ABS

FOUNDED 1862

GUIDANCE NOTES ON

ALTERNATIVE DESIGN AND ARRANGEMENTS FOR FIRE SAFETY

JANUARY 2004 (Updated July 2010 – see next page)

Updates

July 2010 consolidation includes:

- January 2004 version plus Corrigenda/Editorials

Foreword

Background

Fire safety regulations can have a major impact on many aspects of the overall design of ships, including design layout, aesthetics, function, costs, etc. Rapid developments in modern shipbuilding technology have often resulted in unconventional structures and design solutions. As the physical size of ships continuously increases, the complexity of design and functionality also increases. At the same time, there have been great strides in understanding of fire processes and their interrelationship with humans and ships. Advancement has been particularly rapid in the areas of analytical fire modeling. Several different types of such models, with varying degrees of sophistication, have been developed in recent years and are used by engineers in the design process.

The SOLAS regulation II-2/Regulation 17, "Alternative design and arrangements", along with supporting MSC/Circ. 1002 entered into force on July 1, 2002, allows a methodology to be used for alternative design and arrangements for fire safety. It essentially permits the use of a performance-based fire engineering approach to achieve an equivalent level of safety to the prescriptive requirements for all ship types. This approach focuses on the overall performance of specific arrangements and their ability to meet the fire safety objectives, enabling enhanced flexibility in ship design and allowing for arrangements which traditionally had not been permitted within the prescriptive framework.

As a result, the ship design is no longer restricted to the predefined conditions within the regulations. The fire safety measures can now be chosen to address the specific hazards present in each ship. Instead of prescribing exactly which protective measures are required, the performance of the overall system is presented against a specified set of design objectives (such as stating that satisfactory escape should be affected in the event of fire). Fire modeling and evacuation modeling can often be used to assess the effectiveness of the proposed protective measures.

MSC/Circ. 1002, "Guidelines on Alternative Design and Arrangements for Fire Safety", outline the methodology for the engineering analysis required by SOLAS regulation II-2/17, applying to a specific fire safety system, design or arrangements for which the approval of an alternative design deviating from prescriptive requirements of SOLAS Chapter II-2 is sought.

However, in MSC/Circ. 1002, little information has been provided for some crucial parts of fire safety analysis, for example, how to develop the performance criteria and how to select the hazard for analysis. In fact, designers and shipbuilders need the processing guidance on how to carry out the procedures addressed in MSC/Circ. 1002.

In response to industry need, ABS has developed these *Guidance Notes on Alternative Design and Arrangements for Fire Safety* in order to assist in the understanding of MSC/Circ. 1002. These Guidance Notes not only encapsulate the entire contents of MSC/Circ. 1002, but also provide supplemental materials to further explain the guidelines in MSC/Circ. 1002, in particular, in the areas of identifying design fire scenarios, developing trials, selecting design tools for trial alternative designs and developing performance-based criteria, etc. Therefore, these Guidance Notes provide a practical methodology for the situations where an alternative design is being proposed on the premise that it provides the equivalent level of safety to the SOLAS regulations.

Contents of the Guidance Notes

These Guidance Notes follow the section numbering of MSC/Circ. 1002 and provide explanatory appendices for the issues addressed in those sections. The contents of the Guidance Notes take the following order:

Section 1: Application. The purpose and the scope of application of these Guidance Notes are addressed in this Section.

Section 2: Definitions. This Section defines the general terms used with specific technical meanings in these Guidance Notes for the purpose of clarification. Some terms which are not listed in MSC/Circ. 1002, but used in these Guidance Notes, are listed in a separate order.

Section 3: Engineering Analysis. This Section emphasizes the necessity of following an established approach for the process of the alternative design and arrangements. This Section also provides two examples of established approaches, and defines the proper phases of process, i.e., preliminary analysis and quantitative analysis.

Section 4: Design Team. This Section emphasizes the qualification and the responsibility of the design team acceptable to the Administration.

Section 5: Preliminary Analysis in Qualitative Terms. The process of preliminary analysis is outlined in detail in this Section. The Subsections contain a great deal of explanatory material to supplement the original section of MSC/Circ. 1002 regarding the definition of scope, the development of fire scenarios, the development of trial alternative designs and the preliminary analysis report.

Section 6: Quantitative Analysis. The quantitative analysis is the most labor-intensive from a fire safety engineering standpoint. It consists of quantifying the design fire scenarios, developing the performance criteria, verifying the acceptability of the selected safety margins and evaluating the performance of trial alternative designs against the prescriptive performance criteria. All of these issues are discussed in detail in this Section, and some are further discussed in the corresponding Appendices of these Guidance Notes.

Section 7: Documentation. This Section lists the necessary steps of documentation for all design processes.

Appendix A: Report on the Approval of Alternative Design and Arrangements for Fire Safety. This Appendix shows the official submittal form for the approval of alternative design and arrangements for fire safety.

Appendix B: Document of Approval of Alternative Design and Arrangements for Fire Safety. This Appendix shows the official submittal form for the documentation of alternative design and arrangements for fire safety.

Appendix C: Technical Reference and Resources. This Appendix emphasizes the necessary requirements of reliable technical references and resources. Some examples of the technical references and resources are provided in this appendix.

Appendix D: Identifying Design Fire Scenarios. This Appendix discusses the methodology to provide minimum design fire scenarios for evaluation of alternative design and arrangements. Two types of the probabilistic and deterministic design techniques are reviewed.

Appendix E: Developing Trial Alternative Designs. This Appendix focuses on how to develop trial alternative designs to represent fire protection system design alternatives developed to address design fire scenarios to achieve the previously established performance requirements.

Appendix F: Design Tools for Trial Alternative Designs. This Appendix reviews the fundamentals of fire modeling in quantitative fire analysis. It discusses the basics of fire modeling, major assumptions, heat transfer and fire dynamics, explicabilities and limitations of the fire modeling. The main part of this Appendix is devoted to zone modeling and field (CFD) modeling techniques. The final portion of this Appendix lists some available fire models developed for various fire protection applications.

Appendix G: Developing Performance-based Criteria. This Appendix states the effects of life safety and non-life safety criteria on the development of performance criteria. As the consideration of tenability of life safety becomes increasingly important in fire safety design, the effects of various life-threatening hazards are discussed in this Appendix.

Appendix H: Example Analysis - Alternative Design and Arrangements for Containership Cargo Spaces. This Appendix provides an example of alternative design for a carbon dioxide fire extinguishing system in a containership cargo hold. This Appendix outlines the procedures to complete the design process and gives step-by-step illustrations on how the equivalent level of fire protection provided by alternative design can be met against the prescriptive regulations and requirements.

This Page Intentionally Left Blank

GUIDANCE NOTES ON

ALTERNATIVE DESIGN AND ARRANGEMENTS FOR FIRE SAFETY

CONTENTS

S E C T I O N   **1   Application**

1

These Guidance Notes are based on MSC/Circ. 1002, "*Guidelines on Alternative Design and Arrangements for Fire Safety*". They incorporate the entire contents of MSC/Circ. 1002, and are developed for providing additional explanatory materials and a workable example for fire safety design and analysis.

2

These Guidance Notes are intended to outline the methodology for the engineering analysis required by SOLAS regulation II-2/17, "Alternative design and arrangements", applying to a specific fire safety system, design or arrangements for which the approval of an alternative design deviating from the prescriptive requirements of SOLAS chapter II-2 is sought.

3

These Guidance Notes are not intended to be applied to the type approval of individual materials and components.

4

These Guidance Notes are not intended to serve as a stand-alone document, but should be used in conjunction with the fire safety engineering design guides and other literature, examples of which are referenced in Section 3 of these Guidance Notes.

5

For the application of these Guidance Notes to be successful, all interested parties, including the Administration or its designated representative, Owners, operators, designers and classification societies, should be in continuous communication from the onset of a specific proposal to utilize these guidelines. This approach usually requires significantly more time in calculation and documentation than a typical regulatory prescribed design because of increased engineering rigor. The potential benefits include more options, cost effective designs for unique applications and an improved knowledge of loss potential.

This Page Intentionally Left Blank

SECTION **2** **Definitions**

For the purposes of these Guidance Notes, the following definitions apply:

i) *Alternative Design and Arrangements* means fire safety measures which deviate from the prescriptive requirement(s) of SOLAS chapter II-2, but are suitable to satisfy the fire safety objective(s) and the functional requirements of that chapter. The term includes a wide range of measures, including alternative shipboard structures and systems based on novel or unique designs, as well as traditional shipboard structures and systems that are installed in alternative arrangements or configurations.

ii) *Design Fire* means an engineering description of the development and spread of fire for use in a design fire scenario. Design fire curves may be described in terms of heat release rate versus time.

iii) *Design Fire Scenario* means a set of conditions that defines the fire development and the spread of fire within and through vessel space(s) and describes factors such as ventilation conditions, ignition sources, arrangement and quantity of combustible materials and fire load accounting for the effects of fire detection, fire protection, fire control and suppression and fire mitigation measures.

iv) *Functional Requirements* explain in general terms what function the vessel should provide to meet the fire safety objectives of SOLAS.

v) *Performance Criteria* are measurable quantities stated in engineering terms to be used to judge the adequacy of trial designs.

vi) *Prescriptive-based Design* or *Prescriptive Design* means a design of fire safety measures which comply with the prescriptive regulatory requirements set out in parts B, C, D, E or G of SOLAS chapter II-2.

vii) *Safety Margin* means adjustments made to compensate for uncertainties in the methods and assumptions used to evaluate the alternative design, e.g., in the determination of performance criteria or in the engineering models used to assess the consequences of fire.

viii) *Sensitivity Analysis* means an analysis to determine the effect of changes in individual input parameters on the results of a given model or calculation method.

ix) *SOLAS* means the International Convention for the Safety of Life at Sea, 1974, as amended.

In additional to the above definitions, the following definitions shall also apply:

x) *Crew Member* means any person onboard a vessel, including the Master, who is not a passenger.

xi) *Deterministic Analysis* means a methodology based on physical relationships derived from scientific theories and empirical results that for a given set of initial conditions will always produce the same results of prediction. In a deterministic analysis, a single set of input data will determine a specific set of output predictions.

xii) *Fire Model* is a physical or mathematical procedure that incorporates engineering and scientific principles in the analysis of fire and fire effects to simulate or predict fire characteristics and conditions of the fire environment.

xiii) *Fire Safety Objectives* mean the descriptions of the performance benchmarks in SOLAS Chapter II-2/Regulation 2 against which the predicted performance of a design is evaluated.

xiv) *Hazard* means a possible source of danger that can initiate or cause undesirable consequences if uncontrolled.

xv) *Model Evaluation* means the process of quantifying the accuracy of chosen results from a model when applied for a specific use.

xvi) *Model Validation* means the process of determining the correctness of the assumptions and governing equations implemented in a model when applied to the entire class of problems addressed by the model.

xvii) *Model Verification* means the process of determining the correctness of the solution of the system of governing equations in a model. With this definition, verification does not imply the solution of the correct set of governing equations, only that the given set of equations is solved correctly.

xviii) *Passenger* is every person other than the Master and the members of the crew or other persons employed or engaged in any capacity onboard a vessel for the business of that vessel.

xix) *Probability* means the likelihood that a given event will occur. Statistically, this is the number of actual occurrences of a specific event divided by the total number of possible occurrences. Probabilities are inherently dimensionless and expressed as a number between zero and one, inclusive.

xx) *Probabilistic Analysis* means an evaluation of the fire losses and fire consequences, which includes consideration of the likelihood of different fire scenarios and the inputs that define those fire scenarios.

xxi) *Risk* means the product of the potential consequences and the expected frequency of occurrence in the classic engineering sense. Consequences might include occupant death, monetary loss, business interruption, or environmental damage. The frequency of occurrence could be an estimate of how often the projected loss might occur.

xxii) *Stakeholder* means the one who has a share or an interest in an enterprise, specifically, an individual (or a representative) interested in the successful completion of a project. Reasons for having an interest in the successful completion of a project might be financial or safety related.

xxiii) *Trial Design* means a fire protection system design that is intended to achieve the stated fire safety goals and that is expressed in terms that make the assessment of these achievements possible.

SECTION **3** **Engineering Analysis**

1 Process of Alternative Design and Arrangements

The process used to show that the alternative design and arrangements provides the equivalent level of safety to the prescriptive requirements of SOLAS chapter II-2 should follow an established approach to fire safety design. This approach should be based on sound fire science and engineering practice incorporating widely accepted methods, empirical data, calculations, correlations and computer models as contained in engineering textbooks and technical literature.

2 Examples of Acceptable Approaches

Two examples of acceptable approaches to fire safety engineering are listed below:

i) *The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings*, Society of Fire Protection Engineers and National Fire Protection Association, 1999.

ii) ISO/TR 13387-1 through 13387-8, *"Fire safety engineering"*, International Standards Organization, 1999.

Other fire safety engineering approaches recognized by the Administration may be used. See Appendix 3 for guidance and a list of additional technical literature.

3 Phases of Process

The process of the alternative design and arrangements consists of two phases: preliminary analysis and quantitative analysis. The objective of the preliminary analysis is to review and agree upon the scope of the design proposal, identify potential fire hazards, define performance criteria and specify representative fire scenarios which are suitable for detailed analysis and quantification.

The objective of the quantitative analysis is to demonstrate, using standard tools and methodologies, that the vessel design meets the performance criteria agreed to in the preliminary analysis. The quantitative analysis should be based on both probabilistic and deterministic methods, including engineering calculations, computer modeling, Failure Modes and Effects Analysis, event trees and scientific fire tests. The following sections provide more detail regarding completion of the equivalency process and the level of documentation that is expected for equivalency determinations.

This Page Intentionally Left Blank

SECTION 4 Design Team

1 General Requirements

A design team acceptable to the Administration should be established by the Owner, builder or designer and may include, as the alternative design and arrangements demand, a representative of the Owner, builder or designer, and expert(s) having the necessary knowledge and experience in fire safety, design, and/or operation as necessary for the specific evaluation at hand. Other members may include marine surveyors, vessel operators, safety engineers, equipment manufacturers, human factors experts, naval architects and marine engineers.

2 Qualifications

The level of expertise that individuals should have to participate in the team may vary depending on the complexity of the alternative design and arrangements for which approval is sought. Since the evaluation, regardless of complexity, will have some effect on fire safety, at least one expert with knowledge and experience in fire safety should be included as a member of the team.

3 Responsibility of Design Team

The design team should:

i) Appoint a coordinator serving as the primary contact.

ii) Communicate with the Administration for advice on the acceptability of the engineering analysis of the alternative design and arrangements throughout the entire process.

iii) Determine the safety margin at the outset of the design process and review and adjust it as necessary during the analysis.

iv) Conduct a preliminary analysis to develop the conceptual design in qualitative terms. This includes a clear definition of the scope of the alternative design and arrangements and the regulations which affect the design; a clear understanding of the objectives and functional requirements of the regulations; the development of fire scenarios and trial alternative designs. This portion of the process is documented in the form of a report that is reviewed and agreed upon by all interested parties and submitted to the Administration before the quantitative portion of the analysis is started.

v) Conduct a quantitative analysis to evaluate possible trial alternative designs using quantitative engineering analysis. This consists of the specification of design fires, development of performance criteria based upon the performance of an acceptable prescriptive design and evaluation of the trial alternative designs against the agreed performance criteria. From this step, the final alternative design and arrangements are selected and the entire quantitative analysis is documented in a report.

vi)   Prepare documentation, specifications and a life-cycle maintenance program. The alternative design and arrangements should be clearly documented, approved by the Administration, and a comprehensive report describing the alternative design and arrangements and required maintenance program should be kept onboard the vessel. An operations and maintenance manual should be developed for this purpose. The manual should include an outline of the design conditions that should be maintained over the life of the vessel to ensure compliance with the approved design.

4   Setting the Comparison

The fire safety objectives in SOLAS regulation II-2/2 and the purpose statements listed at the beginning of each individual regulation in chapter II-2 should be used to provide the basis for comparison of the alternative design and arrangements to the prescriptive regulations.

SECTION **5** **Preliminary Analysis to Qualitative Terms**

1 Definitions of Scope

The preliminary analysis may begin with a concept review meeting between the Administration and the design team. Depending upon the scope and the level of innovation of the equivalency, such meetings may need to be undertaken at a very early stage to agree on the project's scope. Items to be agreed upon may include a definition of the project scope, level of analysis necessary for this project, and fire safety goals and objectives that the proposed design should meet.

Although much of the information required for the preliminary analysis, as described in Subsection 5/4, may not be known, the design team should be prepared to present a proposed text for such a report at this concept review meeting. The purpose of such a meeting is to achieve agreement on the scope of the proposed equivalency and not for the designer to seek out the Administration's opinion of what they need to do.

1.1 Contents of Scope

1.1.1 Elements of Project Scope

The purpose of this stage is to thoroughly define the boundaries of the problem for the proposed design.

The vessel, vessel system(s), component(s), space(s) and/or equipment subject to the analysis should be thoroughly defined. This includes the vessel or system(s) representing both the alternative design and arrangements and the regulatory prescribed design. Depending on the extent of the desired deviation from prescriptive requirements, some of the information that may be required includes: detailed vessel plans, drawings, equipment information and drawings, fire test data and analysis results, vessel operating characteristics and conditions of operation, operating and maintenance procedures, material properties, etc. Accordingly, the project scope definition must, at a minimum, contain all of the relevant information required by Chapter 4 of the *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Building*.

This stage of the process should be started during the earliest stages of the design conception, i.e., at the first point at which the Owner or naval architect acknowledges that an alternative design or arrangements will be necessary. This stage should also be the opportunity for the naval architect or Owner to arrange the concept review meeting to discuss the scope of the alternative design or arrangements with the Administration. If a basic evaluation is required, then it is likely that all of the project definition can occur during the initial meeting.

1.1.2 Defining Goals

Once the project scope has been defined and agreed upon, the design team should identify and agree upon the fire safety goals and objectives. Goals are identified through discussions with the stakeholders and a review of background materials. The following list presents four interrelated fundamental goals for fire safety:

i) Providing life safety for passengers and vessel crews. Minimize fire-related injuries and prevent undue loss of life.

ii) Protecting property. Minimize damage to the property from fire.

iii) Providing for continuity of operations. Protect the organization's ongoing mission, product or operating capability. Minimize undue loss of operations and business-related revenue due to fire-related damage.

iv) Limiting the environmental impact.

Chapter 5 of the SFPE Guide contains general guidelines for defining the fire safety goals. A goal is normally defined in broad terms by the stakeholders. Section 5, Table 1 provides examples of different goals, which the design teams should understand when conducting a performance-based design.

TABLE 1
Examples of Fire Safety Goals

Fundamental goals
• Minimize fire-related injures and prevent loss of life
• Minimize fire-related damage to the vessel, its structures and fire integrity
• Minimize loss of vessel operations and business-related revenue to fire-related damage
• Limit the environmental impact of the fire and fire protection measures
Other possible goals
• Provide sufficient training and awareness to ensure the safety of the crews and passengers
• Reduce shipbuilding cost while maintaining adequate life safety measures
• Maximize the flexibility of design and innovation

While the stakeholders might share the same global goals, the engineer must understand that the priority and relative weight might vary among stakeholders. Further differences might occur when defining objectives and performance criteria.

1.1.3 Defining Objectives

Once the fire protection goals have been established and agreed to, the fire safety objectives to meet the goals must be defined. SOLAS II-2/Regulation 2 includes a statement of fire safety objectives and the functional requirements to achieve those objectives.

It is recommended that these goals and objectives be the foundation for developing the performance criteria that are specific to the proposal of alternative design and arrangements.

1.2   Documenting Regulations

The regulations affecting the proposed alternative design and arrangements, along with their functional requirements, should be clearly understood and documented in the preliminary analysis report (see Subsection 5/4). This should form the basis for the comparative analysis referred to in Subsection 6/4.

2   Development of Fire Scenarios

2.1   General

Fire scenarios should provide the basis for analysis and trial alternative design evaluation and, therefore, are the backbone of the alternative design process. Proper fire scenario development is essential and, depending on the extent of deviation from the prescribed design, may require a significant amount of time and resources.

(For each of the identified fire hazards, a range of fire scenarios should be developed. The use of event trees is recommended to systematically determine all of the possible fire scenarios resulting from a specific hazard. Because the alternative design approach is based on a comparison against the regulatory prescribed design, the quantification can often be simplified. In many cases, it may only be necessary to analyze one or two scenarios if this will provide enough information to evaluate the level of safety of the alternative design and arrangements against the agreed performance design. Appendix 4 provides a minimum design fire scenario that should be considered.)

This process can be broken down into four areas:

i)   Identification of fire hazards

ii)   Enumeration of fire hazards

iii)   Selection of fire hazards

iv)   Specification of design fire scenarios

2.1.1   Identification of Fire Hazards

This step is crucial in the fire scenario development process as well as in the entire alternative design methodology. If a fire hazard or incident is omitted, then it will not be considered in the analysis and the resulting final design may be inadequate. Fire hazards may be identified using historical and statistical data, expert opinion and experience and hazard evaluation procedures. There are many hazard evaluation procedures available to help identify the fire hazards including HAZOP, PHA, FMEA, "what-if", etc. Further details on the use of these procedures specific to identifying possible fire hazards is contained in other references including the *SFPE Engineering Guide to Performance Based Fire Protection Analysis and Design of Buildings*, and the *SFPE Handbook of Fire Protection Engineering*. As a minimum, the following conditions and characteristics should be identified and considered:

i)   *Pre-fire situations.*   Vessel, platform, compartment, fuel load, environmental conditions

ii)   *Ignition sources.* Temperature, energy, time and area of contact with potential fuels

iii)   *Initial fuels.* State (solid, liquid, gas, vapor, spray), surface area to mass ratio, rate of heat release

iv)   *Secondary fuels.* Proximity to initial fuels, amount, distribution

v)   *Extension potential.* Beyond compartment, structure, area (if in open)

vi)   *Target locations.*   Note target items or areas associated with the performance parameters

vii)   *Critical factors.* Ventilation, environment, operational, time of day, etc.

viii)   *Relevant statistical data.*   Past fire history, probability of failure, frequency and severity rates, etc.

More details of characterizing design fire scenarios can be found in Chapter 8 of the *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Building*.

2.1.2   Enumeration of Fire Hazards

All of the fire hazards identified above should be grouped into one of three incident classes: localized, major or catastrophic. A localized incident consists of a fire with a localized effect zone, limited to a specific area. A major incident consists of a fire with a medium effect zone, limited to the boundaries of the vessel. A catastrophic incident consists of a fire with a large effect zone, beyond the vessel and affecting surrounding vessels or communities. In the majority of cases, only localized and/or major fire incidents need to be considered. Examples where the catastrophic incident class may be considered would include transport and/or offshore production of petroleum products or other hazardous materials where the incident effect zone is very likely to be beyond the vessel vicinity. The fire hazards should be tabulated for future selection of a certain number of each of the incident classes.

2.1.3   Selection of Fire Hazards

The number and type of fire hazards that should be selected for the quantitative analysis is dependent on the complexity of the trial alternative design and arrangements. All of the fire hazards identified should be reviewed for selection of a range of incidents. In determining the selection, frequency of occurrence does not need to be fully quantified, but it can be utilized in a qualitative sense. The selection process should identify a range of incidents which cover the largest and most probable range of enumerated fire hazards. Because the engineering evaluation relies on a comparison of the proposed alternative design and arrangements with prescriptive designs, demonstration of equivalent performance during the major incidents should adequately demonstrate the design's equivalence for all lesser incidents and provide the commensurate level of safety. In selecting the fire hazards, it is possible to lose perspective and to begin selecting highly unlikely or inconsequential hazards. Care should be taken to select the most appropriate incidents for inclusion in the selected range of incidents.

2.1.4   Specification of Design Fire Scenarios

Based on the fire hazards selected, the fire scenarios to be used in the quantitative analysis should be clearly documented. The specification should include a qualitative description of the design fire (e.g., ignition source, fuel first ignited, location, etc.), description of the vessel, compartment of origin, fire protection systems installed, number of occupants, physical and mental status of occupants and available means of escape. The fire scenarios should consider possible future changes to the fire load and ventilation system in the affected areas. The design fire(s) will be characterized in more detail during the quantitative analysis for each trial alternative design. Appendix 4 provides the explanatory materials for design fire scenarios, the methodology of identifying design fire scenarios and some examples of design fire scenarios in NFPA 101.

3   Development of Trial Alternative Designs

At this point in the analysis, one or more trial alternative designs should be developed so that they can be compared against the developed performance criteria. Trial alternative designs are the fire protection strategies developed by the design team that are intended to meet the objectives, functional statements and performance requirements. The trial alternative design should also take into consideration the importance of human factors, operations and management as reflected in part E of SOLAS chapter II-2. It should be recognized that well-defined operations and management procedures might play a large part in increasing the overall level of safety. Appendix 5 provides the explanatory details to assist in developing alternative designs by understanding what the objectives and functional statements are, as well as the performance requirements, and looking at various individual or combinations of subsystems that will allow one to achieve the performance requirements.

Under certain circumstances, such as designing an alternative or innovative fire fighting system, the trial alternative design should be subject to a test conducted by an accredited independent third party (i.e., test facility or laboratory) or the group undertaking the actual alternative design. The test could be modeled or full-scaled experiment; it could be theoretical or practical. If the test is done by computer modeling, further testing may be required. Furthermore, if a practical test is done to the pre-agreed criteria, then the test house should publish a report and conclusions. The test results of trial alternative design should be documented in a report published by the above testing parties. The purpose of the report is to provide an open and available set of conclusive results.

The test report should include all of the data, wherein the test results of the trial alternative design as achieved or obtained are plotted or indicated in a comparative manner in conjunction with the performance criteria, and the results of which are not mathematically scaled from a test of different proportions (i.e., smaller or alternative fire proportions rather than compartment proportions). For example, very often the area or volume is scaled but the fire is not, and then the actual test (physical) being conducted is not indicative of the same results since the proportions and ratios are in fact a little different.

4   Preliminary Analysis Report

4.1   Contents of Report

A report of the preliminary analysis should include clear documentation of all steps taken to this point, including identification of the design team, their qualifications, the scope of the alternative design analysis, the functional requirements to be met, the description of the fire scenarios and trial alternative designs selected for the quantitative analysis.

4.2   Submittal of Report

The preliminary analysis report should be submitted to the Administration for formal review and agreement prior to beginning the quantitative analysis. The report may also be submitted to the port State for informational purposes, if the intended calling ports are known during the design stage. The key results of the preliminary analysis should include:

i)   A secured agreement from all parties to the design objectives and engineering evaluation

ii)   Specified design fire scenario(s) acceptable to all parties

iii)   Trial alternative design(s) acceptable to all parties

This Page Intentionally Left Blank

SECTION 6 Quantitative Analysis

1 General

The quantitative analysis is the most labor-intensive from a fire safety engineering standpoint. It consists of quantifying the design fire scenarios, developing the performance criteria, verifying the acceptability of the selected safety margins and evaluating the performance of trial alternative designs against the prescriptive performance criteria.

1.1 Scope

The quantification of the design fire scenarios may include calculating the effects of fire detection, alarm and suppression methods, generating time lines from initiation of the fire until control or evacuation, and estimating consequences in terms of fire growth rate, heat fluxes, heat release rates, flame heights, smoke and toxic gas generation, etc. This information will then be utilized to evaluate the trial alternative designs selected during the preliminary analysis.

1.2 Risk Assessment

Risk assessment may play an important role in this process. It should be recognized that risk cannot ever be completely eliminated. Throughout the entire performance-based design process, this fact should be kept in mind. The purpose of performance design is not to build a fail-safe design, but to specify a design with reasonable confidence that it will perform its intended function(s) when necessary and in a manner equivalent to or better than the prescriptive fire safety requirements of SOLAS chapter II-2.

2 Quantification of Design Fire Scenarios

2.1 Choosing Models for Quantification

After choosing an appropriate range of fire incidents, quantification of the fires should be accomplished for each of the incidents. Quantification will require specification of all factors that may affect the type and extent of the fire hazard. The fire scenarios should consider possible future changes to the fire load and ventilation system in the affected areas. This may include calculation of heat release rate curves, flame height, length and tilt, radiant, conductive and convective heat fluxes, smoke production rate, pool fire size, duration, timelines, etc. References on suggested example correlations and models that may be of use are listed in Appendix 3.

