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Methodology for Developing and Implementing Alternative Temperature-Time Curves for Testing the Fire Resistance of Barriers for Nuclear Power Plant Applications

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CONTENTS

EXECUTIVE SUMMARY

BACKGROUND

As part of its regulatory responsibilities, the U.S. Nuclear Regulatory Commission (NRC) requires certain provisions for fire protection in U.S. nuclear power plants (NPPs). One aspect of NPP fire safety has to do with the performance of fire barriers designed explicitly to protect components, equipment, etc. on the protected side of the barrier, from potential threatening fire environments on the fire-exposed side. These fire barriers, which are in the form of walls, floor/ceilings, partitions, cladding, or wrapping, are designed to prevent the passage of fire, or excessive heat from a fire, for the time period necessary to shutdown critical equipment safely, or to control the fire prior to its threatening structural elements or areas critical to general plant safety. This property of a barrier to withstand fire or give protection against it is known as ***fire resistance*** and the elapsed time during which a barrier exposed to fire continues to exhibit fire resistance is known as ***fire endurance*** [ES-1].[1] Despite the distinction, the two terms often are used interchangeably.

In the United States, ASTM E 119, "Standard Test Methods for Fire Tests of Building Construction Materials" [ES-2], or one of its counterparts for doors [ES-3], windows [ES-4], or through-penetration fire stops [ES-5], is the generally accepted standard method for evaluating and rating the fire resistance of building fire barriers. The method involves furnace-fire exposure of a portion of a full-scale fire-barrier specimen. The furnace-fire environment follows a particular, monotonically-increasing, temperature-time history, which is defined in the test-method document. This temperature-time history (or curve) of the *standard* ASTM E 119 fire is considered to represent a "severe" fire exposure. The test method specifies explicit acceptance criteria[2] that involve the measured response of the barrier test specimen at the time into the standard fire exposure that corresponds to the desired barrier rating. For example, a barrier design is said to have a 3-hour ***fire-resistance rating*** if the tested specimen meets all specified acceptance criteria during at least three hours of a standard fire exposure. The fire-resistance rating, in turn, *qualifies* the barrier design for certain uses. Here the term ***qualifies*** is intended to mean that the barrier design meets or exceeds the fire-resistance requirements of a building code or other regulation.

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[1] Numbers in brackets with designation [ES-#] refer to literature references listed at the end of this Executive Summary.

[2] These criteria include non-failure of structural components in the test assembly, passage of neither flame nor very high temperature gas to the unexposed side of the barrier, and limits on the temperature rise on the unexposed-surface of the test assembly above its initial temperature.

In 1976, NRC adopted the ASTM E 119 methodology to regulate fire barriers protecting redundant-train safe-shutdown systems in NPPs [ES-6]. NRC set the required ASTM E 119 fire-endurance rating at 3-hours, consistent with requirements for U.S. industrial properties classified by insurance carriers as "Improved Risk" or "Highly Protected Risk" properties [ES-6]. The safe-shutdown regulations supplemented existing, ASTM E 119-based, general regulations for fire barriers in areas critical to general plant safety [ES-7].

Advances in fire science over the past 40 years have offered the potential for developing technically-sound alternative temperature-time curves for use in evaluating fire barriers for areas where fire exposures can be expected to be significantly different than the standard temperature-time exposure. For example, during the 1970s and 1980s, several countries, including the United States, developed and implemented technically-sound alternative curves for testing fire barriers that might be subjected to open-air hydrocarbon pool fires (see Part 2, section 2.4). The NRC staff has initiated the current effort to investigate the feasibility of developing alternative temperature-time curves for the qualification of fire barriers used to protect cabling and equipment necessary to achieve safe shutdown on the basis of realistic fire hazards found in NPPs.

OBJECTIVE

The aim of the current study is to propose a methodology for developing and implementing NPP-specific descriptions of fire environments and associated ASTM-*type* furnace test methods. Here the terminology ***ASTM E 119-type*** test is used to refer to a test method that basically follows the ASTM E 119 test procedures, but where the ASTM E 119 standard temperature-time curve is replaced with a relevant, NPP-specific, alternative curve.

APPROACH

The approach taken in the current study consists of three steps or tasks: 1) review the history of the ASTM E 119 temperature-time curve to assess its current applicability and limitations in simulating real fires; 2) review the history of efforts to develop alternative curves and the methodologies used; and 3) use the findings from (1) and (2), knowledge of NPP construction, fuel types and loads, and state-of-the-art fire science to propose a methodology for developing and implementing NPP-specific descriptions of fire environments and associated ASTM-*type* temperature-time curves and test methods.

RESULTS AND CONCLUSIONS

Part 1. History of Standard Temperature-Time Curve

1. The historical evidence indicates that the ASTM E 119, standard, temperature-time curve was prescribed in 1917 with very little knowledge of the levels and the temporal development of temperatures in actual room fires. The standard curve was basically an idealization of temperature-time curves measured in furnaces at various laboratories, was deemed to represent a severe fire, and was intended only to provide a basis for comparing the fire endurance of building assemblies using a simple test. Full-scale room burnout tests conducted at the National Bureau of Standards in the 1920s established that the actual temperature histories of room fires differed significantly from the standard curve.

2. Using fire-endurance ratings, which were based on the standard curve, and the *equal-area fire-severity hypothesis*[3], Simon Ingberg at the National Bureau of Standards correlated the fire load in a room with the fire endurance necessary to withstand complete burnout of the room. The result was a relatively simple, albeit somewhat technically-weak, system of analysis for determining the fire-endurance required for building elements. Technical shortcomings of the analysis include: no technical basis for the equal-area hypothesis; real room fire intensities are not a sole function of fire load; and temperatures of real fires can rise faster than the standard curve. In spite of these shortcomings, the fuel-load/equal-area/standard-curve method was widely accepted and, indeed, remains a landmark development in the history of fire protection engineering. It simply was better than anything else available. Subsequent work, reported in Part 2 of this document, showed that temperatures of real fires often exceeded the standard curve. Today, the National Fire Protection Association acknowledges that although the fire-load method is technically obsolete, it is still useful in situations that do not involve high heat-release rate combustibles and in which fire conditions do not produce temperatures significantly higher or lower than the standard temperature-time curve [ES-8].

3. Fire-endurance testing in the United States has not changed substantially since the publication of the standard temperature-time curve in 1918. Continued use of the fire-load/standard-curve methodology has been justified on the bases that the analysis: is judged to be conservative (more severe) with respect to the maximum fire exposure in many occupancies; has a proven record with respect to safety; is tied to a standard test; and is relatively simple to use. Arguments against changing the standard curve include: that a large amount of experience has been gained with the existing standard temperature-time curve; re-radiation from the exposed surface makes the exact temporal details of the curve unimportant; and no other curve will eliminate all the objections.

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[3] The ***equal-area fire-severity hypothesis*** is that the area beneath a temperature-time exposure curve is a measure of the intensity or severity of a fire, and all fires with equal-area exposures are equally severe.

4. Critics argue that real fires often rise faster and/or exceed the standard curve. Although the repercussions of the inaccuracies of the standard fire-load analysis were not so great in the era of relatively massive fire barriers (1920s and 30s), the consequences could be much greater now that lighter-weight barriers must withstand fires fueled by modern synthetic materials. Moreover, improved analytical techniques are available that can avoid at least some of the objectionable assumptions inherent in the standard fire-load analysis.

Part 2. History of Alternative Curves

1. The known shortcomings of the standard fire-load analysis/standard temperature-time curve and the availability of new analytical tools provided the impetus in the 1950s and 60s to seek alternatives to the standard analysis/curve.

2. Hydrocarbon Processing Industry (HPI) temperature-time curves (e.g., [ES-9]) appear to be the only alternative curves widely used for fire-resistance testing. The HPI (or, for short, hydrocarbon) curves simulate the direct-impingement exposure from a open-air hydrocarbon pool fire and are a more severe exposure than the standard curve.

3. The NBS recreation-room study in the 1970s produced an alternative curve for testing the fire resistance of residential floor constructions in a furnace. NBS recommended that the new curve be used in a new ASTM fire-resistance test for rating residential floor constructions which require fire-resistance ratings of less than one hour. This recommendation, however, was rejected on the basis that the sixteen full-scale room-burnout experiments were too limited in scope. Although achieving consensus in the highly diversified ASTM fire-protection community may be more difficult than in the smaller, more focused, NPP industry, this NBS experience at least cautions that changes might not be accepted by the NPP industry without substantial experimental underpinnings.

4. No record has been found to indicate that fire-resistance testing has been conducted to qualify a building element or assembly using any curve other than the standard temperature-time curve or a hydrocarbon curve. In the course of the present review, the only record of fire-resistance testing of building elements or systems in a furnace using an alternative curve was that found in the NBS recreation-room study, which was a research, rather than a qualification program.

5. The literature suggests that the development of any new temperature-time curves for compartment applications likely will rely heavily on mathematical modeling (the tool that became available in the 1950s) because of the large number of configurations that need to be considered. Indeed, temperature-time curves generated by mathematical room-fire models are sanctioned by Swedish regulations for design calculations as alternatives to the more traditional classification of building components; namely, by furnace-testing building components against the ISO 834 [ES-10] standard temperature-time curve, which is very similar to the ASTM E 119 standard curve.

6. To date, a major weakness of room-fire models lies in their inability to simulate accurately burning rates of real fuels under real-fire conditions. For example, much of the modeling work aimed at creating alternative temperature-time exposures has been based on the burning characteristics of cellulosic fuels. Also, such models only simulate the simplest type of room ventilation -- an opening to the outside environment. It seems that the development of credible temperature-time curves for nuclear power plant (NPP) applications will require better understanding of the burning behavior of NPP-specific fuel packages -- for example, cable bundles -- and more advanced ventilation considerations.

Part 3. Feasibility of Developing and Implementing NPP-specific Descriptions of Fire Environments for Use in Evaluating the Fire Resistance of Fire Barriers.

1. NPP fire barriers include ***structural*** barriers, useful in isolating a compartment of fire origin from adjacent spaces, and ***wrap assemblies***, used to isolate and protect plant equipment, cables, etc., within a compartment of fire origin, from the effects of exposure to the fire environment.

2. The nature of fire-barrier exposure to an NPP-compartment fire environment can be categorized as a) ***direct exposure*** to the most extreme zones of the fire environment, e.g., direct, sustained exposure of the barrier to the flame, and b) ***indirect exposure***, where the fire barrier is mainly exposed to the average properties of the overall fire environment. Both kinds of threats need to be addressed. ASTM E 119-*type* test methods, employing new, alternative, temperature-time curves, are appropriate for the indirect threats. Other tests may need to be devised to simulate direct exposure threats. Here. the hydrocarbon exposure curve may play a role. Compartment-fire model simulations should be useful in defining quantitatively both the indirect and direct test exposures.

3. A methodology for evaluating the fire resistance of NPP fire barriers is presented that removes weaknesses of and/or introduces flexibility to the traditional ASTM E 119 approach. This relies on a combined experimental and analytic approach that involves the Bounding-Temperature Principle. (i.e., if the temperature-time curve of one fire environment bounds that of another, then, relative to the threat to structural integrity of a NPP fire barrier, the bounding-curve environment is the more severe.) Fire-resistance experiments would involve ASTM E 119-*type* tests employing alternative temperature-time furnace fires deduced from reliable fire-model simulations. Analysis would involve compartment fire modeling methods, where computer simulations would be carried out with a new, advanced, special-purpose, zone-type fire model.

Specifically:

a. The new compartment-fire model must include features particularly relevant to simulating fire environments that threaten NPP fire barriers, from the point of view of <u>both</u> direct and indirect fire exposure. These included: the simulation of ***fully-developed burning*** of extensive dense arrays of cable trays (i.e., all exposed surfaces of a combustible cable are supplying fuel (losing mass) due to either heating by the fire environment or surface combustion), both under fuel-controlled and ventilation-controlled conditions; the simulation of combustible/flammable liquid pool fires; and advanced means of modeling ventilation and radiation-heat-transfer-related phenomena. A new special-purpose model with these features could be developed as a customized advanced version of an existing, two-layer, multi-room, zone-type fire model, e.g., CFAST [ES-11].

b. The new model would be used to simulate a wide variety of potential fire scenarios in rooms of fire origin of selected NPPs. The simulations would lead to new insights on the characteristics of real, fire-barrier-threatening, NPP fire environments. Based on applications of the Bounding-Temperature Principle, the simulated fire scenarios would lead to a series of NPP-specific test fire curves covering a wide range of NPP-type fire severities.

c. An experimental study on available ASTM E 119-*type* test furnaces would be carried out to establish that these new test fire curves (instead of the standard ASTM E 119 fire curve) were achievable for use in ASTM E 119-*type* barrier rating tests. Then ASTM E 119-*type* tests, using the new NPP-specific test fire curves, would be established as the method of evaluating the fire performance of NPP fire barriers.

4. A significant effort will be required to carry out this plan. Due to knowledge gaps in critical areas such as burning rate and ventilation effects in NPP-specific environments, the modeling work will require a substantial experimental component. Indeed, the experimental aspects, including full-scale burnout of fuel packages and furnace fire-resistance tests, are similar in scope to the NBS recreation-room study (see Part 2, section 2.3.3), which was a multi-year effort.

RECOMMENDATIONS

Consistent with the above, it is recommended that the following tasks be carried out with the goal of establishing a reliable methodology for evaluating NPP fire barrier performance:

1. Develop a new, special-purpose, NPP-specific fully-developed fire model capable of simulating fire environments that threaten NPP fire barriers. It is recommended that this be developed as an advanced version of an existing multi-room compartment fire model, e.g., CFAST [ES-11]. The new model should include the advanced modeling features identified in the section 3.7.3, "**Features of a Compartment Fire Model Suitable For Evaluating Direct and Indirect Threats to NPP Fire Barriers**." These include: the simulation of fully-developed burning of extensive dense arrays of cable trays, both under fuel-controlled and ventilation- controlled conditions; the simulation of combustible/flammable liquid pool fires; the simulation of the fire environment in multi-room facilities (at least two adjacent spaces); and advanced means of modeling ventilation and radiation-heat-transfer-related phenomena

2. Carry out full-scale experimental verification of the advanced modeling methods of item 1,

especially those aspects of the new model associated with the simulation of burning cable trays and combustible/flammable fuel fires in enclosed spaces. Also, carry out experiments to better evaluate and characterize the fire hazard in NPPs introduced by electrical panels/cabinets.

3. Use new model simulations to determine the direct-exposure threat to fire barriers, and use these to establish experimental methods to evaluate barrier fire performance relative to the *direct* exposure threat.

4. Use the new model to carry out an extensive simulation study of selected NPP fire areas. Results of this would be used to establish the characteristics of real, fire-barrier-threatening, NPP fire environments and to identify a series of NPP-specific test fire curves to replace the ASTM E 119 standard fire curve.

5. Carry out an experimental study on available ASTM E 119-*type* test furnaces to establish that the new test fire curves of item 4 are attainable and reproducible.

6. Use the results of items 4 and 5 to establish an ASTM E 119-*type* method of evaluating the performance of structural fire barriers relative to the *indirect* exposure; establish corresponding methods for *wrap-assembly* fire barriers.

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PART 1. HISTORY AND USE OF THE ASTM STANDARD TEMPERATURE-TIME CURVE

LIST OF FIGURES - PART 1

SUMMARY - PART 1

The standard temperature-time curve defines the furnace-fire exposure for rating the fire resistance of fire barriers by ASTM E 119, Standard Test Methods for Fire Tests of Building Construction Materials [1-1].[4] The historical evidence indicates that the standard curve was prescribed in 1917 with very little knowledge of the levels and temporal development of temperatures in actual room fires. Indeed, it appears that the curve was deemed to represent a severe fire and was intended only to provide a basis for comparing the fire resistance (endurance) of building assemblies.

Full-scale room burnout tests in the 1920s established that the actual temperature histories of room fires were different from the standard curve. The standard curve, however, was "rescued" by the concept of ***fire severity***, which was considered a measure of the intensity of the fire exposure, and was defined as the area beneath the exposure temperature-time curve. The hypothesis is that all fires with equal-area exposures are equally severe. Severity, therefore, provided the connection between a real fire exposure and the standard temperature-time exposure used to evaluate the fire endurance of building assemblies. In addition, the intensity or severity of a real room fire was assumed to be a function of the fire (fuel) load alone. The result was a relatively simple system of analysis for determining the fire endurance required to withstand a complete burnout of a room containing a given fire load.

Technical shortcomings of this system of analysis include: no scientific basis exists for the equal-area hypothesis; real room fire intensities are not a sole function of fire load; and temperatures of real fires can rise faster than the standard curve. In spite of these shortcomings, the fuel-load/equal-area/standard-curve method was widely accepted and, indeed, remains a landmark development in the history of fire protection engineering. Later work, which is reported in Part 2 of this document, demonstrated that temperatures of real fires often exceeded the standard curve. Today, the National Fire Protection Association acknowledges that although the fire-load method is technically obsolete, it is still useful in situations that do not involve high heat-release rate combustibles and in which fire conditions do not produce temperatures significantly higher or lower than the standard temperature-time curve [1-2].

Continued use of the fire-load/standard-curve methodology has been justified on the bases that the analysis: is judged to be conservative (more severe) with respect to the maximum fire exposure in many occupancies; has a proven record with respect to safety; is connected to a standard test; and is relatively simple to use. Arguments against changing the standard curve include: a large amount of experience has been gained with the existing standard temperature-time curve; re-radiation from the exposed surface makes the exact temporal details of the curve unimportant; and no other curve will eliminate all the objections.

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[4] Numbers in brackets with designation [1-#] refer to literature references listed at the end of Part 1 of this document.

Critics argue that real fires often rise faster and/or exceed the standard temperature-time curve. Although the consequences of the inaccuracies of the standard fire-load/standard-curve analysis apparently were not so great in the era of its inception, when fire barriers were relatively massive and failed at high temperatures, the consequences could be much greater now that lighter-weight barriers must withstand fires fueled by modern materials. Moreover, for the past three decades, improved analytical techniques have been available that can avoid at least some of the objectionable assumptions inherent in the standard fire-load analysis.

The fact remains that fire-resistance testing in the United States has not changed substantially since the adoption of the standard temperature-time curve in 1918.

1.1 OBJECTIVE

The purpose of Part 1 of this document is to review the literature concerning the origin, justification, and use of the ASTM E 119 standard temperature-time curve [1-1] for determining fire resistance according to American Society for Testing and Materials (ASTM) procedures[5]. The scope is limited to the fire-temperature specifications. The merits of a heat flux-time exposure specifications relative to a temperature-time exposure [1-9,1-10,1-11] are not addressed in this review.

1.2 OVERVIEW OF THE ASTM E 119 TEST METHOD

In the U.S., ASTM E 119 is the generally accepted standard method for evaluating and rating the fire resistance of structural-type building fire barriers. The method involves furnace-fire exposure of a portion of a full-scale fire barrier specimen. The furnace-fire environment follows a monotonically-increasing, temperature-time history, which is specified in the test method document. The latter defines the temperature-time history of the *standard* ASTM E 119 fire. The test method specifies explicit acceptance criteria that involve the measured response of the barrier test specimen at the time into the standard fire exposure, referred to as the ***fire resistance*** of the barrier design, that corresponds to the desired barrier rating. For example, a barrier design is said to have a three-hour ***fire-resistance rating*** if the tested specimen meets specified acceptance criteria during at least three hours of a standard fire exposure. The fire-resistance rating, in turn, *qualifies* the barrier design for certain uses. Here the term ***qualifies*** is intended to mean that the barrier design meets or exceeds the fire-resistance requirements of a building code or other regulation.

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[5] The standard curve is employed in ASTM E 119 [1-1], ASTM E 152 [1-3], ASTM E 163 [1-4], and ASTM E 814 [1-5]. The standard curve is also used in National Fire Protection Association (NFPA) standards [1-6 to 1-8], which are nearly identical to first three of these ASTM standards.

1.3 HISTORY OF ASTM E 119 STANDARD TEMPERATURE-TIME CURVE

Several accounts of the history of the ASTM E 119 fire resistance (endurance) test have been published; for example [1-1,1-9,1-10,1-12,1-13,1-14,1-15,1-16]. Of these, the works by Shoub [1-13] and Babrauskas and Williamson [1-15,1-16] are the most complete. Unless noted otherwise, the following section presents a summary of the Babrauskas and Williamson account of the development of the standard temperature-time curve.

Prior to 1903, there were no widely accepted standards specifying the conditions for testing building materials and construction systems for fire endurance. A review of the history of fire testing before 1903 (see APPENDIX - PART 1) shows that each laboratory specified its own test conditions, including the temperatures to which the test materials and assemblies were exposed. In most cases, the furnace temperature, averaged over the test period, had to equal or exceed some specified level.

In 1903, the British Fire Prevention Committee (BFPC) proposed the first widely sanctioned standard test procedure. The standard defined three fire-endurance classifications: Full, Partial, and Temporary protection from the burnout of a room's contents. A minimum exposure temperature and minimum test duration were assigned to each class. For example, the "Full" rating, associated with the most severe of the three classifications, required that the material or assembly not fail when exposed to a minimum temperature of 982 °C for 4 hours. The "Temporary" rating, for the least severe classification, required that the assembly not fail when exposed to an 816 °C environment for 45 minutes.

In 1899, the New York Building Code defined the first standard for fire-endurance testing in the United States. This was not intended to be a national standard. Nevertheless, with the Baltimore conflagration of 1904 as an impetus, a national standard [1-17], very similar to the New York standard, was instituted by the American Society for Testing and Materials (ASTM), committee C-5 (later E-5) in 1907. Like the New York standard, the ASTM standard required that floor assemblies be exposed to a fire in a furnace "hut" for 4 hours at an average temperature of no less than 926 °C. Ira Woolson, a pioneer fire researcher who built the first permanent U.S. facilities for testing fire resistance at Columbia University, was chairman of this ASTM committee.

In 1909, a separate test for walls was included and furnace control was specified further. The furnace was to be heated to 926 °C within the first 30 minutes and then held at that level for the remaining 1.5 hours of the test.

During this period, the BFPC standard of 1903 was gaining international recognition. Acknowledging this, a National Fire Protection Association (NFPA) committee on standards, chaired by Ira Woolson (no longer at Columbia University) recommended in 1914 that further development of the U.S. standard be stopped and that NFPA adopt the BFPC standard with some modifications. NFPA did not accept this recommendation.

Instead, eleven organizations met to discuss U.S. fire test methods. In 1916, the first of these meetings produced a recommendation for a standard temperature-time curve for the testing of columns at Underwriters Laboratory in Chicago [1-18]. The motivation for the curve was the realization that furnace transients needed to be quantified to achieve reproducible results. The proposed curve was basically an idealization of temperature-time curves measured in furnaces at various laboratories.

Babrauskas and Williamson report that the curve published in 1916 has not been changed since then. This apparently is not entirely correct. Figure 1-1, which compares the 1916 curve with the current curve presented in ASTM E 119-88, shows some difference during the initial steep transient period. Babrauskas and Williamson report that in the course of establishing the standard curve, the committee increased the heating rate during the first 10 minutes in order to address concerns that fires might rise faster in some occupancies. It appears that these adjustments were made subsequent to publication of the 1916 document, but prior to the issuance of ASTM C19 (later to become E 119) on February 24, 1917[6]. The standard curve has not been changed since then.

Since the chosen curve was closest to the New York/Columbia curves obtained after 1902, when the average temperature criterion was dropped from 1093 °C to 926 °C[7], the standard curve was known as the "Columbia Curve" in honor of Ira Woolson.

1.4 RELEVANCE OF THE STANDARD TEMPERATURE-TIME CURVE

Ryan [1-14], citing a Southwest Research Institute (SWRI) internal report [1-19], says that, Professor Woolson at Columbia University established a temperature-time curve at the turn of the century for severe fires based on data he obtained from visiting fire scenes, talking with the fire service, and comparing fire debris with known melting points. Since the SWRI report was not available for review[8], the origin of the statement could not be traced. Shoub makes a similar statement that the 1917 E 119 curve

> "... ***apparently***, *was based on temperatures found in the various stages of growth of actual*

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[6] Semantics has confused somewhat the date of ASTM C19. Babrauskas and Williamson [1-16] report that ASTM C19 (later renumbered E119) was **issued** on February 24, 1917 but later refer to the "1918 standard". Ryan [1-14] and Shorter [1-9] report that ASTM E 119 was **adopted** in 1918. The current ASTM E 119-88 standard [1-1] states that C19 was first published in 1918 as C19-1917T, which, in current ASTM notation, would indicate that the standard was **approved** in 1917 and **first published** in 1918.

[7] Indeed, the average temperature over the first 4 hours of the standard curve is 945 °C, which is close to the New York requirement of an average of 926 °C over the same period.

[8] The report could not be located at SWRI.

> *fires in buildings using references such as the observed time of fusion of materials of known melting points."* [1-13] (emphasis added)

No reference is given. In his 1928 report on room-fire experiments, Ingberg makes the related statement

> *"Indications of the intensity of building fires have been obtained from fused metals and from general fire effects on materials on which information is extant as to their reaction to temperature or fire exposure such as in test fires.* ***The fire ruins or reports of fires give, however, little information on the duration of the temperatures in any given portion of the building.*** *The absence of data to enable constructions or devices giving a certain performance in the standard test to be applied as protection against fire conditions in buildings with as much precision as results of strength tests are applied for load carrying purposes, led me to consider the possibility of conducting burning-out tests in suitably designed structures to obtain the needed information."* [1-20] (emphasis added)

Although the last statement neither confirms nor denies a direct link between room-fire temperatures inferred from fire debris and the standard curve, it does point out that little information on the temporal development of a real fire can be gleaned from such data.

Regarding a systematic experimental basis, Ryan states that *"The present curve at its inception was not based on full scale test data."* [1-14]

On this subject, Babrauskas and Williamson report that in 1903 Woolson was conducting tests at 926 °C because, in Woolson's words, *"This particular temperature was chosen because it is given by the New York Building Code as approximately the heat of a burning building."* They add that *"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*[9] *ran his fire tests at that temperature."* [1-16]

The systematic measurement of temperatures during room burnout experiments was not initiated in the U.S. until 1923 [1-16], 6 years after the standard temperature-time curve was prescribed. Although burnout experiments had been conducted in Europe prior to 1917, Babrauskas and Williamson report [1-16] that ASTM committee C-5 was unaware of them. They conclude that *"... the standard curve was prescribed in 1917 without the knowledge of what actual temperatures in buildings might be."* [1-16]

Nevertheless, the standard curve was (and still is) considered to represent a fairly severe fire [1-12,1-21]. At the time of its adoption, the curve was intended only to provide a basis for comparing the fire endurance of building assemblies using a simple fire test [1-14]. Techniques for more sophisticated analyses were not available.

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[9] Superintendent of Buildings in New York, circa 1896.

1.5 APPLICATION OF THE STANDARD TEMPERATURE-TIME CURVE

In 1923, burnout tests were commenced by Simon Ingberg at the U.S. National Bureau of Standards (NBS). Ingberg was interested in the relationship between the extant standard temperature-time curve and the duration of temperatures in a room subjected to the burnout of its contents. Office occupancies were simulated using papers and wooden and steel furniture, which were fairly uniformly dispersed throughout the lower portion of the room. The independent variable of the tests was ***fire load***, which is defined as the average fuel mass per unit floor area of the space. The findings were published in 1928 [1-20].

Figure 1-2 shows spatially-average temperature results for one of the occupancy tests. Also shown is the standard curve that is followed during a furnace test. Attached to the standard curve are post-shutdown cooling curves obtained from furnace tests at NBS. The substantial differences between the experimental and standard-plus-cooling curves led Ingberg to formulate his ***equal-area fire-severity hypothesis***;

> *"An approximate comparative measure of severity is obtained by assuming that the area under the latter curve*[10] *[i.e., the occupancy test], expressed in degree-hours, gives severity equivalent to an equal area under the standard exposure curve and the cooling curve applicable for the given period."* [1-20]

"Severity" became the connection between actual fire intensities and fire test exposures based on the standard temperature-time curve. Severity "validated" the standard curve.

The fire-severity concept allowed Ingberg to translate the full-scale test results into equivalent fire endurances (determined by furnace tests) required by the walls, etc., to withstand complete burnout of the spaces. Analysis of the experiments in this fashion led to Ingberg's 1928 correlation between fire load and fire endurance [1-20], which is displayed as the solid curve in Fig. 1-3.[11] It was also concluded from these experiments that the standard curve represented the maximum severity of a fire resulting from the burnout of a brick wood-joisted building and its contents [1-21]. At least one room-fire experiment, however, produced a faster initial temperature rise than the standard curve [1-20].

The simplicity of the fire-load method, its link to a standard fire test, and Ingberg's publication of detailed fire-load data for a wide range of occupancies [1-22,1-23] led to near-universal acceptance by building code authorities [1-9,1-14].

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[10] The area was computed with respect to a baseline of either 150 °C or 300 °C depending upon the combustibles present.

[11] In this figure, fire load is expressed as combustible content (potential heat), which is the sum of the products of the mass of each fuel and its heat of combustion, divided by the floor area.

Since the fire load method of analysis represents a landmark development in the history of fire protection engineering, it is important to summarize the conditions/assumptions on which it is based, as well as the reasoning behind the assumptions.

