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Fire and Flammability Properties (Fire Performance) of Non Metallic Materials

Literature Review of Technologies and Methods

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Approved by

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Abstract

Damage control is a priority for naval vessels. An important component of damage control is the rapid detection and extinguishment of fires. However, the risk and severity of shipboard fires can also be reduced through the selection of non metallic materials that are less susceptible to ignition, have low rates of flame spread, generate less smoke, and release less heat and toxic gases than competing products.

In this report the standards for the fire performance of non metallic materials, methods and apparatus used to evaluate the fire performance properties required by the standards, and models related to fire are reviewed. The standards include those of the International Maritime Organization (IMO) and the International Standards Organization (ISO), US military specifications (Mil Spec) and Royal Navy Defence Standards (Def Stan) and associated Naval Engineering Standards (NES). The methods include ASTM (American Society for Testing and Materials), Underwriter's Laboratories (UL), ISO, and NES fire performance standards. These standards refer to a broad range of apparatus required to perform the testing. The fire models include one and two zone and computational fluid dynamic models, and detector response, egress, and fire endurance models.

The applicability of small scale/laboratory fire testing to the evaluation of non metallic material performance in larger scale fire tests is discussed. Although there are many small scale/laboratory tests used to assess the fire properties of non metallic materials, no one test or suite of tests was found whose data correlated well with large scale test results for all materials and fire scenarios. However the cone calorimeter was determined to be the most applicable due to the amount of data generated with this test.

Résumé

La lutte contre les avaries constitue une priorité en matière d'entretien des navires militaires. Une de ses principales composantes est la détection rapide et l'extinction des incendies. Les risques d'incendies à bord de navires et leur sévérité peuvent toutefois être réduits en utilisant des matériaux non métalliques qui sont moins susceptibles de s'enflammer, présentent de faibles indices de propagation de la flamme et libèrent moins de fumée, moins de chaleur et moins de gaz toxiques que les produits concurrents.

Le présent rapport comporte un examen des normes qui s'appliquent aux matériaux non métalliques en matière de performance de résistance dans des conditions d'incendie, des méthodes et appareils utilisés pour évaluer les propriétés de performance de cette nature requises dans les normes, ainsi que des modèles relatifs aux incendies. Les normes pertinentes comprennent celles de l'Organisation maritime internationale (OMI) et de l'Organisation internationale de normalisation (ISO), ainsi que des spécifications militaires des États-Unis (MILSPEC), des normes en matière de défense de la Royal Navy (Def Stan) et des normes connexes du génie maritime. Les méthodes comprennent celles de l'ASTM (American Society

for Testing and Materials), de l'Underwriter's Laboratories (UL), de l'ISO et celles associées aux normes de performance du génie maritime. L'utilisation de ces diverses normes exige l'emploi d'une vaste gamme d'appareils d'essai. Les modèles numériques de feu comprennent des modèles à une et deux zones, ainsi que des modèles de la dynamique numérique des fluides, des modèles de la réponse du détecteur, des moyens d'évacuation et de la résistance au feu des matériaux.

Le présent rapport contient une discussion sur la pertinence des essais de résistance au feu exécutés à petite échelle ou à celle du laboratoire pour évaluer la performance de matériaux non métalliques lors d'essais réalisés à plus grande échelle. Bien qu'il existe de nombreux essais de laboratoire ou à petite échelle permettant d'évaluer les propriétés de résistance au feu des matériaux non métalliques, il a été impossible d'identifier un essai ou une série d'essais dont les résultats présentent une corrélation élevée avec ceux d'essais à grande échelle, pour tous les matériaux et tous les scénarios d'incendie étudiés. On a toutefois établi que le calorimètre à cône constitue l'instrument le plus utile à ce chapitre, en tenant compte de la quantité de données produites lors de l'essai.

Executive summary

Fire and Flammability Properties (Fire Performance) of Non Metallic Materials: Literature Review of Technologies and Methods

Charles Williams, Steve Bodzay, Robert Williams and Jeff McCarthy; DRDC Atlantic CR 2009-184; Defence R&D Canada – Atlantic; August 2009.

Introduction or background: Damage control is a priority for naval vessels. Although the rapid detection and extinguishment of fires is a critical component of damage control, the risk and severity of shipboard fires can also be reduced through the selection of non metallic materials that are less susceptible to ignition, have low rates of flame spread, generate less smoke, and release less heat and toxic gases than competing products. In this report, CRW Regulatory Services Inc. reviews standards for the fire performance of non metallic materials, methods and apparatus used to evaluate the fire performance properties required by the standards, and models related to fire and discusses these with respect to their applicability to materials for Navy ships.

Results: There are a large number of standards for the fire performance of non metallic materials. These standards include those of the International Maritime Organization (IMO) and the International Standards Organization (ISO), US military specifications (Mil Spec) and Royal Navy Defence Standards (Def Stan) and associated Naval Engineering Standards (NES). These standards, in turn, reference a large number of methods and apparatus for the evaluation of fire and flammability properties of non-metallic materials. The methods include ASTM (American Society for Testing and Materials), Underwriter's Laboratories (UL), ISO, and NES fire performance standards. The testing apparatus are referenced in the standards. These standards, methods and apparatuses are listed and discussed in the report.

The applicability of small scale/laboratory fire testing to the evaluation of non metallic material performance in larger scale fire tests is discussed. Although there are many small scale/laboratory tests used to access the fire properties of non metallic materials, no one test or suite of tests was found whose data correlated well with large scale test results for all materials and fire scenarios. However the cone calorimeter was determined to be the most applicable due to the amount of data generated with this test.

Models related to fire include one and two zone and computational fluid dynamic models, and detector response, egress, and fire endurance models. As computing power increases and understanding of the fire process improves, these models will help designers and architects understand the risks of using certain materials and designs and how these risks might be mitigated.

Significance: The use of non-metallic materials with improved fire and flammability properties will reduce the fire risk associated with the use these materials on Naval vessels. Although no small scale test (or tests) can be used to evaluate fire properties, the tests can be used to compare the performance of materials under the test conditions. The results of small scale tests are also used as input for fire models that predict fire development in a space. Fire models continue to evolve and as computing power (and speed) increases the ability to test the effect of materials on

the development of fires in ship board spaces will increase. Models can also be used to study the effect of design on the time it takes crew to exit a burning or damaged ship and its compartments.

Future plans: This work was carried out under Project 11gy - Technologies for Fire and Damage Control and Condition Based Maintenance. This project is investigating fire suppression models, new sensor systems, and the evaluation and development of non-metallic materials for Naval vessels. This project continues until March 2011.

Sommaire

Les propriétés d'inflammabilité et de combustion de matériaux non métalliques (détermination de leur performance de résistance au feu) : revue de la littérature portant sur les techniques et méthodes connexes

Charles Williams, Steve Bodzay, Robert Williams et Jeff McCarthy; RDDC Atlantique CR 2009-184; R & D pour la défense Canada – Atlantique; août 2009.

Introduction ou contexte : La lutte contre les avaries constitue une priorité en matière d'entretien des navires militaires. Bien que la détection rapide et l'extinction des incendies constituent une de ses principales composantes, les risques d'incendies à bord de navires et leur sévérité peuvent toutefois aussi être réduits en utilisant des matériaux non métalliques qui sont moins susceptibles de s'enflammer, présentent de faibles indices de propagation de la flamme et libèrent moins de fumée, moins de chaleur et moins de gaz toxiques que les produits concurrents. Le présent rapport contient les résultats de l'examen réalisé par la société CRW Regulatory Services Inc., portant sur les normes relatives à la performance de résistance au feu des matériaux non métalliques, les méthodes et appareils utilisés pour évaluer les propriétés de performance de cette nature requises dans les normes, ainsi que sur des modèles relatifs aux incendies; il comporte aussi une discussion sur ces différents éléments et leur applicabilité dans le domaine des matériaux utilisés dans les navires de la Marine.

Résultats : Il existe de nombreuses normes relatives à la performance des matériaux non métalliques dans des conditions d'incendie, entre autres celles de l'Organisation maritime internationale (OMI) et de l'Organisation internationale de normalisation (ISO), ainsi que des spécifications militaires des États-Unis (MILSPEC), des normes en matière de défense de la Royal Navy (Def Stan) et des normes connexes du génie maritime. Les normes en question mentionnent un grand nombre de méthodes et d'appareils employés pour évaluer les propriétés d'inflammabilité et de combustion des matériaux non métalliques. Les méthodes pertinentes comprennent celles de l'ASTM (American Society for Testing and Materials), de l'Underwriter's Laboratories (UL), de l'ISO et celles associées aux normes de performance du génie maritime. Les normes susmentionnées contiennent aussi des renseignements sur les appareils d'essai adéquats. Le présent rapport contient une liste de ces normes, méthodes et appareils, ainsi qu'une discussion connexe.

La discussion porte entre autres sur la pertinence des essais de résistance au feu exécutés à petite échelle ou à celle du laboratoire pour évaluer la performance de matériaux non métalliques lors d'essais réalisés à plus grande échelle. Bien qu'il existe de nombreux essais de laboratoire ou à petite échelle permettant d'évaluer les propriétés de résistance au feu des matériaux non métalliques, il a été impossible d'identifier un essai ou une série d'essais dont les résultats présentent une corrélation élevée avec ceux d'essais à grande échelle, pour tous les matériaux et tous les scénarios d'incendie étudiés. On a toutefois établi que le calorimètre à cône constitue l'instrument le plus utile à ce chapitre, en tenant compte de la quantité de données produites lors de l'essai.

Les modèles numériques de feu comprennent des modèles à une et deux zones, ainsi que des modèles de la dynamique numérique des fluides, des modèles de la réponse du détecteur, des moyens d'évacuation et de la résistance au feu des matériaux. L'accroissement de la puissance de calcul des ordinateurs et une meilleure compréhension des processus caractérisant les incendies faciliteront l'emploi de ces modèles par les concepteurs et les architectes en leur permettant de bien saisir l'importance des risques associés à l'utilisation de matériaux et de concepts particuliers et les mesures de réduction de ces risques.

Portée : L'utilisation de matériaux non métalliques possédant des propriétés supérieures en matière d'inflammabilité et de résistance au feu permettra de réduire les risques d'incendie généralement associés aux matériaux présents dans les navires militaires. Bien qu'aucun essai à petite échelle (ou aucune série d'essais) ne permet d'évaluer les propriétés de résistance au feu, les résultats d'essai peuvent servir à comparer la performance de divers matériaux soumis à des conditions d'essai identiques. Les résultats des essais à petite échelle peuvent aussi être incorporés aux modèles relatifs aux incendies qui servent à prévoir la propagation spatiale du feu. Les modèles relatifs aux incendies sont en constante évolution et l'accroissement de la puissance et de la vitesse de calcul des ordinateurs se traduira par une meilleure capacité de détermination des effets de la nature des matériaux sur la propagation des incendies à bord des navires. Certains modèles peuvent aussi servir à étudier les effets de la conception de divers éléments sur le temps d'évacuation de l'équipage, dans le cas d'un navire endommagé ou qui est la proie d'un incendie (ou le cas semblable d'un ou de plusieurs de ses compartiments touchés de la même manière).

Recherches futures : Les travaux faisant l'objet du présent rapport ont été réalisés dans le cadre du projet 11gy – Technologies de lutte contre les incendies et les avaries et de maintenance selon l'état. Le projet, dont les activités se poursuivront jusqu'en mars 2011, a pour objectifs d'étudier les modèles d'extinction des incendies et les nouveaux systèmes de détection et d'évaluer et de mettre au point des matériaux non métalliques pouvant être utilisés dans les navires militaires.

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1 Introduction

The horror of ship borne fires is well described in Frank Rushbrook’s seminal book “Fire Aboard” which he fittingly dedicated to his “… hated, but deeply respected enemy, fire”.[1]

The concerns about fire and related products of combustion are appropriately key to the design of all structures. Fire codes at all levels are designed principally to protect occupants and where possible the structure itself. Building codes, such as the Canadian Building Code[2] and the associated Canadian Fire Code[3] or the NFPA Life Safety Code[4], with regards to fire, are written to ensure the safety of the occupants via the incorporation of fire resistant materials, the introduction of measures to ensure early detection and extinction, and perhaps most importantly (for buildings) provide for complete and swift egress from the structure. With ships rapid escape is frequently not an option. Hence the use of appropriate fire resistant materials, along with modes of fire prevention, detection and extinction are paramount.

The requirement for stealth, high strength, low weight materials, reduced maintenance, reduced manning, and reduced cost are resulting in the use for new and alternative materials in naval vessels. The new materials in many cases tend to be non-metallic and organic (combustible) materials. In order to maintain a minimum level of fire safety, the US and British Navies have set performance requirements for new materials in many applications. These include the use of composite materials in ships and submarines. Performance requirements for composites, in most cases, are based on full-scale fire tests. Additional fire safety standards have been set by the International Maritime Organization (IMO) in the Safety of Life at Sea (SOLAS) standards. Although these standards indicate different test methods, they use similar test procedures.

Fire tests generally fall into two categories: tests to measure ignition and the spread of flame from one area to another, and tests to measure fire resistance. Fire resistance tests measure a material's ability to continue to serve its structural role during a fire.

2 Fire and Flammability Standards for Materials (Composites)

2.1 Background

Materials performance and related flammability tests methods are described by numerous organizations including, but not limited to, the Underwriters' Laboratories of Canada (ULC), the American Society for Testing and Materials (ASTM), British Standards, the International Organisation for Standardization (ISO), and Underwriter's Laboratory (UL). These methods are referred to in various materials requirements and specifications. Examples are the International Maritime Organization Safety of Life At Sea, Fire Test Procedures Code (FTP Code) and military standards such as those of the United States and Britain.

A search of standards for fire testing of composites revealed four standards which directly address the use of composite materials for marine applications.

ASTM E1740-07a	Standard test method for determining the heat release rate and other fire-test-response characteristics of wall covering composites using a cone calorimeter
MIL-STD-2031	Fire and toxicity test methods and qualification procedure for composite material systems used in hull, machinery, and structural applications inside naval submarines
DIN 80310-1	Fibre composite materials in shipbuilding - Requirements relating to the fire behaviour - Part 1: Area of application
DIN 80310-2	Fibre composite materials in shipbuilding - Requirements relating to the fire behaviour - Part 2: Fittings

When considering the use of composites on ships (and by extension submarines) there are three organizations that have established fire and flammability standards that deal specifically with marine constructions.

1. International Maritime Organization (IMO)
2. US Military (Department of Defense (DOD))
3. British Military

The majority of national and international shipping standards use fire and flammability standards established by the IMO.

The fire standards that are applicable are summarized below.

2.2 IMO- SOLAS

Introduction and History (Copied from the IMO web site)[5]

The SOLAS Convention in its successive forms is generally regarded as the most important of all international treaties concerning the safety of merchant ships. The first version was adopted in 1914.

The **1960** Convention was the first major task for the IMO after the Organization's creation and it represented a considerable step forward in modernizing regulations and in keeping pace with technical developments in the shipping industry. The intention was to keep the Convention up to date by periodic amendments, but in practice the amendments procedure proved to be very slow. It became clear that it would be impossible to get acceptance of amendments within a reasonable period of time. As a result, a completely new Convention was adopted in 1974 and included not only the amendments agreed upon up until that date but also a new amendment procedure. The tacit acceptance procedure, designed to ensure that changes could be made within a specified (and acceptably short) period of time, provides that an amendment shall enter into force on a specified date unless, before that date, objections to the amendment are received from an agreed number of Parties.

As a result the 1974 Convention has been updated and amended on numerous occasions. The Convention in force today is sometimes referred to as SOLAS, 1974, as amended.

Chapter II-2 - Fire protection, fire detection and fire extinction

This chapter includes detailed fire safety provisions for all ships and specific measures for passenger ships, cargo ships and tankers.