Models for quantification of fire scenarios shall be chosen based upon an appropriate evaluation and verification process. The methodology for evaluating the predictive capability of fire models by which the process can be classified into four areas of evaluation as described in ASTM E 1355-97 is recommended:

2.1.1   Model and Scenario Definition

Sufficient documentation of calculation models, including computer software, is absolutely necessary to assess the adequacy of the scientific and technical basis of the models and the accuracy of computational procedures. Also, adequate documentation will help prevent the unintentional misuse of fire models.

Scenario definition provides a complete description of the scenarios or phenomena of interest in the evaluation to facilitate appropriate application of the model, to aid in developing realistic inputs for the model, and criteria for judging the results of the evaluation.

2.1.2   Theoretical Basis for the Model

An independent review of the underlying physics and chemistry inherent in a model ensures appropriate application of sub-models which have been combined to produce the overall model. This review should include the assessment of the completeness of the documentation, particularly with regard to the assumptions and approximations, and the assessment of whether there is sufficient scientific evidence in the open scientific literature to justify the approaches and assumptions being used. Empirical or reference data used for constants and default values in the code should also be assessed for accuracy and applicability in the context of the model.

2.1.3   Mathematical and Numerical Robustness

The computer implementation of the model should be checked to ensure such implementation matches the stated documentation. The analyses which can be performed include analytical tests, code checking and numerical tests.

Many fire problems involve the interaction of different physical processes, such as the chemical or thermal processes and the mechanical response. Time scales associated with the processes may be substantially different, which can easily cause numerical difficulties. Such problems are called stiff. Some numerical methods have difficulty with stiff problems since they slavishly follow the rapid changes even when they are less important than the general trend in the solution. Special algorithms should be devised for those cases with stiff problems.

2.1.4   Model Uncertainty and Accuracy of the Model

2.1.4(a) Model Uncertainty. Even deterministic models rely on inputs often based on experimental measurements, empirical correlations or estimates, made by engineering judgment. Uncertainties in the model inputs can lead to corresponding uncertainties in the model outputs. Sensitivity analysis is used to quantify these uncertainties in the model outputs based upon known or estimated uncertainties in model inputs. The purpose of conducting a sensitivity analysis is to assess the extent to which uncertainty in the model inputs is manifested to become uncertainty in the result of interest from the model.

2.1.4(b) Experimental Uncertainty. In general, the result of measurement is only the result of an approximation or estimate of the specific quantity subject to measurement, and thus the result is complete only when accompanied by a quantitative statement of uncertainty.

2.1.4(c) Model Evaluation. A model should be assessed for a specific use in terms of its quantitative ability to predict outcomes such as fire growth and spread, rate of flame spread, fire resistance, fire hazard typified by available egress time, tenability, response of active and passive fire protection, and some other property damages, etc. As a result, a model may be evaluated by comparisons with standard tests, full-scaled tests conducted specifically for the chosen evaluation, previously published full-scaled test data, documented fire experience, proven benchmark models, etc.

Obtaining accurate estimates of fire behavior using predictive fire models involves ensuring correct model inputs appropriate to the scenarios to be modeled, correct selection of a model appropriate to the scenarios to be modeled, correct calculations by the model chosen and correct interpretation of the results of the model calculation. Evaluation of a specific scenario with different levels of knowledge of the expected results of the calculation addresses these multiple sources of potential error.

2.1.5   Choosing Tools for Trial Design Scenarios

It should be noted that when using any of these or other tools, the limitations and assumptions of these models should be well understood and documented. This becomes very important when deciding on and applying safety margins. Documentation of the alternative design should explicitly identify the fire models used in the analysis and their applicability. Reference to the literature alone should not be considered as adequate documentation. A summary of the deterministic fire models is provided in Appendix 6. The general procedure for specifying design fires includes fire scenario development completed during the preliminary analysis, timeline analysis and consequence estimation, which are detailed below.

2.2   Developing Fire Scenarios

For each of the identified fire hazards, a range of fire scenarios should be developed. Because the alternative design approach is based on a comparison against the regulatory prescribed design, the quantification can often be simplified. In many cases, it may only be necessary to analyze one or two scenarios if this provides enough information to evaluate the level of safety of the alternative design and arrangements against the required prescriptive design.

2.3   Description of Fire Scenarios

A timeline should be developed for each of the fire scenarios beginning with fire initiation. Timelines should include one or more of the following: ignition, established burning, fire detection, fire alarm, fire suppression/control system activation, personnel response, fire control, escape times (to assembly stations, evacuation stations and lifeboats, as necessary), manual fire response, untenable conditions, etc. The timeline should include fire size throughout the scenario, as determined by using the various correlations, models and fire data from the literature or actual fire tests.

2.4   Consequences of Fire Scenarios

Consequences of various fire scenarios should be quantified in fire engineering terms. This can be accomplished by using existing correlations and calculation procedures for determining fire characteristics such as heat release rate curves, flame height, length and tilt, radiant, conductive and convective heat fluxes, etc. In certain cases, live fire testing and experimentation may be necessary to properly predict the fire characteristics. Regardless of the calculation procedures utilized, a sensitivity analysis should be conducted to determine the effects of the uncertainties and limitations of the input parameters.

3   Development of Performance Criteria

3.1   General

Performance criteria are quantitative expressions of the fire safety objectives and functional requirements of the SOLAS regulations. The required performance of the trial alternative designs is specified numerically in the form of performance criteria. Performance criteria may include tenability limits such as smoke obscuration, temperature, height of the smoke and hot gas layer in a compartment, evacuation time or other criteria necessary to ensure successful alternative design and arrangements.

3.2   Performance Criteria Based Directly on SOLAS Chapter II-2

Each of the regulations in SOLAS chapter II-2 state the purpose of the regulation and the functional requirements that the regulation meets. Compliance with the prescriptive regulations is one way to meet the stated functional requirements. In some cases, the performance criteria for the alternative design and arrangements should be determined by a direct interpretation of the regulations, taking into consideration the fire safety objectives, the purpose statements and the functional requirements of the regulations. The following example is an illustration of this:

"Example of a performance criterion drawn directly from the regulations in SOLAS chapter II-2:

Assume that a design team is developing performance criteria for preventing fire spread through a bulkhead separating a galley from an accommodation space. They are seeking a numerical form for this criteria.

(e.1)   Regulation II-2/2 contains the fire safety objective "to contain, control, and suppress fire and explosion in their compartment of origin."

(e.2)   One of the functional requirements in which this objective is manifest is "separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries."

(e.3)   Regulation II-2/9 contains the prescriptive requirements to achieve this functional requirement; in particular it requires an "A-60" class boundary between areas of high fire risk (like a machinery space or galley) and accommodation spaces.

(e.4)   Regulation II-2/3 contains the definition of an "A" class division, which includes the maximum temperature rise criteria of 180°C at any one point, after a 60 minute fire exposure.

(e.5)   Therefore, one possible performance criterion for this analysis is that "no point on the other side of the bulkhead shall rise more than 180°C above ambient temperature during a 60 minute fire exposure."

3.3   Performance Criteria Developed from a Commonly Used Acceptable Prescriptive Design

If the performance criteria for the alternative design and arrangements cannot be determined directly from the prescriptive regulations because of novel or unique features, they may be developed from a quantitative evaluation of the intended performance of a commonly used acceptable prescriptive design, provided that an equivalent level of fire safety is maintained. This is a useful method for developing performance criteria where it is difficult to quantify the desired performance in terms of absolute values. By stating the performance criteria in terms of the performance of a regulatory design, it can be inherently assumed that the features incorporated in the regulatory design provide an overall acceptable level of safety.

Comparative performance criteria should be specified in terms of a comparison to a similar prescriptive design. Further, since the alternative design will invariably have some difference from the regulatory design, the criteria should also address cases when the regulatory design does not provide a sufficient level of performance. As an example: "*The alternative design shall provide the lesser of: the evacuation time for a vessel built to the requirements of SOLAS II-2/13; or the minimum evacuation time required by the assumed design fires for the proposed design*". When the performance criteria are determined through comparative analysis, it will be necessary for the design team to quantify the performance of both the alternative design and the regulatory prescribed design during the quantitative analysis.

3.4   Specific Performance Criteria and Safety Margins

Before evaluating the prescriptive design, the design team should agree on what specific performance criteria and safety margins should be established. Depending on the prescriptive requirements to which the approval of alternative design or arrangements is sought, these performance criteria could fall within one or more of the following areas:

3.4.1   Life Safety Criteria

These criteria address the survivability of passengers and crew and may represent the effects of heat, smoke, toxicity, reduced visibility and evacuation time.

3.4.2   Criteria for Damage to Vessel Structure and Related Systems

These criteria address the impact that fire and its effluents might have on the vessel structure, mechanical systems, electrical systems, fire protection systems, evacuation systems, propulsion and maneuverability, etc. These criteria may represent thermal effects, fire spread, smoke damage, fire barrier damage, degradation of structural integrity, etc.

3.4.3   Criteria for Damage to the Environment

These criteria address the impact of heat, smoke and released pollutants on the atmosphere and marine environment.

Appendix 7 provides a description of the effects of life and non-life safety criteria.

3.5   Impact on Areas not Specifically Part of the Alternative Design

The design team should consider the impact that one particular performance criterion might have on other areas that might not be specifically part of the alternative design. For example, the failure of a fire barrier may not only affect the life safety of passengers and crew in the adjacent space, but it may result in structural failure, exposure of essential equipment to heat and smoke and the involvement of additional fuel in the fire.

3.6   Evaluation

Once all of the performance criteria have been established, the design team can then proceed with the evaluation of the trial alternative designs (see Subsection 6/4).

4   Evaluation of Trial Alternative Designs

4.1   Process Flowchart

All of the data and information generated during the preliminary analysis and specification of design fires should serve as input to the evaluation process. The evaluation process may differ depending on the level of evaluation necessary (based on the scope defined during the preliminary analysis), but should generally follow the process illustrated in Section 6, Figure 1.

4.2   Analysis of Trial Design

Each selected trial alternative design should be analyzed against the selected design fire scenarios to demonstrate that it meets the performance criteria with the agreed safety margin, which in turn demonstrates equivalence to the prescriptive design.

4.3 Level of Engineering Analysis

The level of engineering rigor required in any particular analysis will depend on the level of analysis required to demonstrate equivalency of the proposed alternative design and arrangements to the prescriptive requirements. Obviously, the more components, systems, operations and parts of the vessel that are affected by a particular alternative design, the larger the scope of the analysis.

4.4 Final Alternative Design and Arrangements

The final alternative design and arrangements should be selected from the trial alternative designs that meet the selected performance criteria and safety margins.

FIGURE 1
Alternative Design and Arrangements Process Flowchart
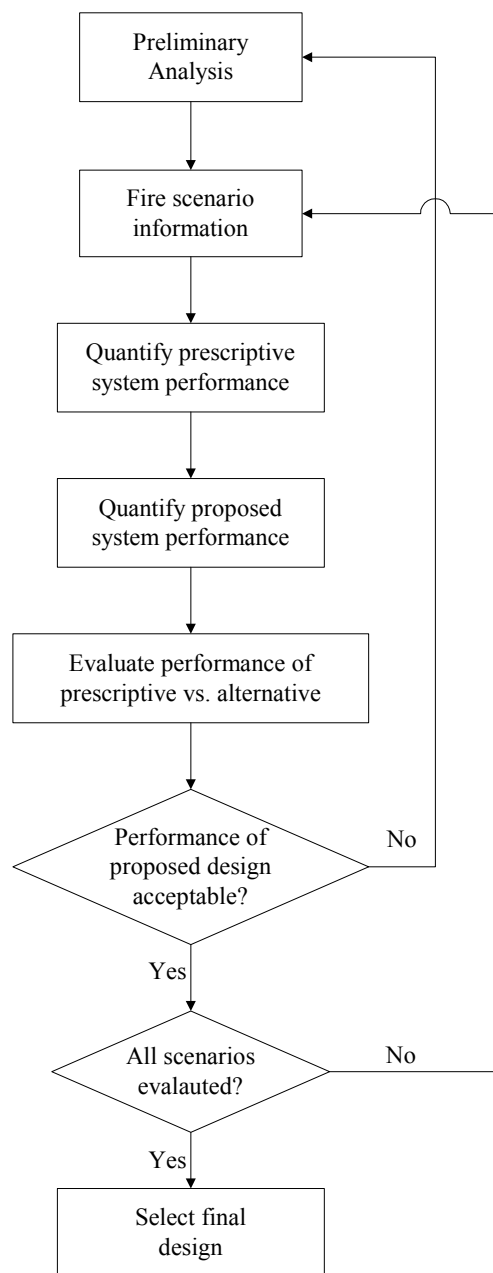
SECTION 7 Documentation

1 Basic Requirements

Because the alternative design process may involve substantial deviation from the regulatory prescribed requirements, the process should be thoroughly documented. This provides a record that will be required if future design changes to the vessel are proposed or the vessel transfers to the flag of another State, and will also provide details and information that may be adapted for use in future designs. The following information should be provided for approval of the alternative design or arrangements:

1.1 Scope of the Analysis or Design

The scope of the analysis or design might include the following:

i)   Design intents (e.g., new construction, renovation or upgrade of an existing facility, or repair of a damaged structure, etc.)

ii)   Project constraints (e.g., effects on other vessel operations, limitations, etc.)

iii)   Stakeholders (vessel owners, flag state, classification society, insurers, design and construction team organization, etc.)

iv)   Project schedules (e.g., length of project)

v)   Applicable regulations (SOLAS, ABS, etc.)

1.2 Description of Alternative Design(s) or Arrangement(s)

Description of the alternative design(s) or arrangements(s), including drawings and specifications:

i)   Qualitative goals of design(s) and arrangement(s), which might include:

- Protection of life safety (e.g., minimize fire-related injuries, and prevent undue loss of life, etc.)

- Protection of property (e.g., minimize damage to vessel structure from fire and exposure to and from adjacent spaces)

- Providing for continuity of operations of vessels due to fires.

ii)   Objectives of design(s) and arrangement(s)

- Fire safety goals and objectives agreed between the engineers and other stakeholders should be included.

- The method by which the design objectives are developed, including any uncertainty and safety factors, should be included.

iii)   All drawings of the alternative design(s) or arrangement(s)

iv)   Detailed vessel plans

v)   Material properties

vi)   Characteristics of occupants

- Response characteristics

    If a fire-extinguishing media is used in the alternative design and arrangements, the hazard assessment and toxic potency of the media on occupants shall be provided for approval.

- Location

- Number of occupants

- Staff assistance

- Emergency response personnel

- Off-site condition

1.3   Results of Preliminary Analysis

Results of the preliminary analysis are to include:

i)   Members of the design team (including qualifications), a resume and other information supporting the qualifications of the engineer(s) performing the analysis should be provided

ii)   Description of the trial alternative design and arrangements being evaluated

iii)   Discussion of affected SOLAS chapter II-2 regulations and their functional requirements

iv)   Fire hazard identification

Description of the procedures of fire hazard identifications should be provided.

v)   Enumeration of fire hazards

vi)   Selection of fire hazards

vii)   Description of design fire scenarios

1.4   Results of Quantitative Analysis

Results of quantitative analysis:

i)   Design fire scenarios:

- Critical assumptions

- Amount and composition of fire load

- Engineering judgments

- Calculation procedures

- Test data

- Sensitivity analysis

- Timelines

ii)   Performance criteria

iii)   Evaluation of trial alternative designs against performance criteria

iv)   Description of final alternative design and arrangements

v)   Test, inspection and maintenance requirements

vi)   References.

- The stakeholders should be provided with sufficient documentation to support the validity, accuracy, relevance and precision of the supposed methods.

- The engineering standards, calculation methods and other forms of scientific information shall be appropriate for the particular application and methodologies used.

2   Documentation of Approval

Documentation of approval by the Administration and the following information should be maintained onboard the vessel at all times:

i)   Scope of the analysis or design, including the critical design assumptions and critical design features

ii)   Description of the alternative design and arrangements, including drawings and specifications

iii)   Listing of affected SOLAS chapter II-2 regulations

iv)   Summary of the results of the engineering analysis and basis for approval

v)   Test, inspection and maintenance requirements

3   Reporting and Approval Forms

3.1   Report

When the Administration approves alternative design and arrangements for fire safety, pertinent technical information about the approval should be summarized on the reporting form given in Appendix 1 and should be submitted to the International Maritime Organization for circulation to the Member Governments.

3.2   Documentation

When the Administration approves alternative design and arrangements on fire safety, documentation should be provided as indicated in Appendix 2.

4   Reference in SOLAS Certificates

A reference to the approved alternative design and arrangements should be included in the appropriate SOLAS certificate.

This Page Intentionally Left Blank

APPENDIX 1 Report on the Approval of Alternative Design and Arrangements for Fire Safety

REPORT ON THE APPROVAL OF ALTERNATIVE DESIGN AND ARRANGEMENTS FOR FIRE SAFETY

The Government of ……………………. has approved on ………………… an alternative design and arrangement in accordance with provisions of regulation II-2/17.5 of the International Convention for Safety of Life at Sea (SOLAS), 1974, as amended, as described below:

Name of Ship ....

Port of registry ....

Ship type ....

IMO Number ....

1. Scope of the analysis or design, including the critical design assumptions and critical design features:

2. Description of the alternative design and arrangements:

3. Conditions of approval, if any:

4. Listing of affected SOLAS chapter II-2 regulations:

5. Summary of the result of the engineering analysis and basis for approval, including performance criteria and design fire scenarios:

6. Test, inspection and maintenance requirements:

This Page Intentionally Left Blank

ABS

FOUNDED 1862

APPENDIX **2 Document of Approval of Alternative Design and Arrangements for Fire Safety**

**DOCUMENT OF APPROVAL OF ALTERNATIVE DESIGN AND
ARRANGEMENTS FOR FIRE SAFETY**

Issued in accordance with provisions of regulation II-2/17.4 of the International Convention for Safety of Life at Sea (SOLAS), 1974, as amended, under the authority of the
Government of .... by...
                        (name of state)   (person or organization authorized)

Name of Ship   ....

Port of registry   ....

Ship type   ....

IMO Number   ....

THIS IS TO CERTIFY that the following alternative design and arrangement applied to the above ship has been approved under the provisions of SOLAS regulation II-2/17.

1.   Scope of the analysis or design, including the critical design assumptions and critical design features:

2.   Description of the alternative design and arrangements:

3.   Conditions of approval, if any:

4.   Listing of affected SOLAS chapter II-2 regulations:

5.   Summary of the result of the engineering analysis and basis for approval, including performance criteria and design fire scenarios:

6.   Test, inspection and maintenance requirements:

7.   Drawings and specifications of the alternative design and arrangement:

        Issued at .... on..

                                 ....
                                  (Signature of authorized official issuing the certificate)
                                  (Seal of stamp of issuing authority, as appropriate)

This Page Intentionally Left Blank

APPENDIX 3 Technical References and Resources

1

Section 3 of these Guidance Notes states that the fire safety engineering approach should be "based on sound fire science and engineering practice incorporating widely accepted methods, empirical data, calculations, correlations and computer models as contained in engineering textbooks and technical literature." There are literally thousands of technical resources that may be of use in a particular fire safety design. Therefore, it is very important that fire safety engineers and other members of the design team determine the acceptability of the sources and methodologies used for the particular applications in which they are used.

2

When determining the validity of the resources used, it is helpful to know the process through which the document was developed, reviewed and validated. For example, many codes and standards are developed under an open consensus process conducted by recognized professional societies, code-making organizations or governmental bodies. Other technical references are subject to a peer review process, such as many of the available technical and engineering journals. Also, engineering handbooks and textbooks provide widely recognized and technically solid information and calculation methods.

3

Additional guidance on selection of technical references and resources, along with lists of subject-specific literature, can be found in:

1. *The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings,* Society of Fire Protection Engineers and National Fire Protection Association, 1999.

2. ISO/TR 13387-1 through 13387-8, *"Fire safety engineering",* International Standards Organization, 1999.

4

Other important references include:

1. *SFPE Handbook of Fire Protection Engineering,* 3rd Edition, P. J. DiNenno, ed., The Society of Fire Protection Engineers, Boston, MA, 2002.

2. *Fire Protection Handbook,* 19th Edition, A. E. Cote, ed., National Fire Protection Association, Quincy, MA, 2003.

3. Custer, R.L.P., and Meacham, B.J., *Introduction to Performance-Based Fire Safety,* Society of Fire Protection Engineers, USA, 1997.

4. NFPA 550, *Guide to the Use of the Fire Safety Concepts Tree,* National Fire Protection Association, 1995.

5. ASTM E 1355 – 97, *Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models*, American Society for Testing Materials, 1997.

APPENDIX 4 Identifying Design Fire Scenarios

1 General

The purpose of this Appendix is to provide minimum design fire scenarios for evaluation of proposed designs. This is necessary to ensure a consistently applied "design load" (i.e., the minimum design fire that the vessel design should be able to withstand while meeting the performance objectives and criteria).

2 Identifying Design Fire Scenarios

Design fire scenarios are at the core of the fire safety engineering methodology. The methodology is based on analyzing particular design fire scenarios and then drawing inferences from the results with regard to the adequacy of the proposed fire safety system to meet the performance criteria that have been set. Identification of the appropriate scenarios requiring analysis is crucial to the attainment of a vessel that fulfills the fire safety performance objectives.

Given the large number of possible fire scenarios for a given performance-based design project, it is usually necessary to reduce the possible fire scenario populations to a manageable number of design fire scenarios for evaluating trial designs. Generally, possible fire scenarios can be filtered into design fire scenarios using the engineer's judgment on what fires will bound the potential hazards. In addition, the development of fire scenarios may include both probabilistic and deterministic approaches, if calculations are necessary.

Each design fire scenario (which is highly specific to support the hazard analysis calculation) is part of a scenario group (which is more general to support the frequency calculation) and is meant to be representative of that group. The scenario group must collectively include all potential scenarios to take into consideration reasonableness, frequency and severity and should cover low frequency/high consequence fires, high frequency/low consequence fires and special challenge fires, where applicable.

Once design fire scenarios have been identified from the list of possible design fire scenarios, then the significant aspects of the crews, vessel and fire characteristics for the selected design fire scenarios that will affect the outcome should be further quantified. These parameters will function as inputs during the analysis stage.

Often there are neither the resources nor data available to quantify every aspect of a design fire scenario. The detailed analysis and quantification should be limited to the more significant aspects. Significant aspects might include a range of different fire types (including smoldering fires), fire growth rates, compartment ventilation rates, etc. In addition, depending on what the particular design or analysis is intended to determine, various aspects may or may not be required to be defined. For instance, assessment of a smoke management system using the clear layer method may not need details regarding soot yields or visibility criteria to be defined, or the details of the decay phase to be defined. Various analysis methods including sensitivity and uncertainty analyses may need to be performed to show which aspects are pertinent and need to be appropriately addressed.

3   Probabilistic Design

3.1   Background

3.1.1   General

Probabilistic procedures exist to quantify ignition, fire growth, flame spread, the movement of combustion products, the movement of people, the reaction to fire and effect on fire of vessel systems and features, and the consequences of fire for the vessel and its occupants.

These procedures are based on fire incident and field survey data, as well as a variety of techniques for producing best subjective estimates. More often, "probabilistic" procedures use a combination of probabilistic methods for phenomena such as ignition and system reliability with deterministic methods for phenomena such as fire growth and development and effects on people and property. A probabilistic design analysis involves the use of these procedures to calculate the performance of a design in a form that can be compared to probabilistic criteria.

There are some advantages and disadvantages to probabilistic procedures vs. deterministic procedures. At a fundamental level, probabilistic procedures provide a basis for addressing and considering all types of fire scenario. Deterministic procedures may mislead if a design is unusually vulnerable to a scenario that is:

i)   Slightly less probable but much more severe than any considered in the analysis;

ii)   Slightly less severe but much more probable than any considered in the analysis; or

iii)   More probable and/or more severe but more unusual (e.g., in location) than any considered in the analysis.

By the extensive use of fire incident and field survey data, probabilistic procedures are better able to reflect all of the aspects of real fires, including the often complex interactions among factors. Probabilistic procedures are also better adapted to quantify uncertainties.

Disadvantages of probabilistic procedures include gaps in needed data that require either expensive data collection procedures or extensive use of subjective estimates, with associated large uncertainties. Also, probabilistic procedures often lack the technical detail and the full use of fire science fundamentals found in deterministic procedures. This can make them difficult to use for design.

3.1.2   Probabilistic Techniques

Basic probabilistic techniques of fault trees and event trees are briefly described later in this Subsection. More detailed descriptions may be found in a number of references, including the *SFPE Handbook for Fire Protection Engineering*.

3.1.3   Fire Scenarios

As already pointed out, the interaction of fire, vessels and people can give rise to a very complex system, which means a nearly infinite number of possible fire scenarios. Full analysis of all scenarios would be impossible, so it is necessary to identify a manageable group of scenarios for analysis. In probabilistic techniques, these selected scenarios must be chosen so that they collectively represent all of the possible fire scenarios. Each detailed scenario is specific enough to permit calculation of its consequences, or anticipated loss, but each detailed scenario is also associated with the other scenarios that resemble it, and probability is estimated for the larger set of scenarios.

The scenarios should be grouped by similar type of hazard. A group should be defined so that a design feature that affects one scenario in the group will affect all of the scenarios in that group in similar fashion. For example, fires originating in the same or similar locations will tend to respond to detection, suppression and compartment features in the same way, across a wide range of initial sizes and speeds of growth of the fires. Choose the most representative or typical fire scenario in each group, and those will be the fire scenarios selected for analysis, with the probabilities calculated for the associated groups. Each scenario will be sufficiently different from the other selected scenarios as to justify separate assessment. Each scenario will be specific enough that it can be defined in sufficient detail for quantitative evaluation. This detailed specification is called a "design fire".

In conducting the risk assessment, it will be possible to ignore many factors and characteristics of fires that can be shown to have negligible effect on probability and severity. Some factors that cannot be ignored will be difficult to quantify, and for these it is important to use assumptions that are neither conservative nor typical of all vessels and passengers, but rather that are typical of vessels and passengers involved in fires. Only in this way will the resulting risk assessment properly reflect patterns of fire development.

3.1.4 Limits of Application and Sensitivity Analysis

Probabilistic techniques are subject to the same limits due to experimental-scale effects, uncertainties of data extrapolation and uncertainties of model validity and applicability, as described for deterministic techniques in Appendix 4, Subsection 4.

The probabilistic models themselves can be adapted to quantify uncertainty by the use of probability distributions for the probabilities in the models. This approach, often called Bayesian analysis, is described in greater detail in any reference on probabilistic modeling.

3.2 Basic Probabilistic Techniques

3.2.1 General

Probabilistic risk analysis begins with a definition of the risk as a function of the probabilities and consequences of scenarios:

Risk = Σf (probability, consequence of a given scenario),   for all scenarios.

There are two commonly used functions defining risk. One is the "expected value" or average-consequence definition of risk:

Risk = Σf (probability × consequence of a given scenario),   for all scenarios.

The other is the probability that consequences will exceed a specified safety threshold:

Risk = Σf (probability of a given scenario),   for all scenarios where the consequences exceed the specified safety threshold.

The complementary definition of safety is the inverse of risk, i.e.,

Safety = Risk^{-1}

A probabilistic risk assessment, using a particular definition of risk, will include the following steps:

i)   Determining what fire scenarios can occur

ii)   Dividing these fire scenarios that can occur into groups and selecting specific fire scenarios for analysis from each group

iii)   Estimating or calculating the probability of each scenario group

iv)   Estimating or calculating the effects and consequences of each fire scenario selected for analysis

v)   Calculating the total risk associated with fire

vi)   If step v) identifies unacceptable risks, identifying the extra measures required to reduce that risk

Items i), iv) and vi) should be considered in detail during the design, just as in a deterministic calculation. Items ii), iii) and v) are unique to probabilistic risk assessment, but have analogous steps in deterministic approaches.

