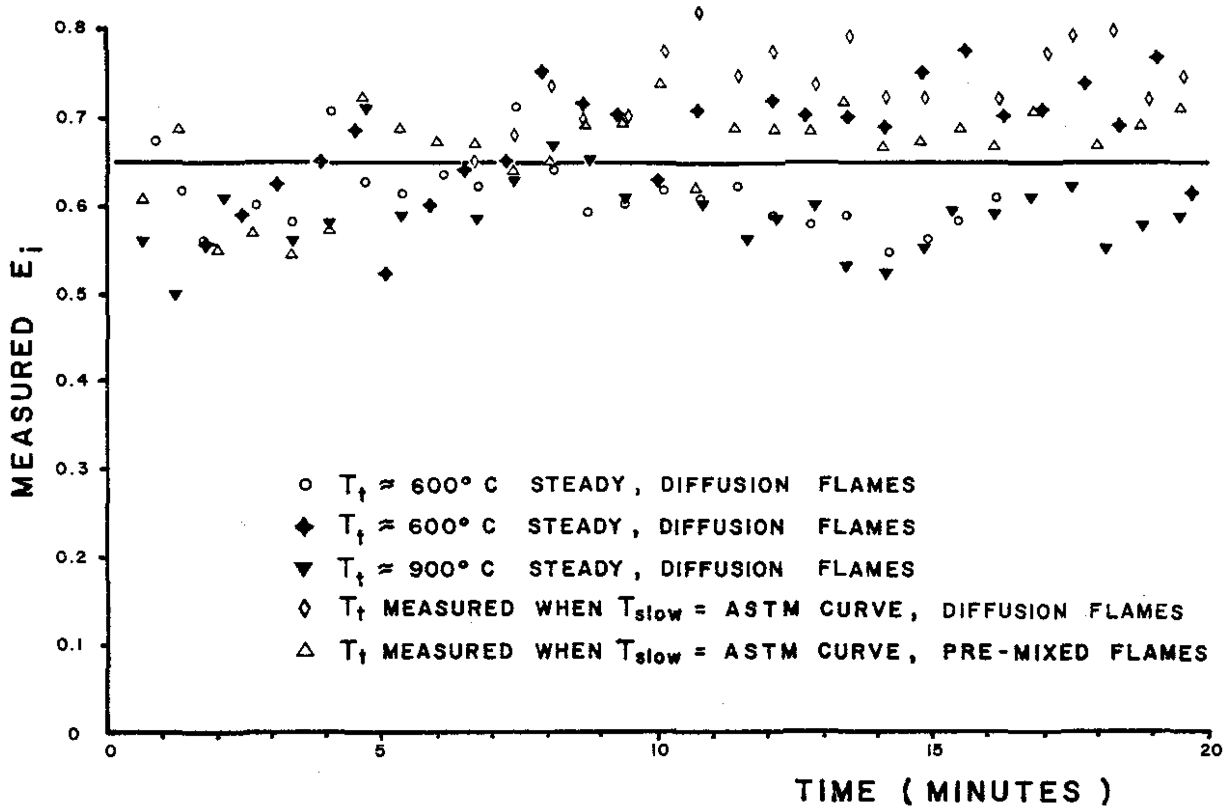


FIGURE 47 MEASURED VALUES OF E_i

will be lower than expected. Since it is hard, in general, to estimate these losses, and since the gas temperature near the specimen, where the thermocouple bead is located may not be quite equal to T_f, it is appropriate to assume that the net effect of the convective and the conductive terms is zero.

A set of measurements has been made in the University of California wall test furnace to investigate the actual values of the furnace efficiency. Gardon type foil wide-angle calorimeters (Model 1000-1 by Thermogage, Frostburg, MD) were used to measure $q_{w\text{-furnace}}$. A Gardon type calorimeter is water-cooled, making the effective surface temperature $T_w << T_f$. T_t was taken to be the reading of 20-gage bare wire thermocouples placed 15 cm in front of the blank test wall.

The net heat flux ratio E_n above is not directly measurable. What can be measured with the calorimeters is the incident heat flux ratio E_i

$$E_i = \frac{q_{c\text{-furnace}}}{q_{c\text{-room}}} \tag{F.5}$$

Here the q_c are calorimeter read fluxes, which can be gotten from the previous equations by letting $T_w \to 0$ and $\varepsilon_w \to 1.0$. Thus in Examples C and D, the values for E_i are found to be 0.80 and 0.75, respectively.

Figure 47 gives the results of several sets of furnace measurements. It is seen that $E_i \simeq 0.65$ under several conditions of exposure, and that the value is independent of time. The constancy of this ratio prompts two observations: (1) the effect of the furnace walls on the flux to the specimen is slight. The cast refractory used in the walls of the present test furnace is by no means one of the best available, low thermal inertia materials. Yet the results do not indicate any significant deviations in E_i that would be attributable to furnace wall warming up. (2) In view of the constancy of E_i a method of correction can be adopted, if the increased precision is judged warranted.

These findings are in contrast to the recent study of furnace heat transfer by Paulsen.[167] He was concerned by the possibility of differences in furnace wall materials and emissivities causing systematic inter-laboratory differences. His proposed solution is a standardizing scheme where each furnace would be rated by a "time constant," τ_k, which would be defined as the time it takes for a 0.15 m thick concrete specimen of known properties to reach 350° C at 0.015 m from the exposed surface when subjected to a standard time-temperature curve heating. Endurances in various furnaces would then be corrected to a standard value by use of these time constants.

A proposal of this nature, while applicable to some special cases, is of little general utility for two reasons. First, Paulsen's method fails to take into account the difference between T_f and T_t. As a result it significantly over-emphasizes the effect of the furnace wall thermal properties. And, second, if despite indications by van Keulen[195] that the average heat fluxes vary less between laboratories than from test to test in the same laboratory, it is still desired to seek improvements, a simpler course is available. Blanket type ceramic fiber refractory linings with a density of only around 100 kg/m^3 can be installed quite easily on the walls of those furnaces most needing improvement. This would attack the problem at its source and eliminate the awkwardness of conversions.

APPENDIX G

RESPONSE TIME OF THERMOCOUPLES

It is instructive to consider a simplified case of convective heat transfer. Radiative transfer is only slightly more complex. It is not important which is chosen since it will only be used for qualitative purposes. Actual thermocouple characteristics cannot be accurately obtained by calculation alone and must be obtained from measurements.