These provisions include the following principles:

- division of the ship into main and vertical zones by thermal and structural boundaries;
- separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries;
- restricted use of combustible materials;
- detection of any fire in the zone of origin;
- containment and extinction of any fire in the space of origin;
- protection of the means of escape or of access for fire-fighting purposes;
- readily availability of fire-extinguishing appliances; minimization of the possibility of ignition of flammable cargo vapour.

There have been two significant recent developments in fire test standards for commercial ships: the “Fire Test Procedures Code” (FTP Code), IMO Resolution MSC.61(67) and the “Standard for Qualifying Marine Materials for High Speed Craft as Fire-Restricting Materials”, IMO Resolution MSC.40(64).

The FTP Code makes the use of the IMO fire test procedures mandatory for showing compliance with the SOLAS regulations and the HSC Code. The FTP Code went into effect in July 1998. This is significant because prior to this point, each Administration (government or other specified regulatory authority) enforcing SOLAS could use any fire test standard they wished. Many of them used their own domestic standards while others used the IMO's recommended fire test procedures.

The table below lists the fire test standards required by the FTP Code for materials to be used on ships.

Table 2-1. Fire Safety Requirements for Some Marine Products- Fire Test Procedures Code (FTP Code) IMO Resolution MSC.61(67)

FTP Code	Type of test	Referred test method	Similar test method
Part 1	Non-combustibility Test	ISO 1182	-
Part 2	Smoke and Toxicity Test	ISO 5659-2	-
Part 3	Fire Resistance Test for Fire Resistant Divisions	IMO A.754(18)	ISO 834-1
Part 4	Fire Resistance Test for Fire Door Closing Mechanisms	-	-
Part 5	Surface Flammability Test	IMO A.653(16) IMO A.687(17)	ISO 5658-2
Part 6	Test for Primary Deck Coverings	IMO A.653(16)	ISO 5658-2
Part 7	Flammability Tests for Curtains and Vertically Suspended Textiles and Films	IMO A.471(XII) IMO A.563(14)	ISO 6940/41 EN 1101/02
Part 8	Test for Upholstered Furniture	IMO A.652(16)	BS 5852-1 ISO 8191-1/-2 EN 1021-1/-2
Part 9	Test for Bedding Components	IMO A.688(17)	EN 597-1/-2
	Fire restricting-materials for High Speed Craft	IMO Res. MSC.40(64)	ISO 9705 ISO 5660

SOLAS II-2 Reg 17 allows for alternative materials where they can be demonstrated to be "equivalent to steel". At a material level it is difficult to consider equivalence between composites and steel as their properties are so different. There are also rules for plastic pipe work and some other materials but many items are not covered under the rules.

For composites, the pass fail criteria for fire test results are important.[6] These are listed in Table 2-2.

Table 2-2. Fire test criteria required by IMO A754 (18) Fire Test Performance. The criteria must be maintained throughout the entire test period (typically 30 or 60 minutes).

Performance Criterion	Measurement Criterion	Impact on Composite Sandwich Structures	Impact on Steel / Aluminum Structures
Stability	No collapse	High levels of insulation needed to prevent collapse / excessive deflection	Un-insulated steel will not collapse Aluminum requires moderate level of insulation to prevent collapse
Integrity	No gaps or cracks through which hot gasses can pass	Not usually a problem as Stability is maintained	Not usually a problem as Stability is maintained
Insulation	Unexposed face temp. rise: < 140 °C average 180 °C maximum	Unexposed face temperature rise is minimal due to high insulation value of the sandwich structure	Main cause of failure in a fire test. Insulation thickness design is critically important.

The test methods and several examples of the performance of composite materials are discussed in the following paragraphs.

The IMO High Speed Craft resolution most directly applies to the use of composites on navy ships.

IMO Resolution MSC 40(64) on ISO 9705 Test: Tests should be performed according to the standard *ISO 9705*, which specifies the choice of ignition source and sample mounting technique. For the purpose of testing products to be qualified as “fire restricting materials” under the IMO High- Speed Craft Code, the following should apply: *Ignition source*: Standard ignition source according to Annex A in ISO 9705, i.e. 100 kW heat output for 10 minutes and thereafter 300 kW heat output for another 10 min. Total testing time is 20 minutes.

High Speed Craft Code - Fire Resistive Materials lists the following criteria for qualifying products as “*Fire Restricting Materials*”

- The *time average of HRR* excluding the ignition source does not exceed *100 kW*;
- The *maximum HRR* excluding the HRR from the ignition source does not exceed *500 kW* averaged over any 30 second period of the test;
- The time *average of the smoke production rate* does not exceed *1.4* m^2/s;
- The *maximum value of smoke production rate* does not exceed *8.3*m^2/s averaged over any period of 60 seconds during the test;
- *Flame spread* must not reach any further down the walls of the test room than *0.5 m* from the floor excluding the area which is within 1.2 meter from the corner where the ignition source is located;
- *No flaming drops or debris* of the test sample may reach the floor of the test room outside the area which is within 1.2 meters from the corner where the ignition source is located

2.3 United States Department of Defense

Although the official definitions differentiate between several types of documents including defense specifications, handbooks, and standards, all of them fall under the general heading of "military standard".

The Naval standards for fire and flammability are listed in Table 2-3. These standards are focussed on ensuring that inappropriate materials are not introduced onboard ships. Eric Green and Associates reviewed the potential use of composites onboard ships and identified the following criteria.[7]

Table 2-3. Naval standards for fire and flammability

Material Selection Requirements, NAVSEA Technical Publication, T9074-AX-GIB-010/100	This document defines the Material Selection Requirements (MSR) that must be met by each design activity responsible for the selection of materials for ships and their systems.
ABS Naval Vessel Rules (NVR)	The NVR was recently developed by ABS & the U.S. Navy to allow the Technical Authority (U.S. Navy) to periodically update Technical Instructions for design and construction of naval vessels. The NVR covers structural aspects of Topside applications.
ABS Guide for High Speed Craft (HSC)	All structure of composite high speed craft are covered in the ABS HSC Guide
Composite Materials, Surface Ships, Topside Structural and Other Topside Applications – Fire Performance Requirements, Design Data Sheet DDS 078-1	This DDS provides the fire performance requirements for various Fiber Reinforced Plastic (FRP) composite materials used in the construction of U.S. Navy surface ship topside structures, and other topside applications.
Insulation, High Temperature Fire Protection, Thermal and Acoustic, MIL-PRF-32161	Addresses passive fire protection for steel decks and bulkheads with stiffeners. (Refer to IMO A.754 (18) for more guidance with composite divisions)
Military Standard ``Fire and Toxicity Test Methods and Qualification Procedure for Composite Material Systems Used in Hull, Machinery, and Structural Applications Inside Naval Submarines" (MIL-STD-2031(SH))	Establishes the fire and toxicity test methods, requirements, and the qualification procedure for composite materials and composite material systems to allow their use inside naval submarines.
Military Standard MIL-STD-1623 "Fire Performance Requirements and Approved Specifications for Interior Finish Materials and Furnishings"	Covers fire performance requirements for bulkhead sheathing, furniture & bedding, deck coverings, and thermal insulation.

There are three defence standards that cover most situations where composites may be employed; MIL-STD-1623E[8], MIL-STD-2031[9] and MIL-STD- 3020[10]. Some criteria are outlined in Design Defense Criteria DDS-078-1. These are described in more detail in the following sections.

2.3.1 MIL-STD-1623 E

Military Standard MIL-STD-1623 E, Fire Performance Requirements and Approved Specifications for Interior Finish Materials and Furnishings is applicable to a number of interior materials. These include: bulkhead sheathing, overhead sheathing, furniture, draperies and curtains, deck coverings, insulation, and bedding applications.

The fire tests specified by this standard are listed in Table 2-4.

Table 2-4. A summary of MIL-STD-1623E specifications for fire tests.

Specification	Description
Surface Flammability	
ASTM D635	Burn rate test
ASTM E84	Tunnel test
ASTM E162	Radiant Panel
ASTM E648	Floor radiant panel
FED-STD-501, Method 6411	Floor covering, fire resistance
UL 94	Flammability of plastics
Vertical Flame Resistance	
ASTM D6413*	Flame Resistance of textiles
Smoke Generation	
ASTM E84	Tunnel test
ASTM E662	Specific optical density of smoke
Test for incombustibility	
46 CFR 164.009	Heated tube test
Fire endurance	
NFPA 267**	Fire characteristics of mattresses
UL 1709**	Hydrocarbon pool fire exposure test

* A minimum of five specimens from each of the warp and fill directions on materials of the same lot shall be tested and their results averaged (arithmetic mean).

** Only one specimen.

2.3.2 MIL-STD-2031

The use of composites for structural applications in submarines is covered by MIL-STD-2031. The recommended fire performance criteria contain requirements for fire growth, smoke toxicity, visibility (ISO 9705), fire resistance and structural integrity under fire (UL 1709). When developing new composite systems, it is expensive to repeatedly conduct these typical full-scale fire tests to determine the performance of the most recent design. Instead, more cost-effective small-scale testing is preferable to evaluate performance. To facilitate the introduction of new and modified fire tolerant materials/systems/designs, and to reduce the financial burden on small business, the US Navy has developed a low cost composite system fire screening protocol which offers the potential of predicting the full-scale fire performance. The applicability of such test are discussed in the Modeling section below.

The requirements of MIL-STD-2031 (SH), “Fire and Toxicity Test Methods and Qualification Procedure for Composite Material Systems used in Hull, Machinery, and Structural Applications inside Naval Submarines” are summarized in Table 2-5. The foreword of the standard states:

“The purpose of this standard is to establish the fire and toxicity test methods, requirements and the qualification procedure for composite material systems to allow their use in hull, machinery, and structural applications inside naval submarines. This standard is needed to evaluate composite material systems not previously used for these applications.”

Table 2-5. Summary of the requirements outlined in military standard MIL-STD-2031.

Test	Description	Criteria	ASTM Test Method
Oxygen-Temperature Index (%)	The minimum concentration of oxygen in a flowing oxygen nitrogen mixture capable of supporting flaming combustion of a material.	Minimum % oxygen @ 25°C 35% oxygen, @ 75°C 30% oxygen, @ 300°C 21%	ASTM D 2863 (modified)
Flame Spread Index	A number or classification indicating a comparative measure derived from observations made during the progress of the boundary of a zone of flame under defined test conditions.	Maximum 20	ASTM E 162
Ignitability (seconds)	The ease of ignition, as measured by the time to ignite in seconds, at a specified heat flux with a pilot flame.	*Minimum* 100 kW/m^2 Flux 60 sec; 75 kW/m2 Flux 90 sec; 50 kW/m^2 Flux 150 sec; 25 kW/m^2 Flux 300 sec	ASTM E 1354
Heat Release Rate (kW/m^2)	Heat produced by a material, expressed per unit of exposed area, per unit of time.	*Maximum* **100 kW/m^2 Flux** Peak 150, Average 300 sec - 120; **75 kW/m^2 Flux** Peak 100 Average 300 sec – 100; **50 kW/m^2 Flux** Peak 65, Average 300 sec – 50; **25 kW/m^2 Flux** Peak 50, Average 300 sec - 50	ASTM E 1354
Smoke Obscuration	Reduction of light transmission by smoke as measured by light attenuation.	*Maximum* Ds during 300 sec 100, Dmax occurrence 240 sec	ASTM E 662
Combustion Gas Generation	Rate of production of combustion gases (e.g. CO, CO_2, HCl, HCn, NOx, SOx, halogen, acid gases and total hydrocarbons.	**25 kW/m^2 Flux** *Maximum* CO 200 ppm, CO_2 4% (vol), HCN 30 ppm, HCl 100 ppm	ASTM E 1354
Burn Through Fire Test	Test method to determine the time for a flame to burn through a composite material system under controlled fire exposure conditions.	No burn through in 30 minutes	DTRC Burn Through Fire Test
Quarter Scale-Fire Test	Test method to determine the flashover potential of materials in a room when subjected to a fire exposure.	No flashover in 10 minutes	Procedure specific to Report
Large Scale Open Environment Test	Method to test materials at full size of their intended application under controlled fire exposure to determine fire tolerance and ease of	Pass	Procedure specific to Report

Test	Description	Criteria	ASTM Test Method
	extinguishment.		
Large Scale Pressurable Fire Test	Method to test materials using an enclosed compartment in a simulated environment under a controlled fire exposure.	Pass	Procedure specific to Report
N-Gas Model Toxicity Screening	Test method to determine the potential toxic effects of combustion products (smoke and fire gases) using laboratory rats.	Pass	Procedure specific to Report

2.3.3 Design Defense Standard 078-1

Fire performance of composite materials is covered under DDS-078-1, "Composite materials, Surface ships, Topside structural and other topside applications – Fire performance requirements." This standard contains fire performance requirements, such as flame spread, smoke generation, fire growth, fire resistance, and structural integrity, for structural composites. In addition, it contains fire performance requirements for non structural composite items such as weather deck gratings, louvers, ducting, and valves.

Revision 1 is under review, and includes; GRP piping requirements, revision of the structural integrity section for composite structures, revision of smoke index and carbon monoxide limits and an addition to the table which lists navy approved composite N-Class divisions.

2.3.4 MIL-STD-3020, "Fire Resistance of U.S. Naval Ships"

MIL-STD-3020 provides the detailed test procedure and acceptance criteria for the fire resistance (i.e., prevention of fire spread through a boundary) of divisions (e.g., bulkheads and overheads/decks) and their penetrations on U.S. Navy ships.

- It institutes two Classes of Fire Resistant Divisions; N-Class and AN-Class
    - N-Class Divisions are those divisions (bulkheads and decks) that are designed to protect against structural failure and prevent the passage of fire and smoke when exposed to a rapid rise hydrocarbon fire exposure (Class B). The minimum fire test duration is 30 minutes. In addition, N-Class divisions are designed to prevent excessive temperature rise for a designated test period such as 30 minutes (N-30).
    - AN-Class Divisions are those divisions (bulkheads and decks) that are designed to protect against structural failure and prevent the passage of fire and smoke when exposed to an IMO A. 754(18) fire exposure (Class A). For all AN-Class divisions, including those with penetrations, the test duration is a minimum of 60 minutes. In addition, AN-Class divisions are designed to prevent excessive temperature rise for a designated test period such as 60 minutes (AN-60).

2.3.5 Wires and Cables

There are also military specification standards for ship cabling and specific fire requirements for these materials. Leonard (2000) summarized the military specifications related to fire and flammability properties of all types of materials.[11]

2.4 British Defence Standards

The United Kingdom recently updated many of their defence standards. A short list of standards applicable to fire testing is given in Table 2-6.

Table 2-6. Summary of British Defence Standards

Standard	**Description**
DefStan 02-711 (70)	Determination of the Smoke Index of the Products of Combustion from Small Specimens of Materials
DefStan 02-713 (64)	Determination of the Toxicity Index of the Products of Combustion from Small Specimens of Materials
DefStan 07-247 (14)	Selection of Materials on the Basis of their Fire Characteristics: • Part 1: Policy • Part 2: Structural Materials • Part 3: System Materials • Part 4: Habitability • Part 5: Paints • Part 6: Insulation Material • Part 7: Miscellaneous Materials • Part 8: Fire Characteristics database
Def Stan 61-12 "Wires, Cords and Cables Electrical - Metric Units"	• Part 0: Wires, Cords, Cables, Electrical General requirements and Test methods* • Part 9: Cables and Wires Electrical for Cables, Radio Frequency Including Limited Fire • Part No: 18: Equipment Wires Limited Fire Hazard • Part No: 25: Cables, Electrical Limited Fire Hazard, up to Conductor Size 10 mm2 Cross-Sectional Area • Part No: 31: Sheaths-Limited Fire Hazard

* Part 0 contains several fire and flammability tests including: Flammability BS 3G 230 Test 28a, Flame Propagation BS 3G 230 Test 28a, Critical Oxygen index BS 2782 Part 1 Method 141, Smoke index Def Stan 02-711, Toxicity index Def Stan 02-713

A brief description of fire tests currently specified by the British Ministry of Defence for materials used on Royal Navy (RN) surface ships and/or submarines are given in Table 2-7. The description was taken from Def Standard 07-247 Part 1[14].