3.2.2   Fault Trees

Fault trees are logic diagrams showing the logical dependence of events on one another. Fault trees are most suitable when risk is defined as the probability that the consequences will exceed a certain threshold, including cases like the example where risk is defined as the probability of an unacceptable event (e.g., structural collapse). The unacceptable event or, more generally, the event of the consequences exceeding the threshold is shown as a "top event" – defined as failure, hence the name "fault tree" – and the fault tree is constructed to show what combinations of events would lead to failure. More detailed descriptions of fault trees may be found in a number of references listed in these Guidance Notes.

If two or more lower-level events must all occur in order for a higher-level event to occur, the fault tree uses an AND gate (see Appendix 4, Figure 1). If the lower-level events are "independent" (i.e., the probability that one will occur is unaffected by knowledge of whether the other lower-level event(s) has(ve) occurred), then the probability of the higher-level event is equal to the product of the probabilities of the lower-level events.

If any one of two or more lower-level events will lead to a higher-level event, the fault tree uses an OR gate (see Appendix 4, Figure 2). If the lower-level events are independent, then the probability of the higher-level event is equal to the sum of the probabilities of the lower-level events.

The methodology may be illustrated by a compartment fire example, in which risk is defined as the probability of an unacceptable consequence, and the unacceptable consequence is defined as structural failure.

Suppose further that the only factors capable of preventing structural failure are prevention of ignition, restriction of fuel load, fire resistance of the structure and fire sprinklers. Suppose that the first two are not treated as design elements, but as uncontrollable random factors:

(a)   Did a fire start which was capable of reaching room burn-out?

- If no, then structural failure is avoided.
- If yes, continue.

(b)   Were sprinklers present?

- If no, go to (e).
- If yes, continue.

(c)   Were the sprinklers operational (a reliability question)?

- If no, go to (e).
- If yes, continue.

(d)   Was the fire scenario one that would render sprinklers ineffective (e.g., a large initial explosion)?

- If no, then structural failure is avoided.

- If yes, continue.

(e)   Was the structural fire resistance intact (both a reliability and a scenario question)?

- If no or yes, continue.

(f)   Based on the answers to the above questions, what was the critical fuel load such that a room burn-out would result in a fire of sufficient intensity and duration as to cause structural failure, and was that critical fuel load present?

- If no, then structural failure is avoided.

- If yes, then structural failure occurs.

Quantification of the analysis can be illustrated by going through the branching. The probability of a fire capable of reaching room burn-out can be estimated from fire incident data (e.g., as the probability of a fire in an unsprinklered enclosure having flame spread beyond the room of origin). The question of whether sprinklers are present or not is a design question, and the analysis should be run both ways, with yes and no answers to the question. Reliability data will answer question (c), but it is important to include the human errors that can render sprinklers non-operational (e.g., the fact that the sprinkler valve had been turned off), as they are more common than mechanical failures. Question (d) can also be answered using an estimate from fire incident data. Some of the scenarios that disable sprinklers can also damage the structure or its fire resistance, but question (e) will mostly be a reliability question, depending upon workmanship and maintenance. Like question (c), it can be answered by field surveys. Question (f) requires a deterministic calculation or use of fire tests to determine the critical fuel loads in each situation (e.g., the critical fuel load with damaged fire resistance would be less than with intact fire resistance). Then a field survey is needed to determine the probability of that critical fuel load being present. The answer to each question is a probability, and the risk for that scenario group is the product of the probabilities for the respective questions.

FIGURE 1
Fault Tree and Gate for Case when
Lower-level Events are Dependent

$$P_y = P_1 \times P_2 \times P_3$$
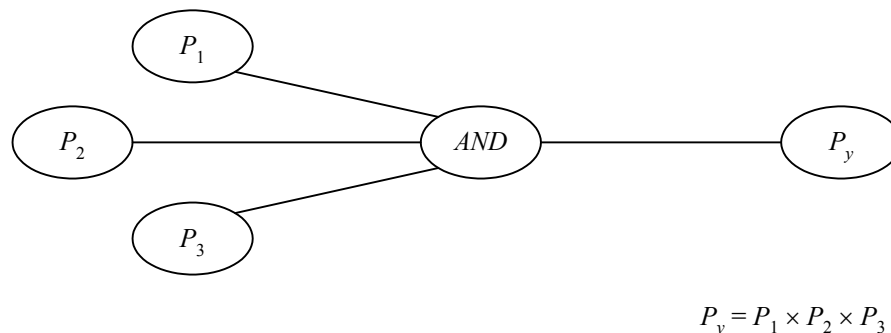
FIGURE 2
Fault Tree and Gate for Case when
Lower-level Events are Independent

$$P_y = P_1 + P_2 + P_3$$
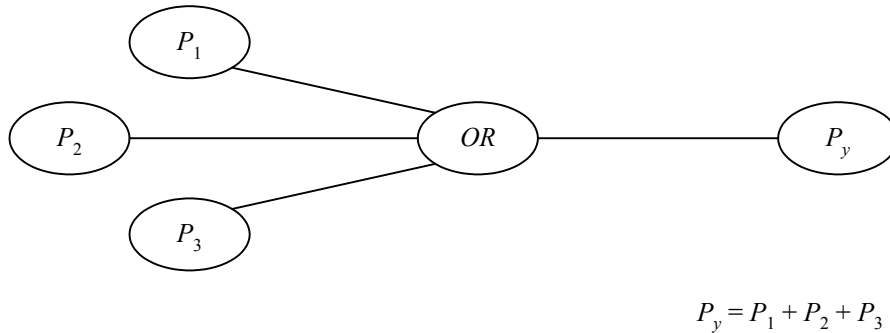
3.2.3   Event Trees

Event trees (see Appendix 4, Figure 3) are diagrams showing events in time in fire development, movement of people, response of systems, etc. Event trees are most suitable when risk is defined as an expected value.

FIGURE 3
Event Tree
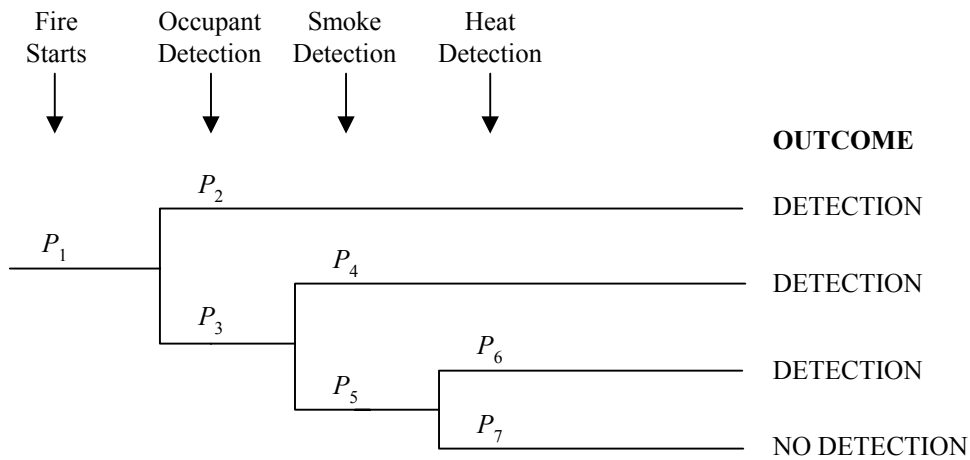
3.3   Data Required

3.3.1   General

The acquisition of reliable data can be one of the most important tasks in performing any risk assessment.

The type of information required can be broadly classified into four main groups:

i)   Deterministic data

ii)   Fire statistics

iii)   Vessel data

iv)   System reliability data

3.3.2   Deterministic Data

Deterministic information regarding the development and possible consequences of fire may be evaluated on the basis of the deterministic procedures (see Appendix 4, Subsection 4) and the subsystems.

3.3.3   Fire Statistics

Fire statistics include statistics that identify the most likely areas of ignition, items first ignited and the likelihood of spread beyond the space of fire origin. Other statistics data, including past fire history, fire frequency and fire ignition frequency, can also be included. The past history data include historical data from fires in a particular existing vessel or group of vessels or in similar types of equipment, contents and other items. The fire frequency is the number of times a fire occurs within a specific time interval.

3.3.4   Vessel Data

Survey data such as fractal fire loads and occupancy levels are available. The continued development of a fire and the potential consequences will depend upon a number of factors such as:

i)   The availability of combustibles and the fractal fire load

ii)   The imposed structural loads

iii)   The number of occupants present and their condition at any given time

Where data are lacking, it is possible to make assumptions regarding occupancy, fire load, etc. However, the use of reliable statistical data will assist in the performance of a realistic risk assessment.

3.3.5   System Reliability Data

All fire protection systems may on occasion fail for reasons such as lack of maintenance, random mechanical failures or inability to cope with an unusually high fire severity.

Manufacturers may be able to provide data on frequencies of mechanical or electrical failure and on severity of fire conditions required to overpower the system. Fire incident data or other published field survey statistics may be able to provide data on the frequency of fire conditions with the severity specified by the manufacturers and the frequency of failure due to human error (e.g., the fact that the sprinkler valve had been closed).

Examples of aspects of automatic fire detection and control systems for which reliability data may be required are:

i)   Detection system response

ii)   Smoke control system operation

iii)   Extinguishing system operation

iv)   Breaches of compartmentation (e.g., insufficient fire stopping, doors being propped open at time of fire, etc.)

3.4   Common Mode Failures

In some instances, the failure of one part of the system can have an adverse effect on the efficiency of another fire protection measure, e.g., an open fire door will not only be an ineffective barrier to fire spread, but may also lead to failure of a gaseous extinguishing system due to loss of agent. Particular care must be taken by the design team and those responsible to ensure that any such common mode failures are identified and accounted for in the analysis.

4   Deterministic Design

4.1   Background

4.1.1   General

Deterministic procedures exist to quantify ignition, fire growth, flame spread, the movement of combustion products, the movement of people, the reaction to fire and effect on fire of vessel systems and features, and the consequences of fire for the vessel and its occupants.

These procedures are based on physical, chemical, thermodynamic, hydraulic, electrical or behavioral relationships derived from scientific theories and empirical methods, or from experimental research. A deterministic design analysis involves the use of these procedures to calculate the performance of a design in a form that can be compared to deterministic criteria.

4.1.2   Deterministic Techniques

In deterministic models, a complete set of differential equations based on laws of physics and chemistry can compute the conditions produced by fire at a given time in a specified volume of air in a well-defined physical scenario. Deterministic fire models can range from simple one-line correlation of data to highly complex models. More detailed descriptions may be found in a number of references, including the *SFPE Handbook for Fire Protection Engineering*.

4.1.3   Fire Scenarios

The interaction of fire, vessel enclosures and people can give rise to a very complex system, which means a nearly infinite number of possible fire scenarios. Full analysis of all scenarios would be impossible, so it is necessary to identify a manageable group of scenarios for analysis. These selected scenarios should be chosen so that a vessel design shown to deliver acceptable safety for these scenarios can be depended upon to deliver acceptable safety for all of the unanalyzed scenarios as well.

A deterministic design will be evaluated using a hazard assessment, which will assess performance against deterministic criteria. Therefore, in selecting scenarios, the first consideration is the type and severity of hazard of each scenario. For many scenarios (e.g., a discarded cigarette on a concrete floor), it may be apparent without analysis that the scenario will not produce a level of hazard that would be unacceptable under the criteria. These scenarios can be ignored.

Some scenarios with an unacceptably large hazard may be excluded, either because of very low probability or because neither their probability nor their severity can be significantly affected by design decisions (e.g., a thermonuclear blast). Such exclusions should be made cautiously. To be excluded due to low probability, these scenarios must have very low probability not only individually but also collectively. And for many severe scenarios (e.g., a bomb in a parking garage in a high-rise office building), loss can be significantly mitigated through design, even if it cannot be entirely prevented.

The scenarios that remain – all having sufficient probability and severity to justify attention – should be grouped by similar type of hazard. A group should be defined so that a design feature that affects one scenario in the group will affect all of the scenarios in that group in similar fashion. For example, fires originating in the same or similar locations will tend to respond to detection, suppression and compartment features in the same way, across a wide range of initial sizes and speeds of growth of the fires. The most severe fire in each group should be chosen, and those will be the "worst credible fire scenarios". Each scenario will be sufficiently different from the other selected scenarios as to justify separate assessment, in order to make sure the design is acceptably safe overall. Each scenario will be sufficiently specific so that it can be defined in enough detail for quantitative evaluation. This detailed specification is called a "design fire".

In conducting the hazard assessment, it will be possible to ignore many factors and characteristics of fires that can be shown to have negligible effect on probability and severity. Some factors that cannot be ignored will be difficult to quantify, and for these, it is important to use simplifying assumptions that are conservative. However, if too many conservative assumptions are used, the overall assessment will be too conservative and may, in fact, be incompatible with any practical design. An iterative process should be used in defining scenarios, so that the degree of conservatism is diminished for each assumption as the number of conservative assumptions increases. Typical current designs that are acceptable to authorities under existing regulations should also be found acceptable under the hazard assessment. Therefore, the hazard assessment can be applied to such designs as a way of calibrating the necessary level of conservatism in the assessment.

4.1.4   Limits of Application

Often, the experimental work used to develop empirical relationships is carried out in scaled-down facilities in research establishments. It is important to appreciate that the application of the models resulting from such work may be limited by the degree of extrapolation that can be made, e.g., in terms of the size of the room or the range of factors that have been examined. This must be carefully considered if extrapolation of test data is unavoidable.

Deterministic techniques provide a useful indication of the development and effects of a fire, but the nature of fire is such that the results are unlikely to be precise. Normally, well-formulated models would be expected to provide conservative predictions within their range of application.

However, in some cases there may be no factor of safety inherent within the model, and the technique should be used with care. In all situations where there is any doubt as to the validity of a model, the user should establish from the literature how the experimental work was carried out and decide whether the design situation is markedly different. If so, factors of safety should be applied.

4.1.5   Sensitivity Analysis

Deterministic design may involve uncertainties. Usually, these can be dealt with by taking a conservative approach, e.g., selecting a fire growth rate that is faster than would normally be expected. However, if this approach is not suitable, then the primary sources of uncertainty should be addressed. These are associated with:

i)   The input parameters, i.e., uncertainties associated with the initial qualitative interpretation of the problem;

ii)   The simplification needed to develop the deterministic techniques and hence make the analysis more tractable.

An indication of sensitivity may be gained by investigating the response of the output parameters to changes in the individual input parameters. This will act as a guide to the level of accuracy required of the input data.

The objective of a sensitivity study should not be simply to check the accuracy of the results, but also to investigate the criticality of individual parameters, For example, it may be important to establish how critical a sprinkler system is to the final consequences. If a single system or assumption is shown to be critical to the overall level of safety achieved, such as heat release rates as input in some fire scenarios, consideration should be given to providing a degree of redundancy in the design of carrying out a probabilistic study.

The simplifications and assumptions made in the input data to aid the full analysis should be tested for their criticality to the fire safety design. For example, it may have been assumed for a comparative study with existing codes that a compartment remains a compartment, and that the possibility of an open door may be ignored. However, an alternative scenario would include the open-door assumption. Thus, a sensitivity test on the qualitative components of fire safety design is possible.

4.1.6 Common Mode Failures

In some instances, the failure of one part of the system can have an adverse effect on the efficiency of another fire protection measure: e.g., an open fire door will not only be an ineffective barrier to fire spread but may also lead to failure of a gaseous extinguishing system due to loss of agent. Particular care must be taken by the design team to ensure that any such common mode failures are identified and accounted for in the analysis.

4.1.7 Property Protection

Property protection objectives may be stated in terms of monetary losses or spatial extent of damage from fire and its effects. Monetary-loss measures are easier to use in combination with information on the costs of design alternatives, but calculation methods and fire tests can only produce estimates of spatial damage. Data on the monetary value of property damage per area or space damaged, by type of damage (e.g., char, smoke deposition), are not generally available, but will need to be developed if calculations of spatial damage are to be translated into predictions of monetary loss.

The extent of acceptable damage is defined by the design team for specific objects or zones, and the calculated deterministic values for heat and smoke spread should not exceed these.

Predicting damage caused by firefighting water from either fire suppression systems (e.g., sprinklers) or the contaminations from fire-fighting activities, in either spatial or monetary terms, is much more difficult than predicting or calculating damage from fire and its effects. It is recommended that the analysis not attempt to include such damage, as the associated uncertainty is likely to be so large as to render the analysis results unusable.

4.1.8 Environmental Protection

The amount of damage done to the atmosphere local to the vessel on fire may be calculated using a large fire plume model capable of predicting the trajectory and dispersion of the fire gases. Contamination of the land and ground water, however, is not easy to calculate.

The extent of acceptable contamination of the air, land and water will have been set for the project during the design process. Calculated contamination values should not exceed the environmental limits.

5 Design Fire Curves

Part of the characterization of the design fire scenario is characterizing design fire curves. A design fire curve describes the heat release rate (HRR) history of a fuel package. A fuel package may be one or more combustible items. Appendix 4, Figure 4 depicts the phases of a design fire curve that may need to be typically defined.

FIGURE 4
Phases of a Design Fire Curve
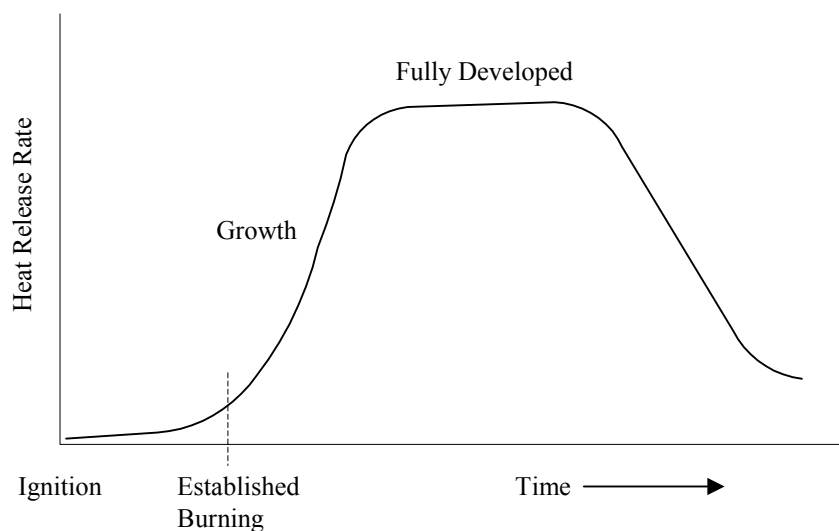
Although HRR is the basic input to most fire effect prediction methods and fire models and would form the basis for the design fire curve, other characteristics such as mass loss rate can be used. However, the information related to HRR or mass loss rates is typically limited to an individual commodity and/or simply arranged fuel packages, and care should be taken in understanding where this data came from (i.e., full-scale tests, small scale tests, theoretical derivation, etc) and how it applies to the specific analysis and to what degree information can be extrapolated.

Fuel loads often involve composite fuel packages with various types of combustible materials and may be contained in a complex geometry and require careful application of the available data, as these will effect how they burn. Frequently, however, the data will not be complete or directly applicable to the fuel package selected. Input data must therefore be applied in a manner that is consistent with the way in which it was generated. If the information comes from actual tests, the user should consider the applicability of those tests to the expected scenario under the proposed design. If the information comes from theoretical analysis, then again the user should consider the applicability, usually by looking at the underlying assumptions and/or test data for the theoretical analysis, and determine the proper manner of use for that analytical method.

Various aspects of the fire curve can be calculated to obtain approximations for predicted behavior. Other aspects can be roughly estimated or may require subjective testing. At the present time, there is no overall framework that provides exact solutions of the entire design fire. Therefore, the fire protection engineer should determine which portions of the design fire curve are important, as it may not always be necessary to quantify each aspect of the design fire curve.

In developing the design fire curve, the engineer needs to focus on the intent of the analysis, the damage mechanisms (smoke, toxicity, thermal, corrosion), the performance requirements that will be evaluated in the given design fire scenario and the fire characteristics of the burning fuel package(s) to determine which aspects are critical. For example, if in a performance-based design, the response of an alternative automatic fire suppression system to standard sprinklers is being examined for equivalence, the design fire scenario might stop at the point of activation of the suppression system, or at complete extinguishment. Or, the growth phase may be of interest in detection actuation analysis, while completion of the fully developed phase may be required to determine whether or not structural failure will occur.

A thorough review of potential and typical fuel packages and ignition sources for the vessel should therefore be performed and presented to the authorities. It is often difficult to obtain specific information about vessel contents (i.e., outfitting, stored materials, etc.) during the design stages of a project. However, an attempt should be made to understand what combustibles will be in the vessel, as well as what may be there in the future. If assumptions are made regarding specific burning characteristics of materials, they should be documented and incorporated into final project specifications.

6   Design Fire Scenarios in NFPA 101

NFPA 101, "The Life Safety Code" (2000 Edition) defines which types of scenarios are to be used and which major assumptions must be made. In all, eight scenarios are discussed where scenarios selected as design fire scenarios could include, but should not be limited to, those specified below.

Scenario 1. An occupancy-specific scenario representative of a typical fire for the occupancy. The scenario shall explicitly account for occupant activities, number and location; room size; furnishings and contents; fuel properties and ignition sources; and ventilation conditions. The first item ignited and its location shall be explicitly defined.

Scenario 2. An ultrafast developing fire (i.e., flammable liquid fire) in the primary means of egress with interior doors open at the start of the fire. This scenario shall address the concern of reducing the number of available means of egress.

Scenario 3. A fire starting in a normally unoccupied room that can potentially endanger a large number of occupants in a large room or other area. This scenario shall address the concern of a fire starting in a normally unoccupied room and migrating into a space that can, potentially, hold the greatest number of occupants in the vessel.

Scenario 4. A fire originating in a concealed wall- or ceiling-space adjacent to a large occupied room. This scenario shall address the concern of a fire originating in a concealed space that does not have either a detection system or suppression system and the fire spreading into the room within the vessel that can, potentially, hold the greatest number of occupants.

Scenario 5. A slow developing fire shielded from fire protection systems, in close proximity to a high occupancy area. This scenario shall address the concern of a relatively small ignition source causing a significant fire.

Scenario 6. An ultrafast developing fire resulting from the largest possible fuel load characteristic of the normal operation of the vessel. This scenario shall address the concern of a rapidly developing fire with occupants present.

Scenario 7. Outside exposure fire. This scenario shall address the concern of a fire starting remotely from the area of concern and either spreading into the area, blocking escape from the area or developing untenable conditions within the area.

Scenario 8. A fire originating in ordinary combustibles in a room or area with each passive or active fire protection system independently rendered ineffective. This scenario shall address the concern of a fire protection system or feature being either unreliable or unavailable.

The probabilistic elements should be integrated by requiring certain types of fires (e.g., ultrafast) and assumptions about operability of systems (e.g., detection and suppression system failure). This approach could be readily modified for shipboard use, and strengthened with respect to defined factors of safety and additional scenarios which require failure assumptions about other fire safety features (e.g., passive systems failure).

APPENDIX **5   Developing Trial Alternative Designs**

1   General

Once objectives and functional statements, performance requirements and design fire scenarios have been identified, then trial alternative designs should be developed. Trial alternative designs represent fire protection system design alternatives developed to address design fire scenarios to achieve the previously established performance requirements.

Trial alternative designs can be developed on a subsystem or system level, depending on the depth of the analysis required. Trial designs may involve comparison with a prescriptive system design requirement or on a system performance basis. Results can be assessed on a comparative basis (i.e., performance of prescriptive requirement relative to the proposed trial design) or compared to the performance requirements.

Trial designs that are developed for assessment using the performance requirement basis should be developed using design features that address the performance requirements. Trial design subsystems can include fire detection and alarm, fire suppression, occupant behavior and egress, passive fire protection, fire initiation and development and smoke management. Some or all of these may comprise the various trial designs. These systems interact with each other to provide an overall level of safety for the vessel. It is possible to assess the performance of individual subsystems, however, the interaction between various subsystems should also be assessed to help reduce the chance that other subsystems may negatively impact the performance of other subsystems.

2   Functional Statements, Performance Requirements and Trial Designs

When selecting performance requirements and trial designs for a given functional statement, there may be more than one set of requirements to achieve each functional statement. For instance, for an objective of no loss of life outside the room of origin, performance requirements and trial designs could be developed around: preventing flashover in the room of origin, containing fire and smoke within the room of origin or maintaining tenable conditions outside the room of origin.

In developing trial designs, it is therefore necessary to first understand what functional statements and performance requirements must be achieved, then to develop trial designs comprised of various subsystems to meet these. Appendix 5, Table 1 provides examples of objectives, functional statements and performance requirements.

Functional statements and performance requirements, once agreed upon by all stakeholders, become the design focus and benchmark for measuring the proposed solutions. It is therefore difficult to effectively evaluate trial designs for conformance without a clearly defined set of functional statements and measurable performance requirements.

TABLE 1
Examples of Objectives, Functional Statements and Performance Requirements

Fire Protection Objectives	Functional Statements	Performance Requirements
Minimize fire-related injuries and prevent undue loss of life.	No loss of life outside of the room or compartment of fire origin.	COHb level not to exceed 12 percent. Visibility greater than 7 meters.
Minimize fire-related damage to the building, its contents, and its historical features and attributes.	No significant thermal damage outside of the room or compartment of fire origin.	Upper layer temperature not greater than 200°C.
Minimize undue loss of operations and business-related revenue due to fire-related damage.	No process downtime exceeding eight hours.	HCl not greater than 5 ppm. Particulate not greater than 0.5 g/m^3.
Limit environmental impacts of fire and fire protection measures.	No groundwater contamination by fire suppression water runoff.	Impoundment capacity at least 1.20 times the design discharge.

To assist in developing trial designs and achieving the desired functional statements, one could use NFPA 550, "The Fire Safety Concepts Tree (FSCT)". While incorporating the logic and structure of a fault tree described in Appendix 4, FSCT describes paths leading to success rather than failure. FSCT assists in showing various elements that should be considered in developing trial designs and their interrelationship with each other.

For example, one of the more common uses of performance-based design is to extend travel distances. Assuming it may be difficult to "Prevent Fire Ignition" for this space, the "Manage Fire Impact" branch is used. Under this branch, one can "Manage Fire" or "Manage Exposed". Hence, one may develop a trial design using the "Control Combustion Process" sub-branch and control the fuel by limiting fuel quantity. In addition, one would also want to manage the exposed, or the occupants, to evacuate them safely. Therefore, the "Safeguard Exposed" and "Move Exposed" sub-branches could be used, which would recommend use of detection and alarm systems to notify occupants, and providing adequate egress facilities to allow the occupants to evacuate to a safe location. As another alternative, should the stakeholders want to maintain flexibility in the space and allow some combustibles, then under the "Manage Fire" branch, the "Control Fire by Construction" sub-branch could be used to control the movement of smoke by either confining/containing the smoke, if appropriate, to the space, or venting the smoke to maintain tenable conditions.

A trial design should express expected fire growth and spread in the context of the fire hazard, available ventilation and compartment geometry. One of a number of trial designs might include strategies to confine a fire to a room or compartment of origin wherein occupants might reasonably be expected to find a safe egress prior to untenable conditions being reached (see "Confine/Contain Fire" sub-branch under the "Control Fire by Construction" branch of the Fire Safety Concepts Tree). This may or may not include the integration with other subsystems, including additional active fire protection to achieve the performance requirements.

As seen, the Fire Safety Concept Tree can be used to develop various alternatives. In addition, some of these alternatives incorporate multiple subsystems which are further described below.

3   Subsystems

When developing trial designs, there are various subsystems that can be used alone or in combination with other systems. Trial designs are developed by understanding what the objectives and functional statements are, as well as the performance requirements, and looking at the various individual or combinations of subsystems that will allow one to achieve the performance requirements. More than one trial design can be developed to meet a given set of performance requirements.

A subsystem is a grouping of similar fire protection strategies (i.e., detection, alarm, suppression, compartmentation, etc.). A proposed performance-based design could include none, one or many subsystems as fire protection strategies to deal with the prevention, control or impact of a fire as part of a solution. These subsystems (redundant) can act independently of one another or in concert to achieve the desired effects. Grouping fire protection strategies into subsystems is intended to facilitate the analysis of trial designs. The following Paragraphs provide an overview of some of these subsystems.