Assume that the thermocouple bead is small enough and of high conductivity so that it is at a single temperature. Then performing a heat balance for the bead

$$\dot{Q}_{in} - \dot{Q}_{out} = \dot{Q}_{stored} \tag{G.1}$$

Assuming also no losses, $\dot{Q}_{out} = 0$. Let

$$\dot{Q}_{in} = hA_t \ (T_f - T_t) \tag{G.2}$$

and

$$\dot{Q}_{stored} = \rho C_p V_t \ \frac{dT_t}{dt} \tag{G.3}$$

where A_t = area of bead

V_t = volume of bead

T_t = indicated temperature

Inserting an initial condition that $T_f = T_o$ at $t = 0$ gives

$$T_t = T_f - (T_f - T_o) \ e^{-t/\tau} \tag{G.4}$$

where $\tau = \frac{\rho C_p V}{h A_t}$ has units of time and is called the time constant.

Thermocouple manufacturers often report catalog values of τ by performing a measurement where T_o = room temperature and T_f = 100° C. It must be emphasized that values of τ derived in this fashion have no relation to thermocouple response at higher, fire temperature. In fact, τ is not a constant solely consisting of thermophysical properties, but is strongly dependent on T_f itself. This becomes evident when radiative transfer is considered, which introduces a term proportional to $(T_f^4 - T_t^4)$ into $\dot{Q}_{in}$.

Slow Thermocouples

The furnace thermocouples to be used in E-119 tests are prescribed as follows: "thermocouples...enclosed in sealed porcelain tubes 3/4 inch (19 mm) in outside diameter and 1/8 inch (3 mm) in wall thickness, or, as an alternative in the case of base metal thermocouples, enclosed in sealed, standard-weight 1/2 inch (13 mm), black wrought steel or black wrought iron pipe... Other types of protecting tubes or pyrometers may be used that...give the same indications ..." Inconel tubes are now commonly used as being equivalent but with better durability. The specifications are silent on the question of the thermocouple wire and whether it is to be grounded. At the University of California Type K 8-gage (3.25 mm) wire is used, in accordance with standard manufacturers' recommendation of minimum size for use at 1260° C environments when enclosed in metal tubes.

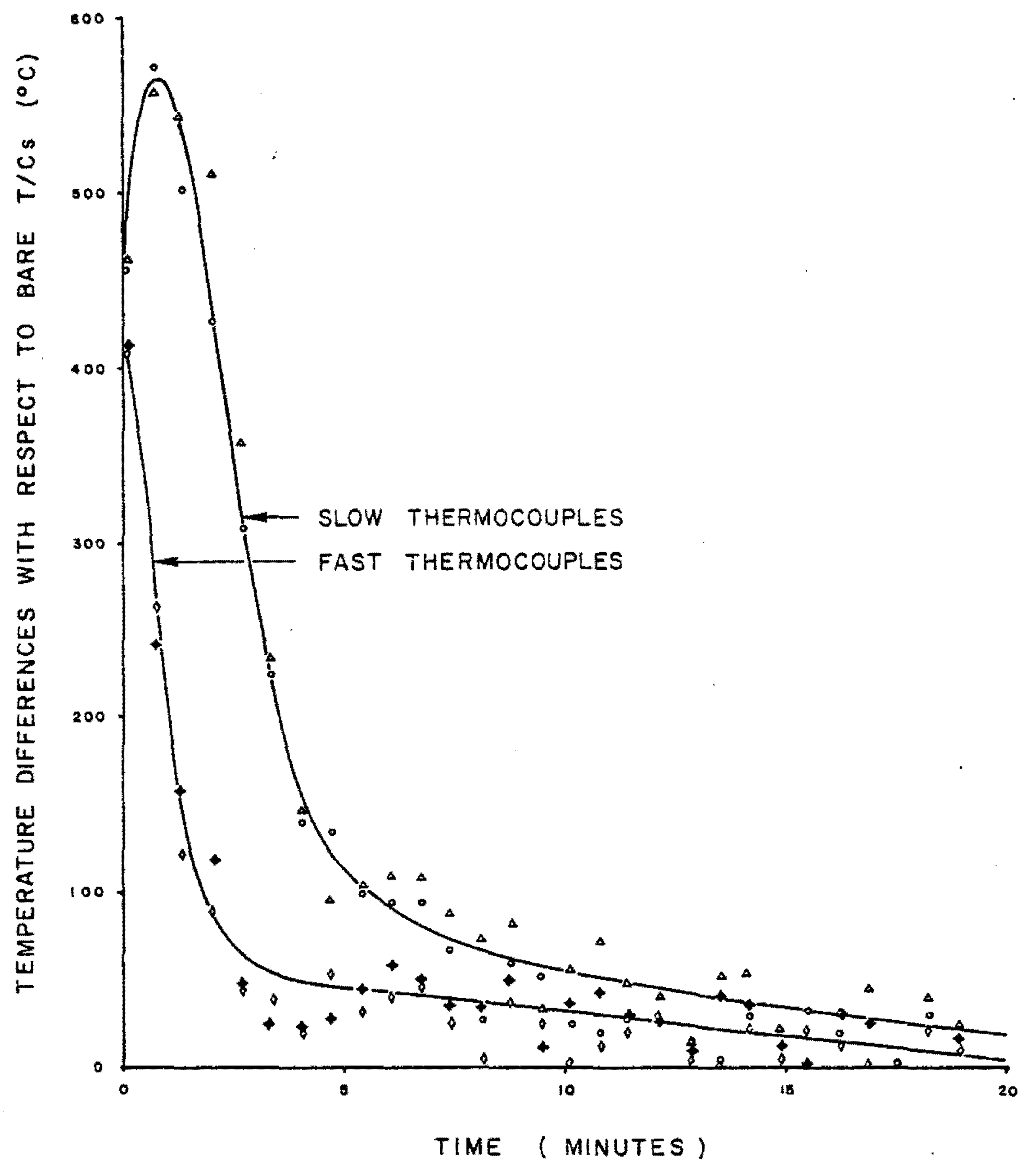


FIGURE 48 THERMOCOUPLE LAG UNDER ASTM CONDITIONS

Fast Thermocouples

In recent years a new variety of shielded thermocouples has become commonly available. They are sufficiently rugged and reliable--although less than the standard slow ones--and offer significantly shorter response times. On these the outside sheath is much smaller and thin gage wires are swaged tightly around a refractory material that fills the inside. It has been found satisfactory to use units with 6.35 mm O.D. sheath and Type K 18-gage (1.016 mm) elements (Thermoelectric Co. part No. 5K0140L-48).