- Equal-area assumption: Although Ingberg was aware of technical problems with this hypothesis (see below), he justified its use by the lack of an alternative simple method.

- Limited experimental basis: Ingberg's experiments involved only wood and paper fuels spread out fairly uniformly over the lower region of the room. He was aware that other occupancies can have different fuels with different calorific content and possibly different burning rates [1-20]. Nevertheless, he concluded that a lot of materials have calorific contents in the range of wood and paper [1-22]. For example, he assigned wood, paper, cotton, wool, silk, straw, grain, sugar, and similar organic compounds their actual weights. Materials with higher calorific contents were assigned larger wood-equivalent weights. For example, he assigned animal and vegetable oils, fats, waxes, petroleum products, asphalt, bitumen, paraffin, pitch, alcohol, and napththelene twice their actual weights.

- Assumption that fire intensity is solely a function of fire load: The intent of the fire load concept was to provide a simple basis for comparisons that was better than anything available at the time. No attempt was made to account for other factors, such as ventilation and the nature and disbursement of the combustibles, all known to influence the behavior of the fire [1-10,1-14].

Despite these technical shortcomings, the validity of the method was not questioned until the 1960s [1-9] when improved analytical techniques were developed. Also, the advent of lighter-weight building assemblies raised concern. Because the heavy, non-melting[12], fire-resistant materials available in Ingberg's time usually had to reach high temperatures to fail, the consequences of the inaccuracies of the method were less important in that era [1-24]. Also, there is the issue of the effect that rapid temperature rise and attendant thermal shock might have on the integrity of lighter barriers. (See section 2.4 and footnote in section 3.9.2).

Nevertheless, the fire load method is still in use today. The current fire load/endurance relationship is shown in Fig. 1-3 as a dashed curve. After first acknowledging that the method is *"technically obsolete"*, the 1991 NFPA Fire Protection Handbook [1-2] states that the method still is useful in many situations because

> *"In many cases, this original fire severity/fire load relationship was more severe than is indicated by more accurate analysis."* [1-2]

and

> *"Although the technique has its limitations, the fire severity/fire load relationship still*

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[12] Here and in section 1.6.1, Babrauskas uses the term "melting" to indicate a phase change in the barrier material.

> *provides an approximate but conservative estimate of the probable maximum fire severity in residential, institutional, and some commercial occupancies.* ***Fire loads should not be used as an approximate indicator of fire severity with combustibles having a high heat-release rate and when fire conditions can produce temperatures significantly higher or lower than the standard temperature-time curve."*** [1-2] (emphasis added)

1.6 CONCERNS ABOUT STANDARD TEMPERATURE-TIME CURVE/FIRE LOAD METHODOLOGY

1.6.1. Equal-Area Hypothesis

Ingberg was aware of the approximate nature of the hypothesis when he wrote

> *"...that equal area under temperature-time fire exposure curves stand for equivalent severity of exposure is an approximation only, since in the heat conductivity equation applicable for the case the exposing temperature enters directly as a factor in the expression for temperature obtaining at any point within an exposed body, while the time, which is the other factor in the time-temperature area, enters as an exponent."* [1-20]

Babrauskas raises four physical objections to the equal-area hypothesis:

> *"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.*[13] *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*
>
> $$dm/dt = A\ \exp(-E/RT)$$
>
> *This relationship is patently not linearly dependent on the gas temperature.*
>
> *3) The main mechanism of heat transfer to the wall, at temperatures above 500 °C is radiation. The radiant flux is proportional to T^4 not T^1.*
>
> *4) Finally, some building materials 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*

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[13] Although this is certainly a theoretical possibility, no information was found during the present review that indicates the extent to which it might be a real problem. To be a practical problem, it seems the critical temperature, T_c, would have to be fairly high, so that it might be reached in one fire but not another.

> *function of temperature."* [1-24]

The hypothesis simply cannot be defended on scientific grounds.

1.6.2. Factors Other Than Fire Load

It has been known for a long time that fire load is not the only important factor that determines the intensity of a fire in a room. Commenting on the accounts of Ingberg's experiments [1-20], Robertson and Gross found clear evidence that ventilation and the nature and disbursement of the room contents *"... had an important influence in modifying fire behavior..."* [1-10]

Lie reports in a 1968 document that factors affecting room-fire temperatures include

> *"1. the average amount of combustible material present per unit floor area (so-called fire load)*
> *2. the form in which the combustible material is present*
> *3. the size of the ventilation openings*
> *4. the dimensions of the interior space*
> *5. the insulating capacity of the walls."* [1-25]

Ödeen identifies a similar list of factors in his statement

> *"When designing a construction from a fire resistance point of view it is necessary to determine the temperature levels to which the construction might be exposed. The extremely simplified method adopted today, assuming the temperature influence upon a construction member to be dependent, in principle, on the quantity of combustion material available (the fire load), is then not satisfactory. Thus no consideration is taken of such factors as rate of combustion (which is influenced by e.g. the air supply and the degree of fineness and particle geometry of the combustible material) the thermal properties of construction enclosing the fire cell, as well as those enclosed within the fire cell and by the dimensions of the fire cell."* [1-26]

Many reports have documented the influence of ventilation on room-fire behavior [1-10,1-27,1-28,1-29,1-30]. For example, Kawagoe [1-29] found that a small window-area-to-fuel ratio produced long duration fires of moderate intensity, but large window-area-to-fuel ratios produced shorter duration fires that often exceeded the standard temperature curve. Similar results reported by Butcher et al. [1-30] are presented in Fig. 1-4.

1.6.3. The Standard Curve Itself (outside context of equal-area hypothesis)

Babrauskas warns

> *"It is sometimes asserted that even though under many conditions the standard curve exposure will not be 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 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*[14]*, 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."* [1-24]

Minor and Berry [1-31] advocated keeping the standard curve, but avoiding use of the equal-area conversion. They suggest using a given barrier only in situations where the anticipated exposures will never exceed the temperature or test duration of the standard curve to which the barrier was actually exposed. Referring to Fig. 1-5, a 1-hour barrier would be acceptable for exposure A, but would be unacceptable for exposures B and C. A logical extension of this approach would be to establish alternative "standard" curves for qualifying barriers for short "hot" fires and long "mild" fires. Indeed, Corson [1-21] in 1953 and Siegel [1-32] in 1967 proposed using a series of different curves to represent different fire loads. The history and use of alternative curves are discussed in Part 2 of the present document.

Regarding the standard curve, it is worth reiterating that the NFPA Fire Protection Handbook cautions that

> *"Fire loads should not be used as an approximate indicator of fire severity with combustibles having a high heat-release rate and when fire conditions can produce temperatures significantly higher or lower than the standard temperature-time curve."* [1-2]

Kanury and Holve [1-33] performed a theoretical analysis of fire-endurance testing of wood and gypsum board panels. This was a thermal model that accounted for charring and desorption processes under the assumption that the degraded panel remained intact; that is, the overall thickness of the panel remained constant. For analysis purposes, they adapted two of the ASTM E 119 critical points as follows:

ASTM E 119 Critical Point	Adapted to
Average unexposed-surface temperature reaches 139 °C above its initial temperature.	Unexposed surface reaches 1.5 times its initial absolute temperature.
Flame or hot gases penetrate barrier.	Significant pyrolysis occurs at unexposed surface.

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[14] T_c denotes a critical temperature, such as the temperature at which a phase change occurs.

Using the adapted criteria, they report that, for a wood barrier, the exact shape of the temperature-time curve has little effect on the theoretical fire-endurance time because surface re-radiation compensates for fairly large changes in exposure conditions[15]. For example, Fig. 1-6 shows results of calculations using both the standard exposure and a "peaked" (fire-growth/decay) exposure. The difference in fire-endurance time is about 12 percent. From these and other calculations involving realistic peaked exposures, they conclude that

> "*... there is no reason to discard the standard $T_f(t)$ curve as a specified exposure source for fire performance evaluation of materials, even though it superficially fails to be a realistic duplicate of any one particular full-scale enclosure fire exposure history.*" [1-33]

It should be noted that the conclusion is drawn from limited results from a theoretical model that excludes mechanical effects.

Other proponents for the existing standard temperature-time curve argue that it should not be changed because a great deal of experience has been gained using this curve, and there is no other curve that will eliminate all the objections [1-31]. The use of multiple standard curves is viewed as a great complication to evaluation of the fire-endurance of constructions that would make comparisons of individual constructions difficult [1-9] and would not be well received by testing laboratories without a rigorous demonstration of its value [1-10].

1.7 CONCLUSIONS

1. The historical evidence indicates that the standard temperature-time curve was prescribed in 1917 with very little knowledge of the levels and the temporal development of temperatures in actual room fires.

2. It appears that the standard curve was deemed to represent a severe fire and was intended only to provide a basis for comparing the fire endurance of building assemblies using a simple test.

3. Although full-scale room burnout tests in the 1920s established that the actual temperature histories of room fires were different from the standard curve, the standard curve was "rescued" by the technically-flawed equal-area hypothesis; namely, that all fires with equal-area temperature-time exposures are equally severe or intense.

4. Using fire-endurance ratings, which were based on the standard curve, and the equal-area hypothesis, Ingberg correlated the fire load in a room with the fire endurance necessary to withstand complete burnout of the room. The result was a relatively simple, albeit somewhat

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[15] That is, the integrated net absorbed heat flux (incident flux minus the reflected and re-radiated fluxes), not integrated exposure temperature, is of primary importance.

technically-weak, system of analysis for determining the fire-endurance required for building elements.

5. Despite technical shortcomings (such as: having no scientific basis for the equal-area hypothesis; real room fire intensities are not a sole function of fire load; and real fires can rise faster than the standard curve) the fuel-load/equal-area/standard-curve method was widely accepted and, indeed, remains a landmark development in the history of fire protection engineering. Today, the National Fire Protection Association acknowledges that although the fire-load method is technically obsolete, it is still useful in situations that do not involve high heat-release rate combustibles and in which fire conditions do not produce temperatures significantly higher or lower than the standard temperature-time curve.

6. Fire-endurance testing in the United States has not changed substantially since the publication of the standard temperature-time curve in 1918. Continued use of the fire-load/standard-curve methodology has been justified on the bases that the analysis: is judged to be conservative (more severe) with respect to the maximum fire exposure in many occupancies; has a proven record with respect to safety; is connected to a standard test; and is relatively simple to use. Arguments against changing the standard curve include: that a large amount of experience has been gained with the existing standard temperature-time curve; re-radiation from the exposed surface makes the exact temporal details of the curve unimportant; and no other curve will eliminate all the objections.

7. Critics argue that real fires often rise faster and/or exceed the standard curve. Although the repercussions of the inaccuracies of the standard fire-load analysis were not so great in the era of relatively massive fire barriers, the consequences could be much greater now that lighter-weight barriers must withstand fires fueled by modern materials. Moreover, improved analytical techniques are available that can avoid at least some of the objectionable assumptions inherent in the standard fire-load analysis.

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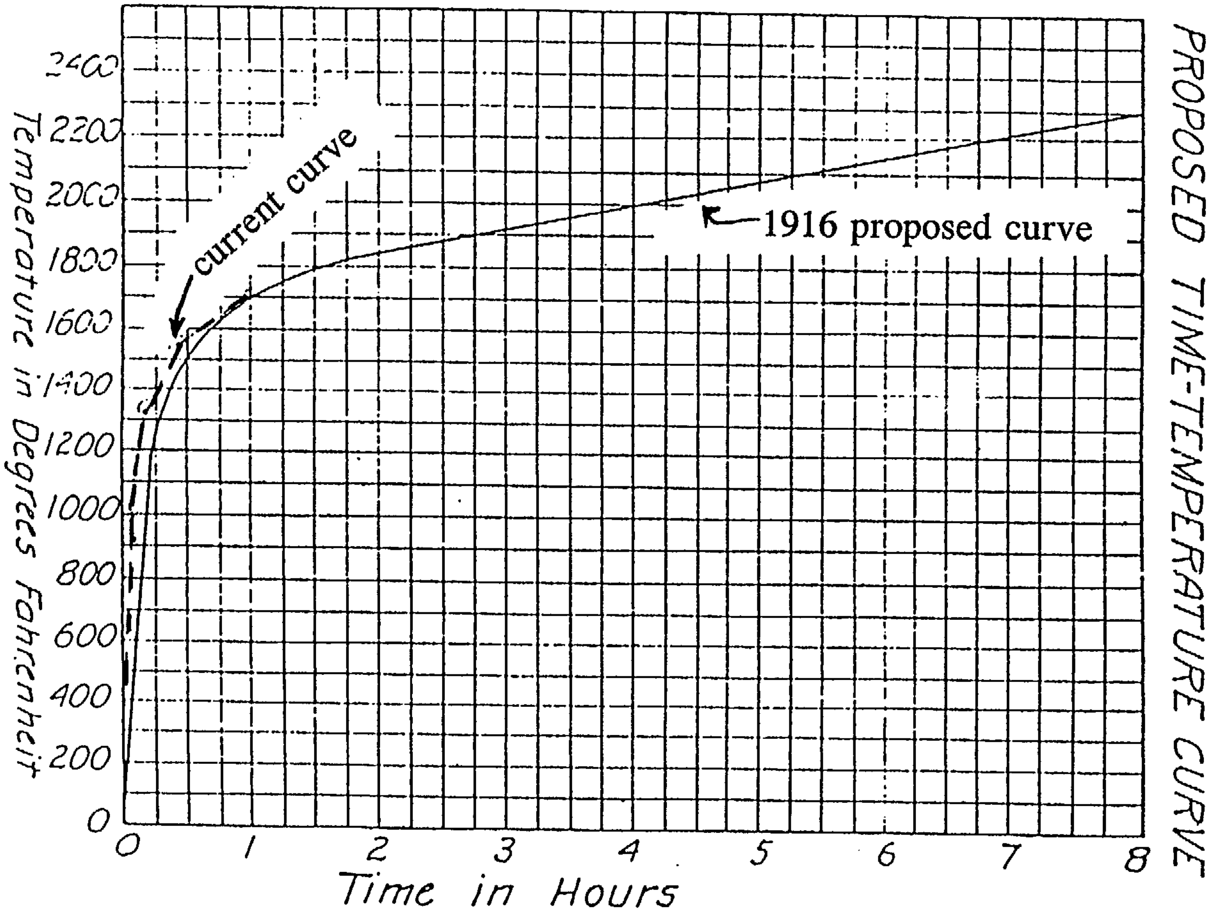

Figure 1-1. Comparison between proposed temperature-time curve for column tests at Underwriters' Laboratories [1-18] and current temperature-time curve [1-1] (main figure reproduced from [1-18]).

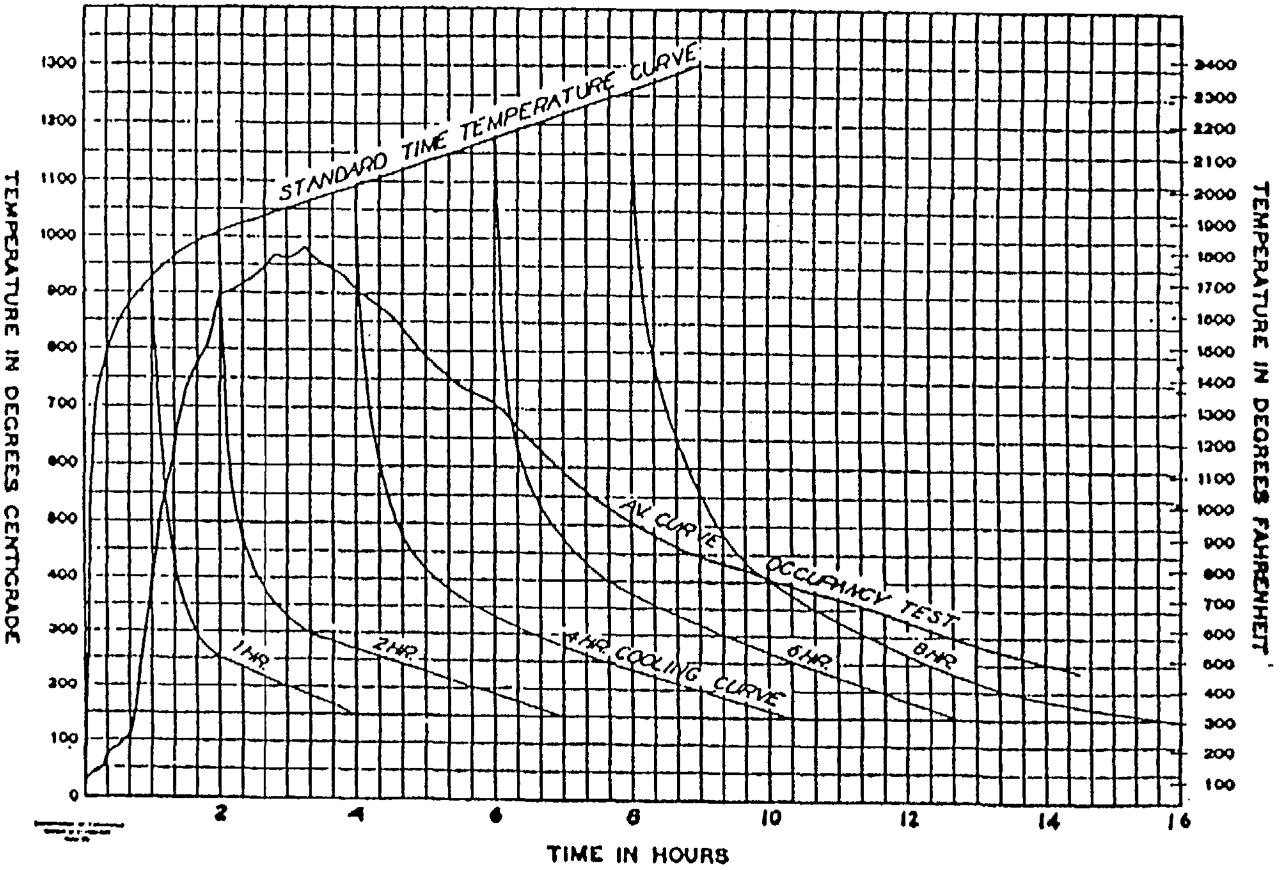

Figure 1-2. Standard temperature-time curve used in furnace tests, cooling curves, and curve representing the average temperature in a typical office occupancy test (reproduced from [1-20]).

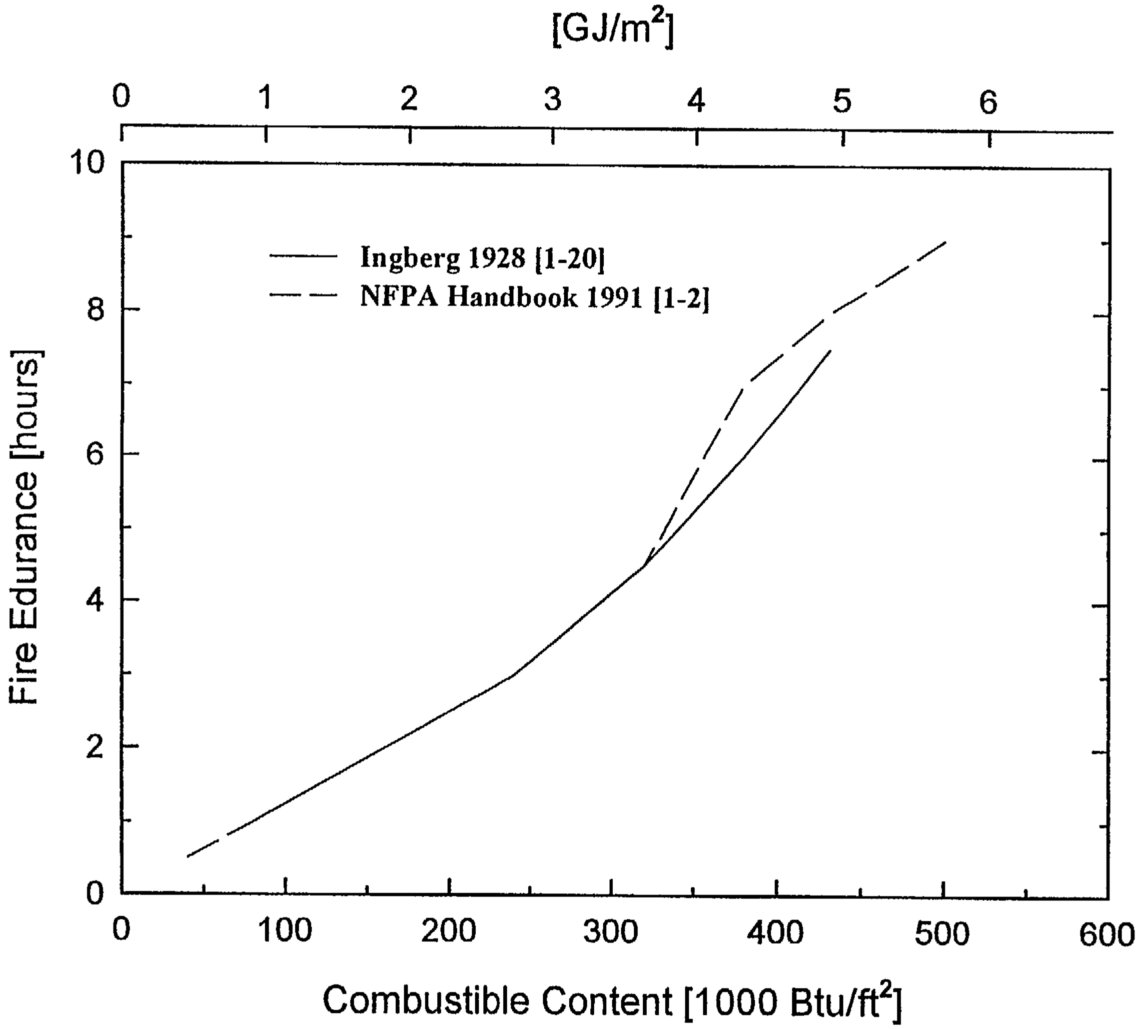

Figure 1-3. Fire endurance verses fire load (combustible content).

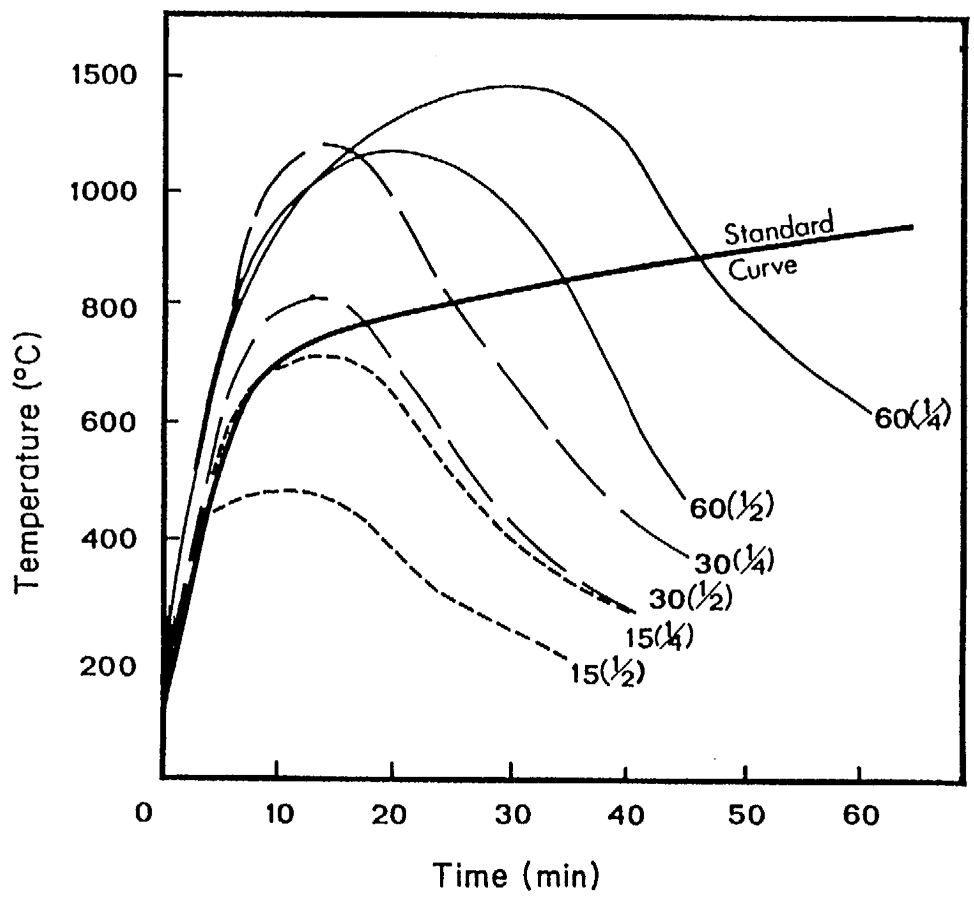

Figure 1-4. Average Gas Temperatures in Compartments, where 60 (½) denotes 60 kg/m^2 fire load and 50 percent open wall (reproduced from [1-30]).

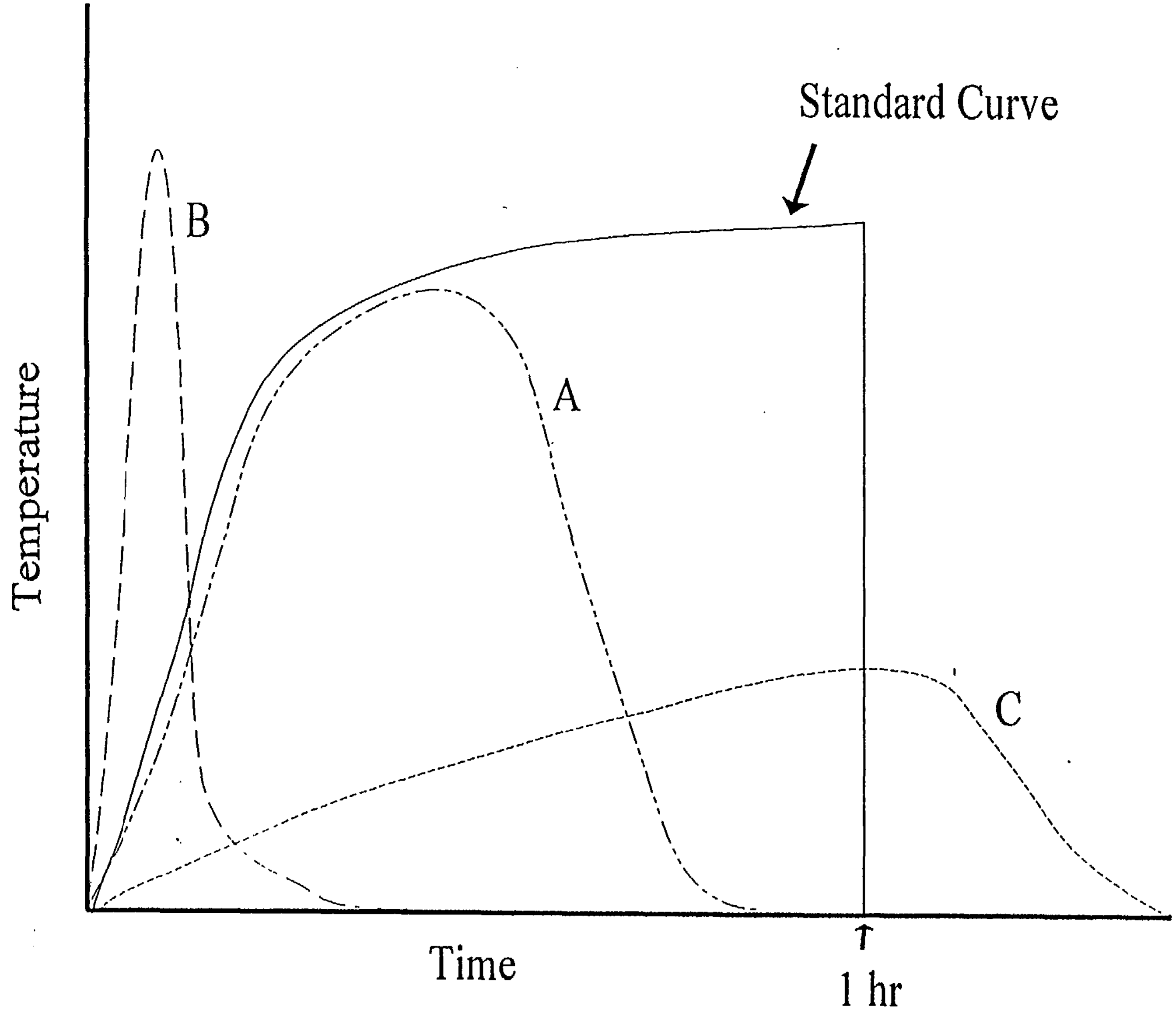

Figure 1-5. **Schematic of standard temperature-time curve and hypothetical curves for room fires.**

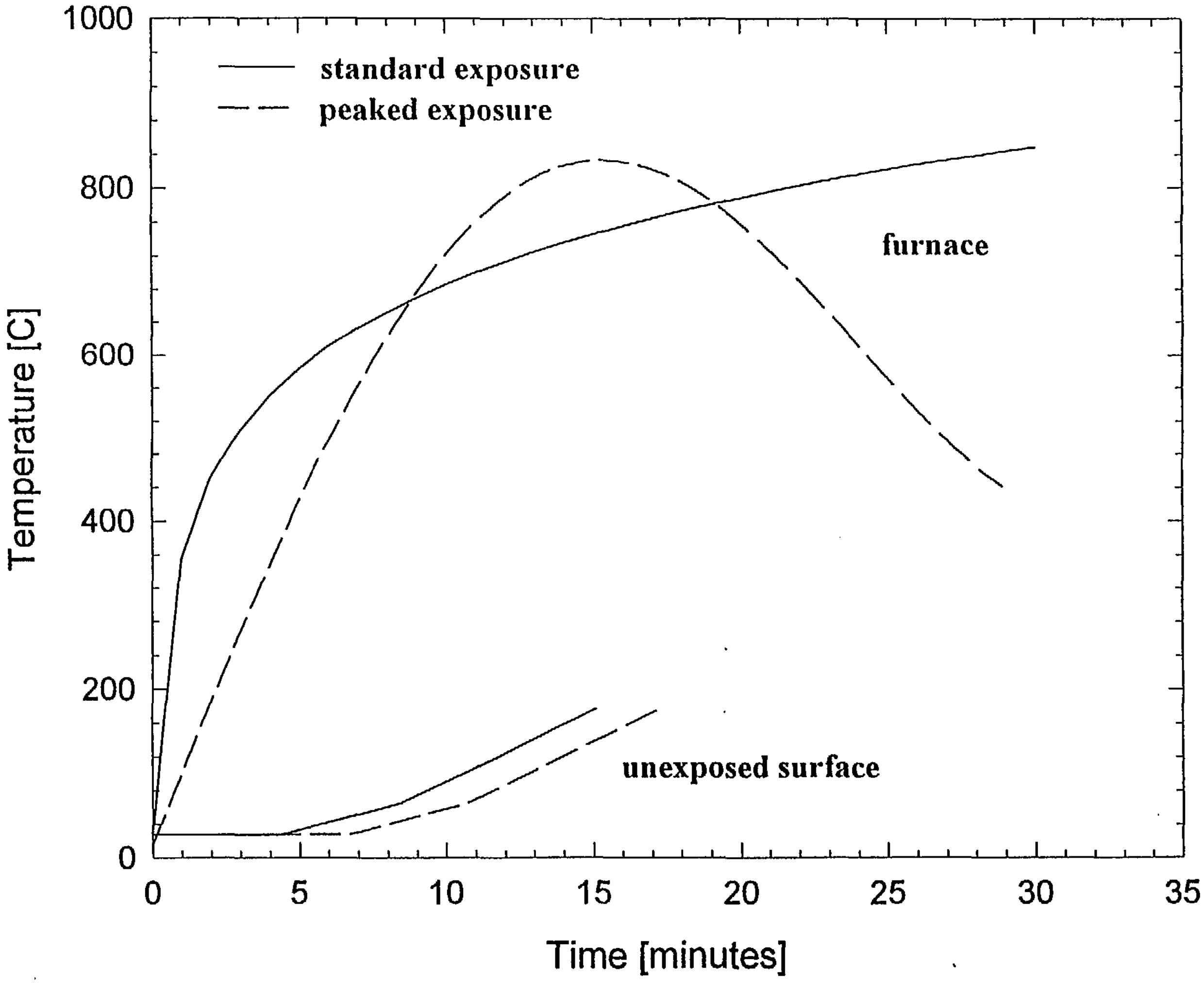

Figure 1-6. Theoretical results of Kanury and Holve [1-33] demonstrating the effect of the form of the temperature-time curve on unexposed-surface temperature.