The functional statements range from controlling the size or effects of a fire to managing the impact of a fire on a facility and its occupants. Typical functional statements might include providing early warning of a developing fire to all facility occupants prior to a prescribed level of smoke in an area or controlling growth of a fire through automatic suppression to prevent flashover.

3.1   Fire Initiation and Development

The fire initiation and development subsystem can be used to either assist in fire prevention or to control the development of the fire once it has started. Fire prevention is intended to reduce the likelihood that ignition will occur. Various concepts that can be employed to achieve this may include controlling ignition sources, controlling materials, selecting materials that are inherently resistant to ignition or implementing fire safety management procedures to assist in controlling ignition sources or accumulations of combustible materials. These concepts are also covered in the 'Prevent Ignition' branch of the Fire Safety Concepts Tree.

Controlling fire development can be used to assist in reducing the development rate of a fire and its associated smoke and heat production. Concepts often employed to assist include selection and placement of contents, selection of interior finishes and construction materials, limiting the quantity of materials and controlling the size and geometry of a compartment and its ventilation.

3.2   Spread, Control and Management of Smoke

This subsystem assists in addressing the hazards resulting from smoke by limiting its production, controlling its movement and/or reducing the amount of it. This subsystem concept can be used to either control materials to exclude those that produce large quantities of smoke and toxic gases, or to manage the smoke through various methods including containment, extraction or pressurization, as well as inclusion of suppression systems to reduce the amount of smoke that is being produced.

Various guides are available providing additional information on smoke management, including *SFPE Handbook of Fire Protection Engineering,* NFPA 92A and NFPA 92B.

Use of this option often entails management procedures to control the quantities and types of combustible materials allowed in various spaces. Interfaces with other subsystems that often need to be evaluated in parallel include suppression systems with regards to their potential effect on the design fire size and duration, as well as detection systems to help determine the activation time of the smoke management system.

Information should be provided to the code official when using the smoke management subsystem that includes detector activation times, fan start up times, controls, interfaces with building management systems, supply air, extract rates, ducting and fan design criteria.

3.3 Fire Detection and Alarm

Fire detection can assist in providing detection of a fire to notify occupants or emergency responders. Detection can also be used as a means of activating ancillary fire protection systems (i.e., smoke management systems, special suppression systems, etc.). Detection can be provided manually by people or by automatic initiating devices.

Detectors usually sense fires through various means including heat, smoke or radiant emissions. In specifying the type of detectors to be used, information should be provided as to the type of fire signature being produced by a fire during the phase where detection is intended to occur. For instance, different fire signatures are produced/available during the smoldering phase (e.g., smoke) versus the fully developed phase (heat, radiant emissions, etc.) and will impact the ability of the detector to perform as intended.

Detector location should also be addressed since the configuration and geometry of the space (volume, ceiling height), as well as configuration of the ceiling (sloped, beams, etc.) can have an impact on the time and ability of the fire signature to reach the detector. Further guidance regarding performance-based designs of detection and alarm systems can be found in NFPA 72, Appendix B, and the *SFPE Handbook for Fire Protection Engineering.*

Notification systems may be initiated either manually or by automatic means. They may be provided by audible and/or visual means.

Notification may also include provision of information to the emergency responders once on-site to assist them in determining the location and possible extent of the fire.

Overall, when assessing the fire detection and alarm subsystem, information should be provided to the code official indicating the fire signatures that the detection system can detect, as well as the location of the initiating devices in relation to the location of the fires. In addition, delays of detection systems in sensing fire signatures, alarm verification and system processing times, and delays in sending signals to emergency responders, including via intermediate monitoring facilities, should be understood and included in the descriptions of the trial designs.

3.4 Automatic Fire Suppression Systems

Fire suppression systems are provided to either extinguish or at least control the development of a fire. Suppression can be either by manual or automatic means.

Automatic suppression systems require no human interaction and typically entail sprinkler, foam or gaseous suppression systems. Different types of fires may require different types of suppression agents. For instance, some flammable liquid fires are better addressed by foam than water. In addition, the size of the fire at the desired point of suppression/extinguishments is important in selecting a suppression system. For instance, in computer/telecommunication rooms where early detection and suppression are desired, an early detection system activating a special suppression system would typically provide earlier suppression (i.e., smaller fire) than an automatic sprinkler system.

Some of these systems are dependent on activation of a fire detection system, and hence, assessment of detection time and time to discharge of the suppression agent is important. The trial design should therefore provide details on the interface and pertinent features of these other integrated systems that impact its effectiveness to activate in a sufficient amount of time and discharge an appropriate quantity and type of suppressant, so they can be appropriately assessed.

The characteristics of the room/space should be included in the assessment to determine the effectiveness of the suppression system in activating and performing as desired. This should include the size and geometry of the space. Sprinklers provided on a high ceiling, for instance in an atrium, may not only be delayed in activating, but also have difficulty in providing sufficient quantities of water on the fire below once the fire has grown to a size sufficient to cause activation.

If it is desired to use manual suppression, whether by crews or by internal fire brigades, various aspects should be part of the assessment, including notification, response time to site, access to site/facility/fire area, number of emergency responders, equipment and fire fighting features provided at the facility, including water supply.

It is important to understand that some types of suppression systems are used to control fires (i.e., sprinklers, water mist systems) while others are intended to extinguish fires (gaseous systems, early suppression fast response sprinklers). In choosing one for a trial design, it should be clear what the suppression system is intended to do. If it is only controlling the fire, then the resultant on-going fire induced conditions should continue to be assessed to ensure functional statements and performance requirements are still achieved.

3.5   Human Behavior and Egress

When developing performance requirements and trial designs to meet the objectives and functional statements, it is critical to define the characteristics of the passengers and crew members and their anticipated behavior during a fire, as well as the egress features and vessel characteristics.

The design team needs to consider several general principles regarding the passengers and crew members and egress features as they relate to their surroundings in developing a trial design:

- What is the minimum and maximum number of people expected/permitted to be in the structure, facility or specific portions thereof?

- What is the maximum length of time the structure is occupied?

- How mobile are the passengers? Do people normally sleep or might they be expected to sleep in their cabins or the facility?

- Can passengers reasonably be expected to be familiar with the vessel layout and means of egress?

- What percentage of crew members and passengers can be considered members of a vulnerable population (e.g., children, elderly, disabled, incapacitated persons, etc.)?

- Are the egress facilities adequate?

- What is the nature of the hazard in the vessel and what are the expected responses of the crew members and passengers?

Once the relevant characteristics of passengers and crew members, egress features and resulting risk factors are assessed, appropriate trial designs can be developed based upon managing fire impact strategies, i.e., whether to provide suitable protected egress routes, defend in place, provide early notification and assisted egress, etc. While a certain level of knowledge regarding egress and human behavior currently exists to evaluate egress in certain trial designs, the design team should undertake various "what if" assessments to help provide appropriate alternatives (i.e., What if the passenger loads are higher? What if an exit is blocked by fire, etc.).

3.6   Passive Fire Protection

Passive fire protection is intended to address two components:

i)   Structural stability

ii)   Issues related to limiting fire and smoke spread in a facility

The structural stability subsystem addresses preventing premature collapse of part or all of a facility. Various approaches and methods are available to assess the necessary protection for structural members to limit the chance of structural failure due to the anticipated thermal loading imposed by the design fire scenarios. In performing these assessments, the inherent stability of an unprotected element may be sufficient, whereas in others, protection in addition to that which is required by code is needed.

In undertaking these assessments, issues including fire performance of structural systems for well-defined design fire loads, fire performance of fire protective materials for agreed fire loads, connection ductility, protection of connections, effect of load transfers, composite actions of floor slabs and frames and susceptibility to progressive collapse may need to be considered.

The subsystem of limiting fire and smoke spread through passive means includes concepts that can be used independently of each other or integrated together to limit the spread of fire and smoke in a space. These features include compartmentation, fire barriers, protection of openings, prevention of external fire spread and controlling the fire by means such as automatic or manual suppression.

Non-fire-rated glazing, glass partitions and unrated construction may all provide some limited fire endurance, but the trial design should thoroughly evaluate the consequences when these are exposed to credible design fire scenarios. It is important to note that there are multiple strategies available that may be considered in developing trial designs that include combinations of active and passive fire protection, one or the other or none at all.

While International Code for Application of Fire Test Procedures (FTP Code) has historically measured fire endurance in the context of components tested to a standard time-temperature exposure in a standardized test facility with fixed laboratory conditions, the performance of these components or systems in the field will vary. This is due to changes in fires and temperature-induced conditions to that which is used in the test furnaces and can either be more or less severe depending on the credible fires for a specific facility. In addition, changes in compartment characteristics will affect the transfer of heat from the fire to the structural or compartment components and thus also affect its ability to perform for its anticipated time. In addition, when structural elements/components are interconnected to other vessel structures and systems, their performance will be affected by heat transfer to these other components, as well as the ability for various components to redistribute their loads. Therefore, these should be included when undertaking a performance-based design that involves passive fire protection.

4   Fire Safety Concept Tree (FSCT)

The concept of NFPA 550, *Fire Safety Concept Tree (FSCT)*, is a useful systematic approach to providing an overall structure with which to analyze the potential impact of various codes and standards on a particular fire safety problem.

FIGURE 1
Top Gate of FSCT
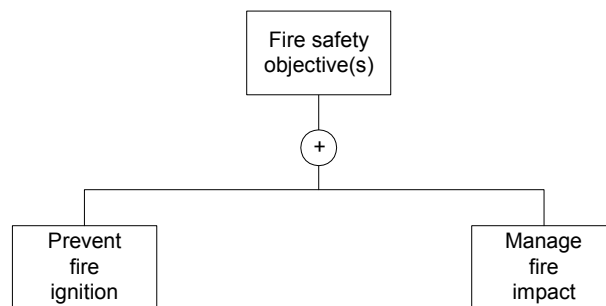
[Reprinted with permission from NFPA 550, *Guide to the Fire Safety Concepts Tree.* Copyright © 2002 National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the National Fire Protection Association on the referenced subject, which is represented only by the standard in its entirety.]

FIGURE 2
Prevent Fire Ignition Branch of FSCT
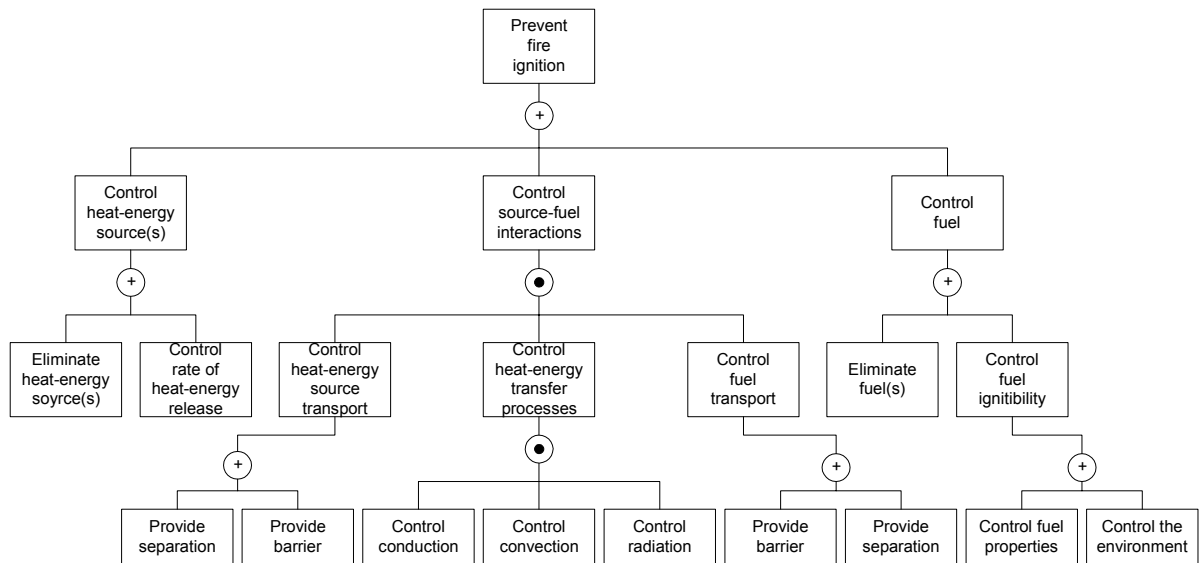
FIGURE 3
Logic Symbols Used in FSCT

Key

$+$ = "OR" gate

$\bullet$ = "AND" gate
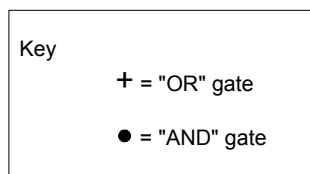
FIGURE 4
Major Branch of Manage Fire Impact
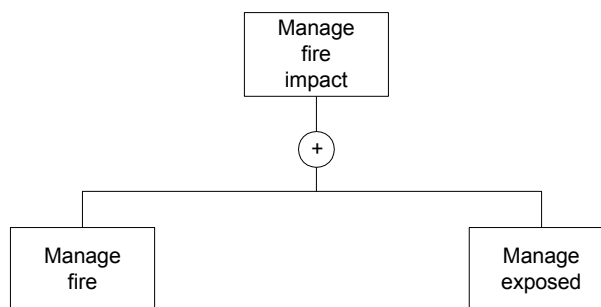
[Reprinted with permission from NFPA 550, *Guide to the Fire Safety Concepts Tree.* Copyright © 2002 National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the National Fire Protection Association on the referenced subject, which is represented only by the standard in its entirety.]

FIGURE 5
Manage Fire Branch of FSCT
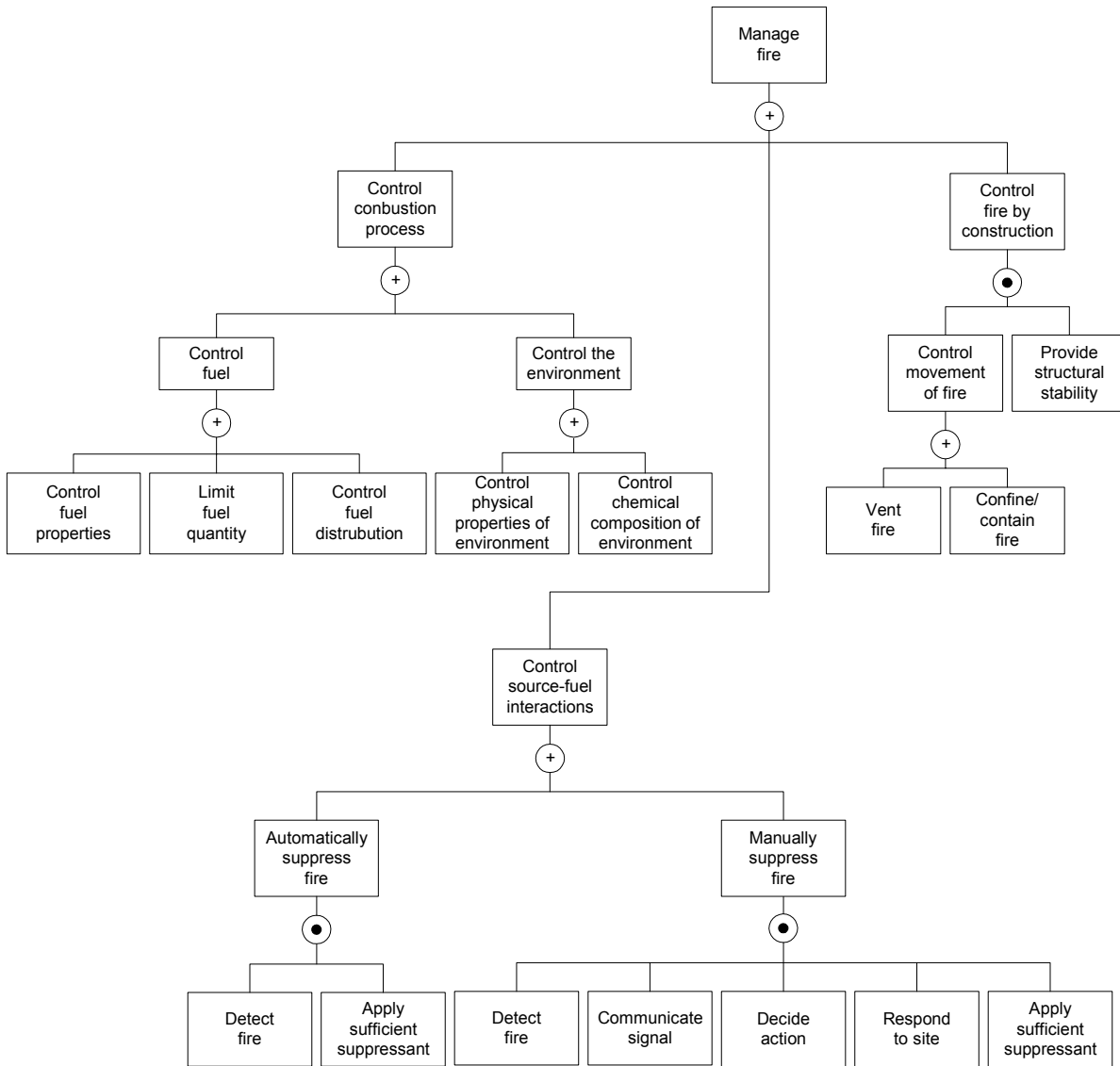
FIGURE 6
Manage Exposed Branch of FSCT
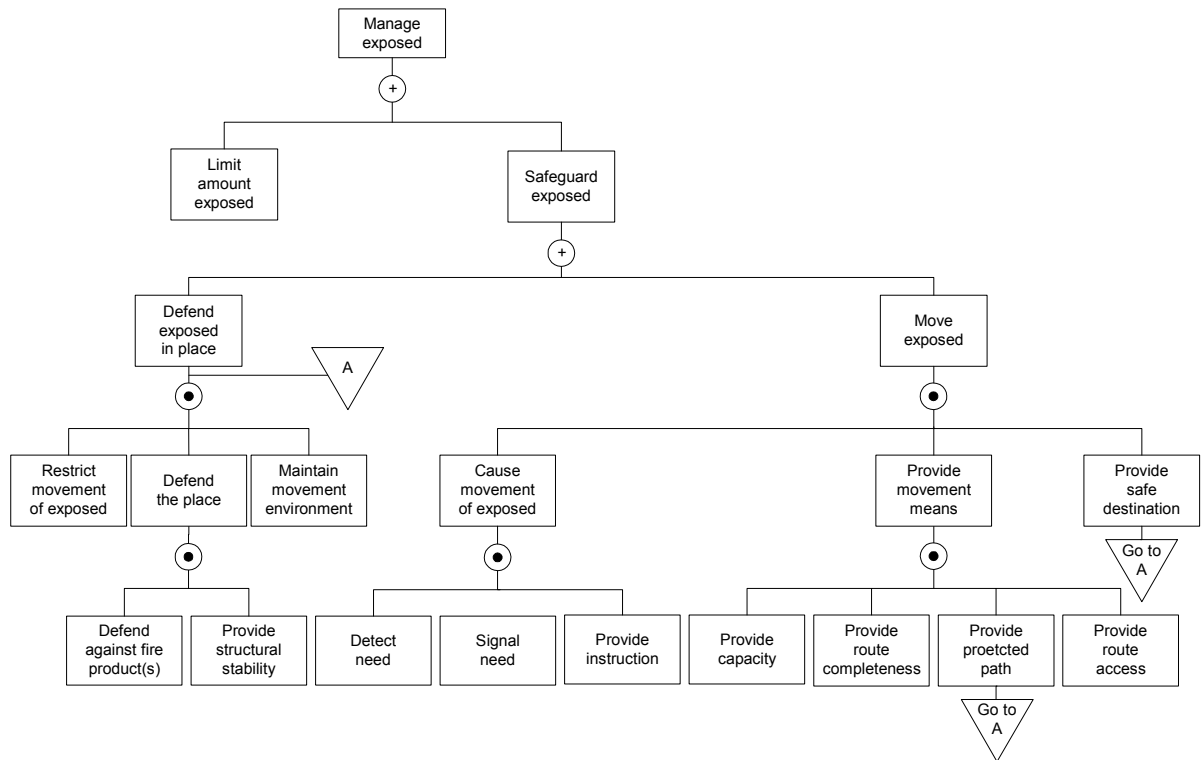
FIGURE 7
Fire Prevent in a Computer Facility
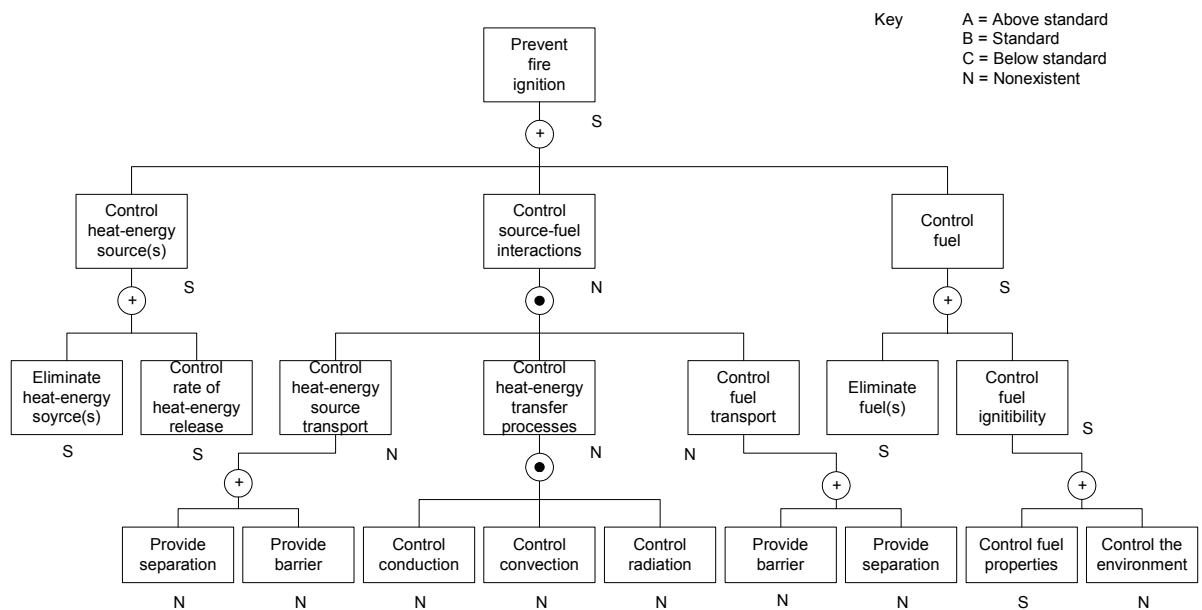
Key   A = Above standard
        B = Standard
        C = Below standard
        N = Nonexistent

[Reprinted with permission from NFPA 550, *Guide to the Fire Safety Concepts Tree.* Copyright © 2002 National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the National Fire Protection Association on the referenced subject, which is represented only by the standard in its entirety.]

FIGURE 8
Administration Action Guide
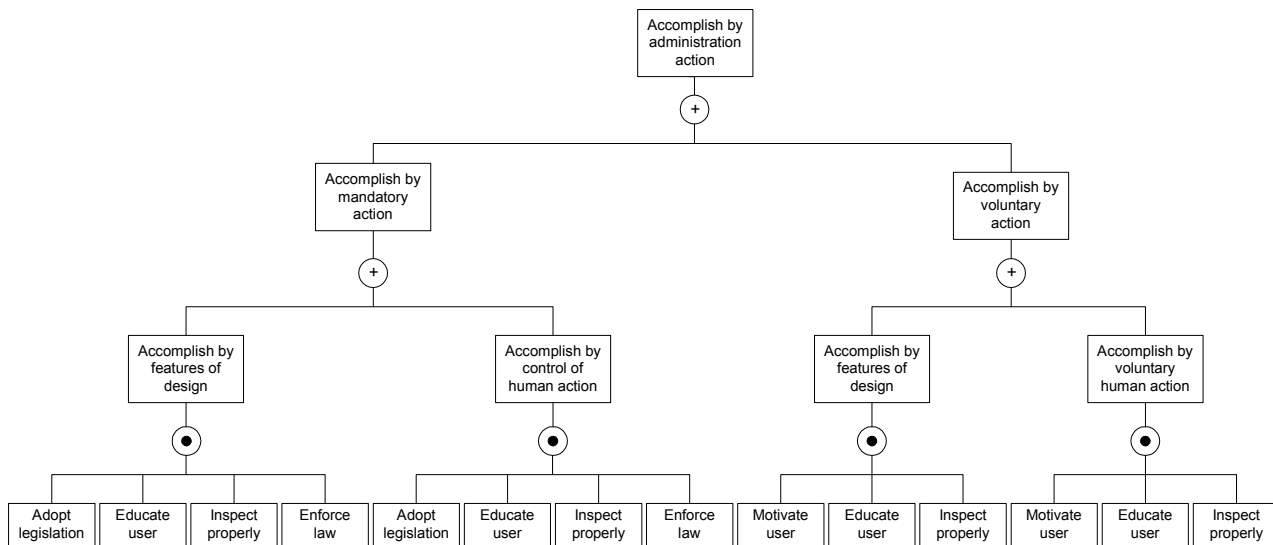
[Reprinted with permission from NFPA 550, *Guide to the Fire Safety Concepts Tree.* Copyright © 2002 National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the National Fire Protection Association on the referenced subject, which is represented only by the standard in its entirety.]

5   References

1.   Milke, J., "Smoke Management in Covered Malls and Atria", *the SFPE Handbook of Fire Protection Engineers*, 3rd Edition, Section 4-13, National Fire Protection Association, Quincy, MA: 2002.

2.   NFPA 550: *Guide to the Fire Safety Concept Tree*, 1995 Edition.

3.   NFPA 92A: *Smoke-Control Systems*, 2000 Edition.

4.   NFPA 92B: *Smoke Management Systems in Malls, Atria, and Large Areas*, 2000 Edition.

5.   NFPA 72: *National Fire Alarm Code*, 1999 Edition.

6.   Schifiliti, R., Meacham, B., and Custer, R. "Design of Detection Systems," *The SFPE Handbook of Fire Protection Engineering,* 3rd Edition, Section 4-1, National Fire Protection Association, Quincy, MA: 2002.

7.   International Code for Application of Fire Test Procedures (FTP Code), IMO, 1998.

8.   Guidelines for Chemical Process Quantitative Risk Analysis, Center for Chemical Process Safety of the American Institute of Chemical Engineers (AIChE), AIChE, New York: 1989.

APPENDIX **6** **Design Tools for Trial Alternative Designs**

1 Introduction

Fire is a dynamic process of interacting physics and chemistry, and fire phenomena include a larger range of time and space scales. Time ranges from the picoseconds involved in molecular rearrangement and vibration transitions to hours needed for the collapse of steel-reinforced barriers. Space scales range from microns in polymer connections to meters in constructions. At present, it is impossible to include the entire range of phenomena in a comprehensive model of such a process. Therefore, the models with a range of approximations are used to describe fire dynamics and the consequence after the fire.

The fundamental conservation equations for fire dynamics include the governing equations of fluid dynamics, heat transfer and combustion, and enormous progress has been made toward the numerical solutions for fluid and thermal applications. The simplest methods to predict fire phenomena are the algebraic equations. Often developed wholly or in part from correlation to experimental data, they represent, at best, estimates with significant uncertainty. Yet, under the right circumstances, they have been demonstrated to provide useful results.

However, it is inappropriate to rely solely on such estimation techniques for fire development or smoke filling calculations. Only fire models should be used. However, due to the inherent complexity of the fire dynamics problem, the practical mathematical models of fire are relatively recent. The difficulties revolve about at least three issues: First, there are enormous numbers of possible fire scenarios to consider due to their accidental nature. Second, the physical insight and computing power necessary to perform all necessary calculations for most fire scenarios are limited. Any fundamentally-based study of fires must consider at least some aspects of bluff body gas dynamics, multi-phase flows, turbulent mixing and combustion and radiative transport, all of which are active research areas in their own right. Finally, the "fuel" in most fire was never intended as such. Thus, the mathematical models and data needed to characterize the degradation of condensed phase materials that supply the fuel may not be available. The mathematical modeling of the physical and chemical transformations of the real materials as they burn is still in the preliminary stage.