Table 2-7. Def Standard 07-247 Part 1- Summary of Listed Test methods

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
1	**BS 476 Part 4** Non-combustibility (See also BS EN ISO 1182)	Materials are classified as combustible or non-combustible by identifying those which make little or no thermal contribution to the heat of the furnace and do not produce a flame, and by calling the remainder "combustible".	Tests carried out in a furnace. The furnace is heated to 750 ±10°C and stabilised for 10 min. The specimen is inserted and the furnace temperature is recorded for a further 20 minutes. The occurrence of any flaming in the furnace is noted.
	Interpretation of Test Data: The material shall be deemed non-combustible if, during the test, none of the three specimens either: (1) Causes the temperature in the furnace to rise by 50°C or more above the initial furnace temperature, or; (2) Is observed to flame continuously for 10s or more inside the furnace. Otherwise, the material shall be deemed combustible.		
2	**BS 476 Part 6** Fire propagation	The test takes account of the combined effect of factors such as the ignition characteristics, the amount and the rate of heat release, and the thermal properties of the product in relation to their ability to accelerate the rate of fire growth. (Note this test is used in UK building (regulations.)	Test carried out in a combustion chamber. The face of the specimen is subjected to gas jets impinging on the bottom edge of the specimen for 20 min and radiant heat applied 2 min 45 sec after start of test.
	Interpretation of Test Data: The index of performance **I** is the summation of sub indices I1, I2 and I3 calculated from the funnel gas temperature/time curve. The smaller the index **I** the more acceptable the material. The value of the sub index I1 is a measure of the heat contribution of the material to the early stages of the fire		
3	**BS 476 Part 7** Surface spread of flame	The test takes account of the combined effect of factors such as ignition characteristics and the extent to which the flame spreads over the surface of the product under opposed flow conditions. (Note this test is used in UK building regulations.)	Vertically oriented specimens are exposed at right angles to a radiant panel and in addition a pilot flame is applied during the first minute of the test. Observations are made of the time required for the flame front to laterally spread along the specimen to reach a series of reference marks. (Note: A small scale test was specified in earlier versions of this standard and was used in preliminary investigations only. It is no longer included standard.)
	Interpretation of Test Data:		

<table>
<tr><th>Test No.</th><th>REFERENCES</th><th colspan="2">PURPOSE OF TEST</th><th colspan="2">DESCRIPTION</th></tr>
<tr><td rowspan="4"></td><td></td><td colspan="2">Flame spread at 1.5 minute</td><td colspan="2">Final spread of flame</td></tr>
<tr><td>Classification</td><td>Limit
mm</td><td>Limit for one specimen in sample
(mm)</td><td>Limit
(mm)</td><td>Limit for one specimen in sample
(mm)</td></tr>
<tr><td>Class 1
Class 2
Class 3</td><td>165
215
265</td><td>165+25
215+25
265+25</td><td>165
455
710</td><td>165+25
455+45
710+76</td></tr>
<tr><td>Class 4</td><td colspan="4">Exceeding the limits for class 3</td></tr>
<tr><td rowspan="2">4</td><td>BS 476 Part 12
Ignitability by direct flame impingement (Supersedes BS 476 Part 5)</td><td colspan="2">To obtain information on the performance of a specimen in the early stages of a fire, by determining the ignitability of materials, composites and assemblies subjected to direct impingement of flames of different size and intensity but without impressed irradiance.</td><td colspan="2">Vertically held specimens are exposed to specified flames of different sizes and intensities and their ignition behaviour observed.</td></tr>
<tr><td colspan="5">Interpretation of Test Data: No acceptance criteria are given but the standard allows specifiers, with experience, to require a product to be tested by a specific ignition source, relevant to the end use application, for a specific flame application time and position.</td></tr>
<tr><td rowspan="2">5</td><td>BS 476 Part 15 ≡ ISO 5660 Part 1
Rate of heat release</td><td colspan="2">To determine the heat release rates for essentially flat materials, assemblies, etc.</td><td colspan="2">A cone calorimeter which determines heat release rate using the oxygen consumption principle is used to burn specimens in ambient air conditions, while being subjected to a predetermined external irradiance within the range 0-100 kW/m^2.</td></tr>
<tr><td colspan="5">Interpretation of Test Data: This test procedure provides a considerable amount of information including data on rate of heat release, mass loss rate, time to ignition and effective heat of combustion. Using additional procedures/ apparatus, that are generally fitted as standard on most instruments, data on rates of production of smoke, CO and CO2 are also collected. No acceptance criteria are given in the standard, so at present the information can be used for direct comparison of materials only. As experience is ‘built-up’, performance requirements, for material types or applications, will be set.</td></tr>
<tr><td rowspan="2">6</td><td>BS 2316 Parts 1 & 2
Specification for radio frequency cables
Flammability test for cables (Part 1, Clause 6.7)</td><td colspan="2">To check that cables will not support combustion or propagate flame.</td><td colspan="2">Specimen cables are supported at an angle of 45° in a draught free chamber. The hottest point of a flame is arranged to impinge on the central position of the specimen for 15 seconds.
Observations are made on any flaming debris, time to cessation of burning and length of burn.</td></tr>
<tr><td colspan="5">Interpretation of Test Data: The material shall be deemed acceptable if no flaming particles fall from the specimen, the cable ceases to burn within a specified time, and total burn length or char does not exceed 75 mm or fourteen times the nominal diameter of the cable, whichever is the greatest.</td></tr>
</table>

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
7	**BS EN ISO 4589 Part 2** Oxygen index (ambient temperature test)	To determine the relative flammability of materials by comparing the lowest level of O2 in a mixture of O2 and N2 at which combustion of a material is just supported at ambient temperature, under specified conditions.	Specimens are supported vertically in a glass chimney through which passes a controlled mixture of O2 and N2 constant flow rate. By testing a series of specimens at different oxygen concentrations, the Oxygen Index is determined as the minimum oxygen concentration that will support combustion of a specimen over a short specified time and/or distance.
	Interpretation of Test Data: The oxygen index **OI** is calculated as the percentage volume of oxygen in the critical mixture. $\textit{Oxygen Index} = \frac{(100) \times (O2)}{(O2) + (N2)}$ Where O2 and N2 are the volumetric flow rates of oxygen and nitrogen respectively. The higher the index **OI** the more acceptable the material.		
8	**BS EN ISO 4589 Part 3 Annex A** Flammability temperature (FT)	To determine the relative flammability of materials by comparing the lowest temperature at which combustion of a material is just supported in air, under specified conditions.	Specimens are supported vertically in a glass chimney through which passes preheated air at a constant flow rate. By testing a series of specimens at different temperatures, the Flammability Temperature (FT) is determined as the minimum elevated temperature that will support combustion of a specimen over a short specified time and/or distance. (Note: This is effectively the temperature at which the OI of the material falls to 20.9 (the oxygen content of air at 23 ± 2°C).
	Interpretation of Test Data: The higher the Flammability Temperature (FT) the more acceptable the material. (Note: This test property was previously described as "Temperature Index" and was specified in NES 715 (see Table 2 Test 42). In this context the terms "Temperature Index" and "Flammability Temperature" have the same meaning, although users should note that where the ISO version of the test specifies different specimen dimensions (e.g. for foams) the results may not be comparable.)		
9	**BS 4735** Horizontal burning characteristics of cellular plastic and cellular rubber materials (foams)	To compare the horizontal burning characteristics of cellular plastics and cellular rubber materials when subjected to a small flame. The results can be of value in controlling manufacturing processes to ensure consistency of production. There is no known evidence of correlation between the results of such tests and	Conducted in a test chamber within a fume cupboard. The specimen is supported on a gauze holder and subjected to a gas flame, 13 mm below the gauze, for a period of 60 sec. The extent and time of burning and mass loss, if required, are recorded. Any warping, charring, melting or dripping of the specimen is to be timed and recorded

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
		burning under actual use conditions. Therefore conclusions cannot and shall not be drawn from such results regarding burning behaviour under actual use conditions.	together with any inclination to produce flaming droplets.
	Interpretation of Test Data: The resulting time and observations are used to compare the horizontal burning characteristics of cellular foams, such as could be subjected to the effects of a lighted cigarette or similar.		
10	**BS 4790** Flammability of textile floor coverings (hot metal nut method)	To determine spread of flame, after-glow and smouldering in carpets, etc.	A Stainless steel nut mass 30g heated to 900°C applied centre of specimen for 30 seconds. The time in seconds from application of the nut and to extinction of any flames, of any afterglow and/or smouldering are measured. Where the effects of ignition reach the clamping ring (125mm internal radius) the time in seconds is also noted.
	Interpretation of Test Data: The resulting time and distance data are used to compare the flammability characteristics of competing textile floor coverings in accordance with **BS 5287**		
11	**BS 5287** Assessment and labelling of textile floor coverings tested to **BS 4790**	To classify the results obtained by test to **BS 4790**	Three classifications are given: **1.** Affected area up to 35 mm -low radius of effects of ignition **2.** affected area between 35 and 75 mm -medium radius of effects of ignition **3.** Affected area 75 mm or more - high radius of effects of ignition
	Interpretation of Test Data: Classification 1 is the best and 3 the worst.		
12	**BS 5438** Flammability of vertically oriented textile fabrics and fabric assemblies subjected to small igniting flame (Partially replaced by BS EN 532, BS EN ISO 6940 and BS EN ISO 6941)	To observe and measure aspects of the flammability of vertically oriented textile fabrics in a single layer or more. This test may also be called up after the material has undergone repeated washing (see BS EN 1102) to ensure durability of FR treatments.	Vertical strip test for textile fabrics. Facts reported are : Time to strip threads severance; Separation of any flaming debris; Duration of flaming; Duration of afterglow.
	Interpretation of Test Data: Characteristics determined are Ignition Time, Spread of Flame and Rate of Flame Spread.		
13	**BS 5946** Punking behaviour of phenol-formaldehyde foam	To assess the resistance of phenol-formaldehyde foam to propagation of slow combustion (known as “Punking”) initiated by localised application of a source of heat	A sample of foam is heated using a Bunsen burner until a measured temperature of 180°C is reached. The Bunsen burner is removed and temperature recorded.

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
		once the heat source has been removed.	
	Interpretation of Test Data: An increase in temperature beyond 360°C indicates that the foam exhibits punking behaviour. A fall in temperature below 100°C indicates that the foam is non-punking.		
14	**BS EN 50267 Parts 1 and 2-1** Halogen acid gases evolved during combustion of cable materials (Formerly BS 6425 Part 1)	Determination of amount of halogen acid gas evolved during combustion of cables.	0.5g to 1g of a sample is placed into a combustion boat which is inserted into a combustion tube in the furnace hot zone. The combustion tube is connected to wash bottles and the sample temperature is raised to 800°C at a rate of 20°C/min and held for 20 minutes. By analysis of the wash bottles the halogen acid content can be found.
	Interpretation of Test Data: The lower the amount of halogen acid expressed as milligrams of hydrochloric per gram the more acceptable the material.		
15	**BS 3G 230 Test 28 (a)** Flammability - Method 1 (Formerly BS 2G 230)	To observe and measure aspects of the flammability of cables.	A 900 mm length of the sample is mounted at 60° and a flame applied 200 mm from the bottom clamp. The duration of flame application depends on the size and type of cable being tested. Observations of flaming debris, time to cessation of burning and length of burning and length of burnt or charred material measured.
	Interpretation of Test Data: During the test no flaming particles shall fall from the specimen. Burning shall cease within 3 seconds and total length burned or charred shall not exceed 75 mm. (Note BS 2G 230 has been superseded by BS 3G 230 and for Test 28(a) the requirement for burning to cease has been revised to 3 seconds. However, this test, with its original 15 second limit, is called up as BS 2G 230 in Def Stan 61-12 Part 0 Clause 13.39)		
16	**BS 3G 230 Test 28 (b)** Flammability - Method 2 (Formerly BS 2G 230) (Note: Def Stan 61-12 Part 0 Clause 13.40 refers to this tests as “Flame Propagation”)	Assessment of propagation of flame on a vertical cable with sheath removed on its lower portion.	Using the same chamber as BS 3G 230 Test 28(a). 50 mm of insulation is removed from one end of a 450 mm long sample which is then placed vertically in the flame of a Bunsen burner. A record is made of the burn length and the time of burning after the removal of the flame.
	Interpretation of Test Data: No flaming particles shall fall from the specimen. Burning shall cease within 15 seconds and burn and char length shall not exceed 90 mm. (Note. BS 2G 230 has been superseded by BS 3G 230, although there are no substantive changes to the requirement.)		

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
17	**DOT Information Sheet FP/1989 Annex**	Determination of flammability of carpets and carpet underlays.	A specimen with its top surface facing down is placed on a metal tripod so that the height of this surface is 8 mm below the top of the gas flame. The gas flame is applied at right angles to the plane of the specimen at its centre and then when all flaming has ceased and the specimen temperature has returned to normal at the edge.
	Interpretation of Test Data: Time and extinction of any flaming is recorded. The shorter the time the more acceptable the material.		
18	**Def Stan 02-137** PU foam components for mattresses, cushions and upholstery Fire resistance test	To assess the fire resistance of composite components: (1) Core foam wrapped in barrier foam (2) Barrier foam wrapped in cotton cover	(1) 4 x No 6 cribs placed in centre of sample to form a square with sides touching and ignite. (2) 4 x No 7 cribs placed in centre of sample to form a square with sides touching and ignite. In each test the following observations are made (a) Time to cessation of flaming, smoking and glowing of barrier foam (b) The integrity of the barrier foam char.
	Interpretation of Test Data: The resulting times and integrity of char are used to compare the fire resistance of the components. Alternatively a specific time could be set by which cessation is achieved for acceptance of components.		
19	**Def Stan 02-345** Flexible rubber pipe assemblies and bellows Flame Test	To assess the fire resistance of flexible pipe assemblies	A flame from a butane gas torch is directed onto a vibrating hose, end fitting, bend or bellows for 15 minutes. Damage is to be observed
	Interpretation of Test Data: An assembly will be deemed to have failed if leakage occurs within a specified time.		
20	**Def Stan 02-641** Vertical flammability of electric cables	Determination of the vertical flammability of electric cables.	850 mm long test specimen consisting of a single cable or a number of cables twisted together is mounted vertically in a stainless steel tube inside a draught free enclosure over a conical fuel tray. Once all the fuel has been consumed the test specimen is allowed to continue to burn until all burning and glowing has ceased. Specimen is then held horizontally 300 mm above floor and allowed to fall. Damage length is measured.
	Interpretation of Test Data: The shorter the damage length the more acceptable the material.		
21	**Def Stan 02-711**	To evaluate the density of smoke	Specimens are exposed in the

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
	Smoke Index	(light obscuration) evolved by materials under conditions of fire	vertical orientation to a constant radiant heat source (25 kW/m^2), inside a sealed chamber ("NBS smoke chamber"). For the first five minutes exposure is to the radiant heater only. After 5 minutes a multi-jet burner is ignited and runs for up to a further 15 minutes. A photometric system is used to monitor percentage light transmission with respect to time. Values of the specific optical density (DS) of the smoke that accumulates inside the chamber are derived from corrected transmission data.
	Interpretation of Test Data: A Smoke Index is calculated from the average rates of change of DS calculated between the start of the test and up to three transmission reference points (70%, 40%, 10%) and also between the start of the test and the minimum transmission point. The computation of the smoke index ensures that materials producing heavy smoke in a short time receive a higher rating; others giving heavy smoke in a longer time, or only light smoke, are lower rated. The lower the Smoke Index the more acceptable the material.		
22	**Def Stan 02-713** Toxicity Index	Measurement of toxic potency of the gases in the products of combustion.	Specimens ~1g are completely burnt inside a sealed chamber using a gas/air burner at 1150°C. The combustion products are then quantitatively analysed for a specified set of gases.
	Interpretation of Test Data: The toxicity index **TI** is derived from the summation of the individual qualities of gas produced relative to the amount considered to be fatal to humans after 30 min exposure. The lower the Toxicity Index the more acceptable the material.		
23	**Def Stan 02-807** Part 1 Welding and burning blankets and hangar fire curtains Flame Cutting Test	To determine the ability of silica fabric blankets to resist molten slag.	A specimen of cloth is held horizontally and a steel plate is mounted above the cloth. A 20 mm wide piece of the steel plate is then flame cut and the molten slag and cut piece are allowed to fall onto the test cloth.
	Interpretation of Test Data: The longer the cloth supports the steel cut-off and prevents penetration of the molten slag, the more acceptable the material.		
24	**ISO 5660 Part 1 ≡ BS 476 Part 15** Rate of heat release	To determine the heat release rates for essentially flat materials, assemblies, etc.	A cone calorimeter which determines heat release rate using the oxygen consumption principle is used to burn specimens in ambient air conditions, while being subjected to a predetermined external irradiance within the range 0-100 kW/m^2.