Bare Thermocouples

For experimental purposes a set of bare Type K thermocouples has also been installed in the wall furnace. Wire of 20-gage (0.813 mm) is used. Starting at about 4 cm from the bead a double bore insulator is slipped on and suspended by hanger wires below the fast thermocouples. The beads are adjusted to all be the same distance from the specimen. These thermocouples would not be suitable for routine testing because the fluctuations, due to gas turbulence, are not smoothed out and would make control difficult. They are mainly useful because there time constant is so short that it can be presumed to be negligible.

Experimental Results

Measurements with the three sets of thermocouples have been taken under several different conditions of exposure. The data can be reduced in the form of a time-dependent variable $\tau(t)$. Rewrite the basic equation as

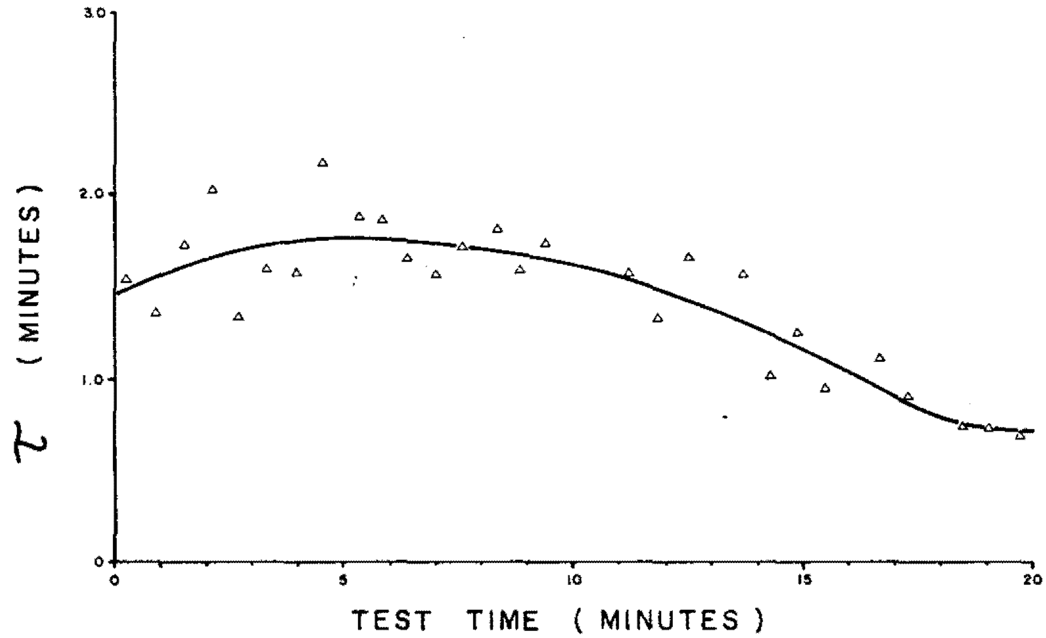
$$(T_f - T_t) = \tau \frac{dT_t}{dt} \tag{G.5}$$

or,

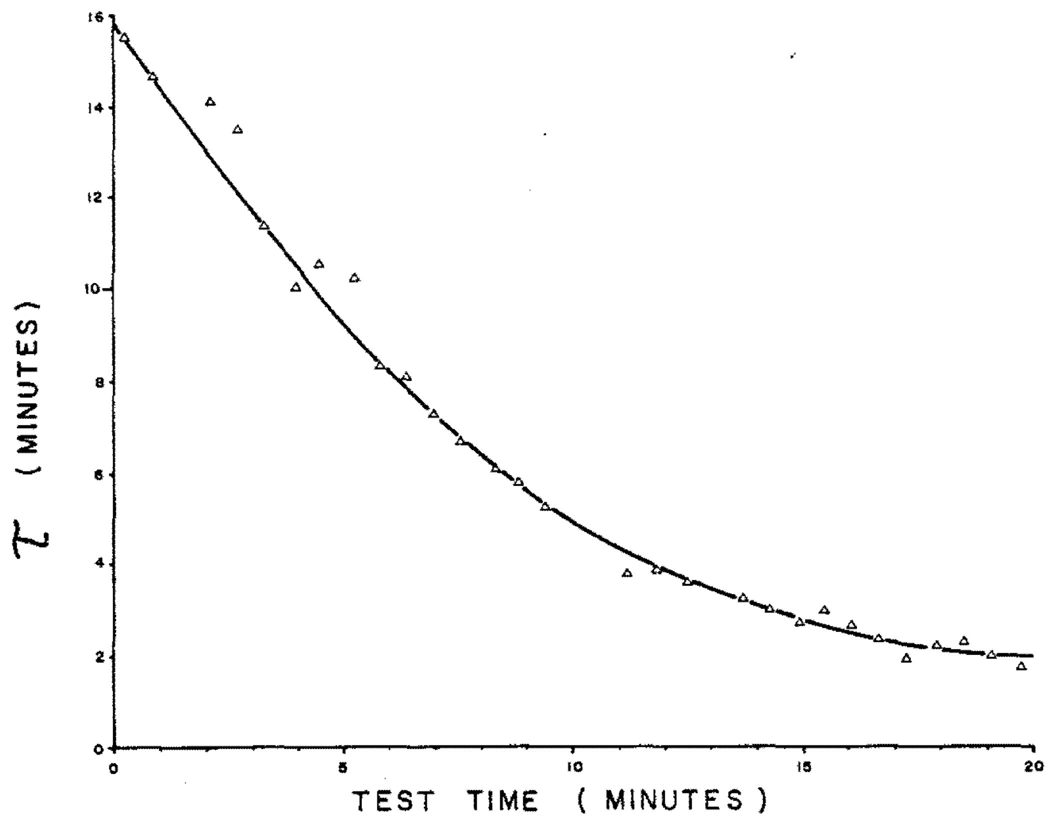
$$\tau(t) = \frac{T_f - T_t}{\Delta T_t/\Delta t} \tag{G.6}$$

Figure 48 shows the results of two tests where the ASTM curve was followed with the flow thermocouples. Temperature differences are given for the fast and the bare thermocouples with respect to the slow ones. It can be seen that in the beginning of a test the slow thermocouples indicate a temperature some 500° C below the T_t obtained from the bare thermocouples. After 20 minutes these differences become insignificant.