Currently there are two fundamentally different approaches to fire modeling: (1) probabilistic and (2) deterministic. The probabilistic or stochastic approach involves the assessment of probable fire risk in an enclosure by associating finite probabilities with all fire-influencing parameters, such as distributions of fuel, numbers of vents and openings, and human behavior, etc. Little or no physics is included in probabilistic-based models. This approach, while useful in suggesting likelihood of a fire in a given enclosure, provides little information about the distribution of fire production, temperature profile and smoke propagation.

In deterministic models, a complete set of differential equations based on laws of physics and chemistry can compute the conditions produced by fire at a given time in a specified volume of air in a well-defined physical scenario. Deterministic fire models can range from simple one-line correlation of data to highly complex models. The more complex models are typically divided into two classes: (1) zone models and (2) field models, based on the strategy used to solve the equations representing the physical processes associated with the fire.

2 Zone Models

2.1 Basic Concepts

The zone modeling concept divides the hypothetical burning enclosure into two spatially homogeneous volumes, i.e., a hot upper layer and a cool lower layer. This two-layer approach has evolved from the observation of such layering in real-scale fire experiments. Hot gases collect at the ceiling and fill the compartment from the top. While these experiments show some variation in conditions within the layer, these are small compared to the differences between the layers. Thus, zone models can provide a fairly realistic simulation under most conditions.

Mass and energy balances are enforced for each layer, with additional models describing other physical processes appended as differential or algebraic equations, as appropriate. Examples of such phenomena include fire plume, flows through windows, ceilings and vents, radiative and convective heat transfer and solid fuel pyrolysis rate, etc.

In the zone model, the conservation equations for the upper and lower gas zones are developed either by using fundamental equations of energy, mass and momentum transport in control volume form applied to the zones, or by using differential equations that represent the conservation laws and integrating them over the zones. However, the momentum equations will not be explicitly applied since information needed to compute velocities and pressure is based on assumptions and specific applications of momentum principles at vent boundaries of the compartments. For example, the mass transfer between control volumes results from the air entrainment of the fire plume and vent flows through openings.

Appendix 6, Figure 1 illustrates a typical zone model for a compartment fire process. The velocity of the control volume along the interface, $\bar{w}$, is equal to the fluid velocity, $\bar{v}$. The properties of the upper and lower zones are assumed to be spatially uniform, but can vary with time.

FIGURE 1
Control Volumes Selected in Zone Modeling
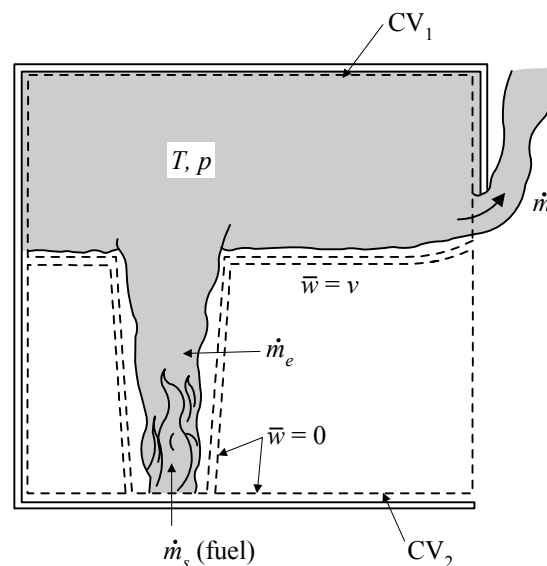
[Figure taken from Ref. 6.]

2.2   Model Assumptions

The most dominant characteristic assumption of the zone models is that it divides the room(s) into a hot upper layer and a cool lower layer. The model calculations provide estimates of key conditions for each of the layers as a function of time. Other assumptions in the application of the conservation of laws in the zone model may also include:

* No diffusion or conduction occurs at the free boundary surface of the control volume.

* Exchange of mass at free boundaries is due to bulk transport of fluid and due to pressure or shear mixes.

* Diffusion can occur at solid boundaries, but is generally ignored.

* The plume instantly arrives at the ceiling.

* The mass or heat capacity of the room contents is ignored compared to the enclosure structural wall, ceiling and floor elements, i.e., the wall or ceiling can be treated as heat sinks or heat sources as flame spreads.

* The horizontal cross-section of the enclosure is a constant.

* The pressure in the enclosure is considered uniform in the energy equation, but hydrostatic variations account for pressure differences at free boundaries of the enclosure, i.e., $P >> \rho g H$.

* Mass flow into the fire plume is due to the turbulent entrainment.

* Fluid frictional effects at solid boundaries are ignored in most models.

2.3   Fires

A fire is a source of fuel which is released at a specified rate. This fuel is converted into enthalpy and mass as it burns. A fire is constrained if the enthalpy conversion depends on the oxygen concentration; otherwise, it is unconstrained. Burning can take place in the portion of the plume in the lower layer (if any), in the upper layer or in a door jet. For an unconstrained fire, the burning will all take place within the fire plume. For a constrained fire, burning will take place where there is sufficient oxygen available. When insufficient oxygen is entrained into the plume, unburned fuel will successively flow into and burn in places such as the upper layer of the fire compartment, the plume in the doorway to the next compartment, the upper layer of the next compartment, the plume in the doorway to the third compartment and so forth until it is consumed or gets to the outside.

Most zone models include the ability to independently track multiple fires in one or more enclosures. These fires are treated as totally separate entities, i.e., with no interaction of the plume or radiative exchange between fires in the enclosure. These fires are generally referred to as "objects" and can be ignited at a specified time, temperature or heat flux.

2.4   Heat Transfer

Gas layers exchange energy with surroundings via convective and radiative heat transfer. While different material properties can be used for the ceiling, floor and walls for each compartment, material thermophysical properties are mostly assumed to be constant, although we know that they vary somewhat with temperature. Radiative heat transfer occurs among the fire(s), gas layers and compartment surfaces (ceiling, walls and floor). This transfer is a function of the temperature differences and the emissivity of the gas layers, as well as the compartment surfaces. Some models ignore the heat conduction through the compartment wall surfaces, whereas some apply a one-dimensional heat-conduction equation to estimate the heat transfer through the wall surfaces.

2.5   Vent Flow

Flow through vents is a dominant component of any fire model because it is sensitive to small changes in pressure and transfers the greatest amount of enthalpy on an instantaneous basis for all of the source terms (except for the fire and plume). Its sensitivity to environmental changes arises through its dependence on the pressure difference between compartments, which can change rapidly. In the realm of the zone model, there are two distinct types of flow: horizontal flow through vertical vents (doors, windows, etc.) and vertical flows through horizontal vents (ceiling holes, hatches, etc.). Vertical flow is particularly important in two disparate situations: a ship, and the role of fire fighters doing roof venting.

Atmospheric pressure is about 100,000 Pa, fires produce pressure changes from 1 Pa to 1000 Pa, and mechanical ventilation systems typically involve pressure differentials of about 1 Pa to 100 Pa. The pressure variables should be solved to a higher accuracy than other solution variables because of the subtraction (with resulting loss of precision) needed to calculate vent flows from pressure differences.

2.6   Plumes and Layers

A plume is formed above any burning object. It acts as a pump to transfer mass and enthalpy from the lower layer into the upper layer. A correlation is used to predict the amount of mass and enthalpy that is transferred. Two sources exist for moving enthalpy and mass between the layers within and between compartments. Within the compartment, a fire plume provides one source. The other source of mixing between the layers occurs at vents, such as doors and windows. The degree of mixing is based on an empirically driven mixing relationship.

As enthalpy and mass are pumped into the upper layer by the fire plume, the upper layer expands in volume, causing the lower layer to decrease in volume and the interface to move downward. If the door to the next compartment has a soffit, there can be no flow through the vent from the upper layer until the interface reaches the bottom of the soffit. Thus, in the early stages, the expanding upper layer will push down on the lower layer air and force it into the next compartment through the vent by expansion.

Once the interface reaches the soffit level, a door plume forms and flow from the fire compartment to the next compartment is initiated. As smoke flow from the fire compartment fills the second compartment, the lower layer of air in the second compartment is pushed down. As a result, some of this air flows into the fire compartment through the lower part of the connecting doorway or vent. Thus, a vent between the fire compartment and connecting compartments can have simultaneous, opposing flows of air. All flows are driven by pressure and density differences that result from temperature differences and layer depths. The key to getting the correct flows is to correctly describe the fire and plume's mass and enthalpy between the layers.

2.7   Species Concentrations and Depositions

When layers are initiated at the start of the simulation, they are set to the ambient conditions. These are the initial temperatures specified by the user, and 23% by mass (20.8% by volume) oxygen, and 77% by mass (79% by volume) nitrogen, a mass concentration of water specified by the user as a relative humidity, and a zero concentration of all other species.

As fuel is pyrolyzed, the various species are produced in direct relation to the mass of fuel burned. Since oxygen is consumed during burning, the "yield" of oxygen is negative, and is set internally to correspond to the amount of oxygen needed to burn the fuel. Hydrogen cyanide and hydrogen chloride are assumed to be products of pyrolysis, whereas carbon monoxide, carbon dioxide, water vapor and soot are products of combustion. Each unit mass of species produced is carried in the flow to the various compartments and accumulates in the layers. The fire model keeps track of the mass of each species in each layer.

No zone model of fire growth and smoke transport incorporates a complete combustion scheme. It is simply not practical at this time. Rather than try to capture the development of all species, it has been deemed more practical to use empirical methods, measure the rate of production of species and use these in the predictive model. For fires, a combustion chemistry scheme based on a carbon-hydrogen-oxygen balance is commonly used. The scheme needs to be applied to at least three places. The first is burning in the portion of the plume which is in the lower layer of the fire origin. The second is in the portion of the upper layer, also in the compartment of fire origin. The third is in the vent flow which entrains air from a lower layer into an upper layer in an adjacent compartment. This is equivalent to solving the conservation equations for each species independently.

There are two significant limitations of zone models inherent in this prescription. One is that it is difficult to capture the effect of transitioning through the layer interface, which is one of the sources of carbon monoxide. The other is the transient nature of the plume, especially in the initial phase of a fire when the plume is developing from a small cloud to a complete plume envisioned by Mortem, Taylor and Turner in their classifications on plumes.

2.8   Predictive Equations

Zone fire models solve a set of equations in the form of an initial value problem for a mixed system of differential and algebraic equations. These equations are derived from a conservation of mass and energy. Subsidiary equations are the ideal gas law and definitions of density and internal energy. These conservation laws are invoked for each zone or control volume.

The basic element of the model is a zone. The basic assumption of a zone model is that properties such as temperature can be approximated throughout the zone by some uniform function. The usual approximation is that temperature, density and so on are uniform within a zone. The assumption of uniform properties is reasonable and yields good agreement with experiments. In general, these zones are grouped within compartments.

There are two reasonable conjectures which dramatically improve the ease of solving these equations. The first is that momentum is ignored within a compartment; the other is that the pressure is approximately uniform within a compartment. However, the hydrostatic variation in pressure is taken into account in calculation of the pressure difference between compartments.

Many formulations based upon these assumptions can be derived. One formulation can be converted into another, using the definitions of density, internal energy and the ideal gas law. Though equivalent analytically, these formulations differ in their numerical properties.

Each formulation can be expressed in terms of mass and enthalpy flow. These rates represent the exchange of mass and enthalpy between zones due to physical phenomena such as plumes, natural and forced convective and radiative heat transfer, and so on. For example, a vent exchanges mass and enthalpy between zones in connected rooms, a fire plume typically adds heat to the upper layer and transfers entrained mass and enthalpy from the lower to the upper layer, and convection transfers enthalpy from the gas layers to the surroundings.

The numerical characteristics of the various formulations are easier to identify if the underlying physical phenomena are decoupled. For example, CFAST [5] uses the formulation in terms of the rates of mass and enthalpy, and assumes that these rates may be computed in terms of zone properties such as temperature and density.

Many approximations are necessary when developing physical sub-models for mass and enthalpy terms. For example, most fire models assume that (1) the specific heat terms c_p and c_v are constant even though they are temperature dependent, (2) hydrostatic terms can be ignored in the equation of state (the ideal gas law) relating density of a layer with its temperature. The detailed derivations of equations for various zone models can be found in their user manuals or technical references.

2.9   Limitations of Zone models

The basic assumption of all zone fire models is that each room can be divided into a small number of control volumes, each of which is internally uniform in temperature and compositions. Beyond the basic assumptions, a model typically involves a mixture of established theory (e.g., conservation equations), empirical correlation where there are data but no theory (e.g., air entrainment coefficients, pre-flashover coefficients) and approximations (e.g., post-flashover combustion theory), etc.

The major limitations of zone models are directly related to the modeling assumptions. The generality and uncertainty of the results can be significant in some particular scenarios. For example, it is often important during the analysis of a design to determine the exact results of small-scale phenomena at a particular location in a compartment. The field model will determine the vertical temperature gradient through the upper layer, whereas a zone model generally gives only average upper layer temperature. The zone models give the same results regardless of the location of fire origin as long as it is with the same layer. Thus, the uncertainty of the modeling results can be significant if the temperature profiles are sensitive to the height of fire origin below the ceiling in a real fire scenario.

Another shortcoming of the zone model is the assumption of instantaneous plume spread upon impingement of the plume with the ceiling. If the compartment is sufficiently large (e.g., a warehouse) or long (e.g., a corridor), the assumption of instantaneous volume filling may be violated. It is well documented that a lag time exists between plume impingement upon a ceiling and arrival of the ceiling jet front at the end of the corridor. While many assumptions and limitations exist in a zone model, it is ultimately up to the engineer and designer performing the analysis to understand and document to ensure that none of the assumptions have been violated, or that the assumption violation has not subsequently invalidated the resulting conclusions.

The development of zone models will be dependent not only on the advancement of computer coding techniques, but also the experimental research needed for the improvement in the model.

2.10   Current Available Models

The following models either have a significant number of users or are currently used:

Model	Country	Descriptions
ARGOS	Denmark	Multi-compartment zone model
ASET	US	One room zone model with no ventilation
ASET-B	US	ASET in BASIC instead of Fortran
BRANZFIRE	New Zealand	Multi-room zone model, including flame spread, multi fires, and mechanical ventilation
BRI-2	Japan/US	Two-layer zone model for multistory, multi-compartment smoke transport
CALTECH	US	Preflashover zone model
CCFM.VENTS	US	Multi-room zone model with ventilation
CFAST/FAST	US	Zone model with a suite of correlation programs-CFAST is the solver, FAST is the front-end
CFIRE-X	Germany	Zone model for compartment fires, particularly liquid hydrocarbon pool fires
CiFi	France	Multi-room zone model
COMPBRN-III	US	Compartment zone model
COMF-2	US	Single-room postflashover compartment model

Model	Country	Descriptions
DACFIR-3	US	Zone model for an aircraft cabin
DSLAYV	Sweden	Single compartment zone model
FASTlite	US	Feature limited version of CFAST
FFM	US	Preflashover zone model
FIGARO-II	Germany	Zone model for determining untenability
FIRAC	US	Uses FIRIN, includes complex vent systems
FireMD	US	One room, two zone model
FIREWIND	Australia	Multi-room zone model with several smaller submodels (update of FIRECALC)
FIRIN	US	Multiroom zone model with ducts, fans, and filters
FIRM	US	Two zone, single compartment model
FIRST	US	One room zone model, includes ventilation
FMD	US	Zone fire model for atria
HarvardMarkVI	US	Earlier version of FIRST
HEMFAST	US	Furniture fire in a room
HYSLAV	Sweden	Preflashover zone model
IMFE	Poland	Single room zone model with vents
MAGIC	France	Two-zone model for nuclear power stations
MRFC	Germany	Multi-room zone model for calculation of smoke movement and temperature load on structures
NAT	France	Single compartment zone model with attention to responses of structures
NBS	US	Preflashover zone model
NRCC1	Canada	Single room compartment zone model
NRCC2	Canada	Large office space with vents
OSU	US	Single room compartment zone model
OZONE	Belgium	Zone model with attention to responses of structures
POGAR	Russia	Single compartment zone model
RADISM	UK	Zone model incorporating an immersed ceiling jet within the buoyant layer, sprinklers and vents
RFIRES	US	Preflashover zone model
R-VENT	Norway	Single room smoke ventilation zone model
SFIRE-4	Sweden	Postflashover zone model
SICOM	France	Single compartment zone model
SMKFLW	Japan	One-layer zone model for smoke transport in buildings

Model	Country	Descriptions
SmokePro	Australia	Zone model for single compartment smoke layer interface position
SP	UK	Preflashover zone model
WPI-2	US	Single compartment zone model
WPIFIRE	US	Multi-room zone model
ZMFE	Poland	Single compartment zone model

Some other models, such as PRETool (US) are based on correlation. Specific applications models, such as ASCOS and Contam, are for designing smoke control systems. Some models, such as LAVENT and JET programs, are for designing sprinkler responding systems.

2.11   Model Selection

To select an appropriate fire model for specific applications, proper validation and verification procedures such as specified in ASTM E 1355-97 should be followed. The theoretical basis of the model should be reviewed by knowledgeable but independent and recognized experts. A key issue in selecting a model is model validation. Comparison of model results with experimental data is valuable for determining the applicability of a model to a particular situation. The model user should carefully examine the model validation comparisons before selecting a model. They will include the comparisons with standard tests, the comparisons with full-scale tests conducted specifically for the chosen evaluation, the comparisons with previously published full-scale data, the comparisons with documented fire experience, and the comparisons with a proven benchmark model, etc.

Only models which are rigorously evaluated and documented should be allowed in any applications involving design, legal consideration such as code enforcement, or litigation. It is simply not appropriate to rely on the model developer's words that the physics is proper. This means that the model should be supplied with a technical reference guide which includes a detailed description of the included physics and chemistry with proper literature references, and estimates of the accuracy of the resulting predictions based on comparisons with experiments. Public exposure and review of the exact basis for a model's calculations, empirical or reference data used for constants and default values in the code, and assumptions are necessary for it to have credibility in a regulatory application.

No zone fire model is "best" for all applications. The selection of a zone fire for a particular application depends on a number of factors. While most of the zone models are based on the same fundamental principles, there is significant variation among different models. The decision to use a model should be based on the understanding of the assumptions and limitations for the particular model.

When using a computer model, it is always a good idea to test the sensitivity of the model. Such a test will help the user understand how changes in model input parameters affect the results generated by the model, determine the dominant variables in the model, define the acceptable range of values of each input variables, and quantify the sensitivity to provide information and cautions on selection of input variables.

3   Field Models

3.1   Basic Concepts

Field (or CFD) models represent the other alternatives of deterministic analysis. This approach is based on basic local conservative laws for physical quantities such as mass, momentum, energy and species concentrations. These equations are solved with spatial and temporary resolutions to yield the distributions of the variables of interest. The set of equations, referred to as the Navier-Stokes equations, consist of three-dimensional, time-dependent, non-linear partial differential equations. Theoretically, this numerical approach should provide the whole history of fire evolution including local characteristics at any given point.

Due the turbulent characteristics of thermally driven flows, the biggest challenge that arose in using CFD methodology is how to properly handle turbulence. Field models are classified based on methods by which they treat turbulence phenomena. The two major groups may be identified as Reynolds-Averaged Navier-Stokes (RANS) models and Large Eddy Simulations (LES) models.

The RANS model computes time-averaging solutions for different variables of the modeled equations over a long time scale. Only the mean flow field will be described by the time-averaged RANS model, whereas local fluctuations and turbulent structures are integrated in the mean quantities and these structures are no longer to be described in the simulation. The time scale used by RANS is long when compared to the turbulent motion within the system; the variable data obtained from this technique provide mean quantities different from the instantaneous ones. Strong unsteady mixing effects, resulting from the rolling up of shear layers, are observed in turbulent flames, but the knowledge of steady statistical mean quantities is not always sufficient to describe the turbulent combustion. It is evident that one of the major limitations of RANS models is the inadequate treatment of turbulent flow. An alternative is to use LES technique.

The object of LES is to explicitly compute the largest structures of the flow (typically, the structures larger than the computational mesh size). The large scale eddies are generally more energetic in turbulent combustion. The assumption behind the space-averaged LES is that only the large scales that carry most of the energy need to be directly resolved in order to present the flow accurately, and that energy dissipation into smaller scales can be modeled. The LES technique is inherently time-dependent, since N-S equations are not time-averaged. Transient problems can be solved quickly using this approach.

3.2   Model Requirements

Although a very wide range of engineering problems can be addressed by CFD models, there is no single CFD code that can incorporate all of the physical and chemical processes of importance. There exist, therefore, only a handful of CFD codes that can be used for problems involving fires. These, in turn, use a number of different approaches to the subprocesses that need to be modeled. Some of the most important of these subprocesses include turbulence modeling, radiation and soot modeling and combustion modeling, etc. Since the modeling of these subprocesses are still very active in their own research perspective, the use of CFD codes in fire safety engineering design is limited to the expert knowledge required for the processes listed above.

3.2.1   Turbulence Modeling

The flow occurring in room fires is turbulent, generating eddies or vortices of varying sizes. The energy contained in large eddies cascades down to smaller and smaller eddies until it diffuses into heat. Such eddies exist down to the sizes where the viscous forces dominate over inertial forces and energy is dissipated into heat. For typical fires, the length scale of eddies is down to a millimeter or so. Thus, the control volume size to discrete N-S equations should be consistent with this scale. Additionally, the fluctuations can occur very fast and can have a frequency in the order of 10 kHz.

A direct solution of the time-dependent N-S equations of fully turbulent flows at high Reynolds numbers, therefore, requires extremely fine geometric grids and extremely small time steps. Thus, the computing requirements for direct solution are truly phenomenal and impractical for fire modeling applications. Certain assumptions must therefore be made to avoid the need to predict the effects of each and every eddy in the flow.

Several such turbulent modeling approaches have been used and depend mostly on the type of engineering problem to be solved. These models can be separated into two broad classes: (1) eddy viscosity models and (2) second-order closure models. Eddy viscosity models specify the Reynolds stresses and fluxes algebraically in terms of known mean quantities. Second-order closure models solve differential transport models for the turbulent fluxes.

The $k - \varepsilon$ model, an example of eddy viscosity model based on the time-averaged Reynolds equations, is widely used to develop the time-averaged approximation to the conservation equations of fluid dynamics. This model results in two additional partial differential equations per control volume. The first equation governs the distribution of turbulent kinetic energy, k, while the second describes rate of the dissipation of local turbulent kinetic energy, ε. A number of variations of the $k - \varepsilon$ model exist. The so-called standard $k - \varepsilon$ model is widely used. One of the main drawbacks of this model is that the eddy viscosity is assumed to be identical for all of the Reynolds stresses, so that the turbulence has no preference direction.

Several modifications to the standard $k - \varepsilon$ model have been used to predict the plume entrainment and jet flows. Most fire scenarios will involve transient fire growth, fueled by radiative feedback between the fire source and confining boundaries. The mass of air entrained into a fire plume controls, to a considerable degree, the process of smoke filling, the concentrations and temperature in the hot layer and the combustion in the flame. Since gravitational force is applied only in the vertical direction, the standard $k - \varepsilon$ model does not model the plume correctly. This has been amended by using a $k - \varepsilon$ model with buoyancy modification.

Another common way of modeling turbulence is termed "Large Eddy Simulation" (LES), where the time-dependent flow equations are solved not only for the mean flow but also for the largest eddy structures characteristic of most fire plumes. The phrase LES refers to the description of turbulent mixing of gaseous fuel and combustion products with the local atmosphere surrounding the fire. The basic idea behind the LES technique is that the eddies, which account for most of the mixing, are large enough to be calculated with reasonable accuracy from the equations of fluid dynamics.

The equations describing the transport of mass, momentum and energy by fire-induced flows must be simplified so that they can be efficiently solved for the fire scenarios of interest. The general equations of fluid dynamics describe a rich variety of physical processes, many of which have little to do with fires. The simplifying equations have been widely adopted by the larger combustion research community, where they are referred to as the "low Mach number" combustion equations. They describe the low speed motion of a gas driven by chemical heat release and buoyancy forces. The Low Mach number equations are solved numerically by dividing the physical space where the fire is to be simulated into a large number of rectangular cells, within each cell, the gas velocity, temperature, species concentration, etc., are assumed to be uniform, only changing with time. The accuracy with which the fire can be simulated depends on the number of cells that can be incorporated into the simulation.

Further work is clearly needed on the turbulence models used in CFD codes for fire applications. Any progress in such modeling must be based on relevant experimental data for a wide range of flow conditions.

3.2.2   Radiation Modeling

The radiative transfer equation is an integro-differential equation, and its solution, even for a two-dimensional, planar, gray medium, is quite difficult. In fires, the multidimensional combustion system consists of a highly non-isothermal and non-homogeneous medium where spectral variation of radiative properties of the medium must be accounted for. It is necessary to introduce some simplifying assumptions and strike a compromise between accuracy and computational effort.

The problem is usually divided into two parts: first, an appropriate solution method must be chosen for the integro-differential equation, and second, an assumption must be made on the radiative properties of the medium (i.e., combustion gases and particles). The solution methods can be divided into the following categories: exact models, statistical methods, zonal methods, flux methods and hybrid methods.

The properties of combustion systems are a complicated function of wavelength, temperature, pressure, composition and path length. The products of combustion usually consist of combustion gases such as H_2O, CO_2, CO, etc, and particles such as soot. The combustion gases are strong absorbers and emitters of radiant energy, but these radiative properties are a strong function of wavelength. Consequently, the variation of the radiative properties with the electromagnetic spectrum must be accounted for.

Spectral calculations are performed by dividing the entire wavelength (or frequency) into several bands and assuming that the absorption/emission characteristics of each species remain either uniform or change smoothly over these bands. The accuracy of the predictions is expected to increase as the width of these bands become narrower. A number of approaches to solve this problem have been suggested. Among them, the total absorptivity-emissivity models, wide-band models and narrow-band models are the most commonly used. From a series of numerical experiments, it has been found that six (6) bands are usually enough. If the absorption of the fuel is known to be important, separate bands can be reserved for fuel, and the total number of bands is increased to ten (10).

3.2.3   Combustion Modeling

The mechanism by which species are formed and destroyed in fire is extremely complex and involves chemical and physical processes on a molecular and macroscopic level. Ignition, combustion and extinction occur at the same time within the microstructure of a turbulent flame. These events occur at high frequencies with spatial separation of only a few millimeters. The mixture of gases can be diluted by complete or incomplete products of combustion at a given location. Thousands of different states can thus exist at different points within the flame, at a given time.

In order to avoid these complications, one can give the heat release rate in a certain control volume as user input, and therefore not deal with combustion at all. But for fire applications, it is important to allow the process of fuel and air mixing so that the heat release rate of the flame can be determined by actual flow conditions and oxygen concentration levels. This also allows the prediction of species concentration and estimation of soot concentrations, which has important significance for the radiation calculations.

The range of models used for combustion fall essentially into two categories: (1) models based on a conserved scalar approach; and (2) flamelet combustion models. One typical choice for the conserved scalar approach is a mixture fraction. The mixture fraction model assumes an infinite combustion reaction. Neither fuel nor oxidizer can co-exist in the fuel or oxidizer streams. Mixture fraction is used to represent that local concentration of fuel, oxidizer (i.e., oxygen) and the products. The mass fractions of all of the major reactants and products can be derived from the mixture fraction by means of the state relationship for the specified fuels.

An extension of the conserved scalar approach is achieved by taking into the consideration a second variable, which concentration is affected by the chemical kinetics. A popular and rather successful example of this approach is the Eddy-Break-up model. Based on some reasonably good correlation with measured data, the eddy break-up model assumes a single, one-step reaction and infinitely fast reactions.

However, the fast chemistry assumption is not always valid. Under the conditions of fuel ignitions and fire extinctions, the production of many important species in turbulent flames is chemically controlled, thus, the finite rate kinetics effects should be modeled. One way to incorporate finite rate chemistry is based on laminar flamelet considerations.

The finite reaction rate model assumes that the combustion occurs locally in thin laminar flamelets embedded within the turbulent flow field. For simple fuels such as methane and propane for which the chemistry is sufficiently well known, the relationships between the instantaneous species concentration and mixture fraction can be calculated directly. This requires that laminar flamelet libraries be established from experiments, where the state relationships of species concentrations, temperature, enthalpy, viscosity, density and soot concentrations are stored as a function of mixture fraction.