APPENDIX - PART 1. CHRONOLOGY OF FIRE TESTING PRIOR TO THE ADOPTION OF THE STANDARD TEMPERATURE-TIME CURVE FOR U.S. FIRE TESTS.

THIS SUMMARY IS LIMITED TO HISTORICAL REFERENCES TO THE EXPOSURE TEMPERATURES USED IN FIRE-ENDURANCE TESTING AND THE NBS WORK RELATING FIRE LOAD TO FIRE ENDURANCE. UNLESS OTHERWISE NOTED, THE FOLLOWING WAS EXTRACTED FROM THE ACCOUNTS OF BABRAUSKAS AND WILLIAMSON [A1-1,A1-2][16]

1884 Column tests were conducted in Munich, Germany by Professor J. Bauschinger. The column was heated in a horizontal orientation in a wood-fired furnace. Column temperature rather than furnace temperature was measured. The column was heated to 300 °C, doused with water, reheated to 400 °C or 500 °C, doused with water, and reheated to 600 °C and doused again.

1892-1895 Additional column testing was conducted in Hamburg by F.A. Meyer. The columns were tested under load in a upright position in a gas-fired furnace. The columns were heated symmetrically to 1200 °C to 1400 °C for up to 7 hours. A standard temperature curve was not followed.

1890 Floor fire tests were conducted in Denver to compare three competing floor systems for use in the Denver Equitable Building. Each system was built over a pit, loaded down, and subjected to a coal fire contained in the pit. The fire exposure was maintained at an average temperature of 815 °C for 24 hours.

1891 Wall tests were conducted by Professor Bohme at Charlottenburg, Germany. The test partition was erected between a burn room and observation room. A fixed mass of petroleum-soaked logs was used to fuel the fire. The test lasted 1 hour. The average gas temperature was 1000 °C

1891 Floor fire test was conducted in St. Louis, MO, by architects for the Wainwright Building. Following the initial heat-up period, the gas-fired furnace was maintained at approximately 815 °C for about 6.5 hours. This is one of the first known gas-fired tests.

1893 Floor testing was initiated in Germany. These were burnout rather than standard tests. Realistic furniture served as the fuel for the tests which were conducted in a Berlin building about to be demolished. Temperatures ranged from 1000 °C to 1300 °C.

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[16] Letter-numeral combinations in brackets with designation [A1-#] refer to literature references listed at the end of this Appendix.

1894 A German floor fire test was conducted using wood, coal, and coke as fuel. The exposure temperature was less than 700 °C.

1895-1900 Wall tests continued at Charlottenburg, Germany. Only maximum exposure temperatures were reported. They varied from 1000 °C to 1100 °C.

1896 Fourteen[17] floor structures were tested by the New York Building Department using a wood fire, 5-hr exposure maintaining an average temperature of 2000 °F (1093 °C) during the last 4 hours [A1-3]. In practice the maximum temperature ranged from 1975 °F to 2575 °F.

1896 Column testing was begun in the U.S. using a gas-fired furnace located at the Continental Iron Works in Brooklyn. Temperatures (presumably column temperatures) reached up to 840 °C and test periods ranged from 25 minutes to more than 2 hours.

1897 British Fire Protection Committee (Edwin O. Sachs) originally built eight[18] brick chambers for testing the fire endurance of building materials and systems of construction [A1-3]. This was the first attempt to compile fire resistance data on materials and systems used in building construction [A1-4]. The exposure simulated a slow smoldering period followed by an increase to about 1093 °C [A1-1].

1899 British Fire Protection Committee began testing walls. Same temperature control as floor test.

1899 New York Building Code included a the first fire-test standard in the U.S. for testing floors.

1901 New York Department of Buildings conducted a series of partition tests. Furnace temperature was raised to 926 °C in 30 minutes and held at that level for the remainder of the test (30 minutes).

1902 Floor testing resumed in New York and the average temperature was lowered from 1093 to 926 °C.

1902 Combined floor, partition, and column tests were conducted for the New York Building Department. Tests were conducted for 4 hours at an average temperature of 930 °C.

1902 First permanent facilities in U.S. for testing the fire resistance of building components were built by Professor Ira Woolson, Columbia University (2 large-scale furnaces; floor and wall).

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[17] Babrauskas and Williamson report [A1-1] that 16 tests were conducted in this series.

[18] Babrauskas and Williamson report [A1-1] that 3 huts were built originally.

Ryan reports [A1-4] that, at the turn of the century Professor Ira Woolson, Columbia University, established a temperature-time curve for severe fires. He based this curve on data from building fire investigations including interviews of firefighters and comparison of materials gathered at fire scenes with melting-point data. Other curves were developed at this time.

1903 U.L. tested doors and windows in a gas-fired furnace. Furnace temperature was raised to 926 °C during the first 30 minutes and then held at that level for an additional 90 minutes.

1904 Unloaded columns were tested in Chicago in a wood-fired furnace operating at 800 °C to 1000 °C. Tests lasted 3 hours.

1916 A description of plans for cooperative fire tests of columns was published in 1916. This included the temperature-time curve that would be employed.

1917 The first standardized column tests were conducted at UL Chicago. Simon Ingberg, from the National Bureau of Standards (NBS), was the director of the program. The National Board of Fire Underwriters (NFBU) and the Factory Mutual companies participated in the program. More than 100 columns were tested under load in a gas-fired furnace. Furnace temperature control was standardized.

1917 ASTM C19 was issued[19] at the February 24, 1917 meeting of a conference made up of 11 organizations.

1918 ASTM C19 was adopted [A1-3,A1-4].[20] Single curve was adopted in recognition of the need for performance evaluation and economy in testing [A1-6].

1922 Burnout tests were conducted at NBS in specially constructed buildings [A1-6]. The objective was to relate the adopted fire test exposure to the actual fire exposures in occupied buildings.

1926 NBS burnout tests representing office occupancies using wood and steel furniture, filing cabinets were described in a brief report [A1-6]. The study found that the decrease following the peak gas temperature in the room was much slower than the cool-down in the typical furnace test. The relationship between the two exposure conditions would require further study. The tests were conducted to obtain information on the intensity and duration of actual fires so that

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[19] Semantics has confused somewhat the date of ASTM C19. Babrauskas and Williamson [A1-2] report that ASTM C19 (later renumbered E119) was **issued** on February 24, 1917 but later refer to the "1918 standard". Ryan [A1-4] and Shorter [A1-3] report that ASTM E 119 was **adopted** in 1918. The current ASTM E 119-88 standard [A1-5] states that C19 was first published in 1918 as C19-1917T, which, in current ASTM notation, would indicate that the standard was **approved** in 1917 and **first published in** 1918.

[20] See previous footnote.

proper exposure conditions could be used in fire endurance tests of construction materials.

1927 First report of Ingberg's correlation for office fire loads of 10 to 160 lb/ft^2 [A1-6].

1928 The most complete report of NBS work was issued [A1-6]. It included a table correlating fire load with fire endurance measured in a standard test. Ventilation was recognized to be important but was not quantified. The furnace cooling process was recognized as part of the thermal exposure. Ingberg recognized technical problems but assumed that matching the area of the average burnout curve with the area below the combined furnace heating and cooling curve would yield equal severity exposures in the furnace test and actual fire.

1928-47 NBS expanded fire-load surveys to residences, schools, medical buildings, mercantile, and manufacturing buildings [A1-6].

REFERENCES - APPENDIX - PART 1

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[A1-2] Babrauskas, V., and Williamson, R.B., The Historical Basis of Fire Resistance Testing -- Part II, Fire Technology, No. 4, pp. 304-316, November 1978.

[A1-3] Shorter, G.W., The Fire Protection Engineer and Modern Building Design, Fire Technology, National Fire Protection Association, pp. 206-213, August 1968.

[A1-4] Ryan, J.F., Perspective on Methods of Assessing Fire Hazards in Buildings, ASTM STP 502, American Society for Testing and Materials, pp. 11-23, 1972.

[A1-5] ASTM E 119-88, Standard Test Methods for Fire Tests of Building Construction Materials, Annual Book of ASTM Standards, Sec. 4, Construction, Vol. 4.07, American Society for Testing and Materials, Philadelphia, PA, 1994.

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PART 2. HISTORY AND USE OF ALTERNATIVE TEMPERATURE-TIME CURVES

LIST OF FIGURES - PART 2

SUMMARY - PART 2

Alternative temperature-time curves for evaluating the fire-endurance of building elements and systems have been proposed since the 1950s, but it appears that only the alternative curves developed for the hydrocarbon processing industry are widely used for fire-endurance testing. Indeed, no record has been found to indicate that fire-endurance testing has been carried out to qualify a building element or assembly using any curve other than the ASTM E 119 standard temperature-time curve, one of its foreign counterparts, or a hydrocarbon temperature-time curve.

During the 1970s, an alternative curve was derived from a series of full-scale burnout experiments involving residential recreation-room occupancies. That study, which was conducted at the U.S. National Bureau of Standards -- now the National Institute of Standards and Technology, included tests of floor-ceiling assemblies in a furnace capable of following either the standard or alternative curve. Although the results showed some dramatic differences in fire-endurance performance for the two exposures, the study was judged too limited in scope to serve as a basis for changing fire-endurance test standards. No follow-up work occurred. In the course of the present review, the only record of fire-endurance testing of building elements or systems with an alternative curve (other than a hydrocarbon curve) was that reported in the recreation-room study.

Since the 1960s mathematical modeling of room fires has been proposed as a means for determining more realistic exposure conditions for evaluating fire endurance of building elements and systems. In general, the fire-science literature suggests that, to be practical, the development of any new temperature-time curves for compartment applications will have to rely heavily on mathematical modeling. This approach has been developed in Sweden to the extent that temperature-time curves generated by mathematical room-fire models are sanctioned by Swedish regulations for certain design calculations.

To date, a major weakness of room-fire models, however, lies in their inability to simulate accurately burning rates under real-fire conditions. For example, much of the modeling work aimed at creating alternative temperature-time exposures has been based on the burning characteristics of cellulosic fuels. Also, such models only simulate the simplest type of room ventilation -- an opening to the outside environment. Development of credible temperature-time curves for nuclear power plant (NPP) applications will require better understanding of the burning behavior of NPP-specific fuel packages -- for example, cable bundles -- and more advanced ventilation considerations.

2.1 OBJECTIVE

The purpose of Part 2 of this document is to review the literature concerning the history of the development of alternatives to the ASTM E 119 temperature-time curve [2-1][21] for assessing the fire-endurance of construction elements and assemblies. In particular, this review attempts to convey the methodology that was used to define non-standard alternative curves and the extent to which these alternative curves are or were used.

2.2 INTRODUCTION

Part 1 of this document dealt with the technical basis for the ASTM E 119 standard temperature-time curve. It is important to note that standard curves similar to the ASTM E 119 curve have been and continue to be used in other countries to test building elements. These national standard curves are shown in Fig. 2-1 [2-5][22]. Curve 3 is the ASTM E 119 curve, used in North America, and curve 2 is the ISO 834 curve [2-4][23], which is used in most of Europe[24]. Note that the differences among these curves are generally small. Indeed, Lie [2-5] argues that all the curves likely are based on the same data as the 1916 curve [2-6] for column testing at Underwriters Laboratories. Consequently, the concerns raised in Part 1 about the technical basis of the ASTM E 119 curve are expected to apply to all of the curves displayed in Fig. 2-1.

Beginning in the 1950s, those concerns led to re-evaluations of what actually constituted a reasonably accurate representation of real fire exposures for assessing fire-endurance requirements of building elements. Impetus for the work included the availability of new

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[21] Numbers in brackets designated by [2-#] refer to literature references listed at the end of Part 2 of this document.

[22] Curve 7 is incorrect. The Japanese curve, which is defined in JIS A 1304 [2-2], has always been within a few degrees of the E 119 curve [2-3] and is not defined beyond 4 hours. The erroneous curve 7 may be a result of an improper evaluation/extension of the following equation which was developed at the Japanese Building Research Institute to **approximate** the JIS temperature-time curve (up to 4 hours) [2-3]:

$$T(t) = 1080 - 340 \exp(-0.8t) - 130 \exp(-5.0t) - 610 \exp(-19t), \quad \text{where } T\ [^\circ\mathrm{C}] \text{ and } t\ [\text{hours}].$$

The JIS curve is used for testing all constructions except 3-story wood-house constructions. The latter are tested using the ISO 834 curve [2-4].

[23] Although the ISO 834 curve and the ASTM E 119 curve are similar, the type of thermocouples used are different. Therefore, the difference in the actual thermal exposure to a test assembly between the two methods is greater than the curves indicate.

[24] Countries participating in the European economic normalization will be required to use the ISO 834 curve.

analytical tools for studying compartment fires, much larger window areas in modern buildings, and a great increase of non-cellulosic fuels in the buildings.

In general these efforts sought to identify realistic heating/cooling temperature-time curves for use in controlling fire-test furnaces or serve as input to mathematical models designed to simulate the response of fire barrier materials. It is these latter, more realistic curves, rather than the standard curves in Fig. 2-1, that are the subject of Part 2.

2.3 ALTERNATIVE TEMPERATURE-TIME CURVES REPRESENTING ROOM FIRES

2.3.1 Qualitative Curves or Curves Based on Qualitative Arguments

2.3.1.1 Corson's Curves

Using the work of Ingberg at NBS as a basis, Corson [2-7] in 1953 proposed a classification system to relate fire duration to fire load in a given occupancy. The system consists of five categories and is defined by the following table in conjunction with Fig. 2-2.

Fire Severity Expected by Occupancy [2-7]

Fire Severity Category	Typical Occupancy	Expected Temperature-Time Curve (see Fig. 2-2)
Slight	Well-arranged office, metal furniture, non-combustible building. Welding areas containing slight combustibles. Non-combustible power house. Non-combustible buildings, slight amount of combustible occupancy.	Curve A
Moderate	Cotton and waste paper storage (baled) and well- arranged, non-combustible building. Paper making processes, non-combustible building. Non-combustible institutional buildings with combustible occupancy.	Curve B
Moderately Severe	Well-arranged combustible storage , e.g. wooden patterns, non-combustible buildings. Machine shop having non-combustible floors.	Curve C

Severe	Manufacturing areas, combustible products, non-combustible building. Congested combustible storage areas, non-combustible building.	Curve D
ASTM Standard Fire Exposure -- Very Severe	Flammable liquids. Woodworking areas. Office, combustible furniture and buildings. Paper working, printing, etc. Furniture manufacturing and finishing. Machine shop having combustible floors.	Curve E

The straight lines in Fig. 2-2 relate fire load to fire-endurance time for each of the categories, while the curved lines denote attendant "expected" temperature-time curves. Note that straight line E is Ingberg's 1928 relationship between fire load and the fire endurance necessary to withstand burnout of that load in an office occupancy, and curved line E is the standard ASTM E 119 temperature-time curve. The justifications for the remaining curves (A through D), however, remain unclear. The shapes chosen for these new temperature-time curves appear to have been motivated by Ingberg's experimental burnout curves which are displayed in Fig. 2-3. Regarding the latter curves, Corson states *"It is interesting to note that in certain of these tests a rapid rise of temperature occurred at the start, while in others the rapid rise was delayed. Also, in most cases, temperatures at the start or very soon thereafter reached the intensity represented by the standard ASTM "time-temperature curve."* [2-7] This observation appears to be the sole basis for the new curves.

Despite the weak scientific basis for the temperature-time curves A through D, they continue to appear in the NFPA Fire Protection Handbook [2-8]. In the course of the current review, no record was found of the actual use of these curves.

2.3.1.2 Seigel's Qualitative Curves

In 1967 Seigel [2-9] concluded that the standard temperature-time curve does not provide a satisfactory representation of fire conditions in modern steel-framed buildings. The fire loads in these buildings usually consist mainly of furnishings that can be easily ignited once a fire occurs. He states that *"A well-ventilated fire in such a building will tend to reach its maximum temperature quickly and will usually burn out in a short time because there will be no contribution from the non-combustible structure."* [2-9] Results of limited tests [2-9] conducted in room-size compartments (Fig. 2-4) support this statement. He also concluded that a high-intensity short-duration fire may constitute a more severe exposure for a fire barrier than a low-intensity long-duration exposure. *"If the temperatures are high enough, explosive spalling of concrete and destructive shrinkage of gypsum may result after a limited exposure. Other materials may also be seriously deteriorated, so that they cannot perform their intended function for the duration of the fire."* [2-9].

In view of these serious deficiencies, Seigel proposed that consideration be given to replacing the standard temperature-time curve with multiple curves such as those shown in Fig. 2-5. He noted that further study would be necessary to quantify the curves to reflect maximum severity and duration for a given fire load or occupancy.

2.3.2 Curves Determined by Mathematical Models

The next significant achievement toward a quantified understanding of room-fire intensities was made by Kawagoe and co-workers [2-10 to 2-13] in Japan. By applying mathematical modeling techniques to room-fire experimental results, they identified ventilation and wall properties as two more important factors (in addition to Ingberg's fire load) that greatly influence the severity of a fire in a room. They used their room-fire model to calculate the temperature-time curve produced by ventilation-controlled fires up to the point of peak temperature (when fuel was gone) and then assumed a temperature decay rate of 10 °C/min. They did not deal with fuel ***burning rate*** (mass loss rate), but rather accounted for fuel effects solely by fire load.

With the mathematical model as a tool, it became possible, in principle, to calculate *deterministic* temperature-time curves for specific room sizes, geometries, fuels, and ventilation conditions. Here ***deterministic*** means that all the necessary variables are known and specified. Kawagoe produced such curves, but then used Ingberg's equal-area hypothesis [2-14] to convert to an equivalent standard temperature-time exposure for fire-endurance testing purposes.

In Sweden Ödeen [2-15] developed a room-fire model similar to Kawagoe's except that burning rate was included as an input variable. For a given amount of fuel, Ödeen demonstrated that the temporal development of the calculated gas temperature was influenced strongly by the burning rate. Model temperature-time results compared well with experiments conducted in a compartment with wood or kerosine fuels.

Ödeen's model was the basis for changes in Swedish Building Regulations, SBN 67 [2-16] in 1967 (effective January 1, 1968) that allowed choosing alternative temperature-time curves for some situations [2-15]. If the fuel is primarily wood or other cellulosic materials and a *ventilation factor*[25] can be assigned to the compartment of interest, then Fig. 2-6, which was generated from the model using the assumption that the bounding surfaces are brick or concrete block, can be used to identify an alternative temperature-time heating curve for fire-protection design. The regulations include procedures for determining fire duration and for appending a cooling curve to the heating curve.

Subsequent work by Pettersson et al. [2-17], which is based on the work of Magnusson and Thelandersson [2-18], produced a refined set of curves which superseded those in Fig. 2-6 in

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[25] For example, the ***ventilation factor*** for a single vertical opening in a compartment is defined as $Ah^{1/2}/A_t$, where A is the area of the opening, h is its height, and A_t is the total internal surface area of the fire compartment.

the Swedish standard. Like the Kawagoe model, the Swedish model assumed a fully-developed, ventilation-limited, wood-fueled fire in a compartment with bounding surfaces with specified thermal properties, and then calculated the temperature-time curve for the contained gas. Figure 2-7 presents results for a room with boundary surfaces having "average" thermal properties. Other curves were determined for a wide range of specific boundary surfaces. Each temperature-time curve, therefore, represents results for a specified ventilation factor, boundary surface, and fire load.

The Swedish regulations also allow for making a case for the effect other fuel properties/geometries may have on the thermal exposure produced by a compartment fire. According to Pettersson et al. [2-17], an alternative exposure defined as follows is permitted by the regulations:

> *"... the Swedish Building Code permits a design procedure which is functionally better substantiated and more rational [than the classification system based on the standard temperature-time curve]. This is based on the gas temperature-time curve relating to the complete fire process. This is determined in the individual case from heat or mass balance equations or in some other way, consideration being given to the combustion characteristics of the fire load, the ventilation characteristics of the fire compartment, and the thermal properties of the structures enclosing the fire compartment and contained in this."* [2-17]

Regardless of how it is determined, the resulting thermal exposure is used as input to a basic heat-transfer model to determine the temperature-time response of key structural elements (usually steel beams, columns, or rods) which are protected by a fire barrier. If this structure is load bearing, then consistent with the appropriate temperature-time curve either the minimum load bearing capacity or the time of failure for the given load is determined by calculation or comparison with available test results. The load bearing determination is usually omitted if the structure only performs a separation function.

In the U.S., Babrauskas and Williamson [2-19] developed a more sophisticated mathematical room-fire model that includes fuel-controlled burning and the ability to switch between fuel and ventilation control. Although their model could be applied in a purely deterministic mode to produce a specific temperature-time curve for a specific set of input data, they sought an alternative approach that would produce a more general result. One such alternative is a series of solutions based on a parameterized fuel load coupled with a limited range of worst-case ventilation conditions. For a given compartment size, fuel load, and boundary thermal properties, the ventilation condition is adjusted, within realistic limits, to produce the highest possible gas temperature at each step in the calculation. Babrauskas and Williamson refer to this process as ***ventilation pessimization***. The result is a reduction of the dimensionality of the problem (ventilation has been removed), and a more general, more conservative[26], but less

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[26] In the course of studying Babrauskas' reports [2-19,2-20] for the present review, evidence emerged that suggests that the ventilation pessimization can produce a room gas temperature that is near but less than

accurate solution.

Figure 2-8 presents results of calculations applied to an office occupancy. Ventilation was pessimized in the range 0.00 - 0.17 $m^{1/2}$ [2-20], corresponding to no-window and one-wall-missing, respectively. The fuel-percentile values shown in Fig. 2-8 represent fuel loads of 20, 35, 50, and 100 kg (wood equiv.)/m^2.

Babrauskas [2-20] suggests that this approach could be used to develop a limited set of temperature-time curves of the type Corson [2-7] was seeking. No evidence has been found, however, that this suggestion was acted upon.

2.3.3 Curve Determined by Full-Scale Burnout Experiments --- The NBS Recreation Room Curve

In the mid to late 1970s, Fang and Breese [2-22] at the U.S. National Bureau of Standards (NBS) (now NIST) conducted a study to establish rational test procedures for testing the fire endurance of residential floor-ceiling assemblies. This work was sponsored by the U.S. Department of Housing and Urban Development (HUD) and was motivated by the concern that the ASTM E 119 temperature-time exposure, which had been adopted 60 years earlier, was not representative of fires in modern residences having furnishings made from synthetic materials and larger window areas.

The study focused on fire behavior in typical recreation (family) rooms in single-family residences. The aim was to characterize the severity of fires originating in these rooms and develop a set of exposure conditions for testing the fire endurance of floor-ceiling systems.

A total of 16 burnout experiments were conducted in two instrumented test rooms, 3.3 m x 3.3 m x 2.6 m (high), and 3.3 m x 4.9 m x 2.4 m (high), furnished with modern household furniture, and lined with typical wall and ceiling finish materials. The 16 experiments represented a range of fire loads, ventilation conditions, and finish materials.

The chosen fire loads, materials, and room geometries were based on a survey of 70 homes located in the Washington, DC area. Total fire loads (movable plus structural) of 21, 28, and 42 kg/m^2 were selected since the survey demonstrated that they represented low, average, and high loads, respectively. Four ventilation conditions were examined: door open with and without forced ventilation supplied to the room in a fashion simulating a forced air heating/cooling system, and door closed with and without forced ventilation.

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the absolute worst-possible temperature. For example, see Fig. 8 in reference [2-19]. It appears that the calculated result may be "path dependent;" that is, affected by the history of the calculation [2-21]. Further investigation of this issue is beyond the scope of the present review.

Figure 2-9 displays the range of average gas temperatures measured in the upper region of the test room for a variety of fuel loadings and configurations. All of these tests were conducted with the door open. The peak temperatures were about the same, but the times to reach the peak varied considerably. Moreover, the experimental temperature-time curves were notably different from the ASTM E 119 curve also shown in the figure. The experimental fires became hotter faster than the ASTM E 119 exposure and began to decay within 15 to 30 minutes after ignition.

Fang and Breese considered Test BSMT09 as representing "standard" test conditions; namely, a 3.3 m x 3.3 m recreation room with plywood paneling walls, gypsum board ceiling, open door, and 23 kg/m^2 movable loading of household furnishings. They fit a polynomial to 7 points on temperature-time curve from Test BSMT09 to produce the "derived curve" shown in Fig. 2-10 and judged the result to be an approximate average over the range of test conditions employed in their study. They concluded that

> *"The rate of development and the intensity of real fires involving the burning of typical furniture and interior linings in a room during the first 20 minutes may be significantly greater than those defined by the ASTM E 119 time-temperature curve. A more realistic time temperature curve for residential occupancies is [the "derived curve" in Fig. 2-10.]"* [2-22]

Subsequent work at NBS [2-23] included another series of burnout tests under the standard conditions defined above, but with a set of selected residential floor/ceiling assemblies. These same systems were later tested by Fang [2-24] in a gas-fired furnace under both an ASTM E 119 exposure and the newly-derived temperature-time curve. This allowed comparisons between the two types of furnace exposure and between the furnace and room burnout tests.

Among Fang's conclusions were

> *"The wood joist floors exposed to the newly developed fire conditions in the gas-fired furnace had a shorter time to failure compared with the earlier residential room fire tests on the same floor constructions. This was due primarily to the increased burning rates of the combustible materials in the test structure with the excess air inside the test furnace."* [2-24]

> *"Individual test assemblies resisted flame penetration in the furnace fire tests for a time approximately 40 percent shorter when tested under the newly developed time-temperature curve as compared with the ASTM fire exposure."* [2-24]

They recommended that the newly developed temperature-time curve should be used in a new ASTM fire endurance test for rating residential floor constructions which require endurance times of less than one hour. This recommendation, however, was rejected on the basis that the room-burnout experiments were too limited in scope [2-25].