A time constant under ASTM-curve conditions is difficult to calculate accurately because of the rapid temperature variations. To illustrate the behavior of τ as a function of time and temperature an additional test was conducted where the $T_{t\text{-bare}}$ rose linearly from 100° C to 900° C in 20 minutes. Time constants calculated according to Equation G.6 under these conditions are shown in Figure 49. Asymptotically the fast thermocouples approach $\tau = 0.6$ min, while the slow thermocouples approach $\tau = 2.0$ min. The curves generally indicate, as expected, faster response at higher temperatures. No definitive explanation is available for the rising response time of the fast thermocouples in the initial period.



(a) FAST THERMOCOUPLES



(b) SLOW THERMOCOUPLES

FIGURE 49 THERMOCOUPLE RESPONSE TIME

APPENDIX H

EVOLUTION OF ASTM ENDURANCE CRITERIA

"+" denotes still current (1976)

MEMBER	EDITION (YEAR)
General	
Safety factor = 0%	1907-1909; 1926+
= 25%	1918
Classify as combustible if burn freely during test or burn after furnace shut off	1933-1953
Floors	
Carry superimposed test load = 150 psf	1907-1908
Carry superimposed test load = maximum working stress	1918+
Re-load = 4 x test load	1907-1908
= 2½ x test load	1918
= 2 x test load	1926-1953
Permanent deflection = 1/96 L	1907-1908
Not pass flame	1907-1918
Cotton waste ignition	1926+
Not pass smoke	1907-1908
Unexposed face temperature rise 139° C avg/181° C max	1926+
Floor beam steel temperatures unrestrained: for rating period restrained: for ½ rating period, but at least 1 hour	1973+
structural steel 593° C avg/704° C max	
bar joists 593° C avg	
concrete reinforcing steel 593° C avg	
prestressing steel 427° C avg	
Hose stream	1907-1953

<u>Walls</u>

(Bearing walls) carry superimposed test load = maximum working stress	1926+
(Bearing walls) re-load = 2 x test load	1926+
Not pass flame	1909-1918
Cotton waste ignition	1926+
Not pass smoke	1909
Not warp, bulge, disintegrate	1909-1918
Unexposed face temperature 149° C	1918
Unexposed face temperature rise 139° C avg/181° C max	1926+
Fire stopping, if any, must function	1926-1933
Hose stream	1909+

<u>Columns</u>

Carry superimposed test load = maximum working stress	1926+
(Alternate) unloaded steel temperature 538° C avg/649° C max	1947+
Hose stream	1918

<u>Beams, Girders</u>

Loaded: carry superimposed test load = maximum working stress	1973+
Loaded: steel temperature unrestrained: for rating period restrained: for ½ rating period, but at least 1 hour	1973+
structural steel 593° C avg/704° C max reinforced concrete steel 593° C avg prestressing steel 427° C avg	
Unloaded: structural steel temperature 538° C avg/649° C max	1953+

<u>Ceilings</u>

Not pass flame	1947+
Not ignite combustible materials above ceiling	1947+
Interstitial temperature	1947+
bottom of noncombustible beams 649° C avg	
sides, top of noncombustible beams 538° C avg	
rise for combustible materials	
139° C avg/181° C max	

<u>Finish Materials, Protective Materials</u>

Not pass flame	1926
Not ignite	1933+
Interstitial temperature rise	
combustible materials 139° C avg	1926+
noncombustible materials 181° C avg	1941+
Hose stream	1926-1933

<u>Doors</u>

Not develop openings	1941+
Deflection (numerous detailed criteria)	1941+
Hose stream	1941+
(Optional) unexposed face temperature	1941

Plus, the following additional criteria contained in UL Standard 10b are generally applied in the U.S.

Flaming on unexposed face
none in first 30 minutes
intermittent, not over 5 min., thereafter

Additional deflection and latching criteria

(Optional) unexposed face temperature

ASTM Standard E-119 can be traced to a floor test procedure adopted in 1907 and revised in 1908 and a partition test method of 1909. The first consolidated method was issued as C-119 in 1918. In

1926 it was withdrawn and replaced by a new tentative edition. A new edition was adopted in 1933. Revised editions followed in 1941, 1947 (renumbered as E-119), 1950, 1953, 1954, 1955, 1958, 1961, 1967, 1969, 1971, 1973, and 1976.

A door test standard was first issued as C-152 in 1941, having been first published as tentative in 1940. In 1955 it was withdrawn and replaced by a tentative edition and renumbered E-152. A revised tentative edition was issued in 1956. A new edition was adopted in 1958. Revised editions followed in 1966, 1972, 1973 and 1976.

APPENDIX J

GAS FLOW CRITERIA

A. Need for Criteria

In Chapter 8 it was mentioned that a systematic basis for evaluating the tendency of walls, doors, and floors to pass gases must be considered. That is, a method for experimentally determining barrier completeness is needed. Under the current E-119 criteria assemblies which do not have openings, cut-outs, etc., generally fail first by load failure or temperature rise before any significantly large cracks have opened up. Thus it may not be immediately apparent that there is a need for measuring "leakiness." However, the following points must be considered.

1) Fire tests have traditionally been run with a negative pressure in the furnace. As detailed in Section 6.4 that practice is inappropriate and should be changed. Since test have usually been run that way, however, the operator cannot see gases flowing out from specimen holes since the flow direction is in fact reversed--from the outside into the furnace.