3.3   Boundary and Initial Conditions

In order to fully specify a problem, a set of boundary and initial conditions must be provided. Boundary conditions place limits on the physical environment. The limits take the form of a specified parameter value (e.g., solid wall with zero velocity), a flux value (e.g., mass flow rate) or a time rate of change at a specified position. Boundary conditions generally can be in two categories: thermal boundary conditions and velocity boundary conditions. There are four types of thermal boundary conditions: adiabatic, constant temperature, thermally thick and thermally thin. Only one can be chosen in one surface. If the surface material is assumed to ignite and burn at certain temperature, the relationship between the pyrolyzing fuel and the rate of energy released should be taken into account. Initial conditions are important for transient problems and specify the status of the physical environment at the start of the simulation.

Wall boundary conditions are used to specify the fluid velocities adjacent to the wall surfaces, the wall shear stresses (related to fluid viscosity), the velocity of the wall (if it is moving) and the heat transfer characteristics. Adjacent velocity boundary conditions affect both the normal and tangential components of the velocity vector at boundaries. The tangential boundary condition can be no-slip, free-slip or something in between. The normal velocity conditions can be specified velocity profiles (e.g., parabolic profile) or a given volume flux. Since a large viscosity gradient can occur next to the wall, many of the fluid properties will vary rapidly in the vicinity of the walls. Very fine meshes are usually required to accurately predict the fluid properties near the wall.

Doors, windows and other types of vents are usually specified as either inlet or pressure boundaries. When using inlet boundary conditions, thermal and velocity boundary conditions must be specified. However, a pressure boundary could be more viable for a vent considered as part of fire analysis. In this case, the pressure is set equal ambient and the derivatives of the velocity components normal to the vent surface are set equal to zero. This permits the flow to enter or leave the computational grid, as required.

A final type of boundary condition is a plane or axis of symmetry. All variables are mathematically symmetrical, thus with no diffusion across the boundary. For example, for a fire located in the center of a room, symmetry planes can be used to model a quarter of room. This would allow a four-fold increase in the number of cells used to model the problem.

3.4   Current Available Models

Over the past decades a number of general-purpose computer programs have been developed that permit the solution of the equations describing fluid flow. A brief review of selected field models is given below.

Model Names	Country	Description	Availability
ALOFT-FT	US	Smoke movement from large outdoor fires	Freely available from NIST
CFX	UK/US	General purpose CFD software, applicable to fire and explosion	May be purchased
FDS (Fire Dynamics Simulator)	US	A 3-D CFD field model specified to fire-driven flow of low Mach number, predicting the smoke and hot flow movement, and response of sprinkler links. User-friendly. Using LES technique. Developed by NIST.	Freely available from NIST
FIRE	Australia	CFD model with water sprays and coupled to solid/liquid phases fuel to predict burning rate and extinguishment	May be purchased
FLOW3D		General-purpose fluid dynamic code developed by a finite-difference, transient-solution algorithm solving the convection equations of fluid dynamics.	May be purchased or leased
FLUENT/ AirPak	US	General purpose CFD software, applicable to flows with heat transfer and chemical reactions	May be purchased
JASMINE	UK	Field model for analysis of smoke movement in enclosure developed for fire simulations (based on PHOENICS).	Restricted
KAMELEON FireEX	Norway	CFD model linked to a finite element code for thermal response of structure	Restricted
KOBRA-3D	Germany	A 3-D field model for smoke spread and heat transfer in complex geometries	May be purchased
MEFE	Portugal	CFD model for one or two compartment, includes time-response of thermocouples	Restricted
PHOENICS	UK	A general purpose, 3-d transient fluid dynamics code	May be purchased
RMFIRE	Canada	A 2-D field model for transient calculation of smoke movement in room fires	Restricted
SMARTFIRE	UK	Field fire model to investigate the spread of fire hazards through an enclosure	May be purchased
SOFIE (Simulation of Fires in Enclosure)	US/Sweden	A CFD program contains a multitude of submodels specially developed for applications. Currently not very user-friendly, requires extensive training.	Restricted
SOLVENT	US	CFD model for smoke and heat transport in a tunnel	Restricted
SPLASH	UK	A quasi-field model describing the interaction of sprinkler sprays with fire gases	Restricted
STAR-CD	UK	General purpose CFD software	May be purchased
UNDSAFE	US/Japan	Fire field model for use in open space, or in enclosure, using 3-D finite difference scheme	Restricted

3.5   Limitations of Field Models

While field models provide more detail than zone models, they do have limitations. The most significant limitation of the field model is the cost. Conventional CFD models do not require the sophistication of a pyrolysis or combustion model. The chemistry and physics of the combustion process is extremely complicated. The field models which predict fire scenarios are thus significantly more expensive than a conventional CFD model. Although the involved costs continue to limit the widespread use of field models in fire protection engineering applications, the fast advance of computer technology and computational techniques will increase the capacity of the usability of field models.

Some of the limitations of field models come from the theoretical approximations of CFD and combustion chemistry. Field models do not have a direct simulation of turbulent diffusion flames. Except for some limited cases, the fire sources must be prescribed by the user. Other major phenomena that can only be approximated include turbulence, particularly large eddies associated with strong plumes and flames, and thermal radiation interchanges between soot, gases and solid surfaces. In some cases, the fuel and oxidizer (air) are initially separate and combustion occurs in the zone where they mix. Field models do not have a direct simulation of turbulent diffusion flames. Some field models even yield incorrect results for small fires in a large enclosure or big fires in a small enclosure. As the development and application of field models continue, these limitations should gradually be eliminated.

In addition, the application of field models requires a great deal of user sophistication to specify the problem and interpret the results. Necessary training is significant to effectively implement field models, which require the model users to develop a thorough understanding of the physics and chemistry behind the fire dynamics models.

3.6   Comparisons between Field Models and Zone Models

Using computer-based fire models to analyze fire protection engineering problems is becoming imperative. Zone models have been successfully applied to a wide range of these problems. As the problems grow more complex, zone models will be inadequate to fully address them. Zone models provide very limited detail, with bulk average values being predicted in a few select locations within the enclosure. Zone models utilize equations employing empirical relationships and constants obtained from experiments. Such empirical expressions used to describe physical behavior in zone models could break down as the geometry becomes more complex. Therefore, the use of zone models for problems that lie outside the range of experiments is very limited.

Field models avoid the simplifications inherent in zone models. In solving the fundamental equations of mass, species, momentum and energy, the compartment is divided into up to millions of computational cells. Thus, mass, enthalpy, flow velocity, temperature, etc., are calculated for each cell in the grid, and the distribution profiles are thereafter provided. In some fire cases, the geometry of the room and its outfitting can have significant effects on the nature of recirculation patterns, thus, the higher spatial resolution of field models can be important. In many cases, the detailed knowledge of the temperature and/or flow fields near sprinklers or smoke detectors is required to accurately predict the activation.

The use of field modeling to analyze fire protection engineering problems is growing dramatically. Its use will become imperative as the complexity of problems increase. The details about fluid flow and heat transfer provided by field models can prove vital in analyzing problems involving far field smoke flow, complex geometry (e.g., sprinkler links, furniture, etc.), and impact of fixed ventilation flows. Fluid dynamics considerations are automatically built into field models, rather than being forced into oversimplified approximations. Thus, field models follow the movement of the plume, rather than assuming that deposition of mass and energy from combustion/plume zone into the upper layers is instantaneous. Similarly, they describe the spread of the ceiling jet into the entire upper layer, rather than assuming the instantaneous mixing within it.

4   Other Special-purpose Programs

Over the past few decades, a number of computer fire models have been developed for various fire protection applications. While the commonly used zone models and field models discussed in previous Subsections serve for multiple applications, there are many other computer models designed for special purposes (e.g., egress, fire resistance, fire suppression, smoke control, etc.). Some are only a collection of several useful calculation routines, some programs are available on the Internet for free download, some require registration and a small handling fee, and a few programs are commercially available at relatively high prices. The following is a collection of some special-purpose models available or cited in fire protection applications:

4.1   Egress Models

Egress models predict the time for occupants of a structure to evacuate. A number of egress models are linked to zone models, which will determine the time to the onset of untenable conditions in a building or a vessel. Egress models are often used in performance-based design analysis for alternative design code compliance and for determining where congestion areas will develop during egress.

Many of these models are quite sophisticated, offering computational methods, as well as interesting features including the psychological effects on occupants due to the effects of smoke toxicity and decreasing visibility. Many of these models also have useful graphic features so that movement of people inside a enclosure can be visualized during a simulation. A brief review of selected egress models is given below.

Model	Country	Description	Availability
Allsafe	Norway	Egress model including human factors	N/A
ASERI	Germany	Movement of people in complex geometries, including behavioral response to smoke and fire spread	N/A
Marinetime EXODUS	UK	A sophisticated evacuation model, taking account of people-people, people-fire and people-structure interactions. It allows evacuation simulation of complex vessel structures with many occupants.	High cost for commercial uses
ESSCAPE	Australia	Evacuation of multi-story building via staircases	N/A
EGRESS	UK	Cellular automatic evacuation of multiple people through complex geometries. Includes visualization.	N/A
EGRESSPro	Australia	Egress Program that includes coping times and sprinkler-detector activations	N/A
ELVAC	US	Egress program for use of evaluators for evacuation	N/A
ERM	Sweden	The Escape and Rescue Model (REM) is based on the same node and arc method as EVACNET+, but is developed especially for hospitals and healthcare facilities.	Free
EVACNET+	Sweden	A classic "network" type of model which determines optional building evacuation plan. The user defines a system of nodes and arcs, where occupants are positioned at the nodes and move along the arcs towards the exit.	Free
EVACS	Japan	Evacuation model for determining optimal plan	N/A
EXIT89	US	Evacuation from a high-rise building	N/A
EXITT	US	Node and Arc type egress model with people behavior included	N/A

Model	Country	Description	Availability
HAZARD I	US	This multi-component fire-hazard program calculates the development of fire effects (thermal, toxic gases, smoke) and the interactions and movements of occupants as well as detector activation times.	Free
PATHFINDER	US	Egress model	N/A
SEVE-P	France	Egress model with graphic output that includes obstructions	N/A
SIMULEX	UK	Coordinate-based evacuation model for use in geometrically complex multi-story buildings with many occupants. It allows input of CAD drawings for a plan of the building.	Free
STEPS	UK	Egress Model	N/A
WAYOUT	Australia	Egress part of the FireWind suite of programs	N/A

4.2   Smoke Control Models

Model	Country of Origin	Comments	Availability
ASCOS	US (NIST)	A program for steady airflow analysis of smoke control systems.	Free
FIRE-1.2	Germany/ Norway	Hydrocarbon fires: eight scenarios	
CONTAMW	US (NIST)	A multi-zone indoor air quality and ventilation analysis program to predict airflows, contaminant concentrations and personal exposures to contaminants.	Free
MFIRE	US	Mine ventilation network	
RISK_COST	Canada	Life and cost in multistory building	
SMACS	US	Smoke in HVAC system	
SPREAD	US	Spreading fires on wall	
UFSG	US	Upward wall fire spread	
WALLEX	Canada	Window Fire Plume	

4.3   Fire Endurance Models

Fire endurance models simulate the response of vessel structural elements to fire exposure. Some of these models are stand-alone while others are incorporated into zone or field models. The concept of fire endurance models is similar to field models. The structural object is divided into smaller volumes, and the equations for thermal heat transfer and mechanical behavior for solids are solved to determine when the structure will fail. Typically, the material properties are required input for the model, as well as the boundary conditions (i.e., the fire exposure) for the structural element.

These models are very useful for determining when a beam or column will deform or fail, and for solving for a temperature versus time curve at a certain depth inside the structural element. Since many structural elements are constructed differently, have different features or have different practical applications, care must be used in selecting a model that properly characterizes the structural element. A brief review of selected fire endurance models is given below.

Model	Country of Origin	Comments
CEFICOSS	Belgium	Fire resistance model
CIRCON	Canada	Fire resistance model of loaded, reinforced concrete columns with a circular cross section
CMPST	France	Mechanical resistance of sections at elevated temperatures
COFIL	Canada	Fire resistance model of loaded, circular hollow steel columns filled with plain concrete
COMPSL	Canada	Temperatures of multi-layer slabs during exposure to fire
FIRE-T3	US	Finite element heat transfer for 1-, 2-, or 3-D conduction
HSLAB	Sweden	Transient temperature development in a heated slab composed of one or several materials
INSTAI	Canada	Fire resistant model of insulated, circular hollow steel columns
INSTCO	Canada	Fire resistant model of insulated, circular concrete-filled tabular steel columns
LENAS	France	Mechanical behavior of steel columns exposed to fire
RCCON	Canada	Fire resistance of loaded, reinforced concrete columns with rectangular cross sections
RECTST	Canada	Fire resistance of insulated rectangular steel columns
SAFIR	Belgium	Transient and mechanical analysis of structures exposed to fire
SAWTEF	US	Structural analysis of metal-plate connected wood trusses exposed to fire
SISMEF	France	Mechanical behavior of steel and concrete composite structures exposed to fire
SQCON	Canada	Fire resistance of square reinforced concrete columns
STA	UK	Transient conduction in heated solid objects
TASEF	Sweden	For 2-3D and axisymmetric shapes, a finite element analysis model of temperature distribution through a structure exposed to fire
TCSLBM	Canada	2-D temperature distributions for fire-exposed concrete slab/beam assemblies
THELMA	UK	Finite element code for thermal analysis of building components in fires
TR8	New Zealand	Fire resistance of concrete slabs and floor systems
WSHAPS	Canada	Fire resistance of loaded, protected W-shape steel columns

4.4   Fire Detection Models

Model	Country of Origin	Comments
DETECT-QS	US (NIST)	Detector actuation-Quasi steady
DETECT-T2	US (NIST)	Detector actuation-Time square
LAVENT	US (NIST)	Response of sprinklers in enclosure fires with curtains and ceiling fires
PALDET	Finland	Unconfined ceiling
TDISX	US	Unconfined ceiling, treats flow transient

4.5   Fire Suppression Models

Model	Country of Origin	Comments
FISCO-3L	Norway	One-room field model, suppression
RADISM	UK	Zone model, including venting
SPLASH	UK	Field model, no suppression
FIRDEMND	US (NIST)	Simulating the suppression of post flashover charring and non-charring solid fuel fires in compartments using water sprays from portable hose-nozzle equipment.

4.6   Fire Models from NIST

Of note is that the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST) has made a large number of programs freely available. In addition to previously introduced programs and models, the following programs are also available at NIST's URL address:

Model	Comments
ALOFT-FTTM	A Large Outdoor Fire Plume Trajectory model – Flat Terrain
ASMET	A set of equations and a zone model for analysis of smoke management system for large spaces such as atria, shopping malls, sport arenas, exhibition halls and airplane hangers, etc.
BREAK1	The program (Berkeley Algorithm for Breaking Window Glass in a Compartment Fire) calculates the temperature history of a glass exposed to user described fire conditions.
CCFM	The program (Consolidated Compartment Fire Model version VENTS) is a two-layer zone-type compartment fire model computer code, and simulates conditions due to user-specified fires in a multi-room, multi-level facility.
FPETool	A set of engineering equations useful in engineering potential fire hazard and the response of the space and fire protection systems to the developing fires. It also provides the estimation of the smoke conditions and human viability resulting from exposure to developing conditions within the room.
FASTLite	A software package that builds on the core routines of FPETool and computer model CFAST to provide calculations of fire phenomena for use.

5   References

1.   Walton, W.D., "Zone Computer Fire Models for Enclosure", *the SFPE Handbook of Fire Protection Engineers*, 2nd Edition, Section 3-7, NFPA, Quincy, MA, 1995.

2.   McGrattan, K.B., et. al, "Fire Dynamics Simulator (Version 2) – Technical Reference Guide", NISTIR 6783, National Institute of Standards and Technology, November 2001.

3.   Stroup, D.W., "Using Field Modeling to Simulate Enclosure Fires", *the SFPE Handbook of Fire Protection Engineers*, 2nd Edition, Section 3-8, NFPA, Quincy, MA, 1995.

4.   Quintiere, J.G., "Compartment Fire Modeling", *the SFPE Handbook of Fire Protection Engineers*, 2nd Edition, Section 3-5, NFPA, Quincy, MA, 1995.

5.   Jones, W.W., "State of Art in Zone Modeling of Fires", Reprinted from 9th International Fire Protection Seminar, *Proceedings of Engineering Methods for Fire Safety*, pp. A. 4/89-126, Munich, Germany, May 25-26, 2001

6.   Forney, G.P., Moss, W.F., "Analyzing and Exploiting Numerical Characteristics of Zone Models", *Fire Science & Technology*, Vol. 14, No. 1 & No. 2, pp 49-62, 1994.

7.   *Standard Guide for Evaluating the Predictive Capacity of Deterministic Fire Models*, ASTM E 1355-97, American Society for Testing and Materials, 1997.

8.   Bukowski, R.W., "Fire Hazard Assessment", *the NFPA Fire Protection Handbook*, 18th Edition, Section 11/7, NFPA, Quincy, MA, 1996.

9.   Peacock, R.D., et al, "Evaluation of Complex Fire Models", NISTIR 6030, NIST, Gaithersburg, MD, 1997.

10.   Veynante, D, Verisch, L., "Turbulent combustion modeling", *Progress in Energy and Combustion Science*, Vol. 28, pp. 193-266, Elsevier Science, 2002.

11.   Karlsson, B., Quintiere, J.G., *Enclosure Fire Dynamics*, CRC Press, 2001.

12.   Rehm, R.G., Baum, H.R., "The Equations of Motion for Thermally Driven, Buoyant Flows", *J. of Research of the NBS*, 83:297-308, 1978.

13.   Novozhilov, V., "Computational fluid dynamics modeling of compartment fires", *Progress in Energy and Combustion Science*, Vol. 27, pp. 611-666, Elsevier Science, 2001.

14.   Cox, G., "Compartment Fire Modeling", *Combustion Fundamentals of Fire*, Chapter 6, Academic Press, London, 1995.

15.   Freites, C.J., "Perspective: Select Benchmarks From Commercial CFD Codes*", Journal of Fluids Engineering*, Vol. 117, pp 208-218, 1995.

16.   Olenick, S. M., Carpenter, D. J., "An Updated International Survey of Computer Models for Fire and Smoke", *Journal of Fire Protection Engineering*, Vol. 13, May 2003.

This Page Intentionally Left Blank

APPENDIX **7** **Developing Performance-based Criteria**

1 Effects of Life Safety Criteria

1.1 Effects of Toxicity

With regard to hazard assessment, the major considerations of human health when exposed to hazards are:

i) The time when partially incapacitating effects are likely to occur which might delay escape.

ii) The time when incapacitating effects are likely to occur which might prevent escape, compared with the time required for escape.

iii) Whether exposure is likely to result in permanent injury or death.

Despite the great complexity in chemical composition of a smoke atmosphere, the basic toxic effects are caused either by a narcotic (asphyxiant) gas or by irritants.

Narcotic gases cause incapacitation mainly by effects on the central nervous system and, to some extent, the cardiovascular system. The two major narcotic gases in fires are (1) carbon monoxide (CO) and (2) hydrogen cyanide (HCN). In addition, low concentrations of oxygen and very high concentrations of carbon dioxide (CO_2) can also have narcotic effects. It is generally recognized that the vast majority of deaths associated with accidental enclosure fires are due to smoke inhalation.

Carbon monoxide combines with hemoglobin in the blood to form carboxyhemoglobin (COHb), which results in toxic level of narcotics by reducing the amount of oxygen supplied to the tissues of the body, particularly brain tissue. It has also been shown that the vast majority of these fire victims have COHb levels in their bloodstream sufficient to induce incapacitation or death. This has led many researchers to conclude that carbon monoxide (CO) is the dominating toxicant present in fire cases. It is also recognized that the elevated carbon dioxide (CO_2) levels (which result in increased respiration rates) and depressed oxygen (O_2) levels associated with the fire cases act together to increase the susceptibility of victims to CO asphyxiation.

Irritant fire products produce incapacitation during and after exposure in forms either of sensory irritation (consisting of eye and respiratory tract pain, lacrimation and breathing difficulties) or of acute pulmonary irritant response.

The degree of toxicity is determined by factors such as the concentration of toxic product in the target organ of the body, and the time period for which a toxic concentration is maintained. The relationships between concentrations inhaled, duration of exposure and toxicity should be properly considered based on the characteristics of fire scenarios (i.e., material compositions, ventilation, etc.).

1.2   Effects of Smoke

Smoke comprises the total effluents from a fire and consists of two major parts: the invisible vapor phase and the visible particulate phase. From a toxicological standpoint, all of the narcotic products occur in the vapor phase, while irritant products may occur in both phases. The particulate phase consists of solid and liquid particles covering a wide range of particle sizes, depending upon the nature and age of the smoke. These particles may contain condensed liquid or solid irritant products; or irritant products including gaseous ones may be dissolved in liquid particles (as in acid mists), or may be absorbed on to the surface of solid, carbonaceous particles.

Particle size is of great toxicological importance since it determines how "deeply" particles penetrate into the respiratory tract and the patterns of subsequent deposition. For example, particles with a mean aerodynamic diameter of less than 5 μm are capable of penetrating deep into the lung, while larger particles tend to deposit in the nasal passages and upper airways.

The other important physiological effects of the particle phase of smoke is visual obscuration, which in conjunction with irritant effects on the eyes, may impair the ability of victims to escape from fires. It is best represented in a hazard model in terms of a tenability limit concentration. Smoke obscuration is usually expressed in terms of smoke density (OD/m) or extinction coefficient, K, ($K - OD/m \times 2.3$).

1.3   Effects of Radiant Heat

Radiation is important in situations where occupants must pass close to the seat of fire in order to escape or in situations where occupants must pass under a hot effluent layer.

Pain occurs when the difference between the rate of supply of heat to the skin surface exceeds the rate at which heat is conducted away by an amount sufficient to raise the skin temperature to 44.8°C (111°F) at a depth of 0.1 mm (0.004 in.). The effects of heating the skin are essentially the same, regardless of the means of heat transfer.

The performance criterion with respect to thermal radiation is the condition when sufficient heat is applied to unprotected or naked skin to induce pain. Pain and damage to skin begin to occur when the temperature at the basal level (approximately 80 micron (0.02 in) beneath the surface of the skin) exceeds 44°C (111°F).

A threshold heat flux on skin is suggested to be approximately 2.5 kW/m^2. Below this level, exposure can be tolerated for several minutes and, above which, tolerance time rapidly decreases to a few seconds.

1.4   Egress Analysis

A quantitative approach to the egress movement of people must be balanced by a qualitative understanding of the context within which the movement takes place. Egress time can be predicted either by hand calculations or by available, reliable egress models. When defining the performance criteria, egress calculations shall be considered as providing only minimum evacuation times. Tenability issues are important both with respect to the time required for escape and the time available for escape.

1.5   Effects of Fire Extinguishing Agents on Occupants

The effects of the by-products of fire extinguishing agents shall be properly addressed if they are used in the alternative design. In their natural state (the state at rest without being actually discharged into a fire), some of these agents may not be toxic, in fact most are not toxic if actually discharged and there is no heat source. However, if inhaled, some agents may have toxicological effects known as cardiac sensitization. Cardiac sensitization occurs when a chemical causes an increased sensitivity of heart to adrenaline, leading to the sudden onset of irregular heartbeats and possibly heart attacks.

Any agent that is to be recognized by these Guidance Notes or proposed for inclusion in the alternative designs should be evaluated in the same manner, for instance, as the process used by the U.S. Environmental Protection Agent's (EPA) SNAP Program. The SNAP Program was originally outlined in *Federal Register*, 59 FR 13044. More details of SNAP program can also be found in the official EPA web site listed in the References. For example, for halocarbon clean agents, the toxicity information (LC_{50} or ALC, NOAEL and LOAEL) and the time for safe human exposure should be evaluated. The LC_{50} is the concentration lethal to 50 percent of a rat population during a 4-hour exposure. The ALC is the approximate lethal concentration. The NOAEL is the highest concentration at which no adverse physiological or toxicological effect has been observed. The LOAEL is the lowest concentration at which no adverse physiological or toxicological effect has been observed. For some fluorocarbon fire-extinguishing agents, the toxicological effects of hydrogen fluoride (HF) should be evaluated. For some inert gas agents, the physiological effects (i.e., no effect level, low effect level, etc.) should be evaluated.

The design team of the alternative design and arrangements should be aware of the characteristics of occupancy. It is important to distinguish between normally healthy individuals, for example, fire fighter crews, and those with compromised health. Exposure to higher concentration of HF would be expected to be tolerated more in healthy individuals, whereas at equal concentrations, escape-impairing effects can occur in those with compromised health.

2   Establishing Performance-based Criteria for Life Safety

The purpose of this Subsection is to provide an example of establishing the performance-based criteria for life safety. Assume that a design team is developing performance criteria to prevent the loss of life outside of the room or compartment of fire origin. The design objective for life safety is to maintain tenable conditions in paths of egress while occupants outside of the room or compartment of fire origin escape to a place of safety. The design team can set detailed performance criteria that ensure that occupants are not incapacitated by fire effects which include heat, temperature, toxicity exposure, etc.

2.1   Heat

The tenable condition is to prevent pain and damage to skin (i.e., skin burn) from heat radiation and hot gas exposure. See A7/1.3, "The Effects of Radiant Heat".

2.2   Visibility

Beside the toxicological significance of smoke, the other important psychological effect of the particulate phase of smoke is visual obscuration. Depending on whether occupants are familiar with the escape route, as well as the use of the space, different obscuration criteria can be established. For occupants familiar with the escape route, a criterion of $OD/m = 0.5$ (approximately 2.5-meter visibility) is used, and for occupants unfamiliar with the escape route, an $OD/m = 0.008$ (approximately 10-meter visibility) criterion is suggested.

2.3   Egress

NFPA 101 A.5.2.2 requires that a design team shall demonstrate that smoke and the toxic gas layer will not descend to a level lower than 1.8 m (6 ft) above the floor in any occupied room so that no occupant is exposed to the effects of fire. A criterion of 1.8 m is a conservative value to ensure that no occupant need be exposed to fire effects, regardless of where occupants are or where they move.

2.4   Toxicity

Carbon monoxide (CO) represents the most common narcotic fire product, which accounts for over half of all fire fatalities due to inhalation. The studies of the relationship between time to incapacitation and concentration in active monkeys show that for CO concentration of 1000 ppm, it takes about 26 minutes, and for CO concentration of 2000 ppm, the time reduces to about 15 minutes. When CO concentration increases to 8000 ppm, it takes less than four minutes for incapacitation. A conservative CO threshold of 1200 ppm may be chosen based on the revised IDLH concentration developed by the National Institute for Occupational Safety and Health (NIOSH), which ensures that occupants will be able to escape without incapacitation due to inhalation.

2.5   Performance-based Criteria

Based on the above analysis, some of the performance-based criteria or threshold values for heat, visibility, egress and toxicity can be summarized as following:

- Temperature $T_{skinburn} < 44°C$ (111°F)

- Heat flux $\dot{q}''_{skin} < 2.5$ kW/m^2

- Egress   Height of upper layer smoke > 1.8 m (6 ft)

- Visibility $OD/m < 0.5$, or about 2 m (6.5 ft) of visibility

- Toxicity   CO < 1200 ppm

With these performance criteria established, the design team can proceed with the evaluation of the alternative design(s).

3   Non-life Safety Criteria

Non-life safety criteria address issues relating to damage thresholds for property. Damage thresholds may relate to thermal energy exposure, resulting in ignition or unacceptable damage. Thresholds might also consider exposure to smoke aerosols and particulate or corrosive combustion products. In some cases, unacceptable damage might result from small exposure levels.

3.1   Thermal Effects

Thermal effects might include melting, charring, deformation, or ignition. Considerations include the source of energy (e.g., convection, conduction and radiation), the distance of the target from the source, the geometry of the source and the target, the material characteristics of the target (e.g., conductivity, density and heat capacity) and the ignition of the target. The surface area to mass ratio of the fuels involved is also a factor.

3.2   Fire Spreads

The spread of fire by progressive ignition should be considered. Factors affecting fire spread include the geometry and orientation of the burning surfaces (horizontal versus vertical) as well as the surface area to mass ratio of the fuels involved. Ventilation and airflow can increase or decrease fire spread. Fire spread can also have an effect on life safety. Rapid fire spread can impair crew and passenger egress.