2.4 TEMPERATURE-TIME CURVES REPRESENTING OPEN-AIR PETROCHEMICAL CURVES

In the 1970s, the hydrocarbon processing industry (HPI) began working on a fire test that realistically represented direct exposure to a petroleum fire (combustible/flammable liquids and gases). This was motivated by the need to protect fire-exposed structural steel for up to 1 hour and cable trays for up to 30 minutes. The tray protection was needed to allow for orderly shutdown of equipment [2-26].

Warren and Corona [2-26] found that the ASTM E 119 test was an unsuitable representation of direct petroleum fire exposure because its temperature rise was too slow and the heat flux to the test assembly is mainly radiative. They report that petroleum fires rise rapidly to about 1100-1200 °C (about 2000-2200 °F), have a high convective flux component, and often totally involve (engulf) the specimen. Resulting rapid temperature rise of an assembly is of concern because thermal shock might have a significant effect on the integrity of some barrier materials.

Warren and Corona considered pool fire tests but concluded that wind made the repeatability poor. Instead they developed a "fire box" test apparatus -- basically an open-top furnace -- with dimensions about 1.8 x 1.1 x 1.2 m-high, which was fired with a liquid propane gas (LPG) burner with its jets directed at the walls of the box. Specimens, such as cable trays with fire-resistance coverings, were placed on top of the box and supported by the side walls. Flame temperature reached 1093 °C (2000 °F) in about 15 minutes producing about a 92 kW/m^2 radiant flux and 134 kW/m^2 convective flux. The resulting temperature-time curve became known as the "Mobil Curve", which is illustrated in Fig. 2-11.

North Sea oil development generated interest in protecting personnel quarters and refuge areas on offshore platforms from hydrocarbon fires [2-27]. The Norwegian Petroleum Directorate (NPD) issued regulations for fire walls based on performance in a "hydrocarbon furnace test"; that is, a test with a steeply rising temperature-time curve similar to the Mobil curve. The NDP curve is shown in Fig. 2-12. The reason(s) for the changes relative to the Mobil curve were not provided in the documents available for the present review [2-27,2-28]. The NDP test also has been used to test structural elements.

In the early 1980s, the United Kingdom (UK) Department of Energy commissioned the Fire Research Station (FRS) at Boreham Wood to assess fire tests for evaluating structural elements for offshore structures. FRS restricted consideration to real-fire scenarios involving open-air spill and open-air pool fires and then gathered more than 300 documents on these topics. This information was reviewed and assessed according to the following plan:

(Extensive quotations are presented here to convey details of the methodology)

> *" 1. Determine typical fuel quantities, types and frequency of occurrence of hydrocarbon spills on or around oil platforms. "*

> *"2. Determine the frequency and causes of fires on off-shore structures, and particularly oil-spill fires, to assess the risks of various types of fire. The environmental conditions around an oil-platform, against which any test will have to be assessed, would be established."*
>
> *"3. Establish typical-case, worst-case and 'expected' worst-case conditions in which a fire might occur, from 1 and 2 above. The three conditions would if possible be characterized by the probability of the fire occurring, the extent of the fuel spill, the flow rate or quantity of fuel, environmental conditions, and whether the spill is on sea or over the structure."*
>
> *"4. Determine the thermal environment around hydrocarbon spill fires both for contained pool fires and for unconstrained fires of fuel floating on water from full scale test data. Various fuels would be considered, and various environmental conditions."*
>
> *"5. Bring together 3 and 4 above to derive a design fire for offshore structures and to define its characteristics, in particular with regard to heat flux and temperature ...."* [2-29]

This analysis identified two salient fire scenarios:

> *"a) A spill on the deck of the structure. This would be a fairly small fire, perhaps involving a minimum of 0.05* m^3 *of fuel. Such fires occur fairly frequently, with a probability of occurrence of* 10^{-4} *to* 10^{-2} *per installation year. It would consist of fuels such as aviation fuel, crude oil, methanol or natural gas liquids which are stored on board offshore structures in varying quantities. Temperatures around 800 °C to 1100 °C were indicated from the data examined and maximum total heat fluxes of around 150* kW/m^2*. These values would be reached in, typically, two minutes.*
>
> *b.) A spill from a tanker on the sea. This could involve 120,000* m^3 *of almost any fuel, carried by a tanker and therefore include LNG [liquid natural gas]. The probability of such an occurrence involving LNG was not estimated, but would be significantly lower than* 10^{-4} *per installation year. However the density of sea traffic in the North Sea is such that it was considered to be appropriate to include an LNG spill. If LNG is considered a possible fuel then temperatures around 1000-1200 °C were indicated by the data examined and maximum total heat fluxes of around 220* kW/m^2*. Again these values would be achieved within two minutes although maintained for only 10 minutes."* [2-28]

FRS chose to propose the following design fire based on a combination of both of the above scenarios:

FRS DESIGN FIRE		
Temperature	Total Heat Flux	Convective Heat Flux
1200 °C within 2 min. and maintained for another 10 min.	220 kW/m^2 achieved within 2 min. and maintained for 10 min.	40 kW/m^2
Drop to 1100 °C at 12 min. and maintain for the duration of the fire	Drop to 150 kW/m^2 at 12 min. and maintain for the duration of the fire	40 kW/m^2

This FRS design curve is plotted in Fig. 2-12.

Meanwhile, in the United States ASTM Subcommittee E05.11 was working on a similar task to standardize hydrocarbon-fire simulations which would lead eventually to ASTM E 1529 "Standard Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies" [2-30]. It was recognized that a hydrocarbon fire gets hotter faster (158 kW/m^2 at 5 minutes) than the ASTM E 119 standard exposure (35 kW/m^2 at 5 minutes and 118 kW/m^2 at 60 minutes).

The approach was to rely on engineering judgement to select a single set of test conditions to represent a reasonable worst case for hydrocarbon-production installations for facility-design purposes. Consequently, with respect to radiant heat transfer from the fire to an object within or adjacent to the fire, worst case conditions would prevail when the view factor between the flame and object was 1.0, the flame emissivity was 1.0, and time continuity (fraction of time the object is located in a flame that generally fluctuates greatly in a given space) was 100 percent.

Bader [2-31] measured heat fluxes in large pool fires and modeled the results. The maximum time-integrated total heat flux measured with a slug calorimeter was 150 kW/m^2. He found that for modeling purposes a blackbody temperature of 1010 °C (corresponding to a 154 kW/m^2 blackbody radiant flux) satisfactorily accounted for the combined effect of radiation and convection from a real pool fire. Other studies [2-32 to 2-39] covering a range of fuels and fire sizes report either radiant or total *cold wall*[27] heat fluxes to engulfed objects, or objects on the perimeter of the fire, in the range 158-161 kW/m^2. Typically, the test object represented a dangerous and/or high-value item such as a weapon or weapon container [2-32,2-33], hazardous material container [2-34], or aircraft fuselage section [2-35].

On the bases of these experimental data and analyses, a total heat flux of 158 kW/m^2 was chosen

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[27] The heat transfer rate to an object depends on the object's temperature. ***Cold wall*** heat fluxes usually refer to fluxes measured with water-cooled gauges located at the surface of the object.

as being representative of a *reasonable worst case exposure*. Although convective heat flux is not specifically called out in the standard, calculations indicate it should be about 10 percent of the total flux to a vertical column. This is consistent with the 9 to 1 ratio observed by Mansfield [2-36] for large pool fires.

In addition to heat flux, the standard specifies the temperature of the furnace gases[28] that produce much of the exposure heat flux. The temperature range of 1010-1180 °C was selected for two reasons a.) actual pool fires range from 927-1260 °C in the luminous region, and the specified range is in middle of this wider range, and b.) specifying a range allows the test operator flexibility for attaining the required heat flux.

ASTM E 1529 FIRE EXPOSURE		
Temperature	Total Cold-Wall Heat Flux	Convective Heat Flux
At least 815 °C after the first 3 min.	Not specified during first 3 min.	Not Specified
Between 1010-1180 °C at 5 min. and maintain for the duration of the fire.	158 ± 8 kW/m^2 at 5 min. and maintain for the duration of the fire	Not specified

The ASTM E 1529 temperature-time curve is plotted in Fig. 2-12.

In 1989 Underwriters Laboratories Inc. issued a similar standard, UL 1709 [2-40], for testing protection materials for structural steel. The test exposure is listed in the table below and the temperature-time curve is plotted in Fig. 2-12. Note the temperature band permitted by UL 1709 is almost identical to that allowed by ASTM E 1529, but the attendant cold-wall heat fluxes differ by about 30 percent. Apparently the higher heat flux specified in UL 1709 reflects the actual furnace-specific characteristics of the UL furnace (wall/flame emissivity, etc.) when operating at the specified temperature.

UL 1709 FIRE EXPOSURE		
Temperature	Total Cold-Wall Heat Flux	Convective Heat Flux
1093 ± 111 °C within 5 minutes and maintained for the duration of the test.	204 ± 16 kW/m^2 within 5 minutes and maintained for the duration of the test.	Not Specified

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[28] More accurately, the average temperature of furnace thermocouples, located in the furnace gases about 150 mm from the exposed surface of the specimen, is specified.

2.5 CONCLUSIONS

1. Hydrocarbon temperature-time curves appear to be the only alternative curves widely used for fire-endurance testing.

2. No record has been found to indicate that fire-endurance testing has been conducted to qualify a building element or assembly using any curve other than the standard temperature-time curve or a hydrocarbon curve. In the course of the present review, the only record of fire-endurance testing of building elements or systems with an alternative curve was that found in the NBS recreation-room study.

3. The literature suggests that the development of any new temperature-time curves for compartment applications likely will rely heavily on mathematical modeling because of the need to consider a wide variety of configurations.

4. Alternative temperature-time curves generated by mathematical room-fire models are sanctioned by Swedish regulations for design calculations.

5. To date, a major weakness of room-fire models lies in their inability to simulate accurately burning rates under real-fire conditions. For example, much of the modeling work aimed at creating alternative temperature-time exposures has been based on the burning characteristics of cellulosic fuels. Also, such models only simulate the simplest type of room ventilation -- an opening to the outside environment. Development of credible temperature-time curves for nuclear power plant (NPP) applications will require better understanding of the burning behavior of NPP-specific fuel packages -- for example, cable bundles -- and more advanced ventilation considerations.

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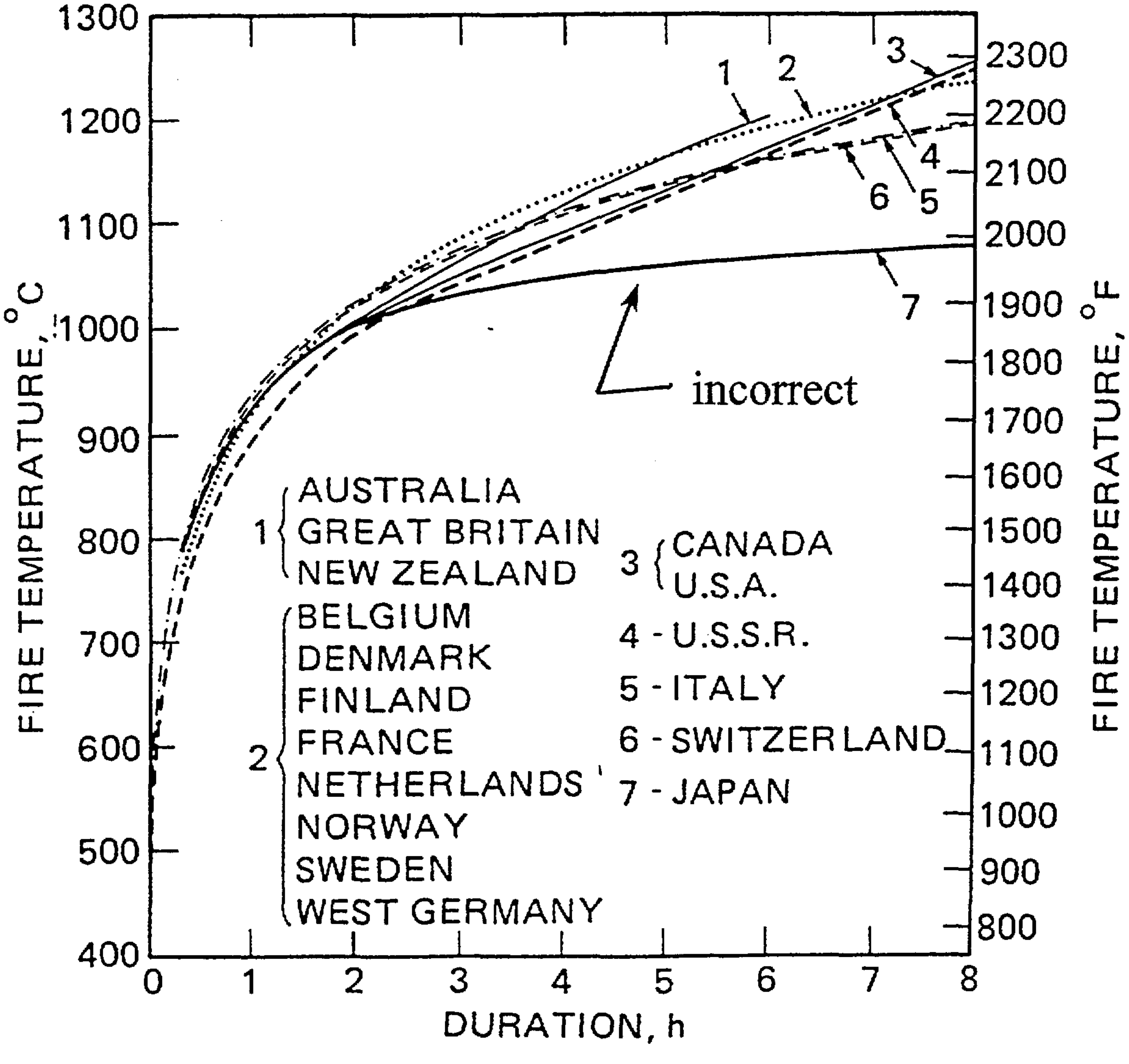


Figure 2-1. Standard temperature-time curves used in various countries for testing of building elements (reproduced from [2-5] and "incorrect" label added). See footnote 22, section 2.2.

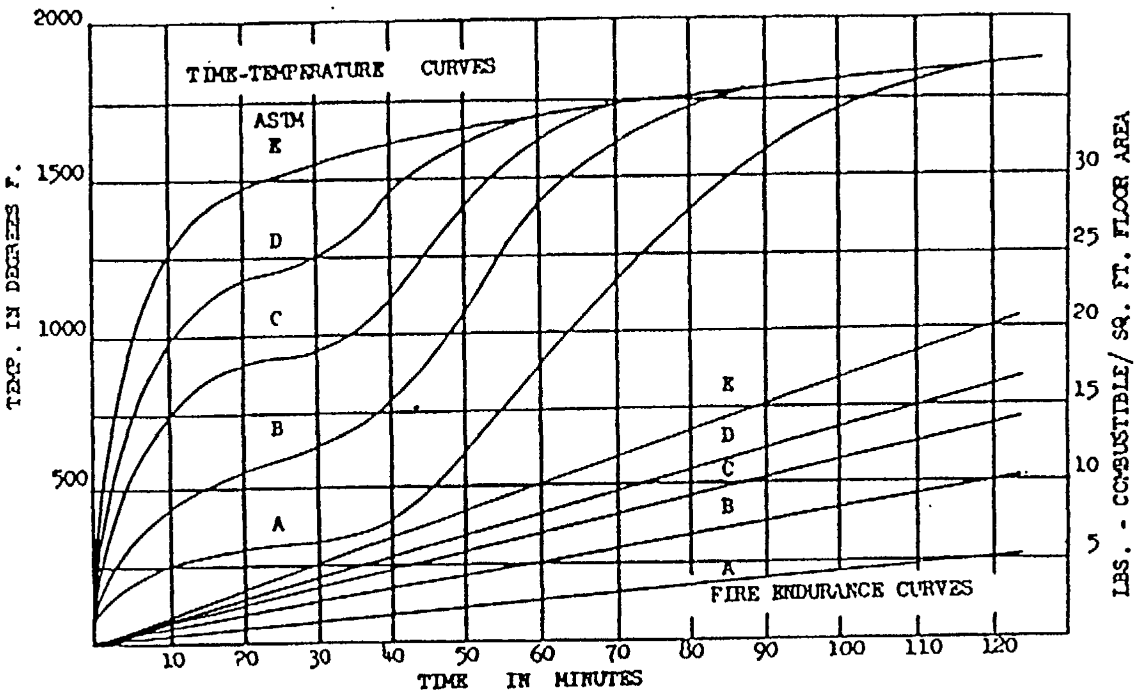
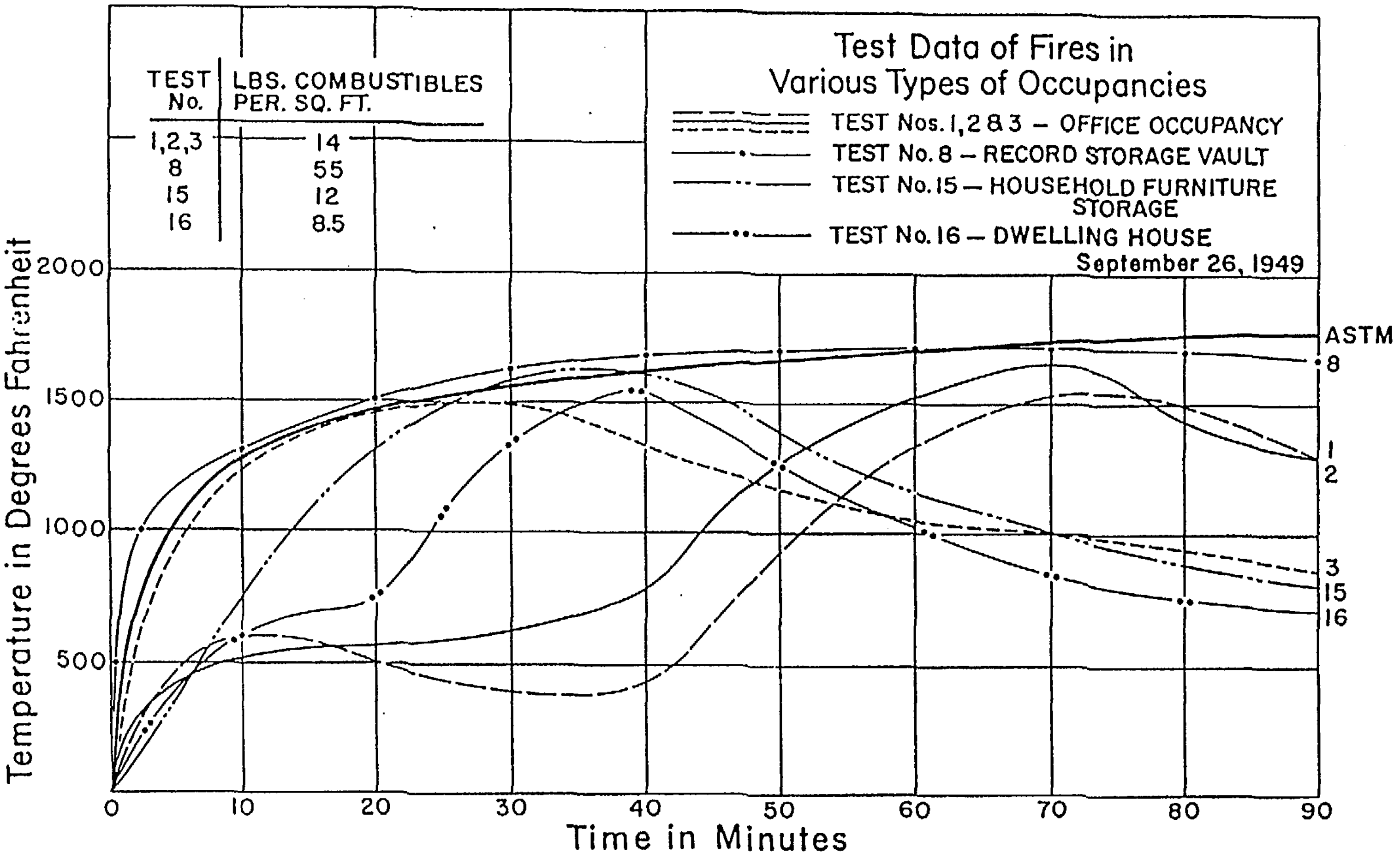


Figure 2-2. Possible classification of building contents for fire severity and duration. The straight lines indicate the length of fire based upon amounts of combustibles involved. The curved lines indicate the severity expected for the various occupancies, see table.. There is no direct relationship between the straight and curved lines, but, for example, 10 pounds of combustibles per square foot will produce a 90-minute fire in a "C" occupancy and a fire severity following the time-temperature curve "C" might be expected (reproduced from [2-7]).



Tests Nos. 1, 2 and 3 show temperature curves for fire in an office occupancy of wooden furniture with a representative amount of paper in files and in and on top of desks. Test No. 8 shows the fire curve for a record storage room in which a representative amount of ordinary paper records was stored on wooden shelves. Test No. 15 shows the fire curve for a household furniture storage area. Test No. 16 shows the fire curve for a dwelling house occupancy containing a living room, dining room and kitchen. The information in this table was supplied the author by Mr. S. H. Ingberg.

Figure 2-3. Ingberg's curves used by Corson (reproduced from [2-7]).

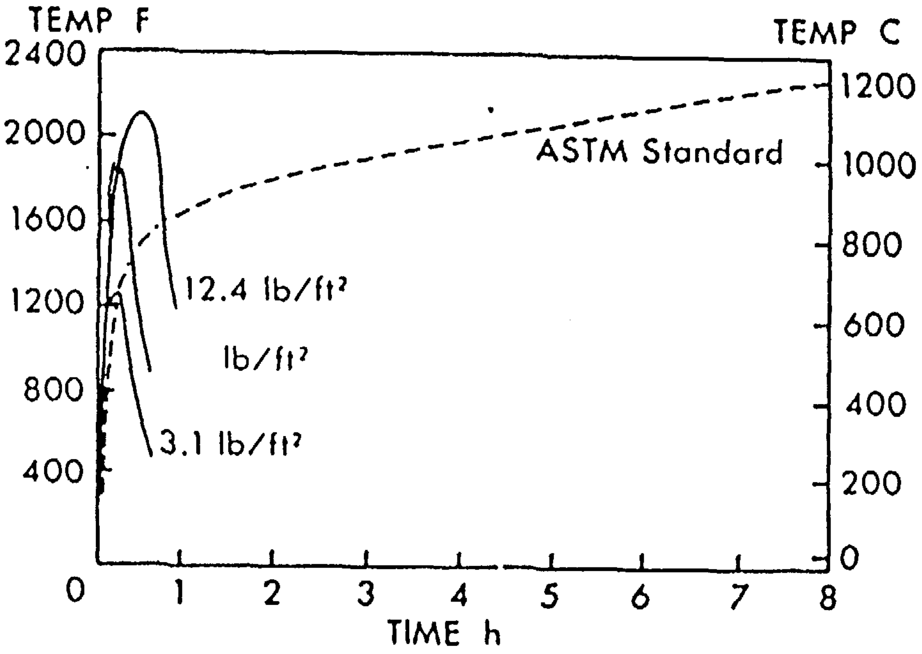


Figure 2-4. Temperatures in compartment fires (reproduced from [2-9]).

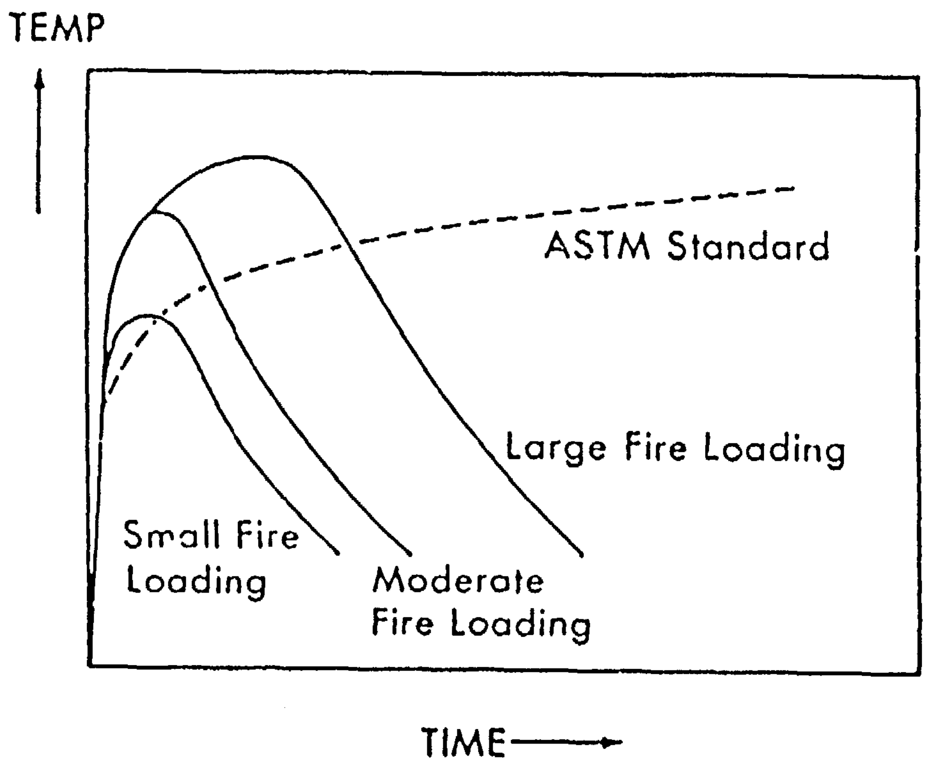


Figure 2-5. Suggested severity curves for fire tests (reproduced from [2-9]).

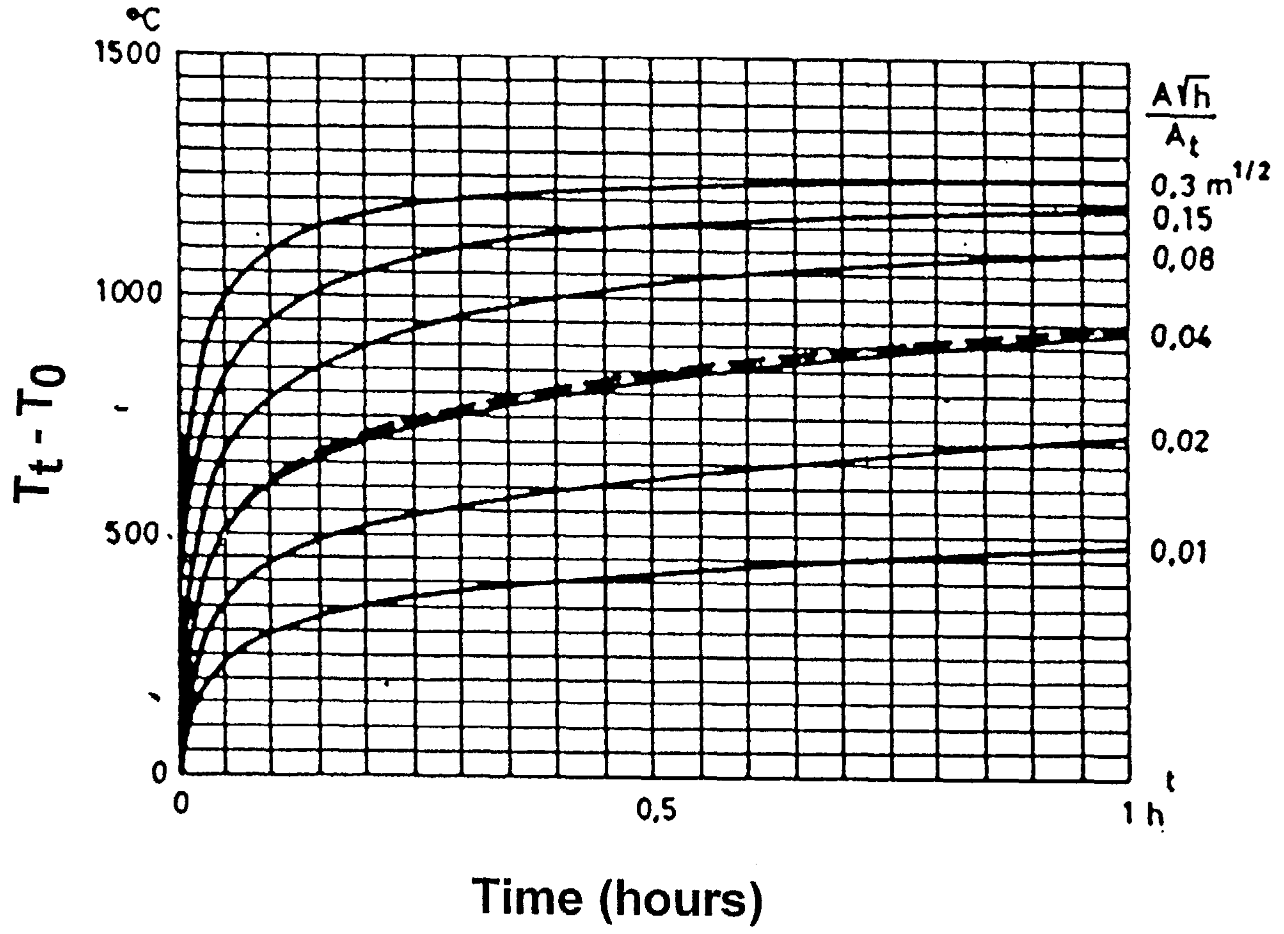


Figure 2-6. Relationship between the fire compartment temperature T_t during the heating phase (flame phase) and the time t according to Swedish Building Regulations SBN 67 for some opening factors $Ah^{½}/A_t$ for a fire load mainly of the wood type. T_0 = fire compartment temperature at t=0. The dashed curve is the standard fire curve ... (reproduced from [2-17]).