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
	Interpretation of Test Data: This test procedure provides a considerable amount of information including data on rate of heat release, mass loss rate, time to ignition and effective heat of combustion. Using additional procedures/ apparatus that are generally fitted as standard on most instruments, data on rates of production of smoke CO and CO2 are also collected. No acceptance criteria are given in the standard, so at present the information can be used for direct comparison of materials only. As experience is 'built-up', performance requirements, for material types or applications, will be set.		
25 26	**Safety of Life at Sea Regulations - 1974** Regulation 3 Fire Resistance **Safety of Life at Sea - 1981** **Regulations (SOLAS 1981** **Regulations)** Class B Panels	To assess and classify the fire resistance of bulkheads and deck panels.	One side of 4.65 m² specimen is exposed on a furnace to a standard time temperature curve which represents a typical cellulosic fire. Observations are made on passage of smoke and flame (integrity), the temperature rise on the unexposed face (insulation) and the rise in temperature of any structural core.
	Interpretation of Test Data: The average temperature of the unexposed side shall not rise more than 139°C above the original temperature, nor will the temperature at one point, including any joint, rise more than a specified amount (Class A 180°C, Class B 225°C) above the original temperature within specified times. Divisions are given a letter classification according their construction type (Class A - steel or equivalent, Class B approved non-combustible material), plus their time to integrity failure (Class A must retain integrity for 60 minutes; Class B must retain integrity for 30 minutes). In addition they are given a numerical time rating, according to their time to insulation failure e.g. an A-30 rated division might be constructed of steel plate protected with a mineral wool fire insulation material, must retain integrity for 60 minutes and take at least 30 minutes for the average temperature of the unexposed face to reach 139°C above ambient. (Note: IMO regulations have been brought together into the SOLAS Consolidated Edition, 2004 and the requirements for classification of the fire resistance of bulkheads are set out in Chapter II-2 Regulation 3. The fire resistance test described above is now specified in detail in IMO Resolution A.754(18), published as part of the IMO FTP Code MSC.61(67)). The test is similar to BS 476 Part 20 (test 36 below) and to ISO 834.)		
27	**ASTM E 648** Critical radiant flux density of floor covering systems	Investigation of the performance of floor coverings	A horizontal specimen is exposed to radiant heat and pilot flame applied at the narrow edge nearest the radiant panel for 10 min and then moved 50 mm above and parallel to the specimen. The test is terminated when any flames are extinguished or if the specimen
	Interpretation of Test Data: The distance travelled by the flame front is converted to critical radiant heat flux required for ignition using a standard radiant heat flux curve.		
28	**Nord Test Method NT Fire 007** Flooring. Fire spread and smoke generation	To determine the tendency of a flooring to spread fire and generate smoke.	A burning wooden crib is placed on the surface of a specimen mounted at 30° to the horizontal and an air flow forced over the exposed

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
			surface. Times of specimen ignition, extinguish of flames and die out of glow are recorded. Damage inflicted on the specimen and its size, and absorption of light by the smoke are observed. Four specimens are tested (two in each direction).
	Interpretation of Test Data: The resulting times, damage distance and smoke generation are used to compare the fire contribution of competing flooring materials.		
29	**BS EN 60332 Part 2-1** Tests on Electric and optical fibre cables under Fire Conditions. Test for vertical flame propagation for single insulated wire or cable. (Formerly BS EN 50265-2-1, formerly BS 4066-1)	The test is intended for type approval testing, and may be referred to in cable standards.	The sample shall be clamped at each end to position it vertically in the middle of a three sided metallic screen.
	Interpretation of Test Data: After burning has ceased, the surface shall be wiped clean and the charred or affected portion shall not have reached within 50 mm of the lower edge of the top clamp.		
30	**BS EN 50266 Parts 1 and 2-1 to 2-5** Common test methods for cables under fire conditions. Test for vertical flame spread on vertically mounted bunched wires or cables. (Formerly BS 4066 Part 3 = IEC 60332 Part 3)	A method of type approval to define the ability of bunched cables to restrain flame propagation in defined conditions regardless of their application, i.e. power, telecommunications etc. If required the Oxygen Index (OI) is also to be measured	Samples are mounted on the appropriate ladder and the burner shall be arranged horizontally at a distance of 75 mm ± 5 mm and the burner flame centred between two cross bars on the ladder for a period of 20 min. If burning has not ceased after a maximum of 1 hr from completion of the flame test the flame should be extinguished.
	Interpretation of Test Data: After burning has ceased, the surface shall be wiped clean. All soot is ignored if the original surface is not damaged. The maximum extent of damage is measured to one decimal place from the bottom edge of the burner to the onset of char. The maximum extent of char should not have reached a height exceeding 2.5 m above the bottom edge of the burner, neither at the front nor the rear of the ladder.		
31	**BS 6387** Specification for performance requirements for cables required to maintain circuit integrity under fire conditions	Lists the applicable tests depending upon the category of cable. Apart from tests relating to Electrical requirements, Bending characteristics, Impact and the requirements of BS 4066 Part 1 there are tests for: Resistance to fire alone Resistance to fire with water Resistance to fire with mechanical shock	The fire tests requires that no fuse shall be ruptured nor any lamp extinguished during the test

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
	Interpretation of Test Data: Cables are categorised by a letter symbol or series of symbols according to the requirements for fire characteristics which they meet		
32	**Def Stan 80-77** **Def Stan 80-78** Fire resistance	To assess the fire resistance of paint on a steel substrate	Specimens are supported vertically in a test cabinet. Flame from a gas burner is allowed to impinge on the unpainted side for 60 seconds. The behaviour of the paint film is observed and tests are made for evolution of flammable gases.
	Interpretation of Test Data: Characteristics determined are blistering, glowing of charred film, detachment from the substrate and evolution of flammable gases.		

2.5 Other Standards

New European fire test standards (ENs) have been adopted, unchanged, as British Standards. Other countries in the European Union have also adopted this policy. This means that the British Standard BS EN ISO 1182 will have technical and editorial equivalence with the German Standard DIN EN 1182 and Dutch standard NF EN 1182.

The NSSN: A National Resource for Global Standards is a search engine that provides users with standards related information from a wide range of standards developers, including organizations accredited by the American National Standards Institute (ANSI), other U.S. private sector standards bodies, government agencies and international organizations. This site has a search engine. It is located at **http://www.nssn.org/search/AdvancedSearch.aspx.**

ASTM has issued a standard for the selection of test methods. ASTM D3814 - 06 Standard Guide for Locating Combustion Test Methods for Polymeric Materials. This guide lists the test methods for the evaluation of the combustion properties of plastics used in various industries. The guide includes standardized North American and global test methods promulgated by ASTM, CSA, NFPA, SAE, Underwriters Laboratories, North American Government Agencies, IEC, and ISO. It does not include industrial tests, user specification tests, or non standard test methods.

2.6 Summary

The design criteria for materials used by the British and US Navies have established the use of standard fire test procedures. In most instances the tests were established by standards testing agencies like ASTM, ISO and British Standards. The Fire Test procedures code of the IMO uses many ISO standards. The various standards/test procedures are very similar and are compared in the next Section.

3 Test Methods

3.1 Background

There are a large number of test methods and apparatus that can be used to evaluate the combustion properties of materials. This can lead to confusion and uncertainties regarding the interpretation of results. There is also considerable overlap of test methods from different international agencies. At present, various testing and standardisation communities are trying to harmonize their methods.[12]

FM Global (Factory Mutual) describes certain test methods in their Property Loss Prevention Data Sheets 1.4 “Fire Tests”.[13] It is noted in this document that “Proper fire protection decisions result from a combination of fire experience and fire testing. As new products formulations arise with little fire experience, fire testing becomes of great importance”.

There are materials performance and related flammability test methods described by numerous organisations including the Underwriters’ Laboratories of Canada (ULC), the American Society for Testing and Materials (ASTM), British Standards, the International Organisation for Standardization (ISO), and Underwriter’s Laboratory (UL). These methods are referenced in materials requirements and specifications such as the Ministry of Defence Standard 07-247 [14] or the United States Mil-Std-2031.[15]

The tests are frequently specific; for example the American Society for Testing and Materials (ASTM) lists dozens of test methods for the evaluation of flammability characteristics of: general building materials[16] (door, windows, roof assemblies, floor coverings and etc.), petroleum products and lubricants,[17] paints and related coatings,[18] plastics and elastomers,[19] composite materials[20] and electric cables.[21] The Underwriters’ Laboratories of Canada (ULC) lists methods specific to complete assemblies such as doors assemblies or tin-clad fire doors.[22,23]

Some test methods are discussed in the next Section.

3.2 Test Methods

3.2.1 Large Scale Tunnel Testing (Flame Spread Index)

Tunnel testing is used for determining the flame spread and smoke density from burning materials placed on a horizontal surface. The apparatus can also be equipped to capture combustion gases for analysis. This method is often referred to as the ‘Steiner Tunnel Test’.

Materials tested in this manner include ceiling and flooring assemblies, light diffusers and lenses and also electric or optical cables with or without cable trays as described in the test methods CAN/ULC-S102,[24] CAN/ULC-S102.2,[25] CAN/ULC-S102.3,[26] CAN/ULC-S102.4,[27] ASTM E-84[28] and UL910.[29] Materials to be tested are placed in the fire test chamber (tunnel), which is 7.6 m long and approximately 0.5 m wide, and exposed to an open high energy flame source. Flame spread, temperature and smoke generation (smoke density) data are recorded.

3.2.2 Radiant Panel Flame Spread

Radiant Panel Flame Spread can be used to measure the surface flame spread of cellular plastics, as described in (ASTM D 3675)[30] and for building materials (ASTM E 162).[31] Samples of the materials to be tested (approximately 150 mm x 460 mm) are mounted vertically and exposed to a radiant heat source.

3.2.3 Bomb Calorimetry

A bomb calorimeter is a bench top instrument used for measuring the calorific value or heat from combustion of the sample being tested. The heat of combustion is determined on the basis of the observed temperature rise in the bomb calorimeter. The method can be used for the testing of a variety of fuels (ASTM D 4809 and ASTM D 240)[32] and numerous organic materials. It is also referenced in ISO 1716 for building materials.[33]

3.2.4 Oxygen Consumption Calorimetry

Oxygen consumption or oxygen depletion calorimetry is used to measure the heat release rates of materials. The method can be used on a large scale (room size), intermediate scale, or for small scale testing (cone calorimeter). The method provides data on the heat release rate (usually in kW or MW) which is defined by the NFPA as “the rate at which heat energy is generated by burning”.[34] The heat release rate per unit area is the heat flux or heat transfer rate from all fire propagation modes (conduction, convection and radiation); it is a principal parameter used to describe fire spread.[35]

The apparatus measures oxygen depletion (or conversely oxygen consumption by the materials being burnt) which is directly proportional to the net heat of combustion.[36] The materials to be tested are placed on a load-cell and weight loss is recorded in real time to afford a determination of the effective heat of combustion as well. The effective heat of combustion is the energy generated by the combustibles in the test and differs from the theoretical heat of combustion which is a measure of the total caloric content of the materials. The theoretical heat of combustion assumes complete combustion of the sample. As materials are not always fully consumed in a fire, the effective heat of combustion obtained from oxygen depletion calorimetry provides a better measure of the heat output of the materials in a real fire scenario.

Parameters that are obtained from this method include: Heat Release Rate, Total Heat Release, Effective Heat of Combustion and Time to Ignition (Ignitability). Smoke density is also measured. The National Fire Protection Agency (NFPA) states that the results of this test method are very useful in evaluating materials or products, as input data for mathematical fire modelling, in the design of new materials or products and in research and development.

The large scale setup is detailed in ISO 9705[37] and ASTM E 2067.[38] The room/corner test (ISO 9705) is ideal for evaluating the fire characteristics of an ‘in room’ fire scenario. The large scale system is especially useful for items, such as furniture and large products with irregular shapes that cannot be evaluated in a small scale test.

The intermediate scale (ICAL) practice is described in ASTM E 1623.[39] A similar intermediate scale method for analysing samples measuring approximately 150mm x 150mm is found in CAN/ULC S128 (using the Ohio State University Oxygen Consumption Apparatus).[40]

The methodology for smaller (bench scale) oxygen consumption calorimetry is detailed in CAN/ULC S135-04[41] and ASTM E 1354.[42] The apparatus used for this test is the Cone Calorimeter. This test method is also described in ISO 5660-1 and ISO 5660-2, [43] and in British Standard BS 476 part 15.[44] Lastly the NFPA (National Fire Protection Association) also specifies the method in their standard NFPA 271 (formerly NFPA 264).[45]

For the Cone Calorimeter test method, the sample, measuring 10 cm x 10 cm (and up to 5 cm thick) is exposed to heat fluxes between $0kW/m^2$ and $100kW/m^2$ using a truncated cone radiant heater (hence the term cone calorimeter) and ignited externally; although, as described in NFPA 271, the test can be done with or without the external igniter. Samples are typically mounted horizontally but allowances are made in the CAN/ULC S135 method for vertical mounting of the samples. Lastly, as with the large scale and ICAL oxygen consumption calorimetric methods, combustion gases can be captured for analysis.

The following methods refer to the oxygen consumption calorimetric technique:

- Full scale room fire tests: ISO 9705, ASTM E 603.[46]
- Testing the contribution of wall coverings: ASTM E 1740[47], NFPA 265 [48]
- Test for Heat Release, Flame Spread, Smoke Obscuration and Mass Loss of Insulating Materials in Electrical of Optical Fiber Cables on both large scale: ASTM D 5537 and ASTM D 5424[49], and UL 1685, [50] as well as on a smaller scale using the cone calorimeter device: ASTM D 6113.[51]
- Fire testing for upholstered furniture on large scale: ASTM E 1537,[52] and on small scale with a cone calorimeter: ASTM E 1474.[53]
- Fire testing of mattresses on a large scale: ASTM E 1590,[54] and on a small scale: ASTM E 1474.

- Foamed Plastics (decorative): UL 1975.[55]

3.2.5 Thermal Capacitance Calorimetry

The rate of heat transfer to a material can be measured using a Thermal Capacitance (Slug) Calorimeter. The method, described in ASTM method E-457[56], measures the rate of transfer of thermal energy per unit area into a known piece of material (slug). Regardless of the source of thermal energy (radiative, convective, or a combination thereof) the measurement is averaged over the calorimeter surface. However, if a significant percentage of the total thermal energy is radiative, consideration should be given to the emissivity of the slug surface. This method has been used to measure the efficiency of fire resistive materials (FRMs).[57]

3.2.6 Combustion Toxicity Test

The combustion process releases smoke which is comprised of gases and suspended particles (soot). Smoke release can start during the incipient (smoldering) stage of a fire and continue as the fire develops.