3.3   Smoke Damage

Smoke damage includes smoke aerosols and particulate or corrosive combustion products. The damage thresholds will depend on the sensitivity of the target to damage. Some works of art, such as paintings, have low thresholds, whereas others, such as statuary, might tolerate more smoke. Many targets, such as electronics, are sensitive to corrosive products at low levels.

3.4   Fire Barrier Damage and Structural Integrity

The loss of fire barriers can result in damage from extension of heat and smoke. Opening protection operations and penetrations are factors. Minimal acceptable performance in terms of amount of potential for extension will depend on the sensitivity of the target to heat and smoke. Structural collapse is an issue in both life safety and property protection. The stability of a structure is important for crews and passengers during the time necessary for egress and for emergency responders during rescue and suppression activities.

3.5   Damage to Exposed Properties

Performance criteria might need to be developed to prevent or limit damage or fire spread to exposed properties. The mechanism of damage can be heat or smoke. Separate distance, material flammability characteristics and geometry are important considerations.

3.6   Damage to the Environment

Performance criteria, by limiting the effluent associated with fire suppression systems and fire-fighting operations, limiting the release of contaminants from combustion and extinguishing media, might need to be developed to protect the vessel environment.

4   References

1.   The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings, Society of Fire Protection Engineers and National Fire Protection Association, 1999.

2.   ISO/TR 13387-1 through 8, "Fire Safety Engineering", International Organization for Standardization (ISO), 1999.

3.   SOLAS, Amendments 2000, IMO, London, 2001.

4.   SOLAS, Consolidated Edition 2001, IMO, London, 2001.

5.   Guide to Establish Equivalency to Fire Safety Regulations for Small Passenger Vessels (46 CFR Subchapter), United States Coast Guard, 2001.

6.   Purser, D., "Toxicity Assessment of Combustion Products", the SFPE Handbook of Fire Protection Engineers, 2nd Edition, Section 3-7, NFPA, Quincy, MA, 1995.

7.   Engineering Guide for Predicting 1st and 2nd Degree Skin Burns from Thermal Radiation, Society of Fire Protection Engineers, 2000.

8.   Pauls, J., "Movement of People", the SFPE Handbook of Fire Protection Engineers, 2nd Edition, Section 3-7, NFPA, Quincy, MA, 1995.

9.   NFPA 101: Life Safety Code, 2000 Edition.

10   NFPA 301: Code for Safety to Life from Fire on Merchant Vessels, 2001 Edition.

11.   Ahlers, H., NIOSH documentation for Immediately Dangerous to Life or Health Concentrations (IDLHs), National Institute for Occupational Safety and Health, CDC, 1995.

12.   NFPA 2001: Standard on Clean Agent Fire Extinguishing Systems, 2000 Edition.

13.   U.S. Federal Register, Volume 59, Page 13044, EPA SNAP Program.

14.   U.S. Environmental Protection Agent (EPA), "Substitutes for Ozone-Depleting Substances", October 9, 2003, <http://www.epa.gov/ozone/snap/>.

This Page Intentionally Left Blank

APPENDIX 8 Alternative Design and Example Analysis – Arrangements for Containership Cargo Spaces

Introduction

SOLAS Chapter II-2 regulation 10.7.1.3 requires that cargo vessels of 2000 gross tonnage and upwards shall be protected by a fixed carbon dioxide or inert gas fire extinguishing system complying with the provisions of Fire Safety Systems Code (FSS Code). FSS Code Chapter 5, section 2.2 stipulates that the quantity of carbon dioxide available shall be sufficient to give a minimum volume of free gas equal to 30% of the gross volume of the largest space to be protected.

During the discharge of carbon dioxide in non-weathertight cargoes, the loss of a certain amount of carbon dioxide is inevitable through the gaps and the labyrinths of hatch covers. Although not mandatory, FP 47/WP 6.2 suggests about 10% increase in CO_2 by taking into account the leakage of CO_2 fire extinguishing media through clear gaps between hatchway covers.

Due to the complexity of fire scenarios, loading conditions of cargoes and toxicity of carbon dioxide, very few data sources are available to correctly predict the leakage. In this study, the nature of the distribution of carbon dioxide is investigated inside cargo holds during its discharge. The object of this project is to provide a clear picture of carbon dioxide discharge and propose a performance-based alternative for fire engineering design. In this project, CFD models are used to simulate the transient distributions of carbon dioxide during the discharge.

Goals of Design

An important consideration in the design of carbon dioxide total flooding systems in cargo holds and machinery spaces is the successful completion of a full discharge test to verify, as required by SOLAS or per NFPA 12, that carbon dioxide is indeed discharged through the system piping, and that the design concentration is achieved and maintained for the required holding time.

For non-tight cargo holds, it is also important to estimate the leakage of carbon dioxide and the duration of discharge to achieve the requirements of CO_2 percent concentrations stipulated in SOLAS. The narrow gaps or passages among containers make it difficult for CO_2 gas to penetrate through, resulting in CO_2 escaping from the openings on the top of the cargo hold.

After several meetings with ABS fire protection specialists, it is decided that the primary fire safety goals for this study should be limited to the following:

- Estimate the amount of CO_2 required to control fires in a cargo space;

- Provide fire extinguishing system to minimize the loss of carbon dioxide through the openings of the non-tight hatch covers;

- Maximize the distribution of carbon dioxide throughout the narrow passages among containers.

Objectives of Design

The design objectives are developed after further refining the accepted goals and are as follows:

- Calculate the minimum amount of CO_2 for effective fire suppression by taking leakage into consideration.

- Propose an alternative design of CO_2 discharge by simulating fire scenarios inside a non-tight cargo hold

Rule Requirements of Carbon Dioxide Systems

The amount of carbon dioxide required in SOLAS regulations is specified in terms of a volumetric concentration. The rules associated with carbon dioxide systems are identified below:

- For cargo spaces, the quantity of carbon carbonate available shall, unless otherwise provided, be sufficient to give a minimum volume of free gas equal to 30% of the gross volume of the largest cargo space to be protected in the vessel (FSS Code 2.2.1.1).

- The volume of free carbon dioxide shall be calculated at 0.56 m^3/kg (FSS Code 2.2.1.4).

- The piping for the distribution of fire-extinguishing medium shall be arranged and discharge nozzles so positioned that a uniform distribution of the medium is sought (FSS Code 2.1.2.1).

- IMO FP 47/WP.6.2 proposes the increase of carbon dioxide by taking into consideration the leakage of carbon dioxide fire extinguishing media through clear gaps between hatchway covers. The amount of increase should be in accordance with of the following formulae, as appropriate:

$$CO_2{}^{INC}{}_{30\%} = 60 \cdot A_T \sqrt{B/2}$$

$$CO_2{}^{INC}{}_{45\%} = 4 \cdot A_T \sqrt{B/2}$$

where

$CO_2{}^{INC}{}_{30\%}$ = increase of carbon dioxide for cargo spaces not intended for carriage of motor vehicles with fuel in their tanks for their own propulsion, in kg

$CO_2{}^{INC}{}_{45\%}$ = increase of carbon dioxide fro cargo spaces intended for carriage of motor vehicles with fuel in their tanks for their own propulsion, in kg

A_T = total maximum area of clear gaps, in m^2

B = breadth of cargo space protected by the carbon dioxide fire extinguishing systems, in m

(Note that FP 47/WP. 6.2 is not mandatory for IMO members.)

No discharge time is specifically required for cargo spaces in the FSS Code, presuming that carbon dioxide can be discharged in a series of stages and more settling time is required for the extinguishments of fires inside cargo spaces.

For reference, land-based NFPA 12 (2000 Edition), "Standard on Carbon Dioxide Extinguishing Systems", requires that for surface fires, the design concentration shall be achieved within one minute (2-5.2.1), and for deep-seated fires within seven minutes (2-5.2.3). For marine systems, NFPA 12 stipulates that cargo spaces other than vehicle spaces shall be supplied with carbon dioxide based on 1 lb/30 ft^3 based on the gross volume (6-2.6).

NFPA 12 also suggests that multiple discharges can be applied to control fires. The initial quantity of carbon dioxide discharged shall be based on the net volume of the space as determined by the amount of cargo in the cargo space. Additional carbon dioxide shall be released as needed to maintain control of the fire [6-2.6 (b)].

The major difference concerning required CO_2 quantities between the marine (IMO, CFR) and the land-based (NFPA 12) is that the land-based requirements are fuel-specific and dependent on whether the design basis fire is a surface fire or deep-seated fire. NFPA 12 requires the determination of proper concentration of CO_2 required for the type of flammable materials involved in the hazard. Deep-seated fires and certain flammable liquids and vapors require substantially higher CO_2 concentrations for extinguishments. For some fires involving either fuel oil or lubricating oil, the concentration requirements for these fires are identical in the land-based and marine standards. Some fires involving electrical equipment and cables have the potential of becoming deep-seated. Therefore, NFPA requires higher CO_2 concentrations for these fires than called for in the CFR and IMO regulations. Table 2-3.2.1, NFPA 12, lists the minimum design CO_2 concentration percent for various materials, ranging from 34% to 72%, depending on materials. In no case shall a concentration be less than 34%, compared to 30% required by IMO.

Performance Criteria

The performance criteria were developed through a further refinement of the design objectives. They represent numerical values to which the trial design will be compared. The performance criteria used for this study are as follows.

- The volumetric concentration of carbon dioxide shall be at least 30% of the gross volume of the cargo space in this study.

- The above concentration shall be achieved within seven (7) minutes after the discharge of carbon dioxide.

Trial Alternative Design and Arrangements

The top of the cargo hold is covered by three partially weathertight hatch covers which are separated by a gap up to 50 mm. Such gaps provide the openings of ventilation for the cargo hold. Labyrinths, gutters and other equivalent means fitted close to the edges of each hatch cover also can cause leakages of carbon dioxide. During the discharge, the cargo hold is partially pressurized which causes the mixture of air and carbon dioxide to leak out through hatch coaming labyrinth bars. The passages of openings are equivalent to 50 mm in width in this study. Such openings are parts of the vessel's structure and cannot be closed or sealed during the CO_2 discharge.

Typical designs of CO_2 extinguishing system place four (4) discharge nozzles either underneath the hatch covers or at the middle of the transverse bulkheads. The latter design seeks to improve the distribution of carbon dioxide throughout the cargo hold.

The alternative design aims to reduce the amount of carbon dioxide fire extinguishing media required by FSS Code 2.2.1.1. Such reduction is based on the numerical calculations of CO_2 concentrations of carbon dioxide for sufficiently controlling fires required by NFPA 12.

Identification of Fire Hazards

A Hazard Identification (HAZID) technique is applied for the risk assessment for fires in cargo holds. A HAZID should look at three factors: sources including likelihood, consequences and mitigation.

1.   Sources of hazards:

The potential hazards inside a container are various in types, ranging from non-combustible materials to highly flammable, dangerous goods. The sources of fire can come from the following types of scenarios:

- *Improper loading*: Improper loading allows movement and friction of goods inside a container, and could cause an ignition of goods such as wetted matches, leather gloves, rubber gloves, plastic toys, outdoor nylon tenting materials, sewing notions, etc.

- *Spontaneous combustion.* Spontaneous combustion is thought to have contributed to a large claims-related fire in 46 percent of cases. Cargoes suffering from spontaneous combustion and smoking included fishmeal, tobacco, cotton, wood pulp and coal.

- *Self-ignition of chemicals*: Most of the fires experienced in recent years have been associated with the chemical calcium hypochlorite in its hydrated form, used amongst others for the sterilization of swimming pools. Containers loaded with this chemical, but not clearly marked, were occasionally loaded in locations exposed to elevated temperatures, such as in a hold adjacent to the engine room. As the self-igniting temperature of this cargo, when stowed in larger quantities may be as low as in the thirties °C, fires did start in containers with mostly devastating results. The information on the contents of the containers was frequently received only when the vessel was already out at sea. The crew was either not aware of any such risk or could not do anything about it.

2.   Consequence

The fires inside cargo holds can be catastrophic both to the vessel and the environment. Heat-damaged containers, along with distorted container cells and loose cargo, cannot be removed by normal offloading systems. The container cargo in the fire area essentially becomes "bulk" – in effect a pile of junk trapped by remaining shells and distorted cell structures. If the fire cannot be extinguishing promptly, all containers in the cargo hold can be damaged; extensive heat can also cause the vessel hull structure to become deformed.

3.   Mitigation

For fire suppression systems that are conventionally located at the top of cargoes, gaseous forms of fire extinguishing agents should penetrate through the narrow gaps of cell guiding racks to reach the fire sites. Therefore, the most demanding conditions can be that of fires originating near the bottom of a cargo hold where adequate length of time and sufficient amount of fire extinguishing agents are required.

Specification of Design Fire Scenarios

Characteristics of fires

The purpose of this study is to demonstrate the equivalency of alternative design and arrangements for carbon dioxide systems. Due to the lack of statistical data of fires in containers, only the most demanding requirement for such systems should be selected to bound all potential fire scenarios. A container near the bottom of the cargo hold is chosen for the analysis of the effectiveness of CO_2 systems.

The heat release rates ranges from 1 MW for goods such as wood, clothes, etc., to 40 MW for explosive chemicals such as calcium hypochlorite, polystyrene, etc. It is often difficult to predict the fuel quantities for an individual container. In order to accommodate for this uncertainty, this study has chosen a standard *t*-squared fast fire to represent fire growth in all possible scenarios.

While it may be considered adequate for the t^2 fire to represent the growth rate of fires up to flashover, it is not realistic to assume that the growth can remain parabolic for long periods. This is particularly relevant in situations where flashover either does not occur or requires a high rate of heat release rate. For the cases of fires inside a cargo space with small ventilation opening, the actual heat release rate is nearly proportional to the size of the ventilation size.

For this study, the heat release rates are estimated up to the order of 8.2 MW within seven minutes. The fire will be confined to one container; heat transfer from fire source to surrounding will be calculated by solving the differential equations of continuity, momentum and energy.

Geometry

Containers operating in the marine mode are often stowed in vertical stacks within cells in a hold. When stowed in this manner, containers will be restrained at the end frames against longitudinal and transverse movement by the cell structure. The reactions of entire stack of containers are taken through the four bottom corner fittings of the lowest container.

A typical containership cargo hold measuring 12.561 m length by 38.164 m width by 23.740 m height is chosen, with a total of 15 stacks of containers in the hold. Appendix 8, Figure 1 demonstrates the cross sectional view of the cargo hold. The lower left and right corner cutouts are the spaces for piping and cables which are not considered in the domain of numerical simulation.

By taking into the consideration the feet height at each corner, the actual size of a container is modified as 12.180 by 2.426 by 2.878 in meter. Due to the complexity of the corner fittings and cell structures, the net volume of such structures are neglected in this study. There are three types of gaps by locations with respect to the longitudinal axis of the vessel: vertical, horizontal, and longitudinal, as shown in Appendix 8, Figure 2.

In this study, all containers are assumed to be made of steel, except the container with fire. Since large volume of air is expected inside a packed container, the interior space of a container is assumed to be void space with air.

FIGURE 1
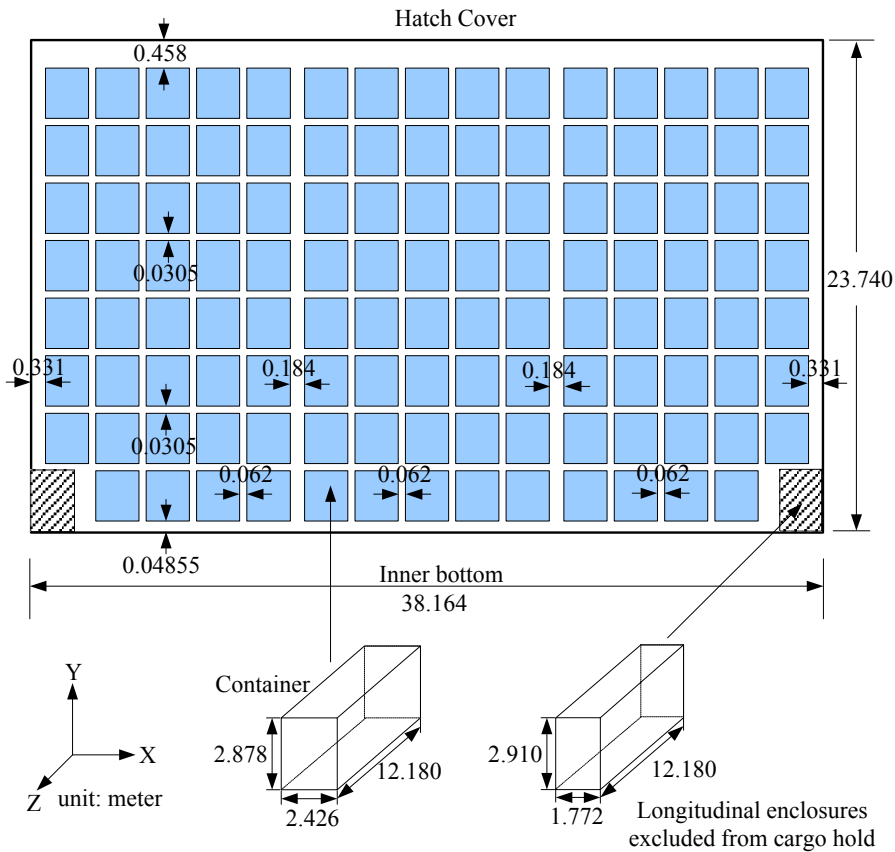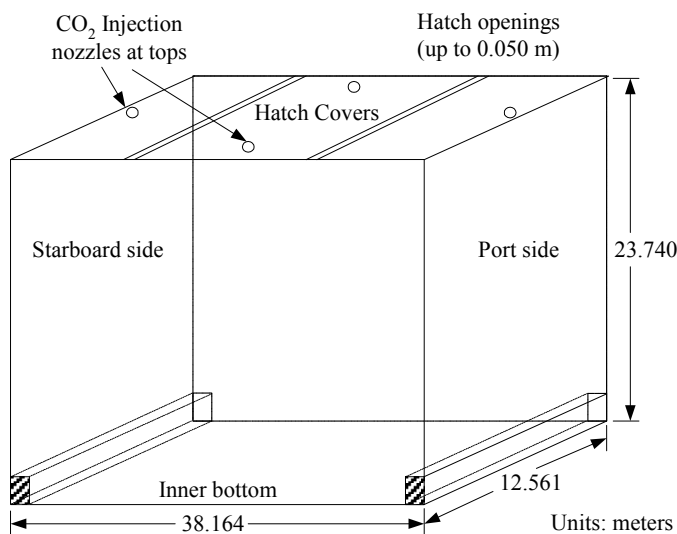## Cargo Hold Fully Loaded with Containers
(not to actual scale)

FIGURE 2
Hatch Cover Opening and CO$_2$ Nozzles at Tops
(not to actual scale)

Quantity of Carbon Dioxide Extinguishing Media

a.   SOLAS Requirement

Dimension of Cargo hold, in meters:	12.561 by 38.164 by 23.740
Total gloss volume of cargo hold, in m^3: (excluding longitudinal enclosures in Appendix 8, Figure 1)	11,253
Carbon dioxide by volume, in m^3:	3,376
Carbon dioxide by weight, in kg:	6,028

If CO_2 is discharged through a 45-kg CO_2 cylinder, then 134 cylinders shall be present on board in accordance with SOLAS regulations.

b.   IMO FP 47/WP.6.2

Area of clear gaps, A_T, in m^2:	2.271
Breadth of cargo space, B, in m:	38.164
$CO_2{}^{INC}{}_{30\%}$ by weight, in kg:	595
$CO_2{}^{INC}{}_{45\%}$ by weight, in kg:	40

Discharge Simulation

Presumably, when liquid carbon dioxide flows from storage tank through pipelines to the discharge nozzles, the pressure drop in the pipeline significantly reduces the temperature inside of the pipes, and therefore, part of the liquid carbon dioxide becomes a solid form and is discharged as a solid. As a result, carbon dioxide is discharged into the cargo space in both gaseous and solid forms. Some of the solid phase CO_2 vaporizes as it settles, and the rest forms an evaporating layer on the surfaces of the containers and the cargo hold. As the solid phase of carbon dioxide evaporates, its gaseous volume expands dramatically. The solid volume of carbon dioxide is negligible, but the gaseous volume can be estimated by free carbon dioxide density as 0.56 m^3/kg.

Several theoretical attempts have been made to calculate the dependent pressure, temperature and gas concentrations developed during the discharge and post-discharge of carbon dioxide into an enclosure. In this project, the homogeneous gaseous discharge of carbon dioxide is assumed.

Discharge Rates

Carbon dioxide is injected into cargo hold in both gaseous and solid forms, with the solid fraction determined by treating the discharge processes as an isentropic expansion from storage temperature and pressure to atmospheric pressure. The actual discharge rate varies by storage pressure, design nozzle sizes and pressure loss in the piping system.

SOLAS Chapter II-2 does not provide any discharge rate or nozzle size specifications. The FSS Code (2.2.1.1) only requires that the piping for distribution shall be arranged and discharge nozzles so positioned that a uniform distribution of the medium is obtained.

According to NFPA 12 (2000 edition), the design concentration shall be achieved within one (1) minute from the start of discharge for surface fires, and within seven (7) minutes for deep-seated fires. However, the discharge rate shall be no less than that required to develop a concentration of 30% percent in two minutes. Since the gaseous form of carbon dioxide is assumed during discharge in this study, for deep-seated fires, the minimum discharge rate is calculated as 482 m^3/min for seven (7) minutes. Note that an average rate of discharge is about 204 m^3/min, according to a series of tests conducted by FM Research Corporation in 1990.

In this study, the discharge rate for each of four (4) nozzles at the end of the carbon dioxide piping system is set at 121 m^3/min. The effective cross-sectional area of each discharge nozzle is estimated to be 1 m^2.

Computational Tool

In this case study, the concentrations and placement of carbon dioxide as a function of time are predicted by a deterministic method in a cargo hold. The passages among the containers provide a unique challenge to field models because they are very narrow compared to the size of a container and require non-structure meshing in model generation.

A commercially available computational fluid dynamics (CFD) program, FLUENT/AirPak, is used in this study to predict the distribution of carbon dioxide inside the cargo spaces. Widely used for HVAC applications, AirPak is capable of multi-species calculations with non-structure meshing. It is also capable of quickly and accurately simulating temperature distribution and air, smoke and suppressant flow patterns. Many reviews and cases of applications have been published to justify the assumptions and approximations over a variety of applications.

Input Parameters

AirPak requires the descriptions of the cargo space, discharge rates of carbon dioxide, ambient and initial temperatures and heat release rates of firing container. The description of the cargo space includes the geometry of cargo hold, the locations of containers and the dimensions of openings and vents (used here in lieu of discharge nozzles). The input data of heat release rates include timeline rates of heat release. The walls of the cargo hold and containers are prescribed to be adiabatic, and the only heat loss is through convective heat transfer in the openings.

Quantitative Results

The transient variables of flow, temperature and species concentrations of CO_2 injection are solved by AirPak to demonstrate the distribution of CO_2 in the narrow passages among containers. The transient solutions of continuity, velocity, temperature and fractions of air and CO_2 are obtained simultaneously by solving the equations of continuity, momentum energy and transport. Discrete cells up to 1.5 millions of hexahedral meshes were adopted for simulations. The mixing and transport of species are modeled by solving conservation equations describing convection and diffusion for each component species. For a turbulent mixing, the diffusion, turbulent viscosity and Schmidt numbers are incorporated to the diffusion terms. In this project, the transport equations were solved for the components of carbon dioxide and air. Due to the inherently non-linear nature of this problem, the solution procedures are highly iterative. The details of the formulation of cell elements and differential equations used in the modeling are explained in many references.

The loading conditions with fully loaded, half loaded and empty cargoes, respectively, are used in this study. Carbon dioxide is injected either from the top of the hatch covers or from the sides of the vertical bulkheads.

Average Volumetric Concentrations of Carbon Dioxide

The effectiveness of CO_2 discharge is measured by the transient volumetric concentrations of carbon dioxide that are averaged over the open spaces inside the cargo hold. The higher the value, the more effective the discharge system. The discharge nozzles are positioned either at the top of the cargo hold or underneath the hatch covers, or at nearly half depth of the transverse bulkheads. The results of the averaged CO_2 percent concentrations are shown in Appendix 8, Figure 3 for a fully loaded cargo.

FIGURE 3
CO_2 Percent Concentrations in a Fully Loaded Cargo
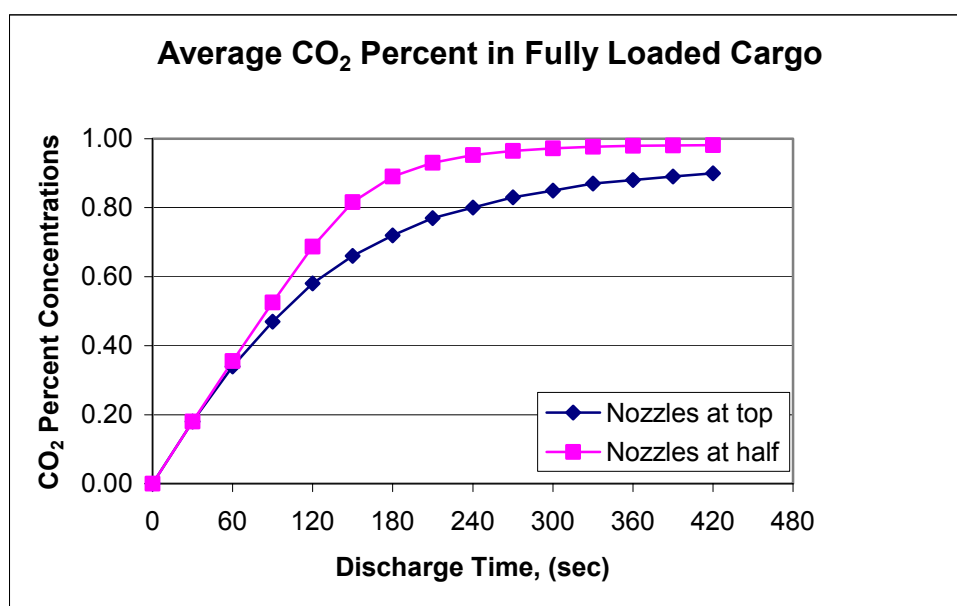
As shown in Appendix 8, Figure 3, the volumetric concentrations of carbon dioxide reach 30% in about one minute for both discharge modes, and the performance criteria are achieved. Appendix 8, Figure 3 also shows that the discharge is more effective if the nozzles are positioned at the half depth of the bulkheads, and CO_2 is more easily dispersed into the narrow spaces between containers. Within three minutes after initial discharge, the CO_2 percent reaches 69%, which is close to the highest minimum requirement in Table 2-3.2.1, NFPA 12.

For various loading conditions, only the concentrations in the effective spaces are comparable and meaningful. In this study, the effective spaces are defined by the spaces separating containers. For fully loaded cargo, the effective spaces include whole open spaces inside the cargo. Similarly, for half loaded cargo, the effective spaces only include the spaces of the lower half of the cargo where containers sit. Appendix 8, Figure 4 shows the CO_2 percent in effective spaces for the cases with the nozzles at the half depth of the bulkheads. In a partially loaded cargo hold, air is pushed out by CO_2 injection from the bottom up, resulting in a high CO_2 percent in the effective spaces.