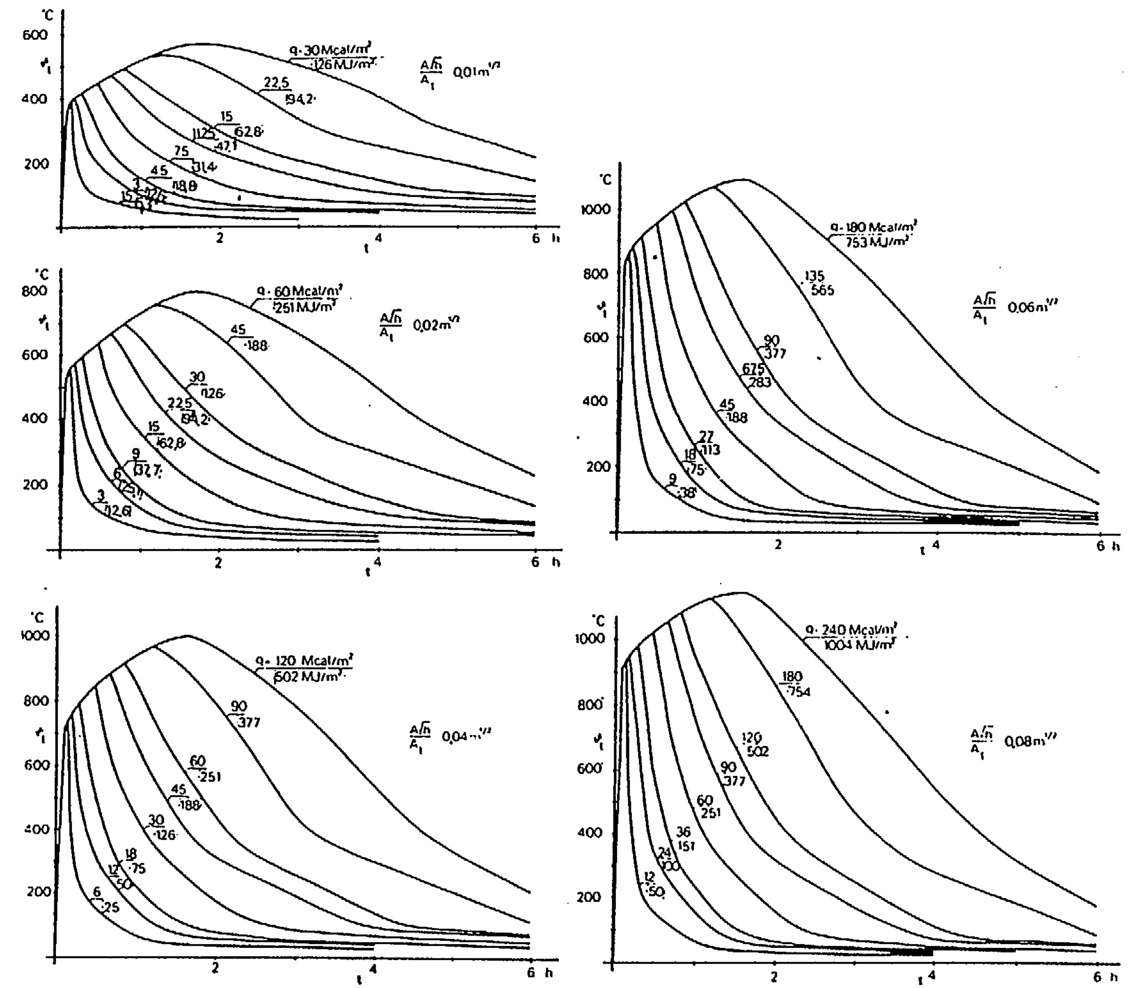


Figure 2-7. Calculated gas temperature-time curves for complete fire processes for different fire loads q and opening factors $Ah^{1/2}/A_t$ in fire compartment Type A (standard fire cell), the fuel being of wooden type ... (reproduced from [2-17]).

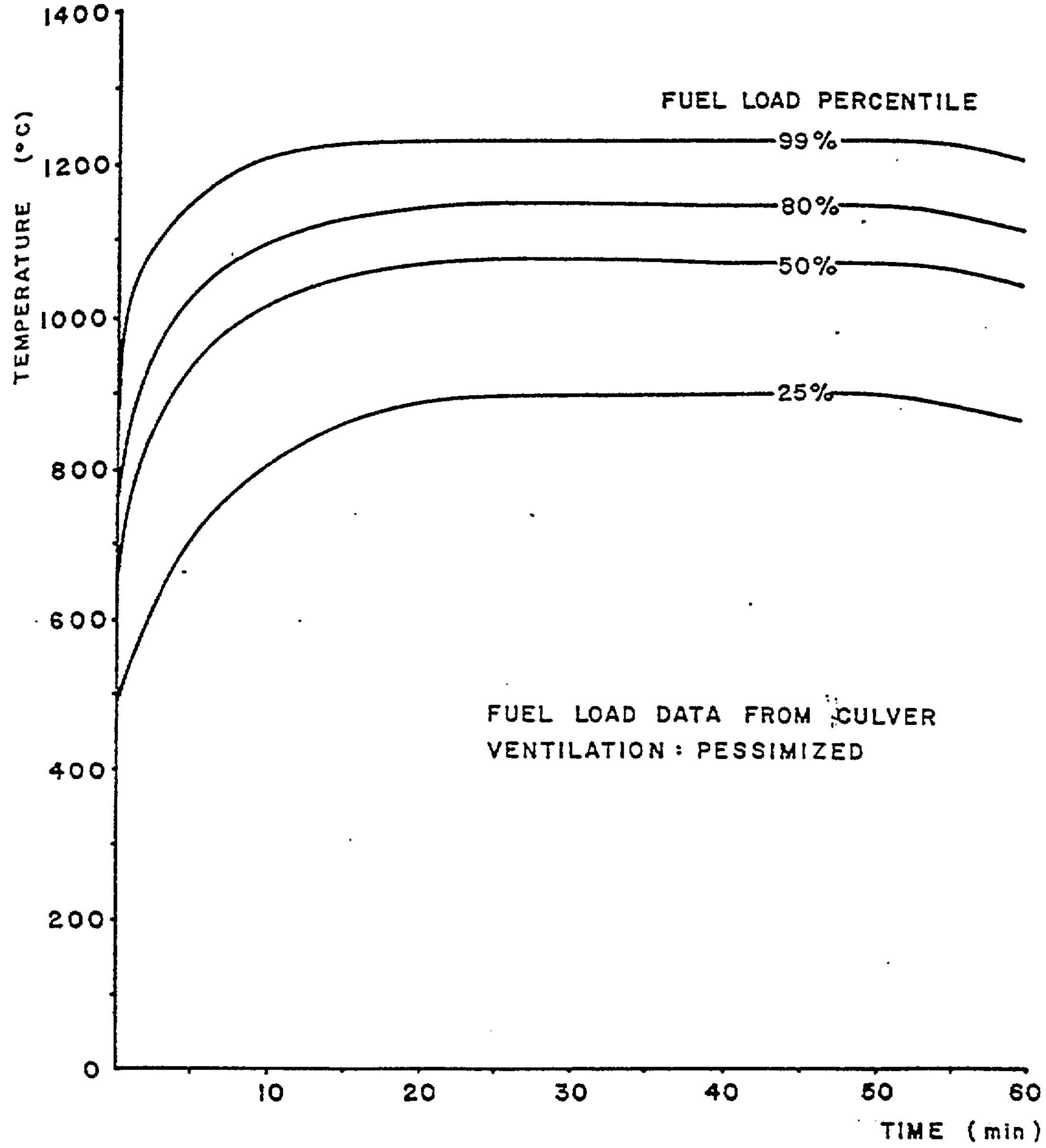


Figure 2-8. Predicted fires in offices (reproduced from [2-20]).

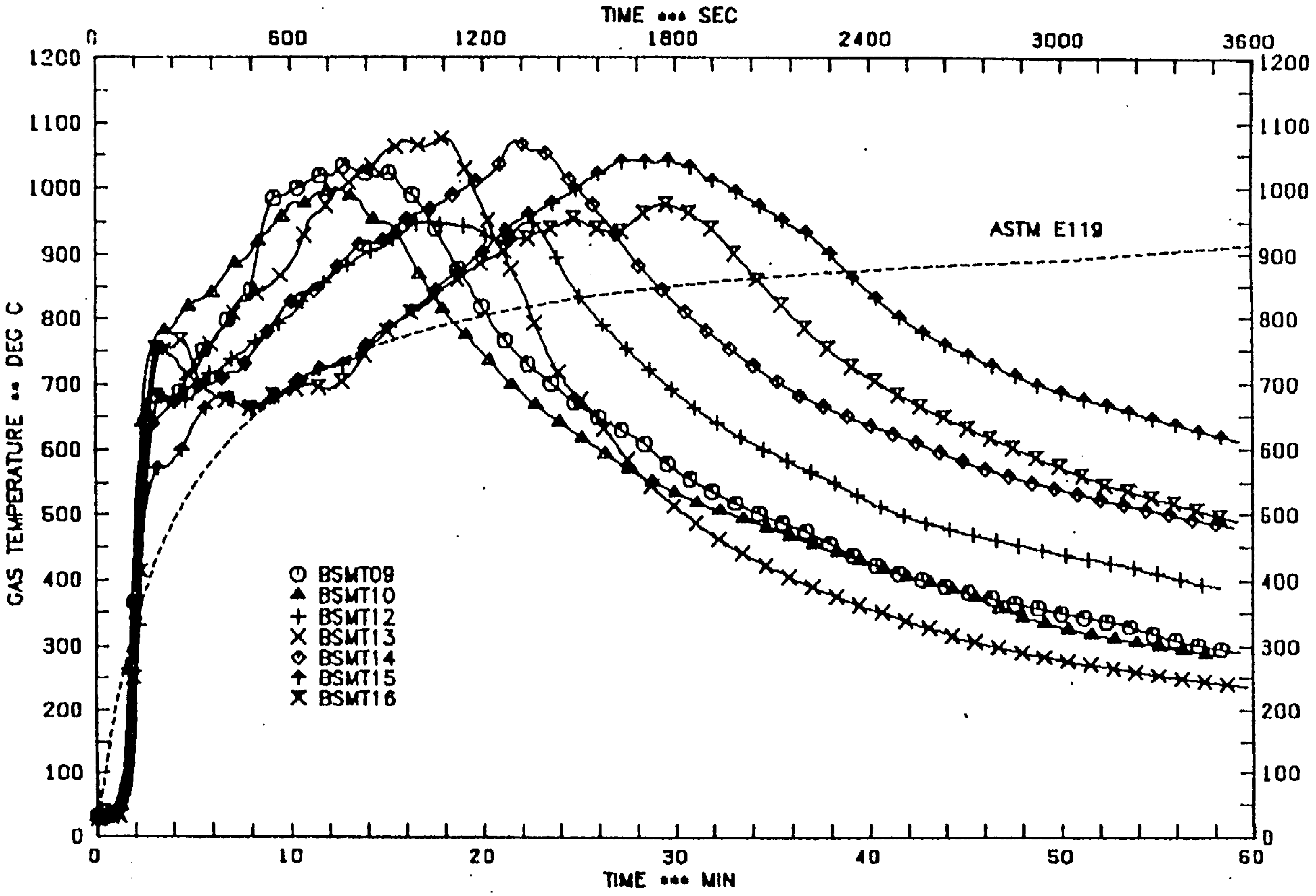


Figure 2-9. The range of variation in average gas temperatures for residential room fires (reproduced from [2-22]).

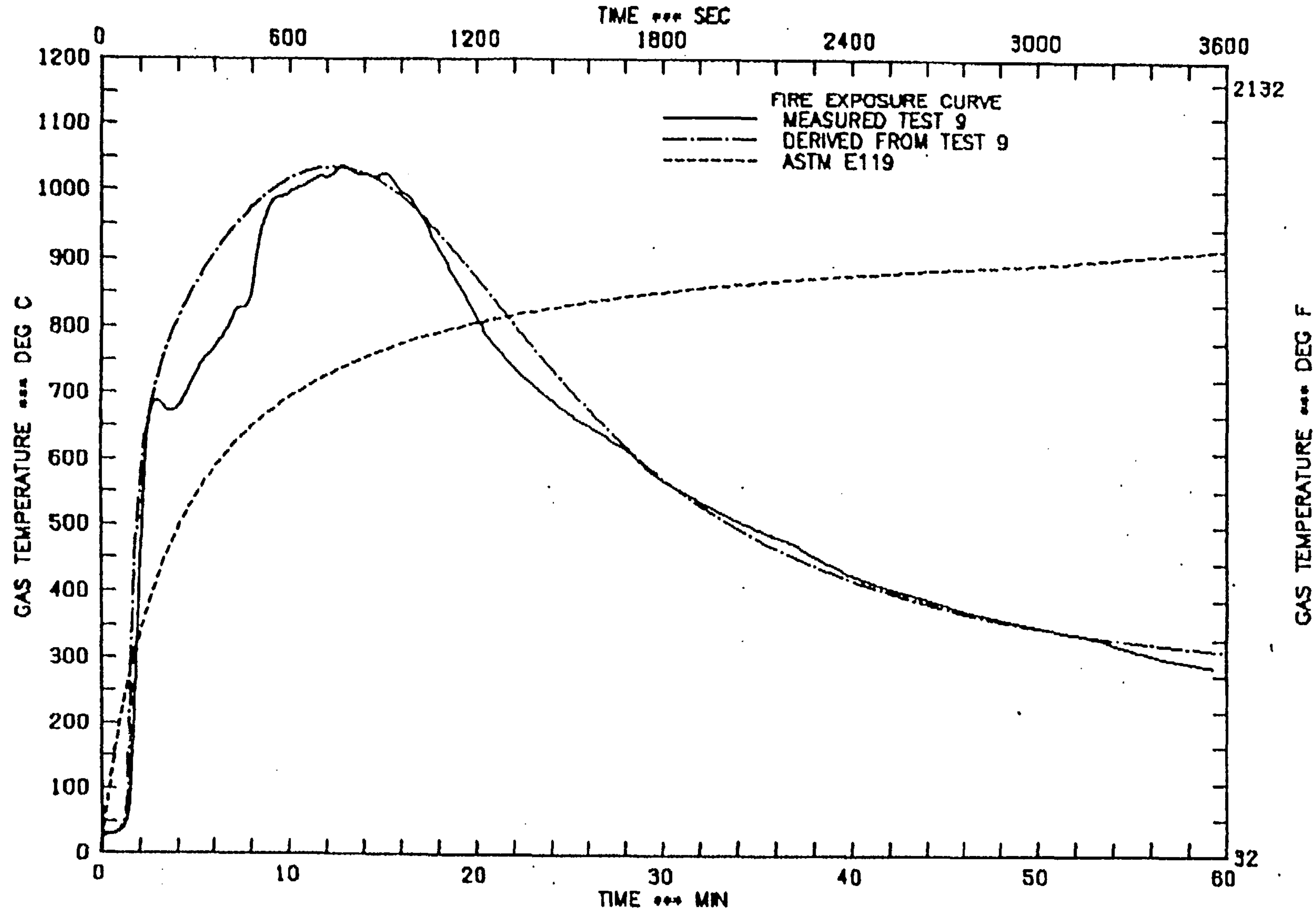


Figure 2-10. Comparison of fire exposure curve derived from room fire test 9 (BSMT09) and ASTM E 119 (reproduced from [2-22]).

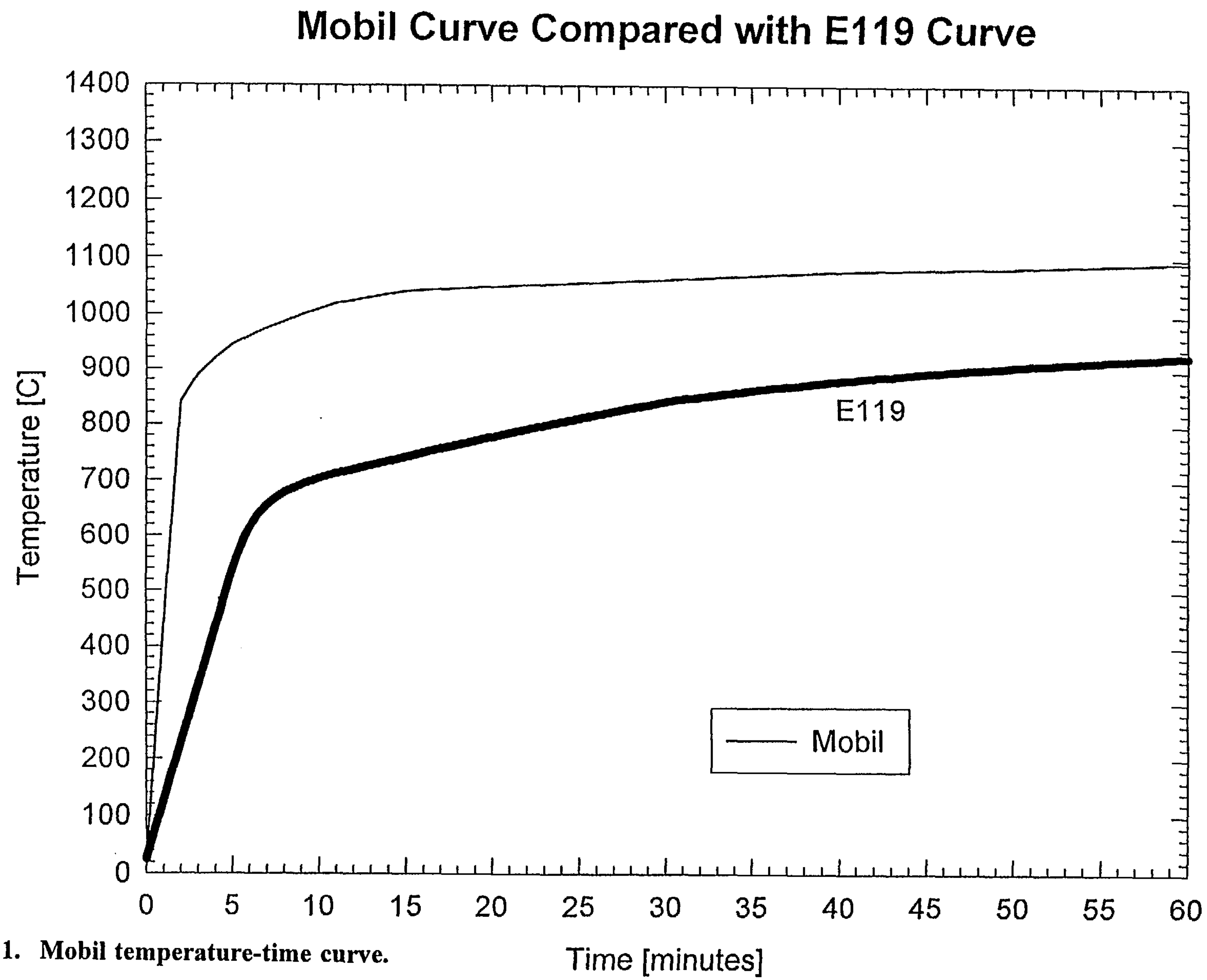


Figure 2-11. Mobil temperature-time curve.

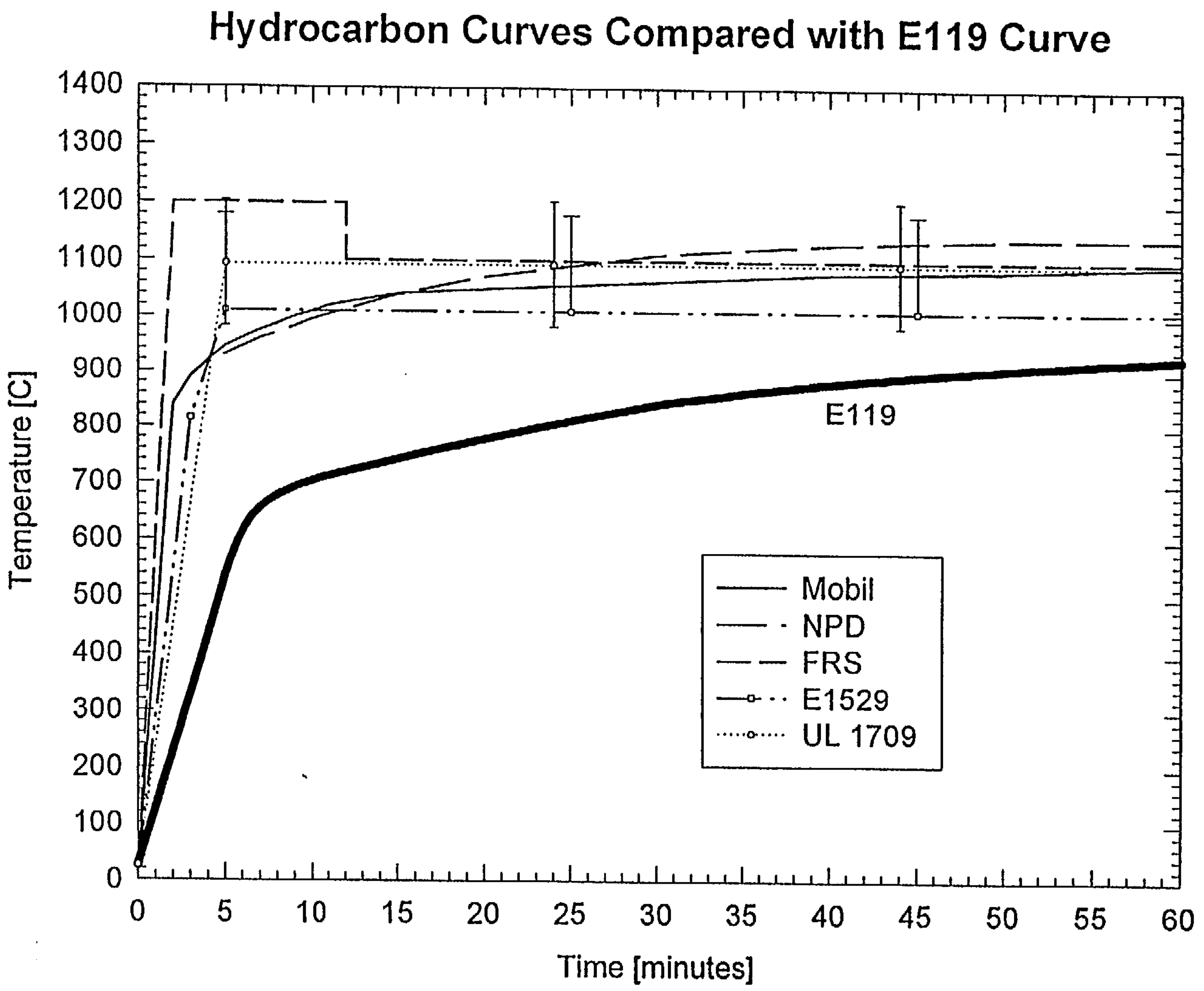


Figure 2-12. Hydrocarbon curves compared with ASTM E 119 curve.

PART 3. FEASIBILITY OF DEVELOPING AND IMPLEMENTING NPP-SPECIFIC DESCRIPTIONS OF FIRE ENVIRONMENTS FOR USE IN EVALUATING THE FIRE RESISTANCE OF FIRE BARRIERS

LIST OF FIGURES - PART 3

LIST OF TABLES - PART 3

Page

SUMMARY - PART 3

Part 3 of this document assesses the feasibility of developing and implementing Nuclear Power Plant (NPP)-specific descriptions of fire environments and alternative ASTM E 119-*type* temperature-time fire curves for evaluating the fire resistance of fire barriers, including structural building components. Advances in fire science over the past 40 years have offered the potential for developing technically-sound alternative curves for use in areas where fire exposures can be expected to be significantly different than the standard temperature-time exposure. For example, during the 1970s and 1980s, several countries, including the United States, developed and implemented technically-sound alternative curves for testing fire barriers that might be subjected to open-air hydrocarbon pool fires.

The NRC staff has initiated the current effort to investigate the feasibility of developing alternative temperature-time curves for the qualification of fire barriers used to protect cabling and equipment necessary to achieve safe shutdown on the basis of realistic fire hazards found in NPPs. The present work 1) begins with a discussion of the problem of defining the fire exposure with which to evaluate fire barrier performance, 2) identifies NPP-specific arrays of combustibles and compartment-configuration characteristics that critically influence fire severity, and 3) proposes a methodology for evaluating NPP-specific fire-barrier performance. This methodology would incorporate: an advanced, practical, mathematical compartment model to simulate NPP-specific fire environments; ASTM E 119-*type* full-scale furnace tests; and additional test methods, to be developed and applied as required, that would simulate barrier response to exposures of sustained direct flame impingement. Key elements of the model are outlined.

3.1 INTRODUCTION: THE OBJECTIVE AND AN OVERVIEW

One aspect of fire safety in NPPs has to do with the performance of fire barriers designed explicitly to protect components, equipment, etc., on the protected side of the barrier, from potential threatening fire environments on the fire-exposed side. It is the objective of this work to propose a methodology of evaluating NPP fire barrier performance that takes into account NPP-specific fire environments.

Advances in fire science over the past 40 years have offered the potential for developing technically-sound alternative curves for use in areas where fire exposures can be expected to be significantly different than the standard temperature-time exposure (see Part 2). For example, during the 1970s and 1980s, several countries, including the United States, developed and implemented technically-sound alternative curves, for testing fire barriers that might be subjected to open-air hydrocarbon pool fires [3-1,3-2][29] (see Part 2, section 2.4).

Part 3 of this document will assess the feasibility of developing and implementing NPP-specific descriptions of fire environments for use in evaluating the fire resistance of fire barriers. These include ***structural barriers***, useful in isolating a compartment of fire origin from adjacent spaces, and ***wrap assemblies*** [3-3], used to isolate and protect plant equipment, cables, etc., within a compartment of fire origin, from the effects of exposure to the fire environment.

A discussion on the nature of fire barrier exposure to the compartment fire environment will be presented. This will distinguish between ***direct exposure*** to the most extreme zones of the fire environment, e.g., direct, sustained exposure of the barrier to the flame, and ***indirect exposure***, where the fire barrier is mainly exposed to the average properties of the overall fire environment. The problem of evaluating the integrity of fire barriers to both kinds of threats will be addressed.

The problem of defining the fire exposure with which to evaluate fire barrier performance is discussed. It is shown that the use of ***ASTM E 119-type*** test methods, where the standard ASTM E 119 fire [3-4] is replaced by alternative temperature-time furnace fires and where the alternative fires would be deduced from reliable fire model simulations, has promise.

A methodology for evaluating the fire performance of NPP fire barriers will be presented. As will be seen, this relies on a combined experimental and analytic approach that involves the ***Bounding-Temperature Principle*** (i.e., if the temperature-time curve of one fire environment bounds that of another, then, relative to the threat to structural integrity of a NPP fire barrier, the bounding-curve environment is the more severe.) Experiments would involve ASTM E 119-*type* tests, to address indirect exposure threats, and other tests that would be devised to deal with direct exposure threats. Analysis would involve compartment fire modeling methods. Computer simulations would be carried out with a new, advanced, special-purpose, zone-type fire model developed to include features particularly relevant to simulating fire environments that threaten NPP fire barriers, from the point of view of both direct and indirect fire exposure.

Based on a review of the literature of NPP-specific combustibles and previously-developed NPP-specific fire models, special features required of the new fire model will be identified. These include: the simulation of ***fully-developed burning*** of extensive dense arrays of cable trays (i.e., all exposed surfaces of a combustible cable are supplying fuel (losing mass) due to either heating by the fire environment or surface combustion), both under fuel-controlled and ventilation-controlled conditions; the simulation of combustible/flammable liquid pool fires; the simulation of the fire environment in multi-room facilities (at least two adjacent spaces); and advanced means of modeling ventilation and radiation-heat-transfer-related phenomena. It is proposed that a new special-purpose model with these features be developed as a customized advanced version of an existing, two-layer, multi-room, zone-type fire model.

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[29] Numbers in brackets with designation [3-#] refer to literature references listed at the end of Part 3 of this document.

The new model would be used to simulate a wide variety of potential fire scenarios in rooms of fire origin of selected NPPs. The simulations would lead to new insights on the characteristics of real, fire-barrier-threatening, NPP fire environments, including both indirect and direct exposures. Based on applications of the Bounding-Temperature Principle, the simulated fire scenarios would lead to a series of NPP-specific test fire curves covering a wide range of NPP-type fire severities. An experimental study on available ASTM E 119-*type* test furnaces would be carried out to establish that these new test fire curves (instead of the standard ASTM E 119 fire curve) can be used in ASTM E 119-*type* barrier rating tests. Then ASTM E 119-*type* tests using the new NPP-specific test fire curves would be established as the method of evaluating the fire performance of NPP fire barriers against indirect threats.