In addition to preventing useful observation, this practice of operating with a completely negative pressure distribution over the specimen has an even worse consequence. For many specimens, especially combustible ones, a positive pressure can cause burning or mass loss along the crack faces. Hot gases being pushed through by a positive pressure will heat up the periphery of the crack faster than bulk thermal conduction alone. See Figure 51. Conversely, as noted by Ryan,[280] negative furnace pressure will cause ambient air to be

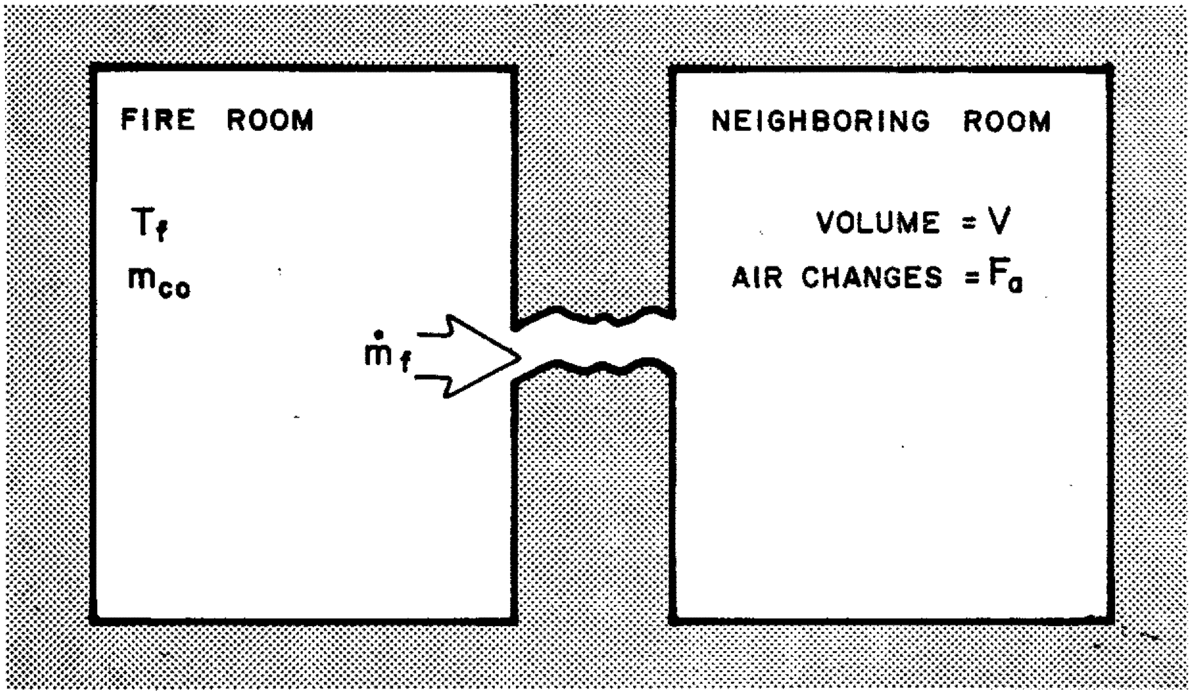


FIGURE 50 MODEL FOR GAS FLOW

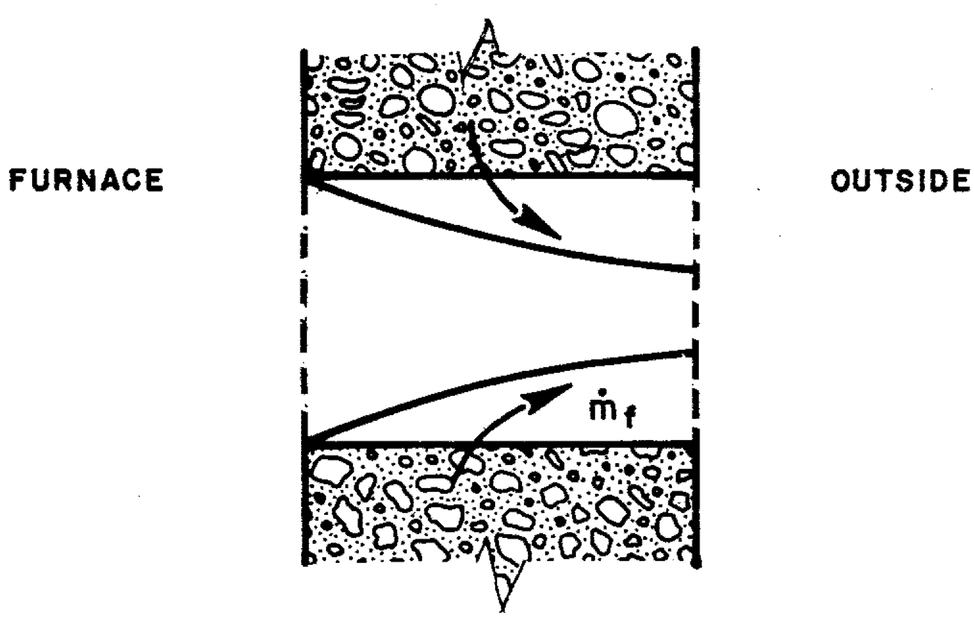


FIGURE 51 SPECIMEN MASS LOSS DUE TO POSITIVE FURNACE PRESSURE

forced through the cracks, giving a cooling effect. In a real fire, we can expect that the major portions of walls and doors plus the entire ceiling will be subjected to positive pressure. Thus in the real fire situation we can expect pressure-exacerbated crack burning. To instead induce flow cooling in a test apparatus is most unrealistic and unwarranted.

Proper pressures are especially important for testing of combustible doors. In many combustible doors failure will occur by burn-through at the top of the door if positive pressure is maintained but will not fail that way in case of negative pressure. The series of tests by Shoub and Gross[275] has been one of the few in the U.S. where positive pressures were used.

2) Increasing use is being made of wall penetrations, poke-thru, and plastic pipe within fire-rated assemblies. The area opened up, or potentially opened up, in these installations is normally moderately small. Even though such an assembly might fail a standard test due to flaming or thermal transmission, it is not likely that this failure would correlate with a greatly increased potential to accelerate flashover in adjacent compartments during an actual fire. What might be strongly reduced, however, is the human habitability on the other side of the barrier. Since it can be expected that the trend for barrier penetrations and interstitial combustibles will keep growing, it is of great interest to evaluate the life safety implications.

B. Definition of Problem

Consider Figure 50. A post flashover fire in a given room will create a stirred temperature T_f and an average CO fraction m_{CO}. It may generate other toxic species, but CO will be used as an example. Some very rough guesses about the CO level can be made. The presence or absence of any other toxic species, such as HCN, HF, acrolein, etc., could only be judged from a detailed description of the fuel load. A description sufficiently detailed for this purpose is not likely to be available in most design instances.