The ASTM method E 1678, Standard Test Method for Measuring Smoke Toxicity for Use in Fire Hazard Analysis,[58] uses the NIBS (*American*, National Institute of Building Science) radiant heat combustion system. The combustion system produces a radiant heat flux of $50 kW/m^2$ for 15 minutes. The test is also known as the NIST radiant furnace method. Tests are done on small samples approximately 75 mm x 125 mm. The method describes both trapping of the products of combustion for chemical analysis and animal lethality studies for a 30 minute exposure period; the method includes animal post-mortem blood testing for carboxyhemoglobin levels.

ISO 13344 also provides a means for estimating the toxic potency of fire effluents.[59] The lethal toxic potency values are determined after 30 minute exposures of test animals. The combustion products analysed include: carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2) (vitiation), hydrogen cyanide (HCN), hydrogen chloride (HCl), hydrogen bromide (HBr), hydrogen fluoride (HF), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), acrolein and formaldehyde. This method also discusses the limitations of small scale tests. The National Fire Protection Agency also uses the ISO 13344 method in its Standard NFPA 269.[60]

Another method uses the steady state tube furnace (also known as the Purser furnace) which was developed to replicate the conditions that lead to the generation of toxic products in real fires under various conditions. This bench scale method is described in ISO TS 19700;[61] and is similar to the British Standard method BS 7990.[62] The sample is moved into the tube furnace that is supplied with air in a manner that replicates different stages of the fire (different ventilation levels). The sample feed rate, furnace temperature and airflow can all be controlled so that all stages of fire development can be investigated.[63] Toxic effluents released during the incipient stage (smouldering), development stage (fuel controlled stage), and full flaming combustion (ventilation controlled stage) can be measured. The International Organisation for Standardisation (ISO) describes the method ISO/TS 19700 as “a tube-furnace method for the generation of fire effluent for the identification and measurement of its constituent combustion products, in particular, the yields of toxic products under a range of fire decomposition conditions.” They state further that, “The test method described can be used solely to measure and describe the properties of materials, products or systems in response to heat or flame under controlled laboratory conditions. It is not suitable to be used by itself for describing or appraising the fire hazard of materials, products or systems under actual fire conditions or as the sole source on which regulations pertaining to toxicity can be based."

The Toxicity Index is described in the newly rewritten version of NES 713.[64] It is based on the combustion products from very small samples (often only 1 gram). Toxic constituents analysed include: carbon dioxide (CO_2), carbon monoxide (CO), ammonia (NH_3), formaldehyde (HCHO), hydrogen chloride (HCl), hydrogen bromide (HBr), hydrogen fluoride (HF), hydrogen cyanide (HCN), hydrogen sulphide (H_2S), nitrogen oxides (NO_X), sulphur dioxide (SO_2), phenol (C_6H_5OH) and acrylonitrile (CH_2CHCN).

A general guideline for the assessment of the fire threat to people is presented in ISO 19706 "Guidelines for Assessing the Fire Treat to People". It encompasses the development, evaluation and use of relevant quantitative information in fire hazard and risk assessment. This information, generally obtained from fire-incidence investigation, fire statistics, real-scale fire tests and from physical fire models, is intended to be used in conjunction with computational models for analysis of the initiation and development of fire, fire spread, smoke formation and movement, chemical species generation, transport and decay, people movement, fire detection and suppression.[65]

The related document ISO 13571 "Life-Threatening Components of Fire - Guidelines for the Estimation of Time Available for Escape Using Fire Data" is, as ISO indicates, "Intended to be used in conjunction with models for analysis of the initiation and development of fire, fire spread, smoke formation and movement, chemical species generation, transport and decay and people movement, as well as fire detection and suppression."[66]

3.2.7 Smoke Obscuration (NBS Smoke Chamber)

Smoke production, or alternatively smoke obscuration, is a significant concern as it will often impede egress from a fire. The most widely used laboratory scale method for quantifying smoke generation from burning materials uses the National Bureau of Standards (NBS) Smoke Chamber. The method is described in ASTM E 662,[67] ISO 5659-2,[68]and related ASTM D 2843[69] for the burning of small plastic samples. It is also referred to in the UK Ministry of Defence standard NES 711.[70]

The materials to be tested are burned in a flaming or non-flaming (smouldering) mode. The optical density of the smoke accumulated in a closed chamber (smoke box) is measured photometrically. Samples can be mounted vertically (typical) or horizontally and the radiant heat flux to which the samples are exposed can be set in a range between $10W/m^2$ and $50kW/m^2$. Typically testing is done using a radiant heat flux of $25kW/m^2$.

3.2.8 Limiting Oxygen Index (LOI)

The Limiting Oxygen Index (LOI) is used to determine the relative flammability characteristics of polymeric materials. The 'LOI' is the minimum concentration of oxygen required to support downward burning of the vertically mounted sample. The measurement is done using a mixture of oxygen and nitrogen that flows in at the bottom of the vertically mounted specimens. The higher the LOI values the greater the resistance of the material to burning (more fire retardant). It is used to test relatively thin materials such as polymer sheets or films, coatings, fabrics, cellulosic materials (paper, veneers and etc.), and elastomers.

The ISO Methods Set 4589 including a general guide ISO 4589 part 1: Guidance[71] and the methods part 2: Ambient Temperature Testing[72]; part 3: Elevated Temperature Testing[73] and ASTM D 2863[74] specify the LOI procedure for measuring the minimum concentration of oxygen to support flaming combustion of plastics. The test specimens measure approximately 80 mm x 150 mm and can be up to 10 mm thick. They can be mounted to test for top surface ignition or propagating ignition. As described in the ASTM procedure, "this test method measures and describes the response of materials, products, or assemblies to heat and flame under controlled conditions, but does not by itself incorporate all factors required for fire hazard or fire risk assessment of the materials, products, or assemblies under actual fire conditions."

3.2.9 Fire Testing of Plastics and Electrical Components

The most referenced method for fire testing of plastics, and hence the method for which there is greatest amount of data for comparison, is UL – 94 and similar ISO and IEC methods.[75] Specimens of the material to be tested are placed in either a horizontal or vertical position, depending on the specification, and are subjected to an open flame ignition source for a specified period of time. The test is a small scale screening procedure that compares a material's tendency either to self-extinguish or to allow flame spread after ignition and was designed for testing small plastic parts and components.

3.2.9.1 UL-94

UL-94 has been harmonized with ISO methods ISO 9772 [76]and ISO 9773 [77] as well as IEC (International Electro-technical Commission) methods 60695 and 60707 [78] IEC is an organization that publishes international standards for all electrical, electronic and related technologies. The IEC procedures refer to testing of plastics as well as other non-metallic materials.

The test methods described in UL-94 (and the related methods) provide classification systems which can be used for the pre-selection of component materials; typically the pre-selection of the material can be considered providing positive results are obtained for a test sample with a thickness equal to the smallest thickness of that material used in the intended application.

UL 94 describes 12 flame classifications that are assigned to materials based on the results of small-scale flame tests. The classifications (listed in descending order) for are for three groupings of materials; A, B and C.

- A. Materials commonly used in manufacturing enclosures, structural parts and insulators found in consumer electronic products. The six classifications are: 5VA, 5VB, V-0, V-1, V-2, HB.
- B. Low-density foam materials commonly used in sound-deadening material. The three classifications are: HF-1, HF-2, HBF.

- C. Very thin films, generally not capable of supporting themselves in a horizontal position; these are usually assigned to substrates on flexible printed circuit boards. The three classifications are: VTM-0, VTM-1, VTM-2.

When reviewing the flame ratings for plastic materials, a material classified as 5VA or 5VB is subjected to a flame ignition source that is approximately five times more severe than that used in the V-0, V-1, V-2 and HB tests. Also, 5VA and 5VB rated specimens may not drip any flaming particles. The HB test, a horizontal burn test, is a less severe test than any of the vertical (V) burn methods. Moreover, a flame rating for one type of material (A. B, or C) cannot be compared to the classification of another type of material; for example a flame rating of VTM-0 cannot be considered equivalent to a V-0 rating as the test methods are quite different. Likewise, VTM-1 and VTM-2 cannot be considered equivalent to V-1 and V-2 respectively.

3.2.9.2 Small Component Testing

Method UL 1694 is related to UL-94 and includes Tests for Flammability of Small Polymeric Component Materials.[79] UL 1694 is applicable to small components that contain non-metallic materials that cannot be fabricated into standardized specimens of the minimum thickness required for UL-94 or related tests. The test is carried out to determine if the test flame causes ignition of the small component, or if a combustible small component ignited by the test flame has a limited extent of burning and burning time, or if a combustible small component that is totally consumed has a limited burning time.

IEC method 60695-11-5 (Needle Flame Test)[80] is related to UL 1694; it specifies a test to simulate the effect of a small flame, which may result from electrical fault conditions, on the sample of interest. It is considered to be applicable to electrotechnical equipment, its sub-assemblies and components and to solid electrical insulating materials. A technically equivalent method for the burning of small samples in a horizontal position is also described in ASTM D635-06. These tests and related requirements do not cover plastics used as building construction or finishing.

3.2.9.3 Resistance to Ignition

A material's ability to resist ignition by electrical ignition sources is an important factor in the selection a material for use in electrical equipment. The evaluation of a material's resistance to ignition and surface tracking characteristics is described in UL 746A (and UL 746C). Similar test procedures are described in IEC 60112 and IEC 60695[81, 82]. Several electrical ignition sources are considered: overloaded (overheated) electrical conductors and components; arcing between components such as the open contacts of switches and relays; and arcing at broken or loose connections, e.g., in splices or at terminals. Polymeric materials in direct contact with or in close proximity to overloaded or arcing electrical parts could ignite.

The basic tests used to evaluate a material's ability to resist ignition are the hot-wire ignition (HWI), high-current (high-amp) arc ignition (HAI), high-voltage arc tracking rate (HVTR) and glow wire ignitability (GWI) tests. The HWI test is used to determine the resistance of a material to ignition when exposed to abnormally high temperatures resulting from a component failure, for instance, or from a component carrying far more than its rated current. The HAI test determines the material's ability to withstand electrical arcing either directly on or just above the surface of the plastic material. This can occur in the presence of open switch contacts or in the event of the failure of an electrical connection. The HVTR for a material is expressed as the rate (in inches per minute) that a tracking path can be produced on the surface of the material under standardized test conditions. This test is related to the establishment of an electrically conductive path on the surface of a solid, insulated material as a result of electrical stress. Lastly, the GWI test measures the resistance of a material to ignition.

3.2.10 Polymer Fire Propagation Testing (FPA)

ASTM method E-2058 is used to determine maximum heat release rates occurring under vertical fire propagation sustained by the materials heat flux rather than an external source (external radiant heat flux).[83] The test is carried out on a vertically mounted 0.3 m (high) and 0.1 m (wide) sample with ignition occurring at the bottom. The heat flux resulting from the relatively small fire will not necessarily represent how the sample might perform in larger scale fires.[84] Testing in oxygen enriched atmospheres (up to 40% oxygen) or in oxygen poor environments (less than 21% oxygen) can be carried out to simulate propagation results from large scale burn tests. This fire test determines and quantifies synthetic polymer material flammability characteristics as they relate to the propensity of materials to support fire propagation. Data obtained includes time to ignition, chemical and convective heat release rates, mass loss rate and the effective heat of combustion.

3.2.11 Flame Spread Index

There are several flame spread test methods; and many of these are described in the ISO methods set ISO 5658 “Reaction to Fire Tests – Spread of Flame”. Guidance on ISO flame spread tests which includes a description of the principles of flame spread and a classification of different flame spread mechanisms is provided in ISO 5658-1[85]. These methods include ISO 5658-2 which measures the lateral flame spread along the surface of a specimen mounted in the vertical position. This test produces data that can be used to compare the performance of materials, composites or assemblies that are used primarily as the exposed surfaces of walls (bulkheads) in buildings and transport vehicles including ships.[86] An intermediate scale method is described in ISO 5658-4.[87]

Flame Spread is also described in ASTM E 1321. The test allows the derivation of relevant material flammability parameters such as minimum exposure levels for ignition, thermal-inertia values, and flame-spread properties.[88] The method is intended for evaluation of relatively flat systems.

3.2.12 Single Burn Item (SBI)

The single burn item (SBI) test, method EN 13823,[89] is required for reaction-to-fire classification of construction products in the European Union.[90] The European commission requires (or will require) that all European Union members use this method rather than their own to evaluate the fire behaviour of most construction materials.

The test is carried out on two samples held at a 90º angle to each other to form an open corner. One sample, referred to as the long wing is 1 m. wide while the second, known as the short wing is 0.5 m. wide; both the long and the short wings are 1.5 m. high. The mounted samples are exposed for 20 minutes to an open propane flame.

The test apparatus has instrumentation in its exhaust ducting to monitor temperature, gas velocity, chemical composition products (O_2, CO_2 and CO) and light obscuration. Smoke production rates and heat release rates can also be monitored; the latter using the oxygen consumption technique. In addition lateral flame spread can be monitored.

3.2.13 Further Large Scale Tests with Applications to Marine Testing; Including the Room/Corner Test

Total room testing can be carried out using the method described in ISO 9705.

The large scale fire exposure testing of building assemblies and construction materials is addressed in ULC S101. This method covers fire endurance tests applicable to walls, partitions, floors, roofs, ceilings, columns, beams, and girders, as well as to some components of these building sub-assemblies. It is noted in the method the fire endurance period established by this test method indicates performance only during the fire exposure period and shall not be construed as having determined suitability for use after fire exposure.[91]

ASTM E 119[92] and/or UL 263[93] evaluate the effects of fire on structural assemblies. The ASTM method scope indicates that “It is the intent that tests conducted in accordance with these test methods will indicate whether structural members of assemblies or fire-containment wall assemblies will continue to perform their intended function during the period of fire exposure.” These tests are not indicative of the suitability of structural assemblies for use after fire exposure. The tests have numerous limitations including: no evaluation of the contribution to the fire hazard through the generation of smoke and toxic gases, no simulation of fire behaviour of joints or connections between structural elements, no measurement of flame spread, and no evaluation of the duration for which certain building elements retain their structural integrity.

UL 1709 describes testing to measure the ability of materials to resist rapid temperature rise.[94] The method is carried out on full scale systems to evaluate the performance of fire resistant coatings applied to structural members. However, the method can also be used to evaluate smaller scale systems.

ASTM method E 1529[95] is a fire standard used for determining the fire response of columns, girders, beams or similar structural members in facilities subject to large hydrocarbon pool fires.

3.2.14 Fire Testing of Cables

Fire test methods for cables include the SBI method (Single Burn Item), the NBS Smoke Chamber and the Limiting Oxygen Index (LOI) tests. Fire testing of cables is also addressed in the section on oxygen depletion calorimetry (in section 2.4).

The Underwriters Laboratories of Canada method ULC-S139[96] describes procedures to determine the ability of cables to maintain circuit integrity while exposed to fire conditions. The IEC describes similar evaluations of cables and circuit integrity in methods set 60331 (parts 1, 2, 3, 11, 12, 21, 23, 25, 31).[97]

Additional tests procedures for combustion gases evolved during the burning of cables are presented in IEC methods set 60754. These include 60754 - Part 1 Determination of the amount of halogen acid gas, and Part 2: Determination of degree of acidity of gases evolved during the combustion of materials taken from electric cables by measuring pH and conductivity.[98]

3.2.15 Flammability of Marine Surface Finishes (Coatings, Fabrics, Veneers and etc.)

The measurement of burning characteristics of marine surface finishes used on non-combustible substrates are described in ASTM method E 1317.[99] It is noted in this method that "This test provides a means for evaluation of the flammable performance of surface finish materials used in construction and outfitting ships." The test evaluates ignitability, heat exposure required for continued burning and heat release data. It closely follows the test procedure described in IMO Resolution A.653 (16).[100]

Bulkhead, ceiling and deck samples having painted finishes, fabric coatings, veneers and/or any associated adhesives are tested on one or both exposed sides. Typically the as-used exposed surface is tested, for instance, the upper side of deck and flooring material or the underside of ceiling finish materials.