Based on all the above, six specific tasks are proposed that would lead to a reliable methodology for evaluating NPP fire barrier performance.

3.2 TWO TYPES OF FIRE BARRIERS: STRUCTURAL BARRIERS AND WRAP ASSEMBLIES

In NPPs, two types of fire barriers are of interest, *structural* fire barriers and the fire barrier *wrap assemblies.*

The ***structural-type fire barrier*** is common to all types of building facilities, including NPPs. Reference here is to certain wall/ceiling/floor elements, designed to define and separate one compartment or room of a facility from another. Such a barrier may or may not be load-bearing. It would be designated as a fire barrier in the sense that, for a specified time interval, a successful design would protect the contents of a compartment, on one side of the barrier, from the effects of a fire in the compartment on the other side of the barrier.

To the extent that the collapse of isolated load-bearing columns and beams would typically lead to the failure of wall/ceiling/floor fire barriers, such columns and beams are also considered to be structural fire barriers. As such, successful designs of these latter structural elements must also be able to sustain exposure to an appropriate compartment fire environment, for a design-specified time interval, without threat of collapse.

The second type of fire barrier, the ***wrap assembly fire barrier***, is particularly important in NPPs. This includes barriers that are more-or-less fully contained within a NPP compartment of potential fire origin. Such barriers enclose and separate protected equipment from the rest of the compartment. They must perform their protecting function when installed under realistic field conditions and while exposed to the compartment fire environment for a design-specified time interval. Thus, in the event that a fire develops within the compartment, a successful fire-barrier wrap-assembly design would be one which will maintain its integrity to the extent that the environment within the barrier enclosure will not be so severe as to lead to fire damage of the protected equipment. In NPPs, a typical wrap-assembly fire barrier is the barrier enclosure that isolates one redundant critical set of cables in a NPP compartment of interest from the other set, the latter set being installed without barrier protection, somewhere within the compartment [3-5].

3.3 ASTM E 119 AND THE ASTM E 119-*TYPE* APPROACH TO THE EVALUATION OF STRUCTURAL-TYPE BARRIER PERFORMANCE

The ASTM E 119 test method involves three major elements: a facility to carry out furnace testing of full-scale test specimens, a standard temperature-time curve that specifies the furnace fire environment, and specified acceptance criteria for establishing structural integrity of the exposed specimens. (For some types of structural elements, acceptance criteria include the ability of a test specimen to sustain a fire and hose stream test. This aspect of the ASTM E 119 test will not be addressed further.) In general, a clear correspondence between the standard fire and real threatening fires is unavailable (see Part 1). However, it should be possible to purposefully develop alternative, achievable, furnace-fire environments, for use in ASTM E 119-*type* test methods, that correspond by design to real fire scenarios of interest. The idea of developing and using such alternative temperature-time curves to replace the standard temperature-time curve in ASTM E 119 has already been used in the case of simulating exposures to large hydrocarbon pool fires [3-1].

Here the terminology ***ASTM E 119-type*** test method is used to refer to a test method that basically follows the ASTM E 119 test procedures, but where the ASTM E 119 standard temperature-time curve is replaced with a relevant alternative curve. Of interest here are NPP-specific temperature-time curves.

3.4 STRUCTURAL BARRIERS, WRAP ASSEMBLIES AND ASTM E 119

3.4.1 A Characteristic that Distinguishes Between Structural Barriers and Wrap Assemblies

For the purpose of the present discussion, a characteristic that distinguishes structural-type from wrap-assembly-type fire barriers is whether or not it is possible for ASTM E 119 to be applied without ambiguity. In the case of structural-type barriers, it is possible. In the case of wrap-assemblies, the nature of the barriers' physical design would preclude an unambiguous application of ASTM E 119.

The above discussion leads to the following questions:

> **Structural-type fire barriers**. Relative to evaluating the fire performance of NPP structural-type fire barriers by ASTM E 119, are there situations where the test method should be modified and/or replaced, and if so, what is the alternative?
>
> **Wrap-assembly-type fire barriers**. Relative to evaluating the fire performance of NPP wrap-assembly-type fire barriers, are the basic features of ASTM E 119 applicable? If so,

then how should the details of the test method (e.g., requirements for type of furnace, specimen extent and placement in the furnace, conditions for acceptance, etc.) be changed to accommodate the characteristics of a particular wrap-assembly-type of barrier of interest? If not, then what is the alternative?

In the case of wrap assemblies the above questions are addressed in NRC Generic Letter 86-10, Supplement 1 [3-8]. It is also noteworthy that the ASTM E5.11 Committee on Construction Assemblies is presently working to respond partially to the above questions on ASTM E 119 applicability. In this regard, the E5.11.08 Sub-Committee on Cable Tray Protection has developed and is now evaluating the new draft standard: Standard Test Methods for Fire Tests of Fire-Resistive-Barrier Systems for Electrical System Components [3-9]. Similarly, the Underwriters Laboratory is in the process of developing a new standard: Standard for Thermal Barrier Systems for Electrical System Components [3-10].

3.4.2 Describing Fire Exposure and Evaluating Fire Barrier Performance

In principle, evaluations of the performance of a particular fire barrier design should be made relative to: 1) fire environments that could conceivably develop on the fire-exposed side of the barrier; 2) time intervals required for protection (i.e., the entire duration of the fires, assuming that they are not suppressed, or some other specified time intervals); and 3) specified bounds that characterize an acceptable environment in the space on the protected side of the barrier, an environment in which satisfactory functioning of the protected equipments is assured. In practice, such performance evaluations must also include the use of good engineering judgement, leading to appropriate levels of margins of safety, i.e., providing enough protection to account for uncertainty in analytic methodology, degradation of a constructed barrier over time, etc.

Assume that a detailed description of the compartment of fire origin and of additional compartments that would potentially influence fire development in it are known. (The description of the compartments would include: dimensions of the spaces; quantity, arrangement, and material properties of combustibles; HVAC system characteristics and its status; characteristics of barrier penetrations, including the opening status of doors and other variable-area vents; and, if relevant, exterior weather conditions, especially wind conditions.) Assume that the details of an ignition source of a particular fire scenario of interest are also known. Then, in principle, one would hope to be able to: estimate characteristics of the developing fire environment; determine the thermal and structural response of the fire-exposed barrier and the environment in the protected space; and, finally, evaluate barrier integrity. However, in practice, it is beyond the scope of current science and technology to describe from basic principles several of the fundamental and critical processes that drive the overall phenomenology of interest. For example, the solution from first principles to the critical generic problem of fire spread and growth through realistic arrays of practical combustibles is not feasible (e.g., fire spread from a specified open flame across a stuffed chair of specified design, or along cables of a specific design, placed, according to a specified cable density and arrangement, in stacked steel trays of specified design and orientation).

Fortunately, the most important problems of fire safety can typically be expressed in terms that successfully avoid the above type of technically intractable formulations, and that can yield solutions of satisfactory reliability. Indeed, a major role and challenge of fire safety science and technology is to formulate tractable problems whose solutions result in fire safe designs and/or design practices that lead to improved reliability and/or economy. For example, while fire safety in a facility can be achieved generally if ignition or early fire growth is completely eliminated, in practical terms such elimination is usually not possible. Therefore, instead of dealing with the issues of eliminating ignition, one often deals with problems of fire safety in facilities by first positing a realistic design-fire threat, and then formulating and solving a now-tractable problem of fire safety in terms of determining how to provide the desired level of safety "given initiation of the design fire."

Examples of currently accepted practices with potential for improved reliability and/or economy are those that depend on the fire barrier ratings methods based on equivalency rules and ASTM E 119. Thus, it is possible that currently accepted practices are unnecessarily conservative, and in some instances, perhaps not conservative at all. When such is the case, application of advanced fire safety science and technology can be used to guide the development of improved practices.

As will be discussed below, careful problem formulation and current technology together can provide important opportunities for future advances and refinements in may areas of fire safety, including the problem area of interest here, *viz.*, the evaluation of NPP fire barrier performance.

3.5 EXPOSURE TO THE INDIRECT AND DIRECT EFFECTS OF THE FIRE: TWO TYPES OF THREAT

Introduced above was the idea that fire barrier performance is evaluated relative to exposure to a particular specified fire environment or a class of fire environments, i.e., the fire or class of fires that could develop in the barrier-bounded compartments of fire origin. In developing this idea further, it will be useful to distinguish between two aspects of such fire exposures, *indirect* and *direct*. This is introduced with the following discussion of fire environments and their simulation.

3.5.1 The One- or Two-Layer Description of the Fire Environment and Zone-Type Compartment Fire Modeling

As a fire grows and spreads through the combustibles in a compartment, it has been observed that the environment of the bulk of the volume of the compartment can be reasonably described by two relatively-uniform stratified layers, a relatively-hot and smokey upper layer and a relatively-cool and uncontaminated lower layer, or, as is the case in many important fire scenarios, by a single relatively-uniform layer that fills the entire compartment. This observation is the basis of two-layer zone-type mathematical compartment fire models.

When a two-layer or single-layer description of the fire environment is appropriate, the thickness of the layers as well as the properties of the layers or layer are typically time-dependent. (In the case of a two-layer environment, when one of the layers effectively shrinks to zero thickness, the bulk environment of the entire compartment is approximated by the spatially-averaged properties of the single remaining layer.) The time dependence is the result of:

- the action of fire combustion zones which continuously generate rising, lateral-entraining plumes of hot combustion products, where the plumes typically rise to the ceiling of the compartment and are deposited and mixed into the upper layer;
- convective and radiative heat transfer exchanges between bounding surfaces of the layers (including the walls, ceiling, and floor of the compartment), the layer gases, and the combustion zone; and
- cross-vent (e.g., cross-door, -window, -HVAC-diffuser or HVAC-exhaust vents) convective heat and mass transfer exchanges between the layers of the compartment of fire origin and adjacent spaces.

Many of these phenomena typically take place within and across relatively small-volume (compared to the volume of the compartment) zones, e.g., the combustion zone, the plume, zones defined by plume-driven near-ceiling boundary flows or near-wall boundary flows, etc., where these zones are submerged within the layers [3-11,3-12]. Fire scenarios involving a burning array of cable trays and a pool fire are depicted in Figs. 3-1 and 3-2, respectively.

In terms of predicting the developing fire environment, the two-layer, zone-type, compartment-fire-modeling methodology has proven to be very useful in the analysis of a variety of different kinds of problems of fire safety, and many such fire models have been developed over the last few decades. Such models are constructed by modeling mathematically the above transfer phenomena in ways that are consistent with conservation of energy, momentum, species, etc. and the basic two-layer description. In this regard, perhaps the most significant differences between the various available models are associated with the number of and sophistication with which individual physical phenomena are taken into account. As a result of such differences, the inevitable limitations of zone models will correspondingly differ one from the other. Examples of zone-type compartment fire models that were developed specifically to simulate fire environments in NPPs are COMPBRN III [3-13] (a two-layer model) and the Fuel Load/Ventilation Model [3-14] (a single-layer model).

3.5.2 The Indirect and Direct Effects of the Fire and Applicability of ASTM E 119-*Type* Test Methods

From the above discussion, it is clear that for any particular compartment fire scenario, the fire-environment exposure of the surface of a barrier in question will vary as a function of position and time. However, even though a full-scale compartment fire experiment can, in principle, yield data on time- and position-dependent exposure for a particular fire scenario and barrier design, and even though it may be possible to simulate such exposure by mathematical modeling methods, it is rarely practical that such detail would be useful in specifying a fire exposure with which to evaluate the performance of a multi-use barrier design. Also, even in a particular application, the nature of possible real fire scenarios typically have significant stochastic aspects (e.g., the actual amount of combustibles, the location of the fire relative to the barrier surface, etc.)

In many practical fire scenarios, all of a barrier surface, or most of a barrier surface for most of the time will be removed from direct exposure to the relatively-small, but particularly threatening zones of a compartment fire environment (i.e., the combustion zone, near-surface boundary zones in the vicinity of plume/surface impingement points above the fire plumes, etc.). Under such circumstances, for evaluating barrier fire performance it is often reasonable to let the spatially-averaged temperature history of the (upper layer) fire environment define the fire exposure. Exposures to such spatially-averaged environments lead to what are designated here as the ***indirect effects*** of the fire.

When the specified temperature-time description of a furnace fire simulates, in some sense, the spatially-averaged temperature of the threatening fire environment, it would appear from the above that use of an ASTM E 119-*type* test method to evaluate barrier fire performance is well justified. Thus, when the ASTM E 119 standard fire is a reasonable and conservative surrogate for the temperature-time history of the average compartment fire environment of real, structure-threatening fire scenarios, ASTM E 119 evaluations of structural barriers would appear to yield valid determinations of barrier performance relative to exposures from the indirect effects of the fire. (It is noteworthy that the methodology developed in reference [3-14] is consistent with this reasoning.) However, it is clear that such evaluations discount the importance of possible severe fire exposures from direct and sustained flame/barrier impingement. Such kinds of intense exposures lead to what are designated here as the ***direct effects*** of the fire.

The latter, unusual, sustained, and problematic type of fire threat to barrier integrity, defined by the direct fire exposure, may be important in NPP applications.

3.5.3 Using the Direct and Indirect Fire Exposure to Define the Fire-Barrier Threat

As mentioned, where the ASTM E 119 test method is used to evaluate fire-barrier performance, sustained direct fire exposures in the real fire scenario are not taken into account. It would appear that the justification for this is that combustibles in building facilities are typically well-distributed throughout the spaces, and that during the course of expected fire scenarios, combustion zone(s) would tend to shift from place to place within the compartment. Under such common circumstances, sole use of an ASTM E 119-*type* test method to evaluate fire barrier performance would be adequate.

However, there are special building compartment designs where sustained localized fuel concentrations exist, and where the ASTM E 119-*type* approach to evaluating barrier fire performance may not be adequate. For example, if the source of most of the fuel load in a building compartment was from a diked, ruptured, diesel-generator fuel tank, then the threatening fire scenario would be defined as that which would be generated by one or a series of geometrically-well-defined pool fires. For such scenarios, an evaluation, e.g., of ceiling fire-barrier performance that depended solely on exposure to an ASTM E 119-*type* furnace fire environment, that simulated well the average temperature-time of the real fire environment, may not be valid. Also recommended would be a second test, where, for some extended specified time interval, say for an interval that corresponds to the duration of the fire (that would have to be determined), the ceiling fire barrier was exposed to a test fire environment that simulated sustained direct-flame/plume impingement from the pool fire which is itself contained in the compartment fire environment.

ASTM E 1529 [3-1] is an example of a test method that is designed to simulate direct-flame/plume exposure, but in outside fire scenarios, rather than in compartment fire scenarios. This test method is used to simulate the fire performance of structural members and assemblies when exposed to large hydrocarbon fires. As reported in Part 2, section 2.4, the test exposure was developed from theoretical considerations and test data from a wide range of real-fire scenarios involving open-air spill and open-air fuel fires. ASTM E 1529 is similar to ASTM E 119, except that instead of using a temperature-time curve, the furnace test fire is specified in terms of heat flux to the exposed surface of the test specimen. The specified flux level must be attained within the first 5 min of testing, and it must be maintained for the duration of the evaluation. Reference [3-2] explains that a furnace with optically opaque walls can lead to a specified ASTM E 1529 fire exposure if the furnace-gas temperature rises to 1020 °C within the first five minutes of the initiation of the test, and if the gases are transparent and have in-furnace flow speeds of 10 m/s. It would appear that this is a more severe exposure than that resulting from the standard ASTM E 119 fire, which is specified as having a furnace gas temperature of 538 °C at 5 min, and which does not rise to 1020 °C until about 2.25 hours into the test.

Examples of scenarios in NPP spaces where the direct fire exposure would be significant are depicted in Figs. 3-1 to 3-3. Figure 3-1 involves *fully-developed burning* of a extended dense array of cable trays. The term ***fully-developed burning*** is intended to mean that all exposed surfaces of a combustible object are supplying fuel (losing mass) due to either heating by a fire environment or surface combustion. In this scenario, only the ceiling structure is exposed to the direct effects of the fire. The protected and unprotected pairs of cable trays at right side of the compartment are only exposed to relatively indirect effects of the fire, i.e., the upper layer environment. Thus, although they are shown as being submerged in the near-ceiling boundary flow, they are located far enough from fire/ceiling impingement that the somewhat more intense environment there, over and above the average upper layer environment, may be regarded as not significant. Figures 3-2 and 3-3 involve a large ruptured-fuel-tank-type pool fire, which can produce sustained and particularly intense exposures to the flame zone by virtue of the fact that the location of the pool, and therefore the flames, is assumed to be fixed (e.g., to a diked area of the pool and above it) throughout the entire fire scenario. In the scenario depicted in Fig. 3-2, only the ceiling above the pool is directly exposed to the flames. In Fig. 3-3, a pair of unprotected cable trays and a pair of wrap-assembly-protected cable trays are also directly exposed to the flames.

3.6 A CONCEPT FOR EVALUATING THE FIRE PERFORMANCE OF FIRE BARRIERS IN NUCLEAR POWER PLANTS - AN ALTERNATIVE TO TRADITIONAL APPLICATION OF ASTM E 119

3.6.1 An Alternative to ASTM E 119

The critical features of the alternative methodology are that it be *rational* (i.e., related to real NPP-specific fire environments and having a firm technical basis), *appropriately advanced* (uses the most advanced, appropriate, modeling methods), and *practical* (i.e., is based on tools of analysis that are readily available to and useable by fire safety practitioners, and realizable experimental methods that use readily available facilities).

3.6.2 A Concept For Evaluating the Fire Performance of Fire Barriers in Nuclear Power Plants

All the previous discussion suggests the following three-point concept for evaluating the fire performance of fire barriers in NPPs:

1. **Determine NPP fire environments**. Determine the characteristics of the real fire environments (direct and indirect exposures) in the compartments bounded by a (structural) barrier of interest, or within which a (wrap assembly) barrier of interest is installed. In making such determinations a mathematical modeling approach will be emphasized here, and modeling concepts for such an approach will be developed below. However, in special cases, full-scale compartment fire experiments may be necessary.

2. **Given the fire environment, define/identify methods for evaluating NPP fire barrier performance**. Define and/or identify methods for determining barrier fire performance when exposed to the real-fire environments determined from the above modeling or experimental methods.

   ***Indirect effects* of the fire:** Define an ASTM E 119-*type* test method for evaluating fire performance of the fire barrier when it is exposed to the indirect effects of the fire. In the test method, the temperature-time history of the furnace fire environment would simulate or, if that is not possible, bound the temperature-time histories of the real fire environments, determined according to the above methods. Here, the ASTM E 119-*type* test is emphasized. However, in special cases, and especially for structural barriers, it may be feasible and appropriate to determine the thermal and structural response of the barrier from mathematical modeling analyses. In such cases, the present task would be to identify the appropriate method of analyzing the fire performance (e.g., available finite-element computer models for simulating the thermal and structural response of the barrier [3-15]).

   ***Direct effects* of the fire**: If the nature of the barrier and compartment designs is such as to make sustained direct fire exposure likely, then the characteristics of this exposure, including its duration, would have been obtained from above methods. The task would be to develop a fire-barrier exposure fire test method and test duration that simulates or bounds these direct fire exposures. This would be used to evaluate fire performance of the fire barrier when it is exposed to the direct effects of the fire. Here, an experimental/test approach is emphasized. However, as in the case for indirect fire exposure, in special cases it may be feasible and appropriate to determine the thermal and structural response of the barrier to direct fire exposures from mathematical modeling analyses. (Note that the methodology presented in reference [3-3] represents an approach that models mathematically the direct fire threat. However, the modeling used there is limited in the sense that it does not include the effects of full room fire involvement.) In such cases, the present task would, again, be to identify the appropriate method of carrying out the evaluation of barrier response to the specified exposure.

3. **Evaluate NPP fire barrier performance**. Evaluate the fire performance of fire barriers by applying the test method(s) and/or method(s) of analysis of items 1 and 2 above.

The remainder of Part 3 will be concerned with the development of modeling ideas consistent with the above concept.

3.7 A COMPARTMENT FIRE MODEL FOR USE IN EVALUATING THE DIRECT AND INDIRECT THREATS TO FIRE BARRIERS IN NPPs

It is a major objective of this work to propose the development of a special-purpose compartment fire model suitable for use in evaluating the performance of fire barriers in NPP facilities exposed directly and/or indirectly to threatening pre- and post-flashover fire environments. Important special features of a such a model are identified in this section.

3.7.1 Mathematical Fire Models and Associated Computer Codes

Over the years, many general- and special-purpose mathematical models and associated computer codes for predicting the dynamics of compartment fires have been developed. For the most part, these can be divided into two categories, *field models* and *zone models.*

Field models incorporate global partial differential equations, which describe the relevant flow and heat transfer processes. They formulate and solve initial/boundary value problems for the unknown variables of compartment fire scenarios of interest.

Zone models describe the phenomena of the fire scenario in terms of coupled submodel algorithms or equations sets. Each algorithm describes a fire-generated process taking place in a particular physical zone of the compartment of interest. The individual algorithm equation sets typically involve the solution of algebraic equations (e.g., to estimate entrainment into and flow rate of a fire plume), integration of algebraic equations (e.g., to estimate the instantaneous total rate of convective heat transfer between a plume-driven ceiling jet and a ceiling surface), or the solution of ordinary or partial differential equations (e.g., to simulate heat conduction through a wall, ceiling, or floor). The mathematical coupling of the algorithm equation sets corresponds to the interdependence of the individual physical processes that occur throughout the different zones of the overall compartment fire environment.

The results of field model simulations typically provide significantly more detail of the fire-generated environment than do zone model simulations. Also, since the governing equations used in field model can describe from first principles the actual physical phenomena being simulated, field-type modeling has the potential for yielding the most accurate possible simulations. (An example of an important class of phenomenon that, in practical terms, currently defies accurate modeling is the combustion process itself.)

In general, field models are significantly more computational intensive than zone-type models and, for any particular simulation, they generally require significantly more effort to develop and implement input data. As a result of this, field models are typically not well-suited for use in parametric studies, e.g., in the trial-and-error-types of analyses often used to solve design problems. Such studies are efficiently addressed by zone-type models.

In view of the above, it is concluded that a multi-room, two-layer, zone-type, compartment-fire-model analysis, with sufficiently detailed submodel algorithms, would provide the best possible means of predicting real fire environments for use in determining the fire performance of NPP fire barriers.

3.7.2 General-Purpose and Special-Purpose Compartment Fire Models

A goal of the technology of zone-type compartment fire modeling is to develop a *general-purpose model* that is so rich in detail as to have near-universal utility and high reliability. A ***general-purpose model*** would be capable of simulating the early growth of fire conditions (i.e., pre-flashover, when not all exposed combustible surfaces are pyrolyzing, and/or burning) and the onset of smoke spread within and beyond compartments of fire origin, phenomena that are typically characterized by time scales of the order of seconds and minutes. Such a model would also be expected to simulate the relatively long-term quasi-steady aspects of fire environments, when available combustibles in compartments of fire origin may be fully-involved in the combustion process (i.e., post-flashover) and where important variations in the changing fire environment are typically characterized by intervals of tens of minutes to a few hours. Besides dealing with large differences in time scales, a general-purpose model would, ideally, also be capable of simulating details of fire growth and smoke spread, taking into account a wide variety of: types and arrangements of combustible assemblies, room-grouping arrangements and interconnections, physical properties of exposed surfaces, forced ventilation designs, etc.

Development toward high-quality general-purpose models has always been, and continues to be a major focus of fire research. In spite of this, when dealing with a particularly important problem area there is often justification to develop ***special-purpose models*** that focus on classes of fire phenomena and issues of special interest. When carrying out such development, appropriate proven concepts used in the general-purpose models are typically adopted, improved on and/or otherwise customized to satisfy the particular modeling requirements.

An important example of a class of special-purpose or customized compartment fire model is the fully-developed post-flashover fire model. Consistent with the concept introduced above (in section 3.6.2, "**A Concept For Evaluating the Fire Performance of Fire Barriers in Nuclear Power Plants**"), fully-developed fire models have been developed specifically to predict the long-term fire environments that threaten structural fire safety, where the simulations are used in the evaluation of structural fire performance. Such models are of particular interest here, since they deal with problems directly related to the class of problem at hand, i.e., determining the fire performance of fire barriers in NPPs. An example of a relatively-simple fully-developed fire model, developed explicitly to predict post-flashover fire environments in NPPs, is the Fuel Load/Ventilation Method fire model of reference [3-14].

Perhaps the most ambitious fire model developed explicitly to simulate NPP fire scenarios, is COMPBRN III [3-13]. This follows existing general-purpose types of models in that it includes the capability to simulate fire growth and early smoke spread phenomena, as well as the relatively late-time environment, provided pre-flashover conditions continue to prevail.

The suitability of using or advancing COMBRN III or the Fuel Load/Ventilation Method fire model for the evaluation of fire barrier performance will be discussed in sections 3.7.4 and 3.7.5, respectively.

3.7.3 Features of a Compartment Fire Model Suitable For Evaluating Direct and Indirect Threats to NPP Fire Barriers

As discussed earlier, the fire barrier threat would be specified from knowledge of both direct and indirect fire exposures. Furthermore, a realistic determination of the direct fire exposure threat is dependent on, and would be determined from outputs of compartment fire model simulations of the overall fire environment, where these outputs would typically provide an explicit description of the indirect fire exposure. Thus, the same zone-type model that simulates the layer temperature histories of the Figs. 3-1 to 3-3 scenarios, would also provide the basis for estimating the intensity of the fire environment local to directly-exposed fire barriers. The main focus of the proposed model will be on achieving realistic simulations of the fire environments, from which both direct and indirect exposures would be determined.

Major features of a compartment fire model that can be expected to provide the necessary simulations include:

1. <u>Simulating fully-developed burning of the most significant combustibles typically found in NPPs.</u> Because of the fact that NPPs typically contain a large variety of fuel arrangements and materials, general analytic methods that are available (or that can reasonably be expected to be developed over the next several years) to describe the details

of fire growth and spread are not (or would not be) reliable. Similarly, because of the large variety of relevant fuel arrangements, etc., detailed empirical descriptions of fire growth and spread that one might hope to develop from experiments on burning arrays of real combustibles (e.g., like the experiments described in references [3-16 to 3-21]), would generally require an unrealistically large amount of resources. Even then, as would be the case with analytic descriptions, such empirical descriptions would be suspect, e.g., because of questions on the significance of interactions between the burning combustibles and the developing compartment fire environment, etc.

While the prediction of *fire growth and spread* in NPP fire scenarios would generally require solutions to intractable problems, it seems that empirically-based analytic models for estimating *fully-developed burning* of the kinds of combustibles that threaten fire barriers in NPPs are achievable and that it would be reasonable to use such models to simulate the complicated combustion processes occurring in these NPP fire scenarios of interest. Also, as will be seen below (in section 3.8.2, "**Simulating Fully-Developed Burning of Cable Trays**"), for the important class of scenario involving burning of extensive dense arrays of cable trays, it is possible that limited, achievable experimental studies would reveal that the time to reach fully-developed burning is generally small compared to the total fire duration of interest. This would support an analysis based on the modeling assumption that fully-developed burning is attained immediately upon ignition. Furthermore, it is reasonable to expect that an assumption of instantaneously-attained fully-developed burning is conservative in the sense that artificially rapid spread to the point of complete and sustained involvement of all combustible surfaces would lead to fire environments that are most threatening to the fire barriers whose integrity is under evaluation. For this reason, it is recommended that a fully-developed fire assumption be adopted for the proposed model. Note that this recommendation is consistent with the opinion expressed in reference [3-14] that "total involvement of the combustibles in a room (i.e., post-flashover) represents the most severe condition for containing a fire with barriers."

In summary, the modeling assumption proposed here is that significant threats to the integrity of fire barriers in NPPs are a result of direct and/or indirect exposures to fire environments generated by sustained fully-developed burning, when all exposed combustible surfaces in the compartment of fire origin are fully involved. Detailed ideas on implementing the fully-developed-fire assumption for specific classes of relevant combustibles will be presented section 3.8 below (under the heading, "**THE THREATENING COMBUSTIBLES FOUND IN NPPs; IMPLEMENTING THE ASSUMPTION OF FULLY-DEVELOPED BURNING**").

2. **Simulations of the fire environment in multi-room facilities.** This involves a capability for simulating the development of the threatening fire environment on both sides of structural barriers, including the environment in a room of fire origin, on one side of the barrier, and in an adjacent space, on the other side of the barrier, into which high temperature gases can be transported *via* significant ventilation penetrations (i.e., a capability for simulating the development of the fire-generated environment in different interconnected rooms of a multi-

room facility).

3. **Simulation of forced and natural ventilation.** The nature of the fully-developed fire environment is strongly dependent on the rate of inflow of ventilation air, i.e., oxygen, to the compartment of fire origin. Because of the wide variety of different spaces found in a typical NPP facility, ventilation to spaces of fire origin during the course of a fully-developed fire scenario involves one or a combination of any or all of the following types of ventilation, some of which are indicated in the sketch of Fig. 3-4:

   - ***Vertical vents to the outside, including wind***: Natural, i.e., buoyancy-driven, venting through vertical vents to the outside environment, e.g., through doors or windows, including the effect of wind [3-22 to 3-25].