To ensure habitability of the adjacent room from a toxicologic basis, we must ensure that the toxic species concentration will not exceed certain values for a given length of time. To do that it is necessary to have a method of predicting $m_{x,a}$ as a function of time, where m is the mass fraction of species x in a room a. It is convenient to consider the normal ventilation in the room as described by F_a, the number of air changes per hour. Then

$$m_{x,a} = \frac{\dot{m}_f}{\dot{m}_a} m_{x,f} \tag{J.1}$$

where:

$\dot{m}_f$ = mass inflow of fire gases from room f

$\dot{m}_a$ = mass inflow of fresh ventilating air

$m_{x,f}$ = fraction of x in fire gases

also,

$$\dot{m}_a = \rho_a V F_a$$

where:

ρ_a = air density in room

V = room volume

then

$$m_{x,a} = \frac{\dot{m}_f m_{x,f}}{\rho_a V F_a} \tag{J.2}$$

Now $\rho \simeq$ constant, V is known for a given room, and F_a is the, presumably known, air change rate. Only $\dot{m}_f$ and $m_{x,f}$ remain to be determined.

At this point the problem can be examined from the viewpoint of uncoupling the variables. The $m_{x,f}$ is almost entirely a function of the fire in the fire room. If the wall cracks are combustible, then a certain fraction of the flow will also depend on the wall material composition. Let us assume, however, that $m_{x,f}$ is described mainly by the fire in room f. On the other hand, $\dot{m}_f$ is mainly a property of the wall. Write

$$\dot{m}_f = C_d \rho_f A_c v \tag{J.3}$$

where:

v = flow velocity

A_c = area of crack

ρ_f = gas density

C_d = discharge coefficient

call

$P_{fa} = P_f - P_a$

= pressure difference between fire room and adjacent room

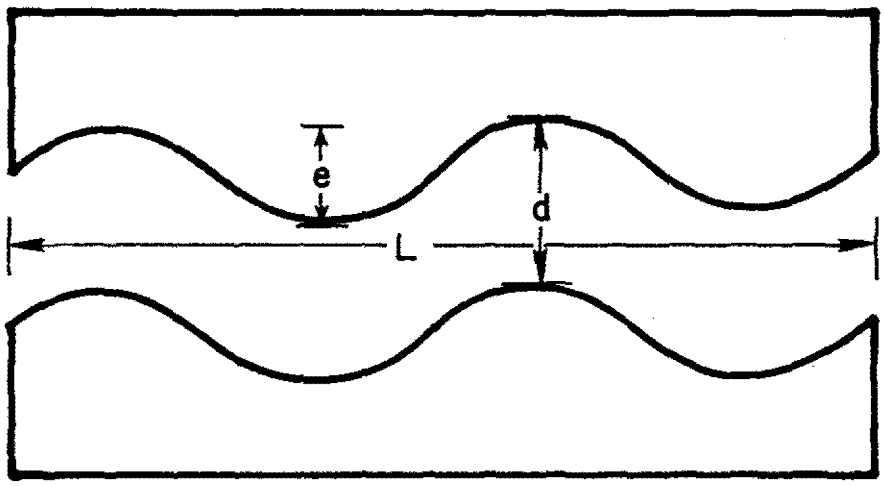


FIGURE 52 TYPICAL SINUOUS FLOW PATH

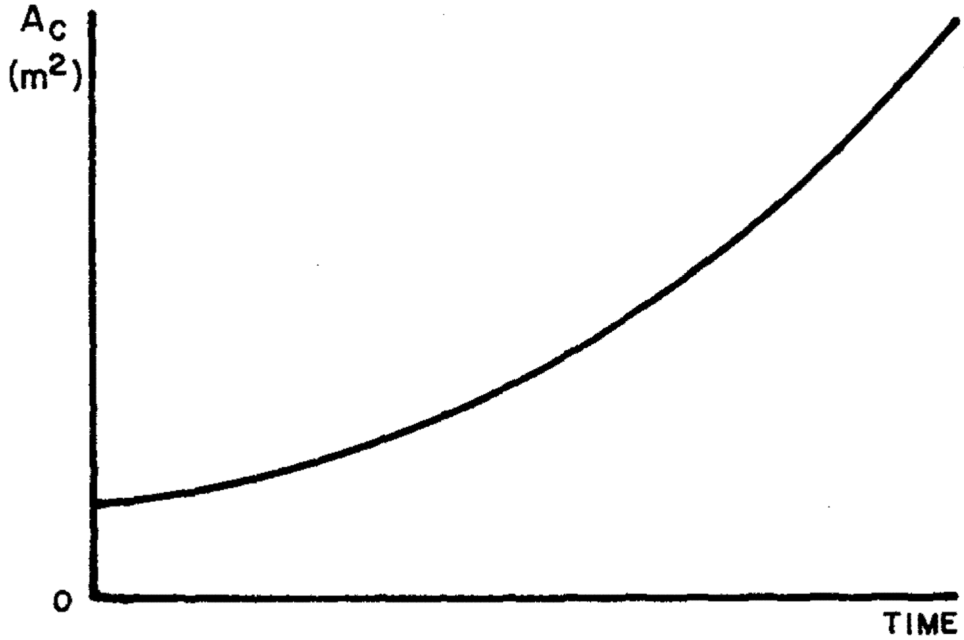


FIGURE 53 GROWTH OF CRACK AREA WITH TIME

Then write Bernoulli's law between two points: point 1 is well inside room f. Here the velocity is zero, the density is ρ_f and the pressure is P_f. Point 2 is just past the crack orifice. The pressure is now P_a, the density still ρ_f and velocity v. Then

$$v = \sqrt{\frac{2P_{fa}}{\rho_f}} \tag{J.4}$$

combining,

$$\dot{m}_f = C_d A_c \sqrt{2P_{fa}\rho_f} \tag{J.5}$$

further, taking $\dfrac{\rho_f}{\rho_\infty} = \dfrac{T_\infty}{T_f}$ and letting

$$\rho_\infty = 1.29 \text{ kg/m}^3 \text{ at } T_\infty = 298° \text{ K}$$

we get

$$\dot{m}_f = 26.5 \quad C_d A_c \sqrt{\frac{P_{fa}}{T_f}} \text{ kg/sec} \tag{J.6}$$

The discharge coefficient C_d depends on many factors. Discharge coefficients have only been measured for openings of regular geometry. In most cases of building assemblies the wall surfaces on both sides of the orifice will be plane and parallel. Thus two main geometrical variations are possible, as shown in Figure 52. The crack ratio of diameter to length is important for determining flow resistance. The longer the crack (i.e., the thicker the fire-rated wall) the more flow resistance there is. For a short crack it is appropriate to consider it an orifice, and its length is immaterial. For a longer crack, however, length becomes important--the crack has to be considered as a pipe. Further, the roughness of the pipe as ratio e/d also becomes a factor for the larger lengths. This can be viewed as the waviness or sinuousness of the crack. Brown and Solvason[114] give some data on the influence of crack length.