FIGURE 4
CO$_2$ Percent Concentrations in Effective Spaces
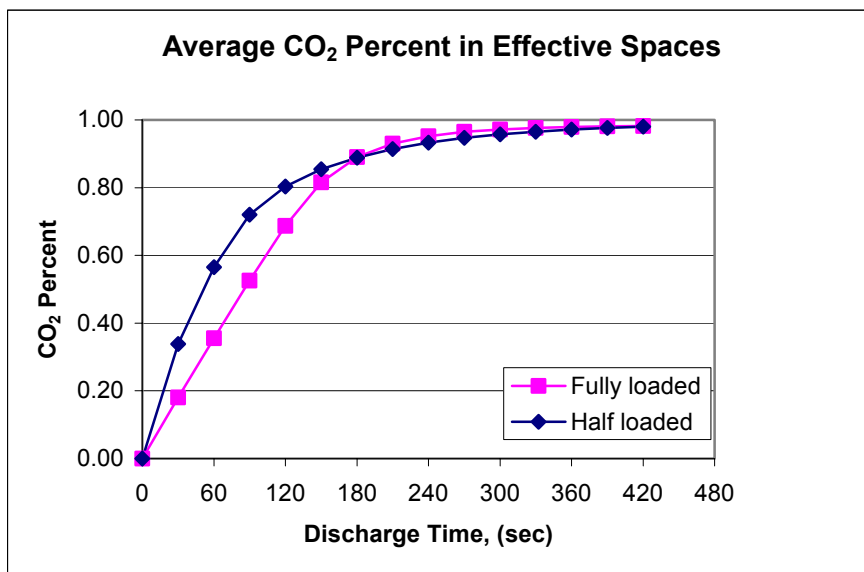
Instant CO$_2$ percent on the surfaces adjacent to the transverse bulkhead, inner skin bulkhead and hatch covers at 120 seconds after discharge is shown in Appendix 8, Figure 5. The blue squares in the figure represent discharge nozzles. Appendix 8, Figure 6 shows the cut-through profiles of CO$_2$ percent in aft view. Detailed flow at the corners of containers is shown in Appendix 8, Figure 7 with the vectors originating from corresponding meshing points.

FIGURE 5
CO$_2$ Percent at 120 Seconds in Isometric View
in Performance-based Design (test # Fullbb)
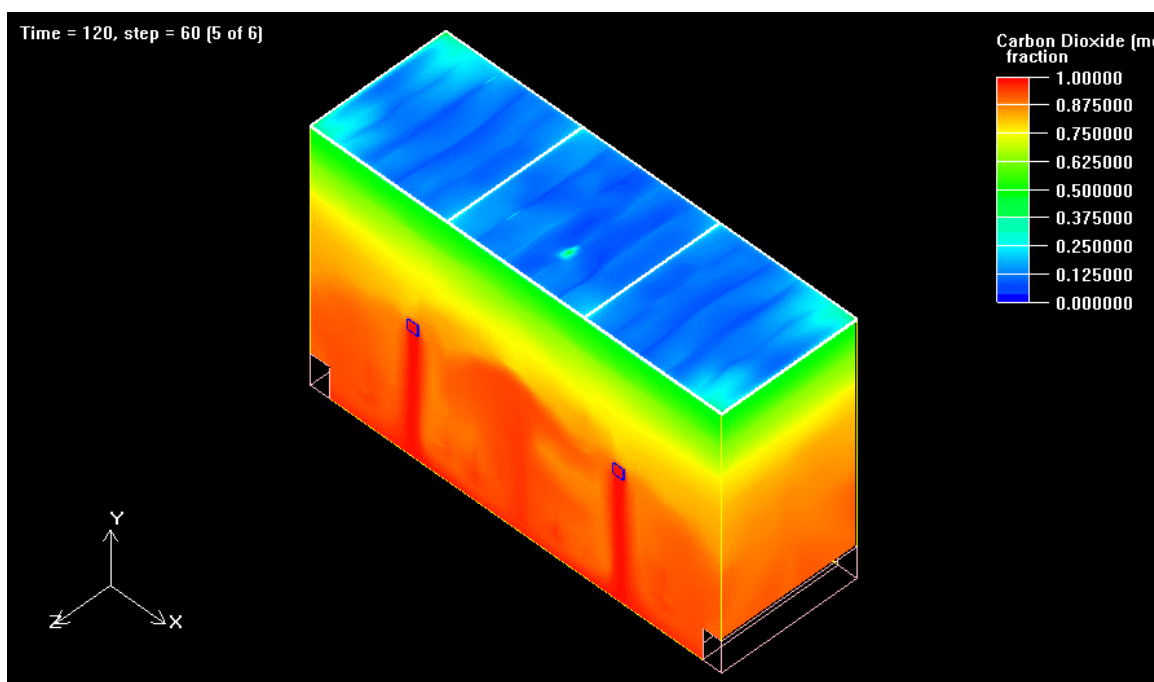
FIGURE 6
CO$_2$ Percent at 120 Seconds in Aft View
in Performance-based Design (test # Fullbb)

FIGURE 7
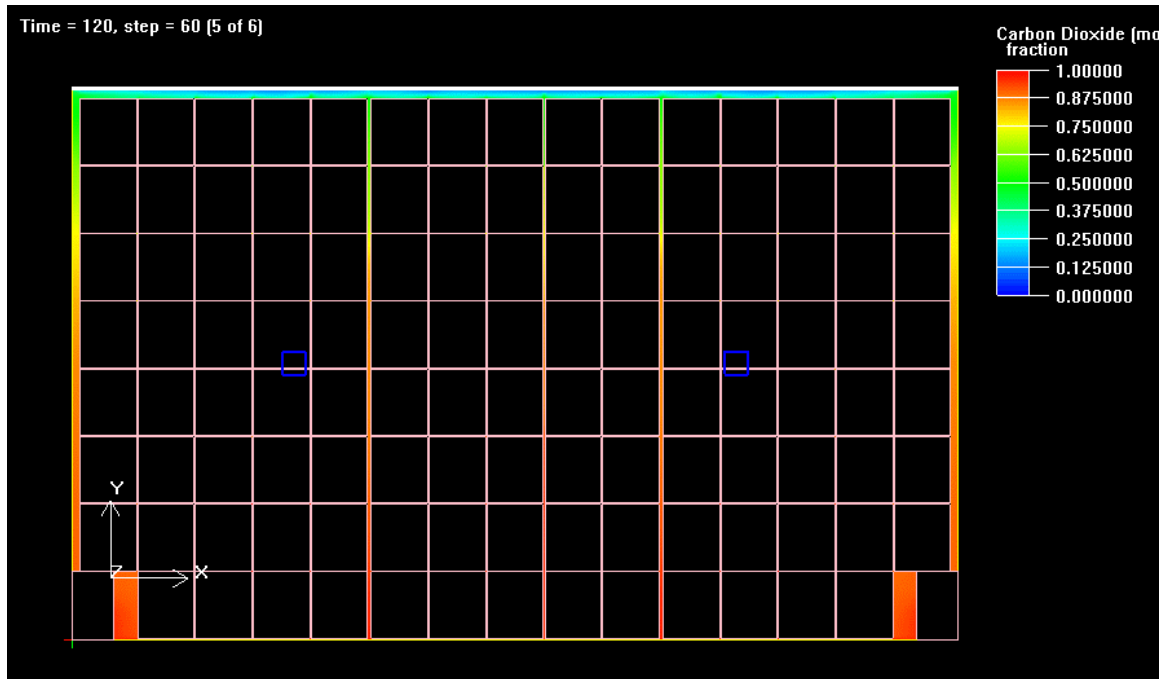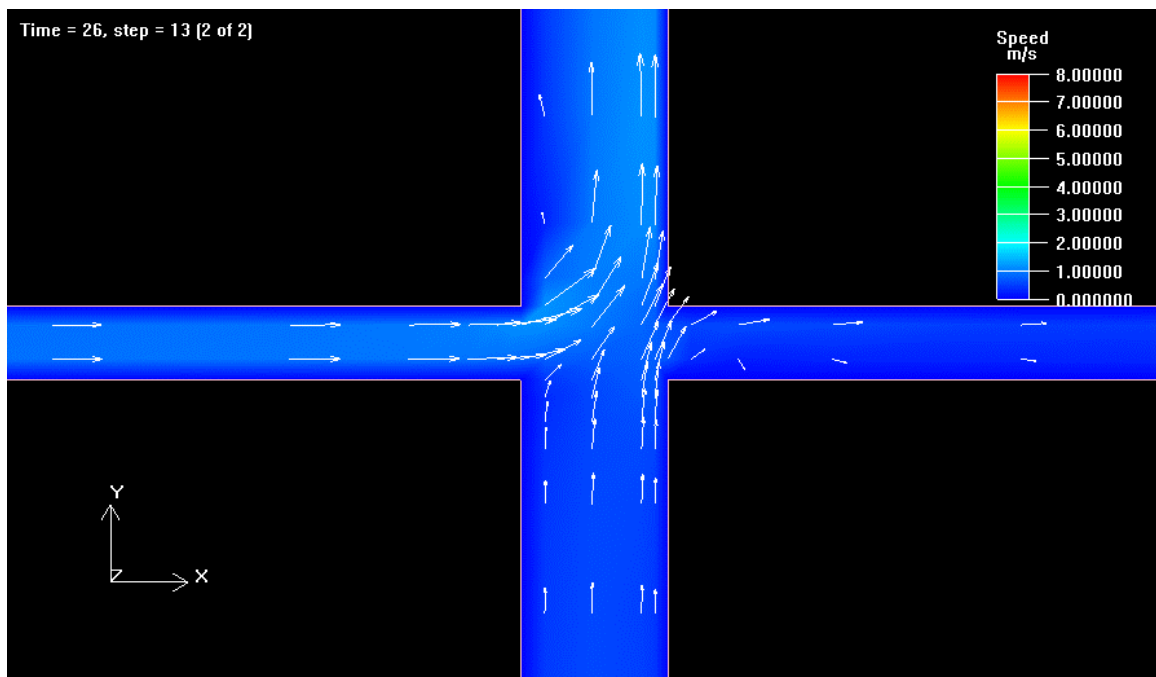**Detail Flow at the Corners of Containers**

Evaluation with Fires Inside the Cargo Hold

The distributions of carbon dioxide and temperature will be affected by the heat and smoke generated by fires. The temperature around the corners of containers is shown in Appendix 8, Figure 8. The white arrows indicate the velocity vectors, the pink solid blocks are non-permeable, conductive containers, and the block in the lower right corner is the container with the design fast fire at 420 seconds. Heat transfer from fire heats up the air around containers, which forms a hot plume and ascends through the gaps among the containers to the top of the cargo hold. Meanwhile, cool air with CO_2 is entrained to fire region, creating a plume of a mixture of air and CO_2 gas, shown as a green vertical plume on the right side of Appendix 8, Figure 9. The color bar at upper right corner indicates the volumetric molar fraction (same as volumetric concentration) of CO_2, from 0.0 in blue to 1.0 in red. Only half of the cargo hold is shown in Appendix 8, Figure 9. The attraction of CO_2 to the fire region helps control fire spread and eventually extinguishes the fire. The influence of fire on the distribution of CO_2 is still under study.

Also shown in Appendix 8, Figure 8, the temperature inside the container could reach up to 1500°C if the fire is not controlled. Such high temperature and intense heat will weaken the properties of steel and could cause the steel structure of the container to collapse.

FIGURE 8
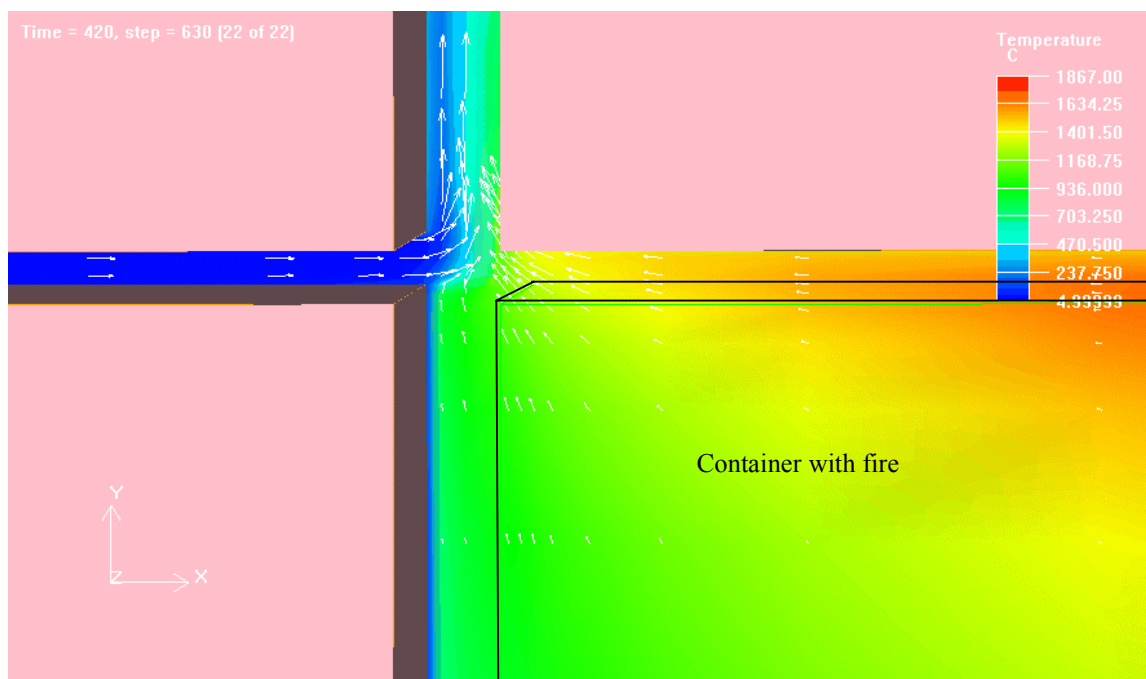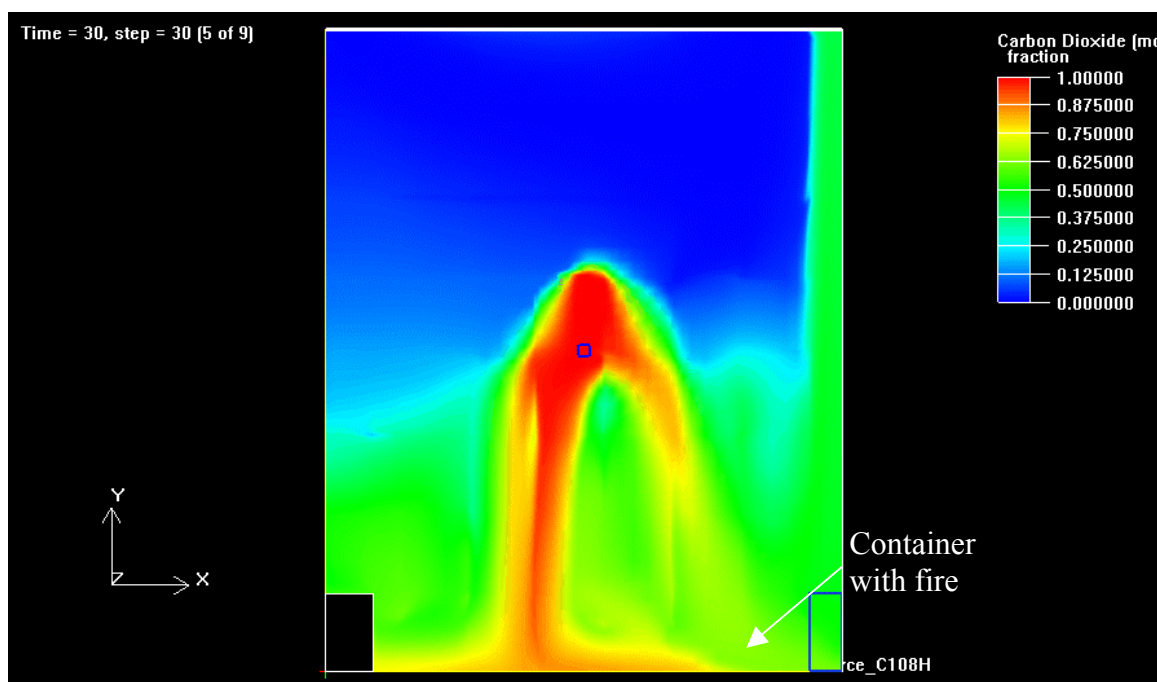## Temperature at Corners of Container Fire

FIGURE 9
CO_2 Concentration in a Design Fire Scenario

Leakage of CO_2 through Openings during Discharge

Appendix 8, Figure 3 also shows that the percentage of CO_2 concentration is far exceeding the
required 30% of open volume in fully loaded cargoes two minutes after discharge. While CO_2 is
dispersed and quickly fills up the gaps, a great amount of CO_2 leaks out of the cargo hold through the
openings at the hatch covers. The loss of CO_2 due to leakage is shown in Appendix 8, Figure 10, and
the rate of total leakage to total discharge is shown in Appendix 8, Figure 11.

From Appendix 8, Figures 10 and 11, it can be seen that a significant amount of CO_2 is lost from
openings of hatch covers. If all of the 138 cylinders of CO_2 are fully discharged into the cargo hold
within seven minutes, over 60% (or 3650 kg) of the CO_2 is actually lost due to the leakage from the
openings of hatch covers, as shown in Appendix 8, Figure 11. This amount of leakage is six times
more than the amount suggested by IMO FP 47/WP 6.2.
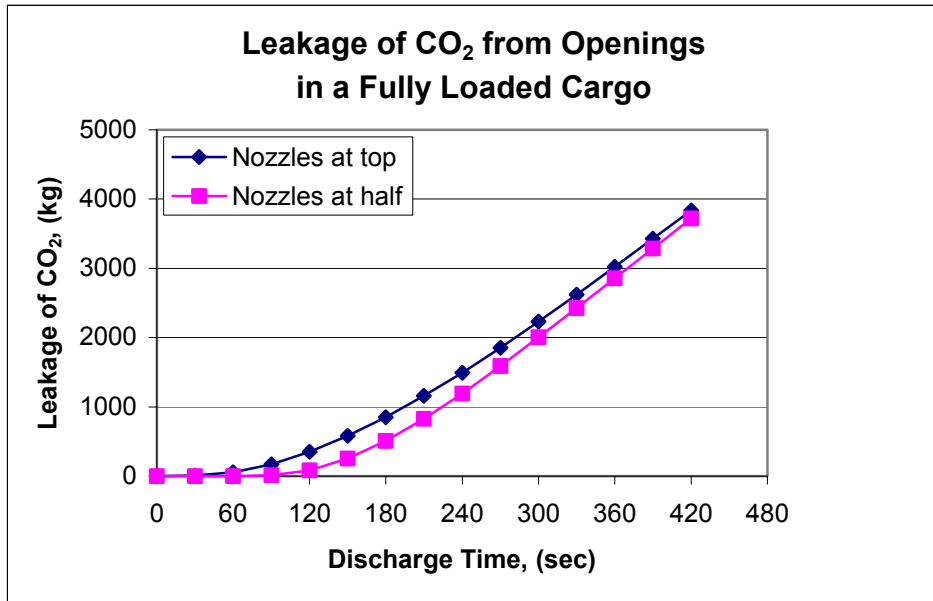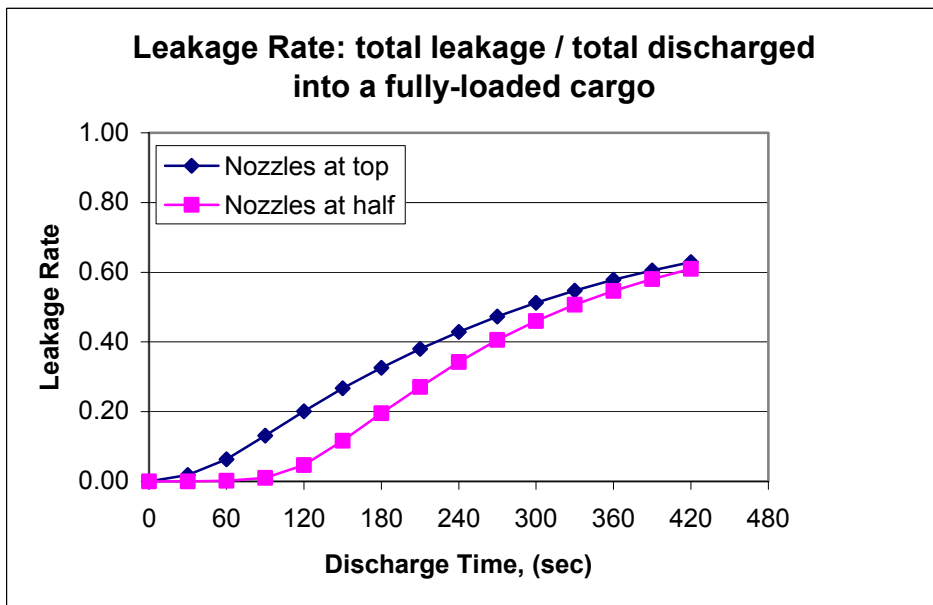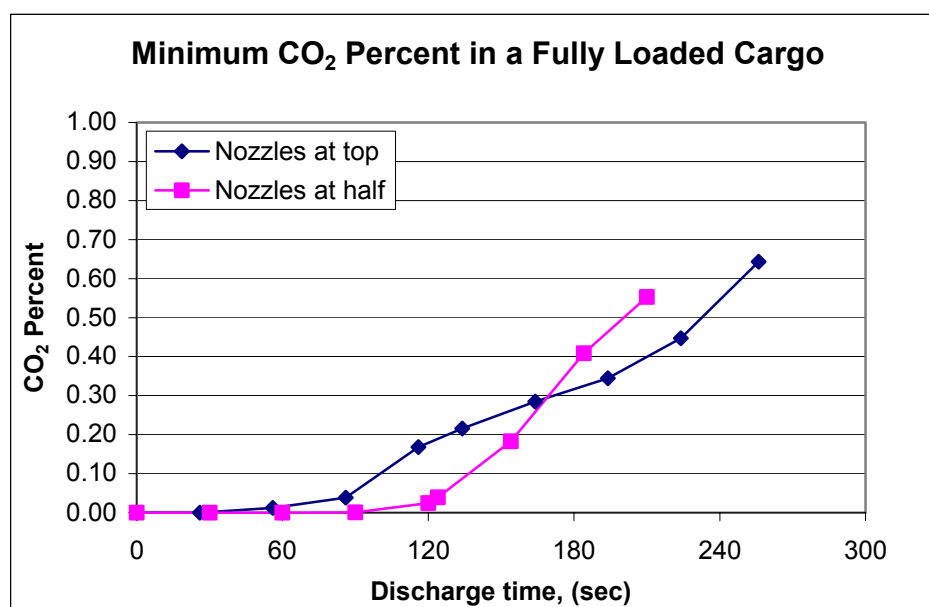
FIGURE 10
Loss of CO_2

Leakage of CO_2 from Openings in a Fully Loaded Cargo

FIGURE 11
Loss Rates of CO_2

Leakage Rate: total leakage / total discharged into a fully-loaded cargo

Minimum Amount of Carbon Dioxide in Multiple Discharging Systems

The results of the CO_2 percent and loss calculations in Appendix 8, Figures 3, 4, 10 and 11 clearly demonstrate that the average CO_2 concentration of 30% can be achieved within two minutes of initial discharge (the assumption of non-penetration container block is applied in this calculation). However, what really matters to effectively control or extinguish fire is to assure that 30% of CO_2 percent is achieved in the every part of open spaces inside of the cargo hold. Therefore, it is essential to calculate the time at which 30% is achieved, and subsequently, the corresponding amount of carbon dioxide. Appendix 8, Figure 12 provides the minimum CO_2 percent concentrations in a fully loaded cargo.

FIGURE 12
Minimum CO$_2$ Percent Concentrations

Appendix 8, Figure 12 shows that the discharge time to achieve minimum concentration of 30% in every open space inside a cargo hold is about three minutes. Note that the average CO_2 concentration is above 70% at three minutes, as shown in Appendix 8, Figures 3 and 4. Therefore, three minutes of discharge can provide the required concentrations stipulated in SOLAS regulations. Accordingly, the needed amount of carbon dioxide is decided by:

$$3 \text{ min} \cdot 482 \text{ m}^3/\text{min} = 1446 \text{ m}^3$$

or 2582 kg of CO_2, which is equivalent to total of 58 cylinders of 45 kg CO_2.

Prescriptive requirements by SOLAS require that 6026 kg or 134 cylinders of CO_2 shall be provided to control and extinguish fires in the cargo hold discussed in this study, with 595 kg (or 14 cylinders) more suggested by IMO FP 47/WP 6.2. The performance-based design, supported by numerical calculations and modeling, clearly shows that without the compromise of fire safety level, not only can the required 134 cylinders be cut down to 58 cylinders, but the increase in CO_2 suggested by IMO FP 47/WP 6.2 is unnecessary.

If the dispersion of CO_2 into non-sealed containers and the continuous leakage of CO_2 through clear gaps between hatch covers after initial discharge are taken into consideration, more cylinders may be needed in addition to 58 to account for the loss and reduction in CO_2 concentrations. The actual number of cylinders should be subject to engineers' judgment.

Sensitivity, Uncertainty and Limitations of Numerical Modeling

The results of sensitivity analysis identify the input parameters that have the greatest effect on the output variables. Among input parameters of model geometry, the small breath of the gaps (from 0.05 to 0.03 m) between containers is very sensitive compared to most other dimensions such as the sizes of containers. The small open spaces inside a cargo hold determine the transport characteristics of flow that dominates the dissipation of heat and CO_2.

The uncertainty of numerical simulations can be evaluated if the full-scale test data are available. Empirical data or general observations from industrial practices may also be used if the test data is not available. While multiple stages of CO_2 discharges are commonly adopted to contain or control a fire inside a cargo hold, no full-scale test data for CO_2 discharge in a cargo hold has been available for comparison. Therefore, the analysis of uncertainty is very limited. The major limitations of numerical simulations came from the following three areas:

- Modeling of cargo hold and containers

- Selection of design fire scenarios

- Algorithms of numerical calculations and discretion

Once the dimensions of the cargo hold and containers are decided, the quality of meshing is critical to the accuracy of numerical results. Even though the nodes in this study range up to 1.2 million for the fully loaded cargo hold, it is still desirable to make finer meshes to account for the thermal-driven flows in narrow gaps among containers.

The selection of design fire scenarios is crucial to accurately predicting the fire and, subsequently, the distribution of carbon dioxide. The results of calculation show that heat transfer from fire heats up air around the fire source, pushing hot air upward to the hatch covers. The uplifting hot air creates negative pressure zones around the fire source while cooler air with injected carbon dioxide is sucked to the fire source. Therefore, the fire actually enhances the movement of air inside the cargo hold, causing quick dissipation of CO_2 to the fire sources.

The inherent algorithms of numerical schemes also determine the accuracy of numerical calculations. Appropriate turbulent model, radiation modeling, species transport, etc., all contribute to the final solutions. The validation of the software is available elsewhere.

Conclusions

The main purpose of this study is to provide performance design for carbon dioxide extinguishing systems in a cargo hold. A CFD model is applied to evaluate the transient distribution of gaseous carbon dioxide inside a cargo hold. Numerical results of multiple loading scenarios with two discharge modes clearly demonstrate that with performance-based design, the 30% of CO_2 concentration can be achieved within three minutes of discharge. Thus, the actual amount of CO_2 needed to get this 30% is significantly less that the amount prescribed by current SOLAS regulations. A reduction in CO_2 cylinders or storage tanks can be implied for the performance-based design. Therefore, the increase in CO_2 suggested in FP 47/WP.6.2 is unnecessary for partially weathertight hatchways covers onboard containerships.

The numerical calculations also show that a significant amount of carbon dioxide is leaking through the clear openings of non-weathertight hatch covers. The actual leakage is more than six times the amount in increase suggested in FP 47/WP.6.2.

References

1. SOLAS 2000 Amendments, IMO, London, 2001.

2. SOLAS, Consolidated Edition, IMO, London, 2001.

3. International Code for Fire Safety Systems (FSS Code), IMO, London, 2001.

4. NFPA 12, Standard on Carbon Dioxide Extinguishing Systems, 2000 Edition.

5. Odense L185 General Arrangement, Building No. L185 Series, Odense Steel Shipyard Ltd., 2001.

6. *Rules for Certification of Cargo Containers*, American Bureau of Shipping, 1998.

7. IMO FP 47/WP.6, "Any Other Business – Draft MSC circular on Guidelines on partially weathertight hatchway covers on board containerships", IMO, London, 2003.

8. Zalosh, R., Huang, C. W., "Carbon Dioxide Discharge Test Modeling", Fire Safety Science-Proceeding of the Fourth International Symposium, pp. 889-900.

9. AirPak Training Notes, FLUENT Inc., 2001.

This Page Intentionally Left Blank