   - ***Vertical vents to adjacent spaces***: Natural venting through vertical vents to adjacent spaces of the facility [3-22 to 3-25]. Here, an accounting of multi-room considerations are critical. See Fig. 3-4.

   - ***Horizontal vents to the outside, including wind***: Natural venting through horizontal vents to the outside environment, e.g., holes in floors or ceilings [3-26,3-27]. See Fig. 3-4.

   - ***Horizonal vents to adjacent spaces***: Natural venting through horizontal vents to adjacent spaces of the facility [3-26,3-27]. Here, as in item 2, an accounting of multi-room considerations is critical. See Fig. 3-4.

   - ***Forced ventilation***: Forced ventilation *via* HVAC systems [3-22,3-23,3-25,3-28], including a capability of simulating effect of the fire environment on specified/designed flow rates.

   In predicting the fully-developed fire environment, an accounting for each of the above types of ventilation requires special considerations (refer to the latter-mentioned references [3-21 to 3-28]).

   In summary, the proposed ventilation-simulation feature involves a capability for simulating a variety of different room-to-room and/or room-to-outside ventilation flow phenomena, including those associated with forced ventilation, natural-ventilation flow exchanges through penetrations in vertical and horizontal partitions, and fire-driven variations to design flow rates delivered by forced-ventilation systems.

4. **Capability to distinguish at some non-trivial level of refinement, and to simulate the changing spacial variation in temperature of partition/barrier surfaces.** This includes a capability of simulating: radiative heat transfer from bounding surfaces of a room to arbitrarily located targets, and the variability across the different partition/barrier structures of their in-depth thermal responses. As will be seen below (in section 3.8.3, "**Simulating**

Burning of Combustible/Flammable Liquid Pool Fires"), this capability would be used in the simulation of fire scenarios involving combustible/flammable liquids. This modeling would be achieved by implementing and extending the ideas presented in References [3-29] and [3-30]. Each wall/floor/ceiling partition of a room would be divided into "several" rectangular segments, each with a pair of rectangular surface elements, one on each side of the partition/barrier. In each room, energy conservation considerations would account for radiative heat transfer exchanges between gas layers, combustion zones and partition/barrier-surface elements. Heat transfer through the depth of the segmented partition/barrier structure elements would be simulated by an appropriate wall submodel. Beside providing a reliable closure on the model equations of energy conservation, as required the latter would also provide the basis for reliable simulations of partition/barrier structural response.

The fully-developed fire modeling features of item 1, the more challenging ventilation-simulation capabilities of item 3, and the relatively sophisticated heat transfer analysis of item 4 each require additional submodel/algorithm development and implementation and/or experimental validation. In contrast to this, the multi-room modeling capability of item 2 and some of the basic ventilation-simulation capabilities of item 3 would tend to already be included in the features of any existing successful multi-room fire model. It is therefore recommended that the proposed model be developed, as a matter of economy, as an advanced version of such an existing model.

3.7.4 Suitability of Using COMPBRN III for the Evaluation of Fire Barrier Performance

As mentioned above, the fully-developed post-flashover fire is particularly threatening to the satisfactory fire performance of fire barriers. Therefore, when there is a possibility that a fire in a particular NPP enclosure can develop to a flashover condition, it is the potential flashover-fire environment that must be predicted and used to evaluate fire barrier performance. Unfortunately, COMPBRN III does not include a capability for making such predictions ("The assumptions made in COMPBRN III are geared towards the modeling of relatively small fires in large enclosures or fire scenarios involving large fuel loads early during their pre-flashover burning period." [3-13]). For this reason alone, COMPBRN III in its current state of development is not suitable for use in the fire barrier evaluations of post-flashover fires.

Regarding experimental validation of COMPBRN III, reference [3-13] provides comparisons between data from pre-flashover enclosure pool-fire experiments and corresponding COMPBRN III simulations. Model predictions of steady-state hot-gas-layer temperatures are described as "reasonably accurate" in tests involving steady combustion of a methane burner. In tests involving a heptane pool fire, the model is described as being "able to bracket actual experimental values" when, in the simulations, the combustion efficiency is taken to be 1.0 and 0.7. The input parameters chosen for the computations analyzed in reference [3-13] are tabulated in that work. It is noted there that "these parameters are empirical and depend on ... detailed characteristics of the particular fire scenario ..." Further, it is explicitly stated that "these parameters are not well-known for the arbitrary scenario" and it is concluded that "significant input uncertainties exist even in the case of well-controlled experiments." Even when used in specific applications for which it was designed, the above observations, reported in what can be considered as a

COMPBRN III source document, do not instill confidence in the accuracy and reliability of COMPBRN III simulations.

There are additional aspects of the COMPBRN III model that would significantly limit its applicability in fire barrier evaluation. Based on the model description in reference [3-13], some of these are:

- COMPBRN III is a one-room fire model (the compartment of fire origin) where the only vent available is a vertical vent to a quiescent outdoor ambient environment. Thus, for example, none of the ventilation flows depicted in the sketch of Fig. 3-4 can be simulated by COMPBRN III.

- In COMPBRN III, there is no mechanism for contamination of the lower layer of the compartment of fire origin. ("The lower region is assumed to be thermally inert and its temperature remains at ambient room temperature all the time.") In real fire scenarios, in the one-room/one-vent configuration, and even more so in more complicated configurations, mixing and heat transfer mechanisms will lead to both contamination (e.g., reduction of oxygen concentration) and heating of the lower gas layer. All this could have important implications on the simulated room fire environment and on the simulated threat to barriers.

- In COMPBRN III, all radiation exchange between the gas layers of the compartment of fire origin and its inside bounding surfaces is assumed to occur between the upper layer and the assumed spatially-uniform-temperature ceiling surface. ("... only the ceiling area is used to compute the radiative heat loss of the hot gas layer to the room boundaries.") Especially at higher upper layer temperatures, and even in the pre-flashover state, radiation exchanges with all exposed surfaces of the compartment of fire origin will have a large effect on the compartment fire environment. Such radiation exchanges will not usually be adequately simulated by the ceiling-radiation limitation.

- There are phenomena modeled in COMPBRN III (e.g., wall jet mass flow rate and doorway mixing rate) that depend on roughly defined values of empirical parameters, where the use of such parameters often have a weak theoretical basis and/or are not well-known. (Refer to above comments on the experimental validation of COMPBRN III.) Furthermore, it would appear that variations of the values of these factors within recommended ranges could lead to significant variations in results of model simulations. Advanced modeling ideas can be used to improve the simulation of these phenomena.

In view of the above shortcomings and limitations of COMPBRN III, and in view of the recommendation that the model for evaluation of fire barrier performance be developed as an advanced version of an existing multi-room fire model, it is concluded that COMPBRN III is not suitable for use in its current state of development, and it is not suitable as a candidate for advancement.

3.7.5 Suitability of Using the Fuel Load/Ventilation Method Fire Model for the Evaluation of Fire Barrier Performance

A major and reasonable assumption of the Fuel Load/Ventilation Method fire model [3-14] is that fully-developed, post-flashover, fire conditions always prevail in the compartment of fire origin. However, as with COMPBRN III, a shortcoming of the Fuel Load/Ventilation Method model, is that it is a one-room fire model that only allows for a single vertical vent to a quiescent outdoor ambient environment. Also, the basic assumption of the model's fuel mass-loss rate (i.e., a specified constant value for fuel-controlled burning, proportional to ventilation rate for ventilation-controlled burning) is such that it can not be expected to provide reliable results when simulating the burning of combustible/flammable liquids fires; and this in spite of the fact that, as discussed in the next section, combustible/flammable liquid fires lead to one of the two major threats to fire barrier integrity. Finally, the model is based on assumptions that are claimed to generally lead to conservative results, in the sense that the simulated environments will presumably always represent a more severe threat to fire barriers than actual environments. Even if true, the level of conservatism of the simulations is not quantified. For this later reason alone, use of the Fuel Load/Ventilation Method fire model in the present application is problematic.

3.8 THE THREATENING COMBUSTIBLES FOUND IN NPPs; IMPLEMENTING THE ASSUMPTION OF FULLY-DEVELOPED BURNING

3.8.1 The Threatening Combustibles

There are a great variety of functions and types and sizes of spaces that make up an operating NPP. In these, it is possible to group all potentially significant combustibles into five categories: cable trays, combustible/flammable liquids, electrical panels/cabinets, waste, and miscellaneous.

Based on a preliminary combustible-load summary of the Watts Bar NPP [3-31], spaces having the five largest density of combustibles were identified and tabulated in Table 1. The primary and secondary combustibles in these spaces are also identified in the table.

Not surprisingly, Table 3-1 indicates that the most significant combustible of NPPs are the cable trays. This continues to hold true for most other categories of relatively high-combustible-density spaces of Watts Bar, not appearing in the table. Also, combustible/flammable liquids are seen to be the major contributor of combustibles in the Diesel Generator/Lube Oil Storage areas, which have the second largest average density of combustibles. Finally, although the miscellaneous category of combustibles appears as the primary contributor in the case of the Shift Engineer office, this particular space has a relatively small area, and other spaces where "miscellaneous" is the primary category of combustibles is only found infrequently throughout the rest of the plant (and then, only with considerably reduced average combustible density).

It is evident that waste and miscellaneous combustibles, and even relatively small amounts of combustible/flammable liquids, can play a significant role in the ignition and in early fire growth and spread of threatening NPP fires.

Results of full-scale experiments on growth and spread of fires initiated in NPP control cabinets are presented in references [3-19] and [3-20]. These indicate that "a cabinet fire can propagate within a single cabinet; however for the limited conditions tested it does not appear that the fire poses a threat outside the burning cabinet except [for] the resulting smoke." [3-19] Nevertheless, "many potential fire-spread paths were not investigated" in the experiments. In this regard, results of the tests suggested that "partial or incomplete barriers and unsealed cable penetrations can be expected to allow further spread of fire, given a fully involved cabinet fire." [3-20]

It seems reasonable to expect and it is tentatively assumed that, as in the case of control cabinets, the general electrical-panels/cabinets category of combustible can play an important potential role as a generic site of fire initiation and spread.

Based on the above, it is reasonable to assume that fire in electrical panels/cabinets and in relatively small amounts of combustible/flammable liquids, waste, and miscellaneous combustibles can play a significant role in the ignition and in early fire growth and spread of threatening NPP fires. In this sense, for example, electrical cabinets such as switchgear and motor control centers, must be recognized as significant fire hazards. However, based on Table 1, and compared to cable trays and combustible/flammable liquids, they are expected to be relatively small contributors to the fully-developed sustained fires that threaten fire barrier integrity.

It is assumed that the Watts Bar NPP is representative of all NPPs considered in this work.

In view of all the above, it is concluded that there are two categories of combustibles that represent a significantly greater fire threat to the integrity of fire barriers in NPPs than all others; namely, cable trays (e.g., see Figs. 3-1 and 3-4) and combustible/flammable liquids (e.g., see Figs. 3-2 and 3-3). For this reason, it is necessary to consider only these two in the modeling and analysis of fully-developed fire-generated environments of interest here. The next two sections will propose the basis of methods on how to model fully-developed burning of cable trays and combustible/flammable liquids, respectively.

3.8.2 Simulating Fully-Developed Burning of Cable Trays

Fully-developed burning of extensive dense arrays of cable trays; a uniform-mass-loss-rate model. The *cable-tray* category of combustibles, so pervasive in NPPs, is deployed primarily in configurations involving extensive dense arrays of loaded cable trays. Compared to more typical distributions of combustibles which are based mainly near floor elevation, arrays of loaded cable trays tend to be well-distributed within and mainly, but not entirely, confined to the upper portion of the volume of the space, i.e., from just above head-height to near-ceiling elevations.

The *cable-tray* category is exceedingly complex and varied. For any particular compartment of potential fire origin, a detailed description would involve: the properties of a variety of (both combustible and non-combustible) material and the configuration of these that make up relevant cable sub-assemblies; the somewhat haphazard grouping of these different cables types onto one or more types of cable tray fixture; and the different possible custom configurations of the cable tray fixtures as they are mounted throughout the compartment. As stated earlier, the problem of predicting fire growth and spread through such arrays of combustibles is not generally tractable. Moreover, the location of many cable trays in overhead regions that, in the event of a fire, are highly susceptible to hot vitiated gases, further complicates the problem since fire spread and growth in vitiated atmospheres is not well understood. Clearly, some judicious simplifications are required if the pyrolysis/burning of cable-tray combustibles is to be simulated.

Using theoretical considerations together with data from grouped-cable-tray fire experiments [3-18], it is the purpose here to present a simple speculative model, a uniform-mass-loss-rate model, for the fully-developed burning (all exposed combustible surfaces are losing mass) of such arrays. Additional experiments would be required to validate, improve, or provide the basis for an alternative to this model. Guidelines for such experiments are proposed below (in sub-section, "**Experiments to validate, improve, or provide the basis for an alternative to the uniform-mass-loss-rate model**").

In the case of cable tray combustibles, the proposed fire scenario threat is one where, immediately after ignition, all cable trays (i.e., the exposed surfaces of all individual cable bundles within the array) in the compartment of fire origin are fully involved in the combustion process. Since the generic configuration involves extensive and dense groupings of cable trays, most of the exposed combustible surfaces within the array exchange radiation with surfaces of near-identical properties that completely surround them. The situation is analogous to the burning of dense cribs in ventilated compartments, where, at least for fuel-controlled burning (i.e., when the rate of ventilation air to the compartment is greater that the rate required to support stoichiometric burning of the combustibles being pyrolyzed), mass-loss rate (i.e., fuel-production rate) is mainly *independent* of the compartment fire environment and phenomena outside the crib. Thus, for fuel-controlled burning of cribs, mass-loss rate is approximately independent of: the temperature of the smoke layers, the temperatures of bounding surfaces of the compartment, and the radiation exchanges between these latter types of surfaces and the outer bounding surfaces of the crib. Other evidence, presented below, suggests that the crib analogy may be appropriate for ventilation-controlled burning/pyrolysis of cable trays as well.

Fuel-controlled burning. Under conditions of fuel-controlled burning, and consistent with Table 2-1.3, Fig. 2-1.3, and Eq. (4a) of reference [3-32], the total mass loss rate of a dense crib, $\dot{m}_{CRIB}$, is proportional to the total exposed surface area of all "sticks" of the crib, A_{EX}, and a characteristic regression rate of the surfaces. The latter regression rate is proportional to a stick-material-dependent constant, C_{SM}, and $D^{-0.6}$, where D is a characteristic dimension of the stick section.

$$\dot{m}_{CRIB} = C_{CRIB}A_{EX};\quad C_{CRIB} = C_{SM}D^{-0.6};\ C_{SM} = C_{SM}(\text{crib material}) \tag{1}$$

Developing further the analogy between the burning of a crib and an extensive dense array of cable trays, consider the total exposed surface area of the latter:

Associated with a single loaded cable tray of the array, is the outward exposed surface area of the combustible jacketing material of the cable bundle contained in the tray. It is reasonable to assume that whatever the mix of type and size of cabling, all cable trays of the array contain few-to-several full layers of cabling. Thus, for typically shallow trays (i.e., $H_T << W_T$, where H_T and W_T are the height and width of the tray, respectively) the exposed area of the cable bundle of one tray is approximately $2W_TL_T$, where L_T is the length of the cable tray. (The factor of two is used when the cable tray is mostly open on all sides, e.g., from below and above, in the case of horizontal trays, where both lower and upper surfaces of the cable bundle are freely exposed to the environment surrounding the tray. When and if the cable tray is closed on the top or bottom, the factor of two is not used, etc.) Also involved is a relatively small additional exposed area corresponding to the exposed sides of the bundle, i.e., $2H_BL_T$, where H_B is the height of the bundle. Here, assume that the average height of the bundle in the cable tray is half the height of the tray, i.e., $H_B = H_T/2$. Assume, further, that the contained cable bundles and all trays of the entire array are approximately the same. Then, analogous to Eq. (1), the total mass loss rate for a burning array of cable trays is

$$\dot{m}_{ARRAY} = C_{ARRAY}A_{EX}; \quad A_{EX} = (2W_T + H_T)L_{TOTAL} \tag{2}$$

where C_{ARRAY} is a function of the cable array design, and L_{TOTAL} is the total length of all cable trays in the array.

C_{ARRAY} of Eq. (2) is analogous to C_{CRIB} of Eq. (1). In general, it is expected to depend on the combustible cable insulation and jacket material properties and on the characteristic grouping of cable trays within the cable tray array (i.e., on the dimension of the tray section and the relative spacing and configuration of trays within the array). However, it seems that the characteristics of cable tray grouping configurations in NPPs are fairly uniform (approximately as in the experiments of [3-16 to 3-18], with tray height and width, 0.1 m and 0.5 m, respectively; vertical tray-to-tray separation, 0.3 m; and side-to-side tray separation, 0.2 m). Therefore, it is reasonable to assume a weak dependence of C_{CRIB} on grouping geometry.

It is possible to extract preliminary estimates of C_{ARRAY} from results of two compartment fire experiments involving the burning of relatively large arrays of cable trays. These experiments, the ones designated as Test 2 and Test 3 in reference [3-18], used cable with polyethylene (PE) insulation and a polyvinyl chloride (PVC) jacket. It will be assumed that a 50-50 mix of PE and PVC was used, with a resulting average heat of combustion of $30\text{x}10^6$ J/(kg burned). For the cable trays used, $W_T = 0.46$ m and $H_T = 0.08$ m. To enhance fire spread in the tests, an extra tight arrangement of cables, including weaving of cables between trays, was utilized. Both tests involved two adjacent (0.15 m side-to-side separation gap) stacks (0.27 m top-to-bottom separation gap) of six, 2.44 m-long, horizontal, loaded cable trays (as depicted in Figs. 3-1 and 3-4) with two(Test 2)-to-three(Test 3) adjacent vertical cable trays. Test 3 involved additional interweaving of tray-to-tray cables. It also included an additional horizontal cable tray directly overhead, but 2.44 m above the main array. (This was connected to the main array by the cables contained in the vertical cable trays.) In both tests, the fire was initiated from a combustible/flammable liquid pool fire below one of the two lowest cable trays. The fire spread through most of the array by the time the first sprinklers were actuated at 289 s (Test 3) and 368 s (Test 2) into the tests. As indicated in Fig. A-1 of [3-18], in the absence of the sprinklers, continued growth to what would have been a fully-developed fire would have been expected. From that figure, it is estimated that for both tests the fire would have been fully-developed by approximately 900-1200 s. Assuming a 70% efficiency for burning of pyrolysis products, the Fig. A-1 plots lead to the following estimate

$$C_{ARRAY} \approx 0.05 \text{ kg/(m}^2\text{s) for PE(insulation)/PVC(jacket) cable} \qquad (3)$$

where a determination of possible significant variations in the above value of C_{ARRAY} for other cable constructions would require additional study.

According to references [3-16] and [3-17], another full-scale test involving two adjacent stacks of seven, heavily-loaded, horizontal cable trays was carried out. In this, "all the cables in the test were completely consumed." [3-17] During the course of the present analysis it was not possible to obtain and include any additional results that may be included in the original report [3-33] of this test. To the extent that such results exist and can be made available, further study of this test is merited.

Ventilation-controlled burning. For burning wood cribs, the mass-loss rate changes when the air supply to the compartment of fire origin is reduced to the point that ventilation-controlled burning prevails [3-32]. However, according to reference [3-34], the "burning [i.e., mass-loss rate] of non-charring fuels [in crib-like arrays] is virtually unaffected by ventilation rate." This statement is based on a set of 15 burn experiments on single non-charring-plastic[30] cribs with specified ventilation rates. In the tests, ventilation was varied over a range from 0.5 to 1.3 of the ventilation-controlled limit (the exact ventilation rate required for stoichiometric burning). The mass-loss rates of the cribs for all test runs were identical to within ten percent of the mean value.

The latter crib-burn behavior is to be compared to the well-known commonly-used behavior observed in burning wood cribs, whereby, for ventilation rates below the ventilation-controlled limit, mass-loss rate is approximately proportional to ventilation rate [3-35].

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[30] Sticks formed from a resin of approximately 60% unsaturated polyester and 40% cross-linking agent, mainly styrene monomer, and 1% hardener (60% methyl ethyl ketone and 40% diethyl phthalate) [3-34].

Because of the crib-like features of the cable tray arrays, it seems reasonable and it is tentatively proposed to adopt the latter result, and to extend to under-ventilated burn scenarios the Eq. (2) results for over-ventilated cable-tray-array burns. Note that such a combustion model should be adopted with confidence only after it is supported and validated by results of an experimental program involving full-scale under-ventilated burns of cable tray arrays. Also, there has to be some low-ventilation-rate limit where the Eq. (2) model becomes invalid, and where additional considerations have to be taken into account. Thus, at some sufficiently low ventilation rate, perhaps when the oxygen concentration near the elevation of the base of the burning array of cable trays is reduced to some specified, non-zero value, associated with flame extinction, it is expected that all combustion within the array will cease, or become insignificant [3-36].

Experiments to validate, improve, or provide the basis for an alternative to the uniform-mass-loss-rate model. The above-proposed uniform-mass-loss-rate model is speculative and it is based on and supported by only a minimum experimental data base. It is important that additional experiments be carried out to validate, improve, and, if necessary, provide an alternative to this model. The new experiments should include some free-burn-type scenarios (i.e., burning of a relatively large-density grouping of loaded cable trays in a space that is so large and/or so well ventilated that the effect of the environment in the enclosure can not be suspected of modifying significantly the burn characteristics of the grouped cable trays), but mainly they should involve enclosed spaces, similar in room scale (possibly somewhat smaller) to that used in reference [3-18] (i.e., 12 m x 12 m x 6 m high). They should involve both natural- and forced-ventilation scenarios, both in the fuel controlled and ventilation-controlled regimes, and scenarios with fuel densities comparable to those indicated in Table 1. Because of the latter fuel-density requirement, such experiments would involve substantially greater amounts of combustibles than those used in the studies of references [3-16 to 3-18].

The experimental fires should be allowed to develop to a burn-out, or at least a burn-down stage. The enclosure structure would have to be robust enough to survive the significant fire environment that can be expected to develop within the test space.

An experimental program that follows the above guidelines would involve a significant effort, and it should based on a well-developed plan with clearly stated objectives.

Until the uniform-mass-loss-rate model is validated or until an improved cable-tray burn model is established, when carrying out model simulations during ventilation-limited combustion, it would be prudent to also carry out parallel simulations that use a traditional crib-type model (i.e., mass-loss rate proportional to ventilation rate during ventilation-limited combustion). Such a model can be developed with full generality (i.e., not confined to scenarios where ventilation is from a single natural vertical vent to an outside quiescent environment) following the ideas presented (on p. 310) in reference [3-35]. However, it is important to point out that for other than cellulosic crib-like combustibles, and in the absence of experimental verification, confidence in the traditional approach is not warranted [3-37].

Note that using the uniform-mass-loss rate model or an improved alternative model, instead of the traditional model, would likely lead to a significant difference in the resulting simulated fire scenarios. It would lead to predictions of much more rapid pyrolysis of the cable bundles, without corresponding increased combustion in the compartment of fire origin. Significant rates of pyrolysis products would be predicted to spread to and burn in adjacent spaces.

3.8.3 Simulating Burning of Combustible/Flammable Liquid Pool Fires

A basis for the model. In the fire scenarios of interest here, flame spread across the surface of a combustible/flammable liquid pool fire and any important transient characteristics of the pool itself develop so rapidly that the fully-developed fire assumption is always relevant. Then, the net mass-loss rate of the fuel at the surface of a pool, $\dot{m}_{POOL}$, is determined by $\dot{Q}_{POOL}$, the net rate of heat transfer absorbed at the pool surface,

$$\dot{m}_{POOL} = \dot{Q}_{POOL}/L; \quad \dot{Q}_{POOL} = \dot{Q}_F + \dot{Q}_E - \dot{Q}_L \tag{4}$$

where L is the heat of gasification of the combustible/flammable liquid, $\dot{Q}_F$ and $\dot{Q}_E$ are the heat transfer from the flame and from external sources (the gas layer and bounding compartment surfaces), respectively, and $\dot{Q}_L$ represents the heat transfer losses through the pool surface [3-35]. Thus, $\dot{m}_{POOL}$ does not depend explicitly on the rate of ventilation to the compartment, or on whether the compartment fire scenario involves fuel-controlled or ventilation-controlled burning.

A single-room, single-vertical-vent fire model for ventilation-controlled burning of a steady-state pool fire is presented in reference [3-37]. The model accounts for radiation heat transfer exchanges between the pool surface, the compartment gases, the inside bounding surface of the compartment, and the vent opening. The pool mass-loss rate is modeled by Eq. (4).

Experimental data have been acquired and presented in reference [3-38] for pool fires (both combustible/flammable liquids and thermoplastics, with areas of 0.186 m^2 and 0.372 m^2) in a compartment (2 m wide x 1 m x 1 m) with a single vent. The experimental configuration corresponded to that modeled in reference [3-37]. In the experiments it was found that, compared to unconfined burning of the pools (i.e., burning in the open, outside the confines of a compartment), for ventilation-controlled burning, the high temperature environment of the compartment had a very strong influence on increasing the radiation to, and the mass-loss rate of the pool. For example, mass-loss rate for an ethanol pool was increased up to 6 times. Good correlation was obtained between measured radiation flux data, $\dot{m}_{POOL}$ data, and the Eq. (4) model. However, the data indicated that an attenuating layer of fuel vapor immediately above the pool surface could be significant in absorbing and attenuating the radiation incident to the pool surface. The effect was observed to be significant in only one of the tests, involving the larger of the PE pools, where the data indicated that only 2/3 of the radiation penetrated the conjectured attenuating layer to actually penetrate the pool surface itself [3-38].

In view of the above, it is proposed that an advanced reference [3-37]-type model, which also incorporates Eq. (4), be used to model combustible/flammable liquid pool fires in the present NPP application. The model should be capable of predicting with reasonable accuracy the net radiation absorbed by the surface of the pool. It should be able to simulate both confined (diked) pools and relatively-unconfined large-area spills. This would require relatively detailed modeling of the radiation exchanges between compartment boundary surfaces, the gas layers, the flame, and the pool surface, a level of detail that goes beyond that existing in any currently-available zone-type compartment fire model and beyond the level of detail used in the reference-[3-37] model. An appropriate level of detail in the modeling of the radiation exchanges would be achieved with the N-surface-element approach of reference [3-29], or an N-surface advancement to the approach of reference [3-30]. The model should be capable of dealing with both ventilation- and non-ventilation-controlled burning, where ventilation could result from flow exchanges through multiple vents to the outside or to multiple adjacent spaces, including any of the various vent configurations discussed earlier. These model features are consistent with and included in the list of model features outlined above in section 3.7.3.

Note that the comparison between data and theory reported in reference [3-38] is between plots of Eq. (1) and plots of radiation *vs* $\dot{m}_{POOL}$, from experimental values. Comparisons between actual $\dot{m}_{POOL}$ predictions from the compartment fire model of reference [3-37] and corresponding $\dot{m}_{POOL}$ measurements from reference [3-38] are not provided. In this regard, it is important that the validity of the model, developed according to the above guidelines, be verified with relatively-large-scale reference [3-38]-type compartment pool-fire data.

3.9 A NPP-SPECIFIC FIRE MODEL AND SCENARIO-SPECIFIC THREATS TO FIRE BARRIERS

It is proposed that the above modeling ideas be developed and implemented. The result would be a new, special-purpose, NPP-specific, fully-developed fire model capable of simulating fire environments that threaten NPP fire barriers. The outputs of such a model would include an estimate of the *indirect* threat exposure and the variables required to estimate possible significant *direct* threat exposures.

3.9.1 NPP-Specific ASTM E 119-*Type* Temperature-Time Curves and Indirect Threat Exposures

In simulating a fire scenario defined by a particular NPP facility, room of fire origin, and ventilation configuration, the new model would predict, along with a variety of other output variables, the temperature-time curve that characterizes the elevated-temperature history of the upper layer. In principle, this curve would represent a scenario-specific alternative to the temperature-time curve of the standard ASTM E 119 fire. If it were feasible to replicate such a temperature-time-curve environment in an ASTM-type test furnace, the curve would be the basis for an ASTM E 119-*type* test for verifying the integrity of fire barrier designs against indirect fire exposures, used in the scenario-specific NPP room of fire origin.

Even if the new fire model could be relied on to produce accurate simulations, and if ASTM E 119-*type* test furnaces could be controlled to generate perfect replications of the simulated temperature-time curves, a strict application of the above approach can never be practical. For example, when considering a particular facility and room of fire origin, including specified combustibles, it is appropriate to consider possible variations in the room ventilation, e.g., one, two, or no doors may be opened to a relatively large adjacent space or to the outside, ceiling vents may be open or closed, forced ventilation systems can be operating or not, etc. Such variations can lead to significantly different fire environments and to different levels of threat to the fire barrier whose performance is being evaluated. Thus, in principle, a barrier design under evaluation would have to be tested multiple times to show that it performs adequately when exposed to each of the simulated threats. Also, a particular barrier design would typically be used in multiple locations throughout a NPP (each location requiring its own set of simulations), indeed, it may be used throughout a variety of different NPPs. The number of required temperature-time curve simulations and corresponding ASTM E 119-*type* tests of the barrier would typically be very large and completely impractical.