Two remaining variables can readily be measured. P_{fa} is simply the pressure in the fire room or furnace, at the level of the crack. T_f is a bit more complex; it would be equal to the temperature in the furnace if the flow path through the crack were adiabatic. It is not; if T_f is greater than surrounding crack temperatures, there will be heat loss to the surroundings and the exiting T_f will be less than the furnace T_f. Thus it is appropriate to use

$$T_f = \frac{T_{f\text{-furnace}} + T_{f\text{-exit}}}{2}$$

C. Existing Measurement Techniques

While flow measurements have never been systematically taken, there has on occasion been some interest taken in the problem, but only as it relates to doors. Measurement techniques can be subdivided into whether the collection system is open or closed. The simplest open device is a canopy hung over the door. Collected gases flow out from underneath as in spillage from an upside down weir. The ISO standard for doors[193] provides for an optional canopy of this kind. The rate of flow is gauged by the temperature registered by thermocouples placed within the canopy. This method has not been quantified and is, of course, also affected by back face radiation.

A similar, although larger, canopy is used on an exploratory basis at Underwriters' Laboratories in door tests.[276] The intent of the method there is somewhat different since the furnace is operated at negative 2.5 ± 2.5 Pa at the top of the door. The measurements are taken not of through flows but of smoke generated from the back face of the specimen. Smoke density is measured by attenuation of a light beam placed vertically within the canopy.

The most comprehensive measurements have been those of Oksanen.[277,278] He has tested doors with a closed plenum covering the entire door frame. The flow is out through a small pipe where the velocity is measured. The velocity measuring instrument is the critical constraint here. According to Oksanen's findings[278] hot wire anemometers are too easily influenced by gas temperature and composition, while fan-type anemometers are not commercially available with ratings of over 65° C.

D. Measurement Technique Used

From Equation J.6 it can be seen that under specified test conditions the variables $\dot{m}_f$ and A_c are directly related. Thus it is possible to use the measurement of $\dot{m}_f$ to obtain A_c. The opening area, A_c, will in the general case be a function of time, as shown in Figure 53. It is important to be able to measure both the A_c in the unburned condition, at $t = 0$, and to follow its increase with time. The importance of A_c as the experimental variable must be emphasized. It is completely independent of the furnace gas pressure or composition, and depends on furnace temperature only insofar as the temperature determines the crack forming.

Tests have been conducted in the University of California wall furnace to verify the expected behavior. Appendix E contains a description of the test furnace. The basic instrument for measuring