Flame resistance testing specific to textiles using vertically mounted samples is described in ASTM D 6413-08 "Standard Test Method for Flame Resistance of Textiles (Vertical Test)."

3.2.16 Fire Stops

A method for the evaluation of fire stop materials such as those used to fill openings in walls or floors where cables, cable trays, conduits ducts or pipes or any 'poke-through device' are used is described in ULC-S115.[101] This test method was established in accordance with standard ULC-S101 on building construction and materials. Testing of fire resistive materials is also described in method UL 1709 (section 2.13).

3.3 Listing of Test Methods Described

Test methods used to evaluate the fire and flammability properties of non-metallic materials are listed below.

ULC (Underwriter's Laboratories of Canada)

- CAN/ULC-S101-07 (2007) "Standard Methods of Fire Endurance Tests of Building Construction and Materials" CAN/ULC-S102-07 (2007) "Standard Method of Test for Surface Burning CAN/ULC-S102.2-07 (2007) "Standard Method of Test for Surface Burning Characteristics of Flooring, Floor Covering, and Miscellaneous Materials and

Assemblies". CAN/ULC-S102.3-07 (2007) "Standard Method of Test of Light Diffusers and Lenses". CAN/ULC-S102.4-07 (2007) "Standard Method of Test for Fire and Smoke Characteristics of Electrical Wiring and Cables".

- CAN/ULC-S103-83 (1983) "Standard Specification for Tin-Clad Doors"
- CAN/ULC-S104-80 (1980) "Standard Method of Tests of Door Assemblies"
- CAN/ULC-S115-05 (2005) "Standard Method of Fire Tests of Firestop Systems" CAN/ULC-S128-1992 (1992) "Standard Method of Test for Determination of Degrees of Combustibility using an Oxygen Consumption Principle (Ohio State University Apparatus)"
- CAN/ULC-S135-04 (2004) "Standard Method of Test for Determination of Degrees of Combustibility of Building Materials using an Oxygen Consumption Calorimeter (Cone Calorimetry)"
- CAN/ULC-S139-00 (2000) "Standard Method of Fire Test for Evaluation of Integrity of Electrical Cables"

<u>ASTM (American Society for Testing and Materials)</u>

- D 240-02 (2007) "Standard Test Method for Heat of Combustion of Light Hydrocarbon Fuels by Bomb Calorimeter".
- D 457-08 (2008) "Standard Test Method for Measuring Heat-Transfer Rate Using a Thermal Capacitance (Slug) Calorimeter"
- D 635-06 (2006) " Standard Test Method for Rate of Burning and/or Extent of Time of Burning of Plastics in a Horizontal Position"
- D 1623-04 (2004) "Standard Test Method for Determination of Fire and Thermal Parameters of Materials, Products, and Systems Using an Intermediate Scale Calorimeter (ICAL)"
- D 2067-08 (2008) "Standard Practice for Full-Scale Oxygen Consumption Calorimetry Fire Tests"
- D 2843-99, 2004 (2004) "Test Method for Density of Smoke from the Burning or Decomposition of Plastics"
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4 Fire Testing Parameters

4.1 Introduction

There has been a huge amount of research in the areas of fire tests and fire testing. For instance, an ISI Web of Science search using “fire test” as a key word gave 73561 hits. Searching “fire test” and “composite” gave 688 hits but further searching (IEE explore, Goggle Scholar, Firedoc) showed that this was only a fraction of the material available. It appears that much of the research is conducted in Government Laboratories and Research Institutes and has not been published in the open literature.

The stages of a fire, ignition, developing fire and fully developed fire are shown in Figure 1. Parameters such as ignitibility, flammability, flame spread and heat release are related to these stages. These parameters can be evaluated using a number of lab scale tests.

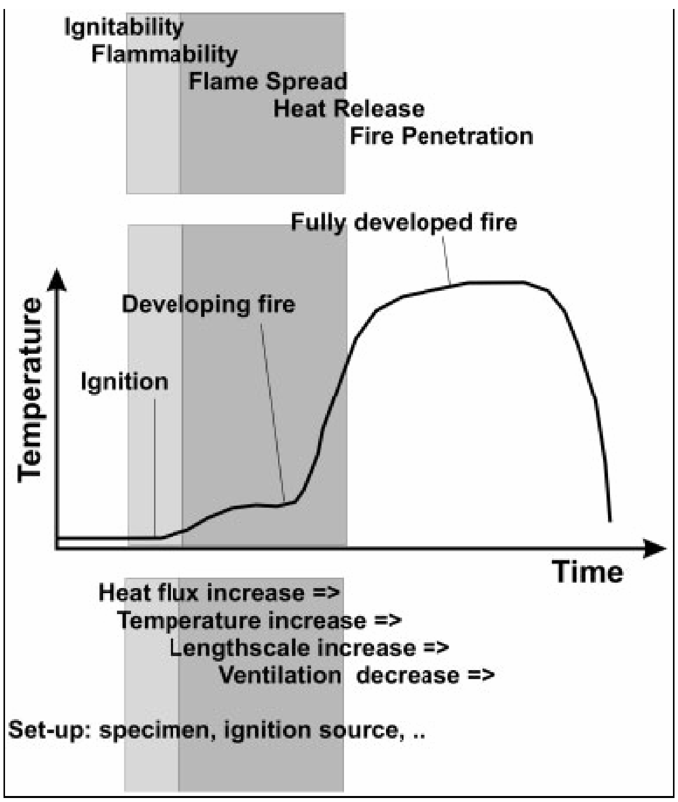

Figure 1. The stages of a fire.

4.2 Oxygen Temperature Index

The Oxygen Index Test is perhaps the most economical and precise quality control test of combustible materials. The ease of use and high level of precision have made this technique a primary characterization and quality control tool for the plastic and electric cable industries. The test is specified by several military and transport groups. It is the basis of an ISO test for plastics.[102]

The Oxygen Index describes the tendency of a material to sustain a flame. The test provides a convenient, reproducible means of determining a numerical measure of flammability. The test method uses inexpensive equipment and requires a small sample. The method has been used to systematically investigate the relative flammability of fire-retarded materials.

The standard procedure involves the ignition of the top of the sample using a gas flame which is withdrawn once ignition has occurred and the determination the lowest oxygen concentration in an upward flowing mixture of nitrogen and oxygen which just supports sustained burning. The critical criterion typically is a minimum burning length: either specifying that the sample must burn for a certain length of time or that a specified length of material be consumed. The effectiveness of fire retardants is measured by studying the change in the critical oxygen concentration that the fire retardants produce as a function of their concentration.

4.3 Ignitability

Early ignitability testing was based on exposure of a small specimen to temperature in a furnace. The test procedure consisted of determining the furnace temperature at which ignition was first observed. A widely used procedure utilized the Setchkin furnace, developed in the late 1940s. However, this test could not be used to study composite materials or to compare results for specimens with different thicknesses.

As the technique evolved, larger specimens could be accommodated and the time needed to achieve ignition for a given heating flux was determined. Consequently, ignitability apparatuses have been designed where the heating source was primarily: (1) radiant heat, (2) convective heat, or (3) heating from direct flame impingement. This method has been successfully used in the cone calorimeter and the results are accepted as the blue ribbon standard for ignitability.[103]

4.4 Flammability

Any material capable of burning with a flame is considered flammable. A flame is a stream of the gaseous fuel and oxidizing agent involved in the combustion process. It produces heat and combustion products. The most elementary view of flammability is that three things, fuel, oxidizing agent, and heat, are necessary to start a fire. Highly reactive molecular species must be present in sufficient concentrations to insure the continuation of chemical chain reactions involved in the combustion process.

Although it may be simple to determine if a material is capable of supporting flaming combustion, measuring or predicting the flammability hazard of a material is a challenging and complex task. The flammability hazard of a material is dependent on its fuel content and factors such as ventilation, oxygen concentration, and radiation feedback from the surroundings. The difficulty of extinguishment of the burning material should also be considered when assessing its flammability hazard. There is no single test or simple index for flammability that adequately captures the effect all these parameters.

The Oxygen Index apparatus (see above) or the Oxygen calorimetry[104] can be used to measure the flammability of a material.[105]

4.5 Flame Spread

Flame spread is an extremely important parameter especially in enclosed spaces where the spread of flame may have direct impact on survivability in that space. Flame spread testing is a measure of material flammability and the ability of material to limit the severity of fires. Four of the standard flame spread tests were recently reviewed.[106] Those four standard tests are:

- ASTM E1321-97a – Standard Test Method for Determining Material Ignition
- BS476: Part 7: 1997 – Method of test to determine the classification of the surface spread of flame of products,
- ASTM E84-99 or ANSI/NFPA 255-2000 – Standard test method for Surface Burning Characteristics of Building Materials, and
- ISO 9705: 1993(E) Fire Tests – Full-scale room test for surface products.

The four tests are compared below.

ASTM E1321 and BS476: Part 7 are bench-scale tests for assessing material specimens of smaller size than the actual construction in which they will be used. It is difficult to assess the structural performance of a material or construction component in real fires using these methods. Thermostructural failures and falling of non-structural members in actual fire conditions might affect the flame spread.

Horizontal flame spread using ASTM E1321 and BS476: Part 7 is evaluated with materials mounted in the vertical position. This may be problematic for the evaluation of materials such as carpets that are used in horizontal orientation.

ASTM 1321, BS476: Part 7 and ASTM E84/NFPA 255 allow testing a product by itself or attached to another product. Flame spread from a wall material to a ceiling material or from a ceiling material to a wall material cannot be studied. In actual fires, droplets of the burning material might fall from the ceiling onto the wall or floor. This and the heat flux from the hot gas layer would accelerate the flame spread.

Using ISO 9705, wall and ceiling materials can be tested in their normal orientations. Flame spread from one wall to adjacent walls and ceiling can be observed. Experimental results for materials in different configurations, for instance testing wall and ceiling materials separately and together as a unit, are different.

Flame spread is an especially important parameter for composites and especially when they in closed spaces.[107] Flame spread has also been modeled[108,109].

4.5 Heat release rate [adapted from[110]]

When the cause of a serious fire is being investigated, one of the most commonly asked questions is: Why did the fire get so large? For many years the 'large' question could only be answered qualitatively, since a means of quantifying a fire size in engineering units did not exist. Eventually it was recognized that since heat is the energy output of the fire and scientific means exist for measuring energy, the problem was solvable. Heat is measured in units of Joules. What is usually of more interest is the rate at which heat is released, not the total amount heat released. The heat release rate (HRR) is in Joules per second or Watts.

For polymer manufacturers and others developing new materials, it is often sufficient to use bench-scale testing. This is because they want to determine the relative differences in fire behaviour of materials, while the actual product performance may not be relevant to them since they do not make the end product.

Bench-scale measurement of HRR

The cone calorimeter is considered the most significant bench scale instrument in fire testing. The cone calorimeter analyses the combustion gases and measures smoke released from a burning sample, and oxygen, carbon monoxide and carbon dioxide concentrations. This apparatus has been adopted (ISO 5660-1 and ASTM E 1354) for measuring the heat release rate (HRR) of a sample. It has been shown that most fuels generate approximately 13.1 MJ of energy per kg of oxygen consumed. Therefore, HRR is based on the fact that the oxygen consumed during combustion is proportional to the heat released. The data collected from this bench scale fire test can be used for fire modelling, prediction of real scale fire behaviour, and pass/fail tests.

HRR is considered by many fire engineers to be the single most important variable in describing fire hazard. There are three reasons for this. The first is that HRR is the driving force for fire, i.e., heat makes more heat. This does not occur, for instance, with carbon monoxide. Carbon monoxide does not make more carbon monoxide. Secondly, most other parameters are correlated with the HRR. Smoke, toxic gases, temperature and other fire hazard variables generally increase as HRR increases. The third is that a high HRR indicates a high threat to life. Some fire hazard parameters do not relate directly to threats to life. For instance, if a product is easily ignitable or has a high flame spread rate, this does not necessarily mean that fire conditions are expected to be dangerous. Such behaviour may merely suggest that a material has a propensity to be involved in nuisance fires. High HRR fires, however, are intrinsically dangerous. This is because high HRR causes high temperatures and high heat flux conditions, which are often lethal to occupants of a space.

Although HRR has been studied for years, there is still considerable amount of research on HRR especially with respect to methods to correlate HRR with other fire parameters [111], [112], [113] and the uncertainty inherent in these correlations as well as other methods to test for HRR. In fact there were over 700 reports since 2000 (FireDoc) with HRR as a keyword.

Recently the various methods used to evaluate HRR have been reviewed.[114] The heat release rate of a material can be measured by the cone calorimeter or the fire propagation apparatus[115] as well as other apparatus. It is applicable to all materials including non-combustible materials, polymers,[116] and energetic materials.[117] An important new study showed that of heat release rates are additive and they are potentially useful tool in testing products made from more than one material[118]

Recently the possibility of increasing heat release rate testing throughput by correlating HRR with flame size has been investigated[119]. The applicability of this approach is limited by the production of smoke and flame spread issues.

4.6 Smoke

Smoke is regarded as a major hazard in fire situations as it hinders visibility and therefore movement. Numerous methods have been devised for quantifying smoke generation from burning materials, but the most widely used laboratory-scale technique is the National Bureau of Standards (NBS) Smoke Box (ASTM E 662) Test. Test specimens are burned in either the flaming or non-flaming (smouldering) mode. The optical density of the smoke is measured photometrically and data are presented graphically as cumulative optical density versus time curves. Maximum values are quoted either as measured or as normalized values that account for specimen mass loss during the test. Although specimens are usually mounted vertically and the incident radiant heat flux is usually set at 25 kW/m^2, horizontally mounted specimens (an advantage for testing certain thermoplastic materials which drip away from the flame in the vertical assembly), and heat fluxes in the range 10 – 50 kW/m^2 can be used.

Testing of materials in the horizontal orientation is preferred, especially for regulatory purposes, because such testing is much more reproducible and repeatable than testing performed in the vertical orientation and usually represents a more severe exposure condition. When the vertical orientation is used, it is more difficult to control and ignite the pyrolysates released from the material's surface. Convective heat flow along the exposed surface of the sample is also a complicating factor.

Much of the research into the effect of smoke has now shifted towards the identification of toxic ingredients within the smoke. Smoke and toxic gas generation have been extensively reviewed with respect to their effect on human health[120,121,122] Recently the measurement of smoke and combustion products using small scale tests has been reviewed.[123] Many groups use the cone calorimeter (444 hits in the last 9 years in science direct), while others are developing the tube furnace[124] . Smoke generated by the components of high speed craft has been studied[125] .

4.7 Combustion Gas Generation (adapted from 120)

Along with heat, the burning of every combustible material produces smoke -gases and aerosols - that, in sufficiently high concentration, present hazards to people in the vicinity. Materials near those already burning may also contribute to the smoke as they decompose from exposure to the heat from the fire. Hazards associated with smoke include sensory irritation of the upper and/or lower respiratory tract which can affect movement and the ability to negotiate escape. At higher exposure levels smoke can lead to incapacitation or death. Inhalation of asphyxiant fire gases results in central nervous system depression which is manifested in impaired judgment, disorientation, loss of motor coordination, unconsciousness, and ultimately death

The nature and concentration of smoke depends on a variety of factors. These include the quantity of the material that is burning, whether the material is pyrolyzing or combusting, ventilation conditions and the distance from the fire source. Thus, smoke toxicity is not a singular property of a product.

4.7.1 Generation of fire gases

Smoke is commonly defined as “the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion.” The particulates and aerosols produced affect visibility in a space. The formation and toxicity of the gases commonly produced in fires are discussed in the following sections.

The main gases released in fire are carbon based; carbon monoxide and carbon dioxide. The relevance of these gases has been studied for many years but new interest has arisen from the investigation of polymers (see for example.[126]).