3.9.2 The Bounding-Temperature Principle and NPP-Specific Fire Curves

The multiple-test difficulty can be resolved by invoking the following *"Bounding-Temperature" Principle*:

> ***"Bounding-Temperature" Principle***: Consider threats to the integrity of a fire barrier design when it is exposed to two different fire environments, each characterized by its own temperature-time curve. If one of the two curves bounds the other at all times up to a time, t, then up to that time the fire environment associated with the bounding curve poses the greater of the two threats to the fire barrier.

The bounding-temperature principle can be applied as follows:

1. Draw a bounding temperature-time curve over all, or a distinguished group of the above-conjectured simulated temperature-time curves (e.g., the distinguished group of curves can be those curves that characterize all simulated fires associated with those rooms of the original NPP where the barrier design of interest will be deployed).

2. Let the bounding curve define a *design-basis* temperature-time fire environment (i.e., compared to the simulated *real* fire environments) that is reproducible in an available ASTM E 119-*type* test furnace. This is designated as the new, ***NPP-specific, test fire curve.***

3. Evaluate the integrity of the barrier while it is subjected to an ASTM E 119-*type* test carried out with the new test fire curve. From the test, determine that the integrity of the barrier is maintained for the fire resistance rating time interval, $t_R \leq t$. Then the fire barrier in question is given a fire rating of t_R relative to the new test fire curve. It follows from the bounding-temperature principle that the fire barrier in question is also considered to have (at least) a t_R fire rating relative to all individual simulated fires of the distinguished group of

fire threats.

Although not explicitly stated in the above terms, the bounding-temperature principle was used as an integral part of the Fuel Load/Ventilation Method fire model [3-14], and it seems reasonable to accept generally its validity when evaluating the performance of NPP fire barriers. Indeed, the above concept of a NPP-specific fire resistance rating system and a NPP-specific test fire is dependent on the general validity of the bounding-temperature principle.

While it is reasonable to expect that the bounding-temperature principle is valid and useful for evaluating the performance of most fire barriers, it is should be mentioned that the principle is not universally valid.[31]

3.9.3 Developing Multiple, NPP-Specific, Temperature-Time Curves

In the above discussion, it was seen how a *single group* of simulated fire curves could be used to define a *single*, bounding, NPP-specific test fire curve. In carrying out model simulations for the different fire scenarios expected in a variety of different NPPs, it would, in an analogous way, be possible to identify meaningful *multiple groups* of such simulated fire curves, and corresponding *multiple* NPP-specific test fire curves. The most appropriate one of these test fire curves (the one that bounds all relevant simulated temperature-time curves) could then be recommended for selection and use in an NPP-specific ASTM E 119-*type* furnace test to evaluate the fire performance of an arbitrary existing or proposed NPP fire barrier design.

Development of the above concept is dependent on the availability of the proposed special-purpose NPP-specific fire model. With this in hand, implementation of the above ideas involves two complementary efforts.

First would be a significant modeling effort involving simulations of a wide variety of conjectured fire scenarios in at least a few NPPs. The simulations would provide invaluable information on the general characteristics of real, fire-barrier-threatening, NPP fire environments. By studying, categorizing, etc. the broad range of these simulations, it is envisaged that

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[31] That the bounding temperature principle is not universally valid is proven by the following counter-example: Consider a nonreacting unconstrained structural barrier exposed to a fire environment along its length, on one side, and insulated on the other. Consider two temperature-time fire curves, both of which start at ambient temperature and reach the same maximum steady temperature. Let one curve grow linearly with time with an arbitrarily small slope. Let the second one not grow at all until relatively late in time, when there is a near step-change in temperature to a value somewhat below the first curve. In the case of the first curve, the temperature will always be effectively uniform through the depth of the structure, and it will always have an arbitrarily small stress field. For the second curve, a non-uniform temperature distribution and a non-zero stress field, possibly leading to failure, will develop. Therefore, in this particular case the bounding-temperature principle is not valid, since the structural response in the second scenario is more severe than that of the first even though the fire curve of the first bounds that of the second.

meaningful NPP-specific distinguished groupings of them would be identified. These would then be used to define the sought-after NPP-specific test fire curves.

After the modeling effort, there would be an experimental study to determine the capabilities of existing ASTM E 119 test furnaces relative to generating reproducible, temperature-time, test-fire environments other than that of the standard ASTM E 119 fire. In this regard, for a given furnace facility the most important characteristics of such achievable furnace fire environments would be those associated with the maximum (bounding), achievable, temperature-time curve: the peak temperature; the minimum time-to-peak-temperature; and the actual temperature-time curve corresponding to the fire initiated and sustained with the maximum possible supply rate of fuel gas. It is anticipated that such a study of existing test furnaces would lead to the identification of a limited number of easily reproduced (from facility-to-facility) test fire curves having a wide range of "severity." (In the sense of the bounding-temperature criterion, a set of curves having a wide range of "severity" would be associated with a set of curves having a wide range of "bounding capability." A reasonable measure of a curve's bounding capability would be its peak temperature and time-to-peak-temperature.) These test fire curves would be selected for their relevance to the previously-determined, NPP-specific, simulated-fire groupings.

When evaluating the fire performance of NPP fire barriers, multiple NPP-specific temperature-time fire curves determined according to the above ideas would replace the standard ASTM E 119 fire curve.

3.9.4 NPP-Specific Direct Fire Exposures

As is the case with indirect fire exposure threats, when evaluating the performance of a particular barrier component relative to sustained direct fire exposure, inordinate numbers of possible NPP facility fire scenarios would lead to inordinate numbers of different possible direct exposure threats. While these could be calculated with the proposed advanced fire model, it is again clear that implementing the multitudes of corresponding direct exposure simulation tests that could be devised, in principal, would not be practical. Rather, a presumably conservative "Bounding Direct-Fire-Exposure" Principle, corresponding to the Bounding-Temperature Principle, would be adopted, and applied. For example, in cases where a barrier design can be subjected to actual sustained flame exposure, perhaps ASTM E 1529 test exposures, applied for a calculated time interval, say the predicted maximum possible duration of the considered fire scenarios, could be shown to be a valid basis for such a principle.

3.10 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

3.10.1 General Summary and Conclusions

Part 3 of this document assessed the feasibility of developing and implementing Nuclear Power Plant (NPP)-specific descriptions of fire environments for use in evaluating the fire resistance of fire barriers. These include *structural* barriers, useful in isolating a compartment of fire origin from adjacent spaces, and *wrap assemblies*, used to isolate and protect Plant equipment, cables, etc., within a compartment of fire origin, from the effects of exposure to the fire environment.

A discussion on the nature of fire barrier exposure to the compartment fire environment distinguished between *direct exposure* to the most extreme zones of the fire environment, e.g., direct, sustained exposure of the barrier to the flame, and *indirect exposure*, where the a fire barrier is mainly exposed to the average properties of the overall fire environment. The problem of evaluating the integrity of fire barriers to both kinds of threats was addressed.

The problem of defining the fire exposure with which to evaluate fire barrier performance was discussed. This included ASTM E 119-*type* test methods (i.e., exposure of full-scale barrier specimens to specified furnace environments that simulate indirect-type fire exposures), the need to develop other tests that would be devised to simulate direct exposure threats, and the applicability of compartment fire model simulations.

A methodology for evaluating the fire performance of NPP fire barriers was presented that removes weaknesses of and/or introduces flexibility to the traditional ASTM E 119 approach. This would rely on a combined experimental and analytic approach that involved the Bounding-Temperature Principle. (I.e., if the temperature-time curve of one fire environment bounds that of another, then, relative to the threat to structural integrity of a NPP fire barrier, the bounding-curve environment is the more severe.) Experiments would involve ASTM E 119-*type* tests, where the standard ASTM E 119 fire is replaced by alternative temperature-time furnace fires, and where the alternative fires would be deduced from reliable fire model simulations. Analysis would involve compartment fire modeling methods, where computer simulations would be carried out with a new, advanced, special-purpose, zone-type fire model. This model would be developed to include features particularly relevant to simulating fire environments that threaten NPP fire barriers, from the point of view of both direct and indirect fire exposure.

Based on a review of the literature of NPP-specific combustibles and previously-developed NPP-specific fire models, special features required of the new fire model were proposed. These included: the simulation of fully-developed burning of extensive dense arrays of cable trays, both under fuel-controlled and ventilation- controlled conditions; the simulation of combustible/flammable liquid pool fires; and advanced means of modeling ventilation and radiation-heat-transfer-related phenomena. It was proposed that a new special-purpose model with these features be developed as a customized advanced version of an existing, two-layer, multi-room, zone-type fire model.

The new model would be used to simulate a wide variety of potential fire scenarios in rooms of fire origin of selected NPPs. The simulations would lead to new insights on the characteristics of real, fire-barrier-threatening, NPP fire environments. Based on applications of the Bounding-Temperature Principle, the simulated fire scenarios would lead to a series of NPP-specific test fire curves covering a wide range of NPP-type fire severities. An experimental study on available ASTM E 119-*type* test furnaces would be carried out to establish that these new test fire curves (instead of the standard ASTM E 119 fire curve) can be used in ASTM E 119-*type* barrier rating tests. Then ASTM E 119-*type* tests using the new NPP-specific test fire curves would be established as the method of evaluating the fire performance of NPP fire barriers.

A significant effort will be required to carry out this plan. Due to knowledge gaps in critical areas such as burning rate and ventilation effects in NPP-specific environments, the modeling work will require a substantial experimental component. Indeed, the experimental aspects, including full-scale burnout of fuel packages and furnace fire-resistance tests, are similar in scope to the NBS recreation-room study (see Part 2, section 2.3.3), which was a multi-year effort.

3.10.2 Recommended Tasks

Consistent with the above, it is recommended that the following tasks be carried out with the goal of establishing a reliable methodology for evaluating NPP fire barrier performance:

1. Develop a new, special-purpose, NPP-specific fully-developed fire model capable of simulating fire environments that threaten NPP fire barriers. It is recommended that this be developed as an advanced version of an existing multi-room compartment fire model, e.g., CFAST [3-25]. The new model should include the advanced modeling features identified in the section 3.7.3 "**Features of a Compartment Fire Model Suitable For Evaluating Direct and Indirect Threats to NPP Fire Barriers.**" These include: the simulation of fully-developed burning of extensive dense arrays of cable trays, both under fuel-controlled and ventilation-controlled conditions; the simulation of combustible/flammable liquid pool fires; the simulation of the fire environment in multi-room facilities (at least two adjacent spaces); and advanced means of modeling ventilation and radiation-heat-transfer-related phenomena

2. Carry out full-scale experimental verification of the advanced modeling methods of item 1, especially those aspects of the new model associated with the simulation of burning cable trays and combustible/flammable fuel fires in enclosed spaces. Also, carry out experiments to better evaluate and characterize the fire hazard in NPPs introduced by electrical panels/cabinets.

3. Use new model simulations to determine the direct-exposure threat to fire barriers, and use these to establish experimental methods to evaluate barrier fire performance relative to the *direct* exposure threat.

4. Use the new model to carry out an extensive simulation study of selected NPPs. Results of this would be used to establish the characteristics of real, fire-barrier-threatening, NPP fire environments and to identify a series of NPP-specific test fire curves to replace the ASTM E 119 standard fire curve.

5. Carry out an experimental study on available ASTM E 119-*type* test furnaces to establish that the new test fire curves of item 4 are attainable and reproducible.

6. Use the results of items 4 and 5 to establish an ASTM E 119-*type* method of evaluating the performance of *structural* fire barriers relative to the *indirect* exposure; establish corresponding methods for *wrap-assembly* fire barriers.

3.11 NOMENCLATURE

A_{EX}	total exposed surface area in a crib or in an array of loaded cable trays.
C_{ARRAY}	constant of cable array design.
C_{CRIB}	Eq. (1).
C_{SM}	crib-material-dependent constant, Eq. (1).
D	characteristic dimension of a crib's "stick" section.
L	heat of gasification of the fuel.
L_T	length of cable tray.
L_{TOTAL}	total length of all cable trays in the array.
$\dot{m}_{ARRAY}$	mass loss rate of array of cable trays.
$\dot{m}_{CRIB}$	mass loss rate of array of crib.
$\dot{m}_{POOL}$	net mass loss rate of fuel at the pool surface.
$\dot{Q}_E$	rate of heat transfer from external sources (the gas layer and bounding compartment surfaces).
$\dot{Q}_F$	rate of heat transfer from the flame.
$\dot{Q}_L$	rate of heat transfer lost through the pool surface.
$\dot{Q}_{POOL}$	net rate of heat transfer absorbed at the pool surface.
W_T	width of cable tray.

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Table 3-1. A Preliminary Combustible Load Summary of the Spaces at the Watts Bar NPP Having the Largest Density of Combustibles.

Building/Room Name	Area	Avg. Density of Combustibles	Primary (Secondary) Contributor
Control/Spreading Room	823 m^2	601×10^7 kJ/m^2	cable trays (panels/cabinets, < 10%)
Diesel Generator Lube Oil Storage	38 m^2	484×10^7 kJ/m^2	flammable liquid (miscellaneous, < 1%)
Auxiliary/Mechanical Equipment	65 m^2	346×10^7 kJ/m^2	cable trays (miscellaneous, < 1%)
Control/Shift Eng. Office	29 m^2	286×10^7 kJ/m^2	miscellaneous
Auxiliary/480-V Board Room	200 m^2	277×10^7 kJ/m^2	cable trays (panels/cabinets, < 10%)

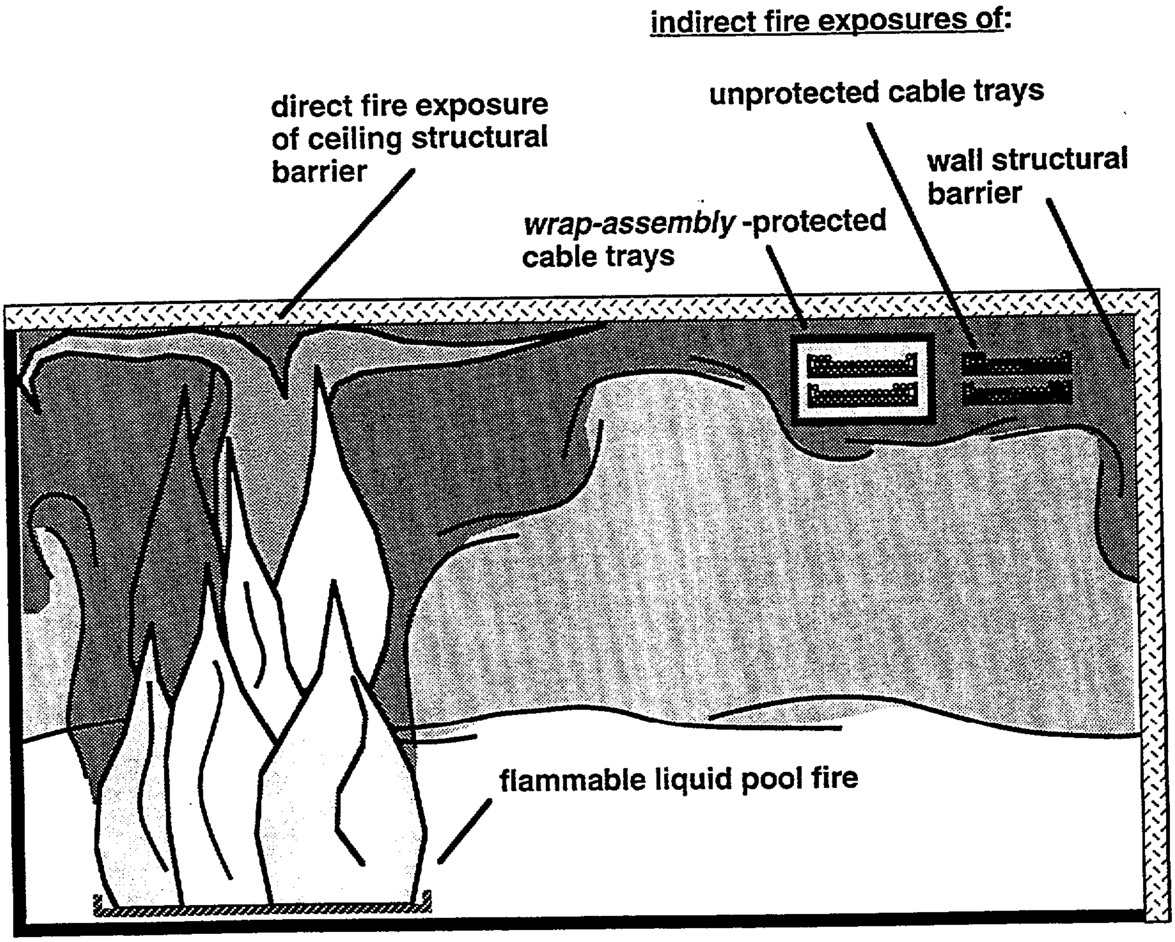

Figure 3-1. NPP compartment fire involving fully-developed burning of an extensive dense array of cable trays.

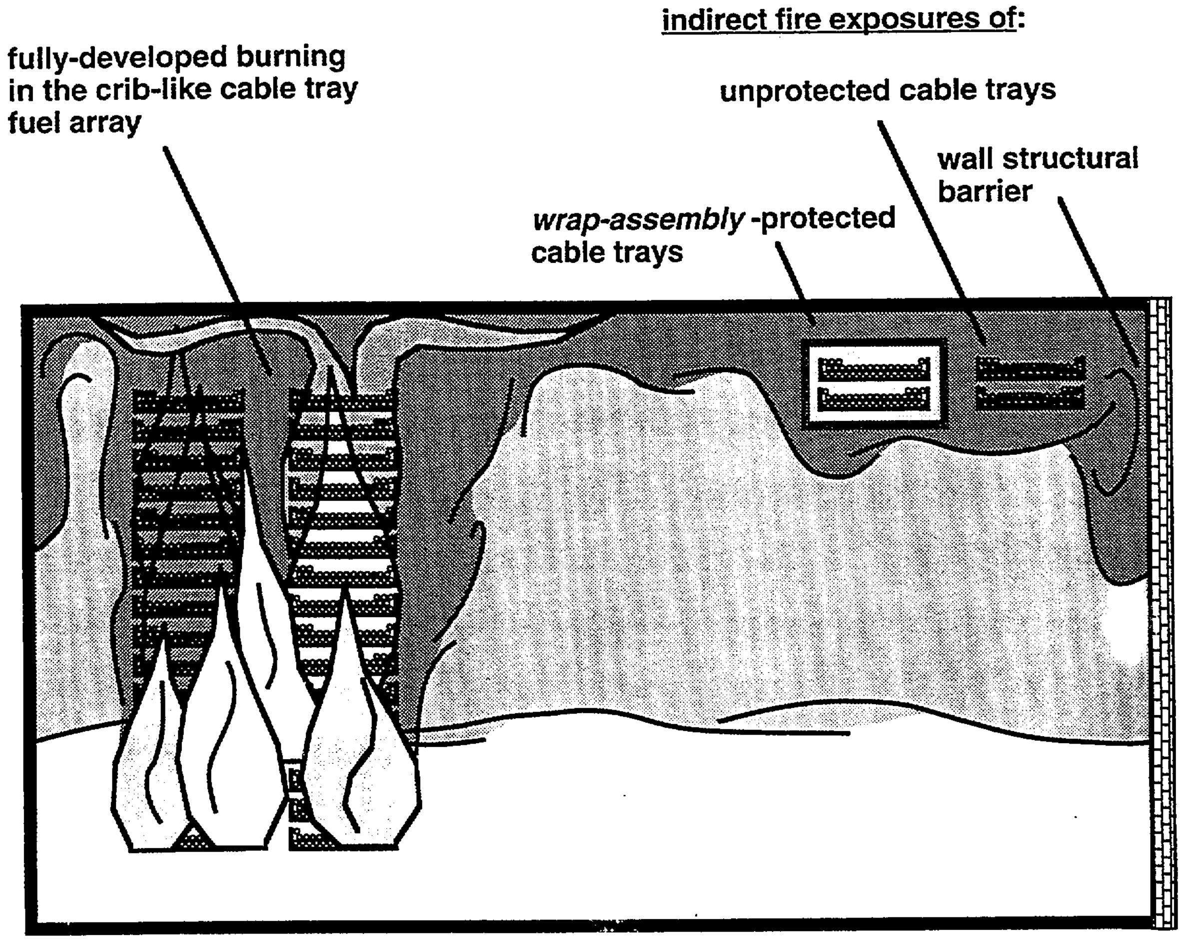

Figure 3-2. NPP compartment fire involving burning of a combustible/flammable liquid.

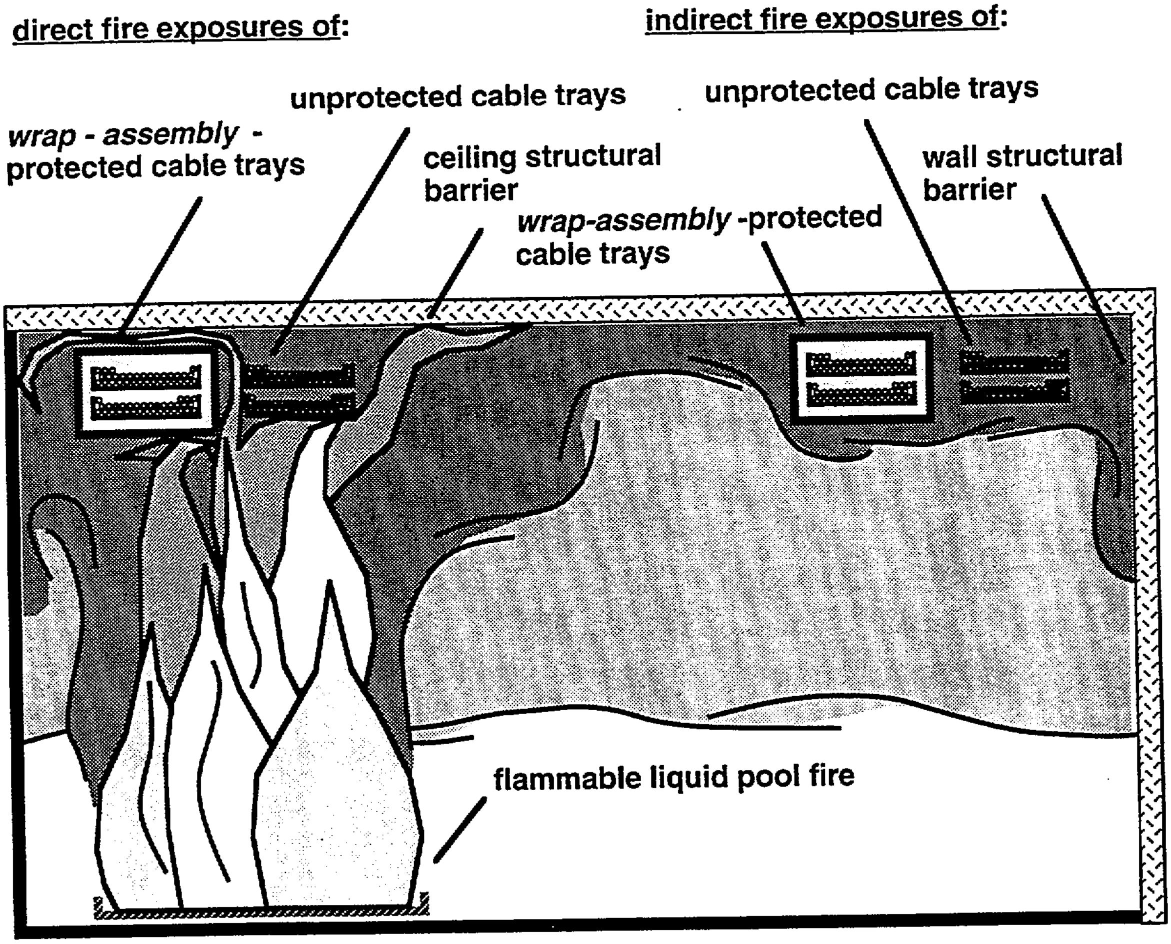

Figure 3-3. NPP compartment fire involving burning of a combustible/flammable liquid and direct fire exposure of unprotected and wrap-assembly-protected cable trays and of the compartment ceiling structure.

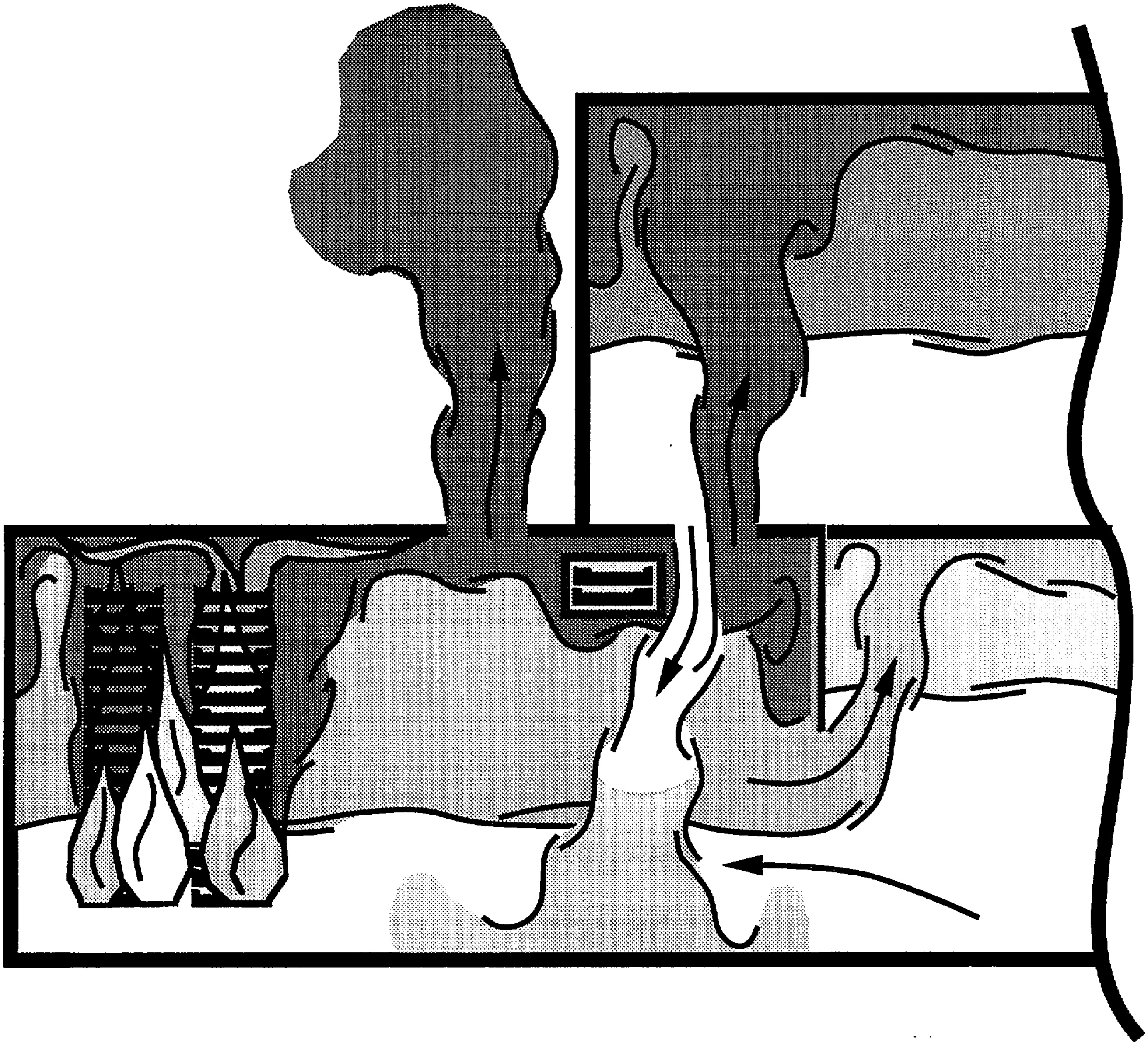

Figure 3-4. **Multi-room NPP compartment fire involving fully-developed burning of an extensive dense array of cable trays and a combination of different types of ventilation configurations.**

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Advances in fire science over the past 40 years have offered the potential for developing technically-sound alternative temperature-time curves for use in evaluating fire barriers for areas where fire exposures can be expected to be significantly different than the ASTM E 119, standard, temperature-time exposure. The U.S. Nuclear Regulatory Commission (NRC) staff initiated the current effort to investigate the feasibility of developing alternative temperature-time curves for the qualification of fire barriers used to protect cabling and equipment necessary to achieve safe shutdown on the basis of realistic fire hazards found in nuclear power plants (NPPs).

The approach taken in the current study consists of three steps or tasks: 1) review the history of the ASTM E 119 temperature-time curve to assess its current applicability and limitations in simulating real fires; 2) review the history of efforts to develop alternative curves and the methodologies used; and 3) use the findings from (1) and (2), knowledge of NPP construction, fuel types and loads, and state-of-the-art fire science to propose a methodology for developing and implementing NPP-specific descriptions of fire environments and associated ASTM-*type* temperature-time curves and test methods.

Results of each task are reported. The proposed methodology calls for a combination of zone modeling and large-scale fire experiments.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

ASTM E119; cables; fire barriers; fire endurance; fire models; fire resistance; histories; nuclear power plants; temperature; zone models.

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