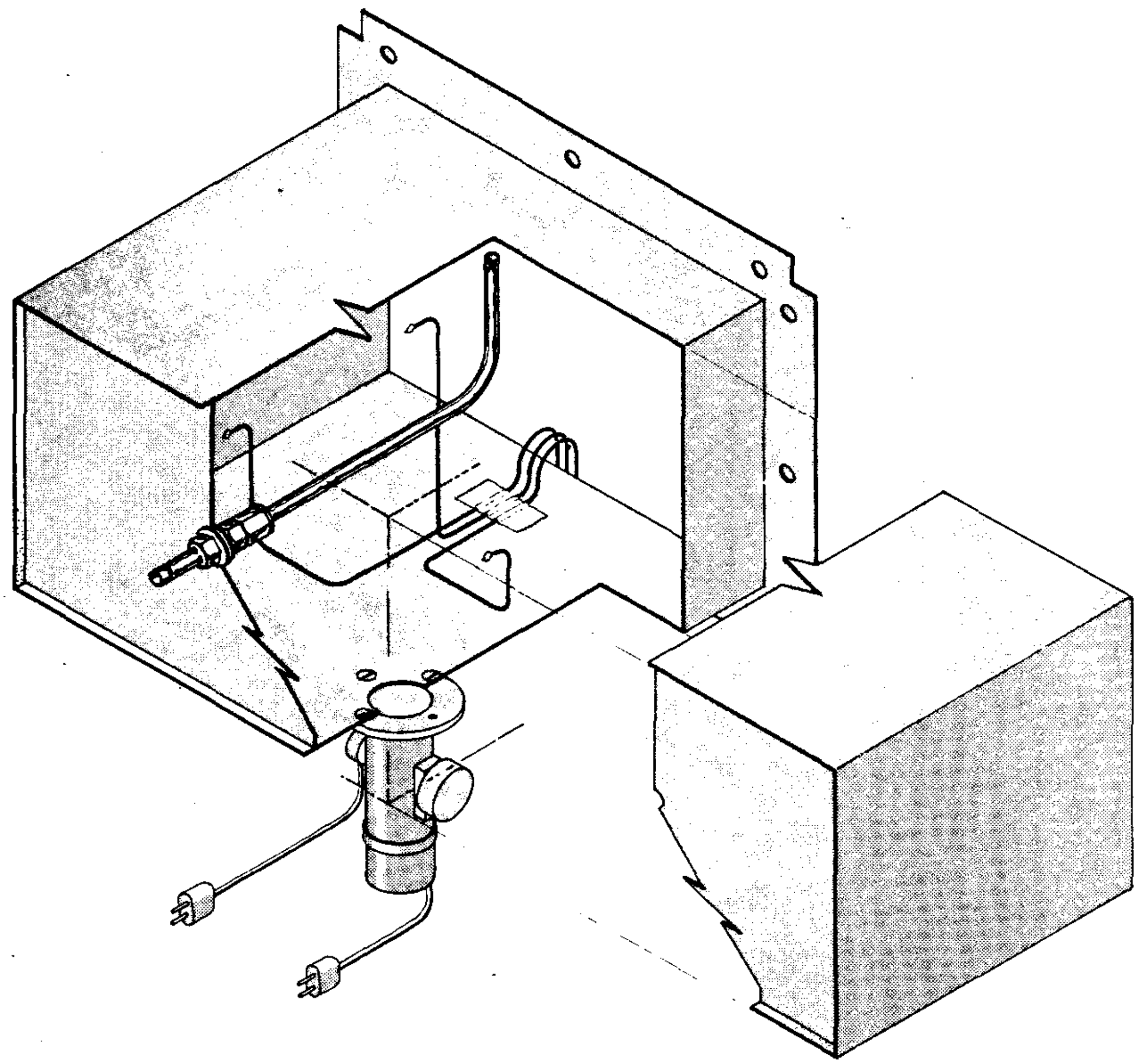


FIGURE 54 (a) GENERAL VIEW OF EXPERIMENTAL PLENUM

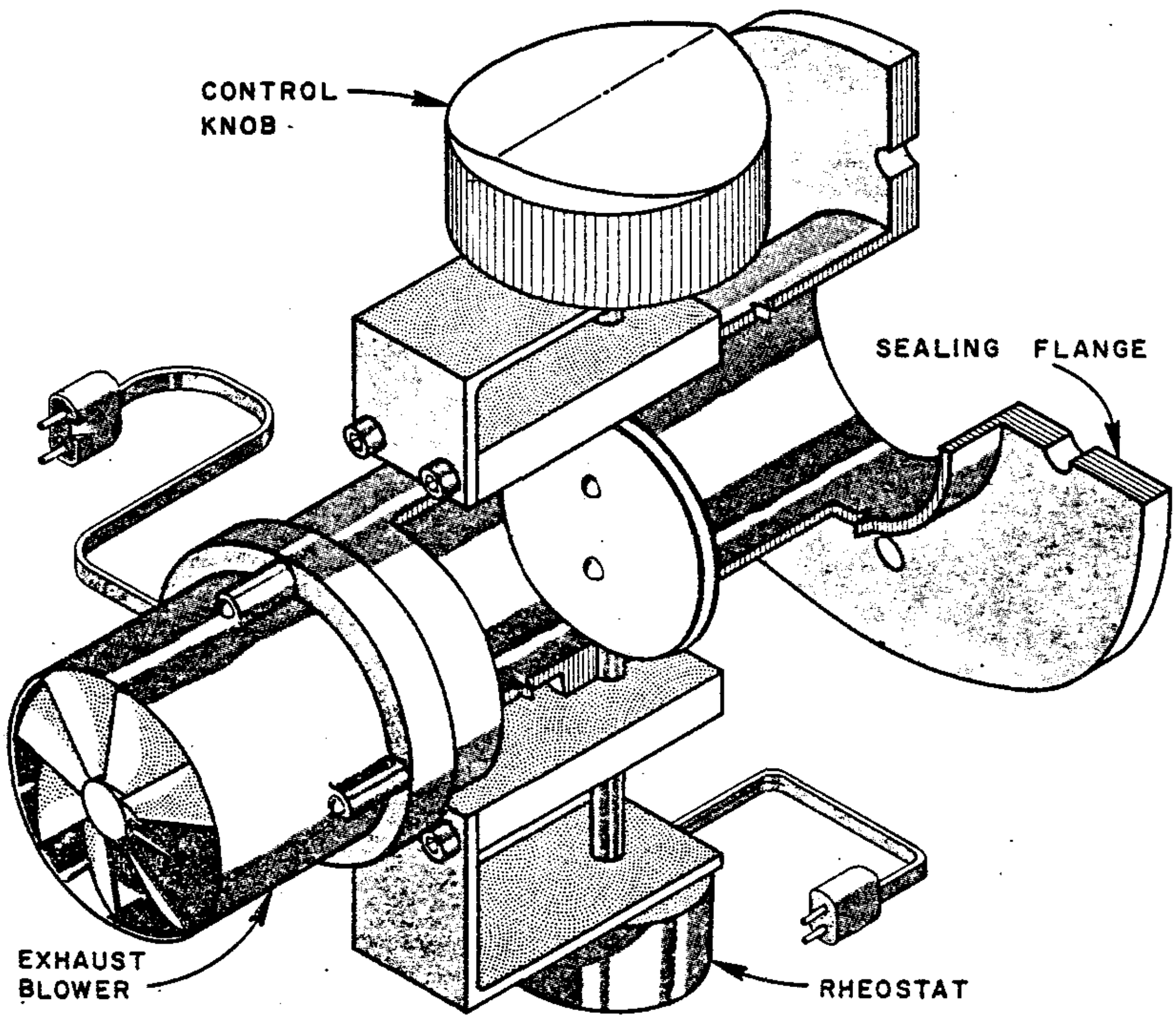


FIGURE 54 (b) DETAIL OF PLENUM BLOWER

the mass flow is a plenum collector. Since the exact location or extent of a crack may not be known a priori, a way of collecting gases has to be used which will include all the cracks that can potentially open up. To obtain reliable numerical results a closed collector is needed where accurate mass accounting can be done. An additional requirement is that the pressure in the collector box can be varied and be negative with respect to ambient. Most existing wall furnaces are limited in the amount of positive pressure they can produce. If the collector plenum were positive with respect to ambient, then the pressure difference between the furnace and the plenum would not be great enough to adequately model the room fire.

The drawing of the plenum used is shown in Figure 54a. It is constructed of 20-gage galvanized sheet steel. The flanges provide an air-tight seal against the test wall. Either high-temperature silicone sealant is applied under the flange, or an asbestos cloth strip is slurried over the flange, or, preferably, both. The plenum pressure is measured with a tube connected to the same pressure scanning system that measures the furnace pressure.

The exhaust arrangement consists of a butterfly valve and a small blower. The blower is a Rotron Aximax 368 YS, nominally rated for 26 ℓ/sec at 115 volts and 400 hz. The output of the blower can be regulated by varying the frequency of the power supply. A drawing of the butterfly valve is given in Figure 54b.

Plenum Calibration

To obtain a calibration of the plenum blower assembly, a plenum is attached securely to an air-tight wall. A fitting is provided to accept an air hose for the intake air supply. Compressed air from a

0.7 MPa building supply is fed to a high-volume pressure regulator, then to a rotameter and finally into the plenum. The same transducer system as used for the furnace tests is used to measure the pressure difference between the inside of the plenum and the ambient atmosphere. In the present test series the differential was set at 12.5 Pa (0.05 in H_2O). The exhaust valve is provided with a position indicating transducer and the flows calibrated against rotameter readings.

Flow Test

A calibration wall of 6 inch solid grouted lightweight masonry block was constructed to conduct flow tests. A circular aperture of known size--1.90 cm diameter--was drilled. The pressure P_{fa} was varied in the range of 17 to 27 Pa and the value of C_d, which is the only unknown when a known aperture is used, was solved for. The results indicate that $C_d = 0.8$ for the wall tested.

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