4.7.2 Carbon Dioxide

In well-ventilated, flaming fires, nearly all the carbon lost from the combustibles is converted to carbon dioxide (CO_2). Even in post flashover fires, the fraction of carbon converted to CO_2 is fairly high. Thus, the yield of CO_2 has been used to estimate the burning rate of products when a direct measurement of mass loss is not possible. Carbon dioxide is also generated in smouldering fires, but the carbon monoxide released from a smouldering fire is far more hazardous.

4.7.3 Carbon Monoxide

Carbon monoxide (CO) is produced by both smouldering and flaming combustion. The production of CO from smouldering fires is quite slow, but these fires are not accompanied by vigorous mixing and diluting of the combustion products with room air. Thus, lethal concentrations of CO can be generated in the immediate vicinity of the fire within 10 minutes. The build up of lethal concentrations of CO elsewhere in the room may take 1 to 3 hours. By then, smouldering may have ceased or may have undergone transition to flaming combustion. The production of CO from flaming combustion is a gas phase process. The fuel vapour or carbon-containing decomposition products react in a complex sequence with the oxygen in the air to form carbon monoxide. Subsequent reaction further oxidizes the CO to CO_2. The completeness of this process is largely dependent on the local supply of oxygen.

4.7.4 Hydrogen Cyanide

The generation of hydrogen cyanide (HCN) in a fire is both material and temperature dependent. HCN can be produced by thermal decomposition of some nitrogen-containing materials in both smouldering and flaming fires.

If sufficient oxygen is present, oxides of nitrogen (NOx) may also be formed from nitrogen-containing materials. Although one study reported NOx production from nitrogen containing fuels to be far less than that for HCN, there are conflicting data in the literature. HCN can be oxidized to NOx when gases from a flashed-over fire exit a space and continued to burn outside the space.

4.7.5 Halogen Acids

The thermal degradation of materials containing halogen atoms (fluorine, chlorine, or bromine) results in the formation of the halogen acids— hydrogen fluoride (HF), hydrogen chloride (HCl), and hydrogen bromide (HBr). The halogen acids are formed in the pyrolysis step of the combustion process and are therefore produced even if flaming combustion does not occur. They are not oxidized further.

4.7.6 Other Gases and Aerosols

Pyrolysis and/or incomplete combustion of organic materials can lead to the release of a wide range of organic compounds. Those considered to be the most important toxicologically are formaldehyde, unsaturated aldehydes (especially acrolein), and isocyanates (from nitrogen-containing polymers). The first two result from partial oxidation of the carbon in the material. Further oxidation leads to the formation of CO and then CO_2. Acrolein, in particular, has been demonstrated to be present in many fire atmospheres. It is also formed from the smouldering of all cellulosic materials and from the oxidative pyrolysis of polyethylenes.

Depending on the composition of the combusting products, additional toxic components of smoke can be produced in a fire. For example, phosphorus-containing fire retardants can result in the production of phosphoric acid aerosol, and sulfur-containing polymers can generate sulfur oxides. The ability to predict the yields of such species does not exist. The release of nitrogen oxides from some materials is considered a major toxic species[127].

4.8 Acceptance Criteria for the Various Test Methods[128]

Some fire test methods and criteria for a pass are summarized in Table 4.1.

Table 4-1. Acceptance Criteria for the Various Test Methods

Test	Description	Criteria	Test Method
Oxygen-Temperature Index (%)	The minimum concentration of oxygen in a flowing oxygen nitrogen mixture capable of supporting flaming combustion of a material	Minimum % oxygen @ 25°C 35% % oxygen @ 75°C 30% % oxygen @ 300°C 21%	ASTM D 2863 (modified)
Flame Spread Index	A number or classification indicating a comparative measure derived from observations made during the progress of the boundary of a zone of flame under defined test conditions	Maximum 20	ASTM E 162
Ignitability (Seconds)	The ease of ignition, as measured by the time to ignite in seconds, at a specified heat flux	*Minimum* 100 kW/m^2 Flux 60 75 kW/m^2 Flux 90 50 kW/m^2 Flux 150 25 kW/m^2 Flux 300	ASTM E 1354
Heat Release Rate (kW/m^2)	Heat produced by a material, expressed per unit of exposed surface per unit of time.	*Maximum* **100 kW/m^2 Flux** Peak 150 Average 300 secs 120 **75 kW/m^2 Flux** Peak 100 Average 300 secs 100 **50 kW/m^2 Flux** Peak 65 Average 300 secs 50 **25 kW/m^2 Flux** Peak 50 Average 300 secs 50	ASTM E 1354
Smoke Obscuration	Reduction of light transmission by smoke as measured by light attenuation	*Maximum* Ds during 300 secs 100 Dmax occurrence 240 secs	ASTM E 662

Test	Description	Criteria	Test Method
Combustion Gas Generation	Rate of production of combustion gases (e.g. CO, CO_2, HCl, HCn, NOx, SOx, halogen, acid gases and total hydrocarbons	**25 kW/m2 Flux** *Maximum* CO 200 ppm CO_2 4% (vol) HCN 30 ppm HCl 100 ppm	ASTM E 1354
Burn Through Fire Test	Test method to determine the time for a flame to burn through a composite material system under controlled fire exposure conditions.	No burn through in 30 minutes	DTRC Burn Through Fire Test
Quarter Scale Fire Test	Test method to determine the flashover potential of materials in a room when subjected to a fire exposure	No flashover in 10 minutes	Navy Procedure
Large Scale Open Environment Test	A method to test materials at full size for their intended application under controlled fire exposure to determine fire tolerance and ease of extinguishment	Pass	Navy Procedure
Large Scale Pressurable Fire Test	Method to test materials using an enclosed compartment in a simulated environment under a controlled fire exposure.	Pass	Navy Procedure
N-Gas Model Toxicity Screening	Test method to determine the potential toxic effects of combustion products (smoke and fire gases) using laboratory rats.	Pass	Navy Procedure

4.9 Recent relevant studies

Fire parameter testing has been used to study materials that might be used for marine applications. The trends in the use of composites for marine applications have recently been reviewed.[129] A number of studies have investigated the fire and flammability performance of marine composites[130,131,132], and others the testing of composites[133], the behaviour of laminates[134] and intumescent coatings.[135] Tests are still being developed to assess materials for marine applications,[136] and how materials function as passive fire protection materials[137],[138].

5 Fire Models

5.1 Introduction

Fire modeling is an area of active research. In the last 9 years, 626 reports have been published with “fire model” as a key word (Firedoc).

A comprehensive review examined fire models in use up to 2003[139] (and references therein). This review is an update of a review paper published in 1992.[140] A more recent review was completed in 2007 and includes both updated and new models[141]. This database is inclusive in that it contains all available models identified by the fire engineering community, those listed in the 1992 survey, and others found in the fire literature.

A brief description of fire models types are presented below.

5.2 Zone Models

A zone model is a computer program that predicts the effects of the development of a fire inside a space or volume. In most applications, the volume is not totally enclosed and has doors, windows, and vents. Zone models for compartments have been developed for both single-room and multi-room configurations.

The ‘zonal’ approach theory to modeling fire plume and smoke layer development in confined spaces was applied to fires by several groups in the 1970s. The ‘zonal’ approach divides the area of interest into a number of uniform zones that when combined describe the area of interest as a whole. Within each of these zones the pertinent conservation laws, in the form of mathematical equations describing the conditions of interest (i.e. mass and energy), are solved. The ‘zonal’ model approach usually divides the enclosure into two distinct zones: a hot upper layer and a cool lower layer.

The plume acts as an enthalpy pump between the cool lower layer and the hot upper layer. In reality, depending on the room size and heat release rate of the fire, there is no perfectly defined ‘interface’ between the smoky, hot upper layer and cool lower layer. The smoky hot upper layer is not at a uniform temperature (as higher temperatures are observed closer to the fire and plume); however, the use of two uniform zones allows for a reasonable approximation of the development of a fire in a space under a range of conditions. Few new zone models have been identified since the original fire model survey.

The most widely studied model is CFAST. This model is available free from the Building and Fire Research Laboratory (see NIST). CFAST has been used to model scenarios that are especially important in marine situations. There are studies on smoke including its subleathal effects[142] and smoke after a weapons hit.[143] This model has also been used to study ship fire specification parameters.[144]

Other zone models exist that predict the fire in compartments. These include single zone models[145] and many recent relevant studies on fires in compartments and enclosures[146, 147]. There is also a recent paper of the application of fluid dynamics to zone models.[148]

5.3 Field Models

Field models, like zone models, are used to model fire development inside a compartment or a series of compartments. While a zone model divides the compartment into one or two zones, and solves the conservation equations (i.e., mass, energy, and momentum) within these zones, a field model divides the compartment into a large number (on the order of thousands) of control volumes or zones and solves the conservation equations inside each. This allows for a more detailed solution compared to those from the one and two zone models. Because there are more than two zones, a field model can be appropriate for use in spaces with more complex geometries.

While field models provide very detailed solutions, they require detailed input information and more computing resources to model the fire. In this study, nearly twice as many field models were identified than that in the original survey (2003). The increasing numbers of field models stems from improved computer hardware which allows for faster, more complex computational techniques.

The Fire Dynamics Simulator[149,150] uses a computational fluid dynamics approach to modeling. (http://fire.nist.gov/bfrlpubs/). This simulator has been used in a number of studies over the years.[151] Recently this model was expanded to include a smoke simulator,[152] known as Smokeview. This will be discussed below.

In addition, a variety of other models have also been put forward.[153]

5.4 Detector Response Models

Detector response models predict the time to activation of an initiating device. While most of these models predict the response of thermal detectors, sprinklers, or fusible links to a fire-induced heat flow, some predict the response of smoke detectors.

Typically these models utilize the zonal approach to calculate smoke and heat transport and submodels to determine the response of the thermal elements in the detectors to the heat and flow field. The inputs to the submodels are usually the characteristics of the thermal element (such as Response Time Index (RTI) and activation temperature), location of the thermal element, and the heat release rate of the fire. For some of the more sophisticated detection zone models, details such as compartment geometry and building material characteristics are required.

The model then uses simplified modeling of the fire and calculates the heat transfer at the thermal element to determine the time to activation. Care should be taken in selecting a model as some are valid only for flat ceilings, while others are valid only for unconfined ceilings. These factors limit the applicability of each model.

Since the original survey (Friedman 1992), a few new detection models have been developed. There have not been many improvements in the detection models identified in the original survey. This is due to the fact that detector response, particularly thermal detector response, is a well-known phenomenon and is modeled fairly accurately by the current models. A growing number of field models also allow for smoke and thermal detection. The majority of these models are well documented but a some more recent studies are available.[154, 155]

5.5 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 determine the time to the onset of untenable conditions in a building, but there are also stand-alone versions available. Egress models are often used in performance-based design analyses for alternative design code compliance and for determining where congestion areas will develop during egress.

Many of these models are quite sophisticated, offering unique computational methods and features including the psychological effects of smoke toxicity and decreasing visibility on people. In addition, some models have useful graphical features that allow the movement of people in a building to be visualized during a simulation.

Approximately four times more egress models were identified in this work than were identified in the original survey. This is due to improved computing that allows egress models to be created for more complex building (structure) geometries that involve the movement of larger groups of people. This development of new models is also due to the move towards performance-based design of buildings and the requirement to study the evacuation of occupants from these buildings using different fire scenarios.

There is a NIST publication that describes the capabilities of egress models.[156]

5.6 Fire Endurance Models

Fire endurance models simulate the response of building 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 the same as that of the field models. The structural object is divided into smaller volumes, and the equations for thermal heat transfer and mechanical behaviour for solids are solved to determine when the structure will fail. Typically, the material properties and the boundary conditions (i.e., the fire exposure) for the structural element are required input for the model.

These models can be very useful for determining when a beam or column will deform or fail, and for solving how temperature varies with time at depths within the structural element. Since structural elements are constructed differently, have different features, and have different practical applications, care must be used in selecting a model that properly characterizes the structural element.

The fire endurance models continue to be developed. This trend is due to improved computing resources that allow more complete and complex finite element calculations to be conducted on structural elements. Also, the trend towards performance-based design has led to the development of models for structural elements.

A variety of models have been developed that are directly related to the use of composites in marine applications.[157,158,159] Fire modeling of composites that could be used in naval applications have been completed.[160,161,162,163]

5.7 Miscellaneous Models

Models which do not fit into any of the above categories, either developed with a significantly different approach or having features of two or more types of models, are classified as miscellaneous. As computing power expands and models that contain many submodels are developed, the number of miscellaneous models will undoubtedly increase.

Programs which model unique aspects of fires, such as radiation or risk in specific scenarios, are also included under the term miscellaneous. The number of these types of fire modeling programs has also increased substantially since the earlier survey was compiled.

The Society of Fire Protection Engineering has established a task force (www.sfpe.org/technical.aspx) to draft a position paper on substantiating whether a computer model is appropriate for a given application (design or analysis). It is envisioned that the position paper will be similar in format to the position paper on guidelines for peer review in the fire protection design process.

5.8 Fire Models Available from the Building and Fire Research Laboratory (NIST).

The fire simulation programs listed below were developed or sponsored by the Building and Fire Research Laboratory. (http://www.bfrl.nist.gobv/omfo/software.html)

- ALOFT-FT™ - A Large Outdoor Fire plume Trajectory model - Flat Terrain
- ASCOS - Analysis of Smoke Control Systems
- ASET-B - Available Safe Egress Time - BASIC
- ASMET - Atria Smoke Management Engineering Tools
- BREAK1 - Berkeley Algorithm for Breaking Window Glass in a Compartment Fire
- CCFM - Consolidated Compartment Fire Model version VENTS
- CFAST - Consolidated Fire and Smoke Transport Model
- DETACT-QS - Detector Actuation - Quasi Steady
- DETACT-T2 - Detector Actuation - Time squared
- ELVAC - Elevator Evacuation
- FASTLite - A collection of procedures which builds on the core routines of FIREFORM and the computer model CFAST to provide engineering calculations of various fire phenomena,
- FIRDEMND - Handheld Hosestream Suppression Model

- FIRST - FIRe Simulation Technique
- FPETool - Fire Protection Engineering Tools (equations and fire simulation scenarios)
- Jet - A Model for the Prediction of Detector Activation and Gas Temperature in the Presence of a Smoke Layer
- LAVENT - Response of sprinkler links in compartment fires with curtains and ceiling vents
- NIST Fire Dynamics Simulator and Smokeview - The NIST Fire Dynamics Simulator predicts smoke and/or air flow movement caused by fire, wind, ventilation systems *etc.* Smokeview visualizes the predictions generated by NIST FDS.

ALOFT-FTTM (A Large Outdoor Fire plume Trajectory model - Flat Terrain) is a computer based model to predict the downwind distribution of smoke particulate and combustion products from large outdoor fires. It solves the fundamental fluid dynamic equations for the smoke plume and its surroundings with flat terrain. The program contains a graphical user interface for input and output and a user modifiable database of fuel and smoke emission parameters. The output can be displayed as downwind, crosswind and vertical smoke concentration contours. Information on using the program is available with on-line help commands in the program. ALOFT-FT was written by W.D. Walton and K.B. McGrattan.

ASCOS (Analysis of Smoke Control Systems) is a program for steady air flow analysis of smoke control systems. This program can analyze any smoke control system that produces pressure differences with the intent of limiting smoke movement in building fire situations. The program is also capable of modeling the stack effect created in taller buildings during extreme temperature conditions. The program input consists of the outside and building temperatures, a description of the building flow network and the flows produced by the ventilation or smoke control system. The output consists of the steady state pressures and flows throughout the building. ASCOS was written in FORTRAN by J.H. Klote. A newer program, CONTAM, may be more appropriate to some applications than ASCOS.

ASET-B (Available Safe Egress Time - BASIC) is a program for calculating the temperature and position of the hot smoke layer in a single room with closed doors and windows. ASET-B is a compact easy to run program which solves the same equations as ASET. The required program inputs are a heat loss fraction, the height of the fire, the room ceiling height, the room floor area, the maximum time for the simulation, and the rate of heat release of the fire. The program outputs are the temperature and thickness of the hot smoke layer as a function of time. ASET-B was written in BASIC by W.D. Walton.

ASMET (Atria Smoke Management Engineering Tools) consists of a set of equations and a zone fire model for analysis of smoke management systems for large spaces such as atria, shopping malls, arcades, sports arenas, exhibition halls and airplane hangers. ASMET is written in C++ language. For program documentation and a description of the input data, the user should refer to NISTIR 5516, Klote, J. H., Method of Predicting Smoke Movement in Atria with Application to Smoke Management, NIST.

BREAK1 (Berkeley Algorithm for Breaking Window Glass in a Compartment Fire) is a program which calculates the temperature history of a glass window exposed to user described fire conditions. The calculations are stopped when the glass breaks. The inputs required are the glass thermal conductivity, thermal diffusivity, absorption length, breaking stress, Young's modulus, thermal coefficient of linear expansion, thickness, emissivity, shading thickness, half-width of window, the ambient temperature, numerical parameters and the time histories of flame radiation from the fire, hot layer temperature and emissivity, and heat transfer coefficients. The outputs are the temperature history of the glass normal to the glass surface and the window breakage time. BREAK1 was written in FORTRAN by A.A. Joshi and P.J. Pagni, Department of Mechanical Engineering, University of California at Berkeley supported by a grant from the National Institute of Standards and Technology.

CCFM (Consolidated Compartment Fire Model version VENTS) is a two-layer zone-type compartment fire model computer code. It simulates conditions for user-specified fires in a multi-room, multi-level facility. The required inputs are a description of room geometry and vent characteristics (up to 9 rooms, 20 vents), initial state of the inside and outside environment, and fire energy release rates as a functions of time (up to 20 fires). If simulation of concentrations of products of combustion is desired, then product release rates must also be specified (up to three products). Vents can be simple openings between adjacent spaces (natural vents) or fan/duct forced ventilation systems between arbitrary pairs of spaces (forced vents). For forced vents, flow rates and direction can be user-specified or included in the simulation by accounting for user-specified fan and duct characteristics. Wind and stack effects can be taken into account. The program outputs for each room are pressure at the floor, layer interface height, upper/lower layer temperature and (optionally) product concentrations. CCFM (version VENTS) is supported by four-part documentation: Part I - Physical Basis, L.Y. Cooper and G.P. Forney; Part II - Software Reference Guide, G.P. Forney and L.Y. Cooper; Part III - Catalog of Algorithms and Subroutines, L.Y. Cooper and G.P. Forney, Eds.; and Part IV - User Reference Guide, G.P. Forney, L.Y. Cooper, and W.F. Moss. CCFM (version VENTS) was written in FORTRAN by G.P. Forney and L.Y. Cooper.

CCFMPLT is a graphics program which runs in conjunction with CCFM. The results from CCFM are sent to a user specified data file at each prescribed time step. CCFMPLT plots this data on an IBM-PC compatible microcomputer and can optionally provide hardcopy output. CCFMPLT was written in FORTRAN by G.P. Forney.

CFAST is a zone model that predicts the effect of a specified fire on temperatures, various gas concentrations and smoke layer heights in a multi-compartment structure.

DETACT-QS and DETACT-T2

DETACT-QS (DETector ACTuation - Quasi Steady) is a program for calculating the actuation time of thermal devices below unconfined ceilings. It can be used to predict the actuation time of fixed temperature heat detectors and sprinkler heads subject to a user specified fire. DETACT-QS assumes that the thermal device is located in a relatively large area, the fire ceiling flow heats the device, and there is no heating from the accumulated hot gases in the room. The required program inputs are the height of the ceiling above the fuel, the distance of the thermal device from the axis of the fire, the actuation temperature of the thermal device, the response time index (RTI) for the device, and the rate of heat release of the fire. The program outputs are the ceiling gas temperature and the device temperature as a function of time and the time required for device actuation. DETACT-QS was written in BASIC by D.D. Evans.

DETACT-T2 (DETector ACTuation - Time squared) is a program for calculating the actuation time of thermal devices below unconfined ceilings. It can be used to predict the actuation time of fixed temperature and rate of rise heat detectors, and sprinkler heads subject to a user specified fire which grows as the square of time. CT-T2 assumes that the thermal device is located in a relatively large area, the fire ceiling flow is the only source of heat, and there is no heating from the accumulated hot gases in the room. The required program inputs are the ambient temperature, the response time index (RTI) for the device, the activation and rate of rise temperatures of the device, height of the ceiling above the fuel, the device spacing and the fire growth rate. The program outputs are the time to device activation and the heat release rate at activation. DETACT-T2 was written in BASIC and FORTRAN by D.W. Stroup.

ELVAC (Elevator Evacuation) is an interactive computer program that estimates the time required to evacuate people from a building with the use of elevators and stairs. It is possible to design elevator systems that are for fire emergencies, and ELVAC can be used to evaluate the potential performance of such systems. ELVAC calculates the evacuation time for one group of elevators. If a building has more than one group of elevators, ELVAC can be run on each group separately. Input consists of floor to floor heights, number of people on floors, number of elevators in the group, elevator speed, elevator acceleration, elevator capacity, elevator door type and width, and various inefficiency factors. The output is a table of elevator travel time, round trip time, people moved, and number of round trips for each floor plus the total evacuation time. ELVAC was written in compiled BASIC by John H. Klote and Daniel M. Alvord.

FASTLite is a user friendly software package which builds on the core routines of FPEtool and the computer model CFAST to provide calculations of fire phenomena for use by building designers, code officials, fire protection engineers, and fire-safety related practitioners.

FIRDEMND simulates the suppression of post flashover charring and non-charring solid-fuel fires in compartments by water sprays from portable hose-nozzle equipment. The output of the Fire Demand Model (FDM) shows the extinguishing effects of water spray at various flow rates and droplet sizes. The calculations are based on a heat and mass balance accounting for gas and surface cooling, steam-induced smothering, water-spray induced air entrainment, direct extinguishment of the fire by water and the energy transport via inflow and outflow of heat and products of combustion. This model can be complicated, but it is very powerful.

FIRST (FIRe Simulation Technique) is the direct descendant of the HARVARD V program developed by Howard Emmons and Henri Mitler. The fire may be entered either as a user-specified time-dependent mass loss rate or in terms of fundamental properties of the fuel. In the latter case, the program will predict the fire growth rate by considering the changing oxygen concentration and smoke layer conditions in the space. It can also predict the heating and possible ignition of up to three targets. The original fire and targets may also be user specified fires. The required program inputs are the geometrical data describing the spacess and openings, and the thermophysical properties of the ceiling, walls, burning fuel, and targets. The generation rate of soot must be specified, and the generation rates of other species may be specified as a yield of the pyrolysis rate. Among the program outputs are the temperature, thickness of, and species concentrations in the hot upper layer and cooler, lower layer in each compartment. Other outputs are wall surface temperatures, heat transfer rates and mass flow rates. The FIRST program was written in FORTRAN and is maintained by H. Mitler.

MASBANK is used to create and maintain a data base of materials and their fire properties for use by the FIRST program. MASBANK can accommodate 20 properties for up to 50 materials. The program has the capability to add, delete, change, alphabetize and view the properties of materials in the data bank. Material properties from MASBANK may be transferred directly into the FIRST program. MASBANK is written in FORTRAN.

FPETool is a set of engineering equations useful in estimating potential fire hazard and the response of the space and fire protection systems to the developing fire. Version 3.2 incorporates an estimate of smoke conditions developing within a room receiving steady-state smoke leakage from an adjacent space. Estimates of human viability resulting from exposure to developing conditions within the room are calculated based upon the smoke temperature and toxicity. Documentation in PDF format is available. This version of FPE Tool was written by S. Deal.

LAVENT is a program developed to simulate the response of sprinkler links and the conditions in a space with draft curtains and fusible link operated ceiling vents. The model, used to calculate the heating of the fusible links, includes the effects of the ceiling jet and the upper layer of hot gases beneath the ceiling. The required program inputs are the geometrical data describing the compartment, the thermophysical properties of the ceiling, the fire elevation, the time dependent energy release rate of the fire, the fire diameter or energy release rate per area of the fire, the ceiling vent area, the fusible link response-time-index (RTI) and fuse temperature, the fusible link positions along the ceiling, the link assignment to each ceiling vent, and the ambient temperature. A maximum of five ceiling vents and ten fusible links are permitted in the compartment. The program outputs are the temperature, mass and height of the hot upper layer, the temperature of each link, the ceiling jet temperature and velocity at each link, the radial temperature distribution along the interior surface of the ceiling, the radial distribution of the heat flux to the interior and exterior surfaces of the ceiling, the fuse time of each link, and the vent area that has been opened. LAVENT is supported by two-part documentation which includes: Part I - Theory, L.Y. Cooper; and Part II - User Guide, W.D. Davis and L.Y. Cooper. LAVENT was written in FORTRAN by W.D. Davis and L.Y. Cooper.

GRAPH is a graphics program which runs in conjunction with LAVENT. The results for LAVENT are sent to the data file, GRAPH.OUT, after each prescribed time step. GRAPH then allows the user to choose two sets of variables to be plotted on the screen and has the additional capability of hardcopy output. GRAPH was written in FORTRAN by W.D. Davis.

6 Scale Up

6.1 Introduction

The use of small scale tests (Cone calorimeter, fire propagation apparatus, tube furnace, etc.) and their results to predict the results of intermediate (e.g. SBI test, ICAL) and large scale testing (ISO room corner test) remains an inexact science. Although there are many potential correlations, problems remain with the use of small scale test results to predict fire performance because the fire results from different tests are dependant on the experimental set-up and the fire response of the specimen.

However, studies on the applicability of small scale test results to larger test results have been completed. In some cases there are significant correlations between the results but in others there are major discrepancies. It is also important to note that no ISO or ASME test will categorically state that results from a small scale test are applicable to full scale fires. As such the scale up tends to be based on single materials. However, many of the models discussed in this report require small scale test data to model larger and full scale fire test results.

The main apparatus for developing and testing for the fire parameters (discussed in Section 4) is the cone calorimeter and fire propagation apparatus. There have been some excellent reviews on the use of cone calorimeter and comparison of data from cone calorimeter testing with data from larger scale tests and actual fires[164].

6.2 Comparisons of Data from Small Scale Tests with Data from Other Tests

6.2.1 Cone Calorimeter

The cone calorimeter measures a range of fire and flammability parameters and provides some insight into materials properties. Attempts to use simple empirical approaches to correlate cone calorimeter results with other fire tests results have not met with much success. Any correlations that have been found are limited to certain classes of materials.

6.2.2 Cone Calorimeter: Bench-Scale Tests

The cone calorimeter involves the use of forced combustion, largely eliminates dripping and wicking effects, and targets the fire response in a developing fire. Most other bench-scale flammability measurements use free burning scenarios on a single item allowing dripping and wicking to influence the outcome.

6.2.3 Cone Calorimeter: ISO Furnace

It is not possible to use the cone calorimeter (with the standard procedures) to perform a flammability test similar to UL 94 or LOI although the cone calorimeter test is based on a specimen of length scale typical of such flammability tests. Although some good correlations have been found, the correlations are test related. For instance, the averaged HRR from the cone calorimeter for low applied[165] heat fluxes (25–35kWm^{-2}) correspond roughly with UL 94 and LOI results. A rule of thumb used by many laboratories, is that materials with HRRs less than a certain value (ranging from 80 to 300kWm^{-2}) for low applied heat fluxes tend to be self-extinguishing in UL 94.

Recently results from the cone calorimeter, UL 94, and glow wire ignition temperature tests for 19 different flame-retarded polymeric materials were compared and showed limited correlations[166]. A loose correlation was found between the HRR from the cone calorimeter and the UL 94 classification. This correlation was improved when the HRR values were extrapolated to zero heat flux. No reasonable correlation was found between the UL 94 classification and V-2 (self-extinction with dripping). The glow wire ignition temperature correlated with the cone calorimeter critical heat flux for ignition for 17 of the 19 materials.

6.2.4 Cone Calorimeter: Intermediate and Full-Scale Tests

Although the cone calorimeter measures fire parameters for a developing fire, direct prediction of flame spread or HRR measured in established fire tests such as the intermediate-scale European SBI test or the full-scale room-corner test using cone data is not easy. The may be the result of the larger specimen used in the larger or full scale tests which impacts the fire scenario. In the past, empirical or simple correlative approaches have had rather limited success. However recently, approaches based on empirical flame spread modeling have shown increasingly satisfactory correlations, particularly for the SBI test[167,168], the room-corner test,[169,170], and for fire growth test[171]. Papers describing the use of cone calorimeter and other small scale test data to make reasonable predictions of the results of other fire tests are starting to appear in the literature.

6.3 Fire Parameters Small scale: large scale

6.3.1 Flame Spread

Advanced flame spread modeling is now able to provide reasonable predictions based on cone calorimeter data. An example is the prediction of the correct FIGRA (Fire Growth Rate Index) for approximately 90% of the products in a SBI test study.[172] However, using the horizontal sample orientation in the cone calorimeter ignores melt dripping and may also ignore wicking effects. This limits the comparability of results with those from tests with vertical sample orientation where dripping can play a significant role. The correlation between cone calorimeter data and SBI and the ISO test data for wall linings has recently been reviewed.[173] The upward spread on materials was compared and the main conclusions were (1) the SBI test is more “clean” and consistent test than the room corner test for wall lining classification, (2) there is a good correlation between the FIGRA parameter of SBI test and a simple parameter derived form cone calorimeter measurements but not between the ISO room corner test and the cone calorimeter, and (3) because of progress in fire safety science, there is no reason to use empirical indices to correlate SBI or ISO room corner tests with small-scale tests.

These conclusions are in direct contrast to the "The International FORUM of Fire Research Directors: A position paper on small-scale measurements for next generation standards.[174] The directors of this forum feel that the SBI was implemented with serious shortcomings when performance-based codes are being promoted which demand reliable flammable properties.

6.3.2 Smoke and Toxins

Comparisons of smoke production results are very difficult as smoke depends on both the material and the applied heat flux. An approach based on multivariate statistical analysis was reported for cone calorimeter and SBI data that could predict the Euroclasses for smoke in 75% of the cases.[175]

In addition to smoke, the release of toxins has also been investigated[176]. Product yield data of CO2, CO, HCN, NOx, total hydrocarbons and smoke particulates using the steady-state tube furnace (ISO TS19700) test and large-scale ISO room test showed a good general agreement for the five materials tested. Very good models also exist for smoke[177], which use data inputs from small scale tests and in some cases large scale tests.[178]

6.3.3 Heat Release Rate

Heat release rate (HRR) may be the single most important parameter in the development of small scale tests that predict the performance of materials in larger scale fire tests. HRR studies have been conducted on configurations of materials.[179] In the small-scale test series, the propagation tests with a vertically oriented sample in air containing 40% oxygen give the best correlation with the behaviour observed in the intermediate-scale parallel panel test series. There have also been studies on the uncertainties inherent in the test methods with respect to scale-up.[180]

6.4 Materials

6.4.1 Cables

The fire performance of cables is of great concern on ships especially in areas where the cables are hidden. The interest was so great the European Union developed a research group, FIPEC, to look at the fire properties of cables.[181] This was given the mandate to further cable testing in the European Union.

The results from this study were:

- A full-scale test, based on IEC 60332.3 has been established with a high discrimination level.
- Small-scale test procedures have been established for cables and materials, which can be used for modelling of full-scale tests and for product development.

- The methods can be used for prescriptive codes, for example, Euroclasses, for cables or for fire performance based codes.

The SBI test also developed in Europe has been considered to have serious drawbacks but recently it was compared to FIPEC.[182]. It was found that the SBI test data does not enable the cables to be ranked in terms of flame spread. However, for other parameters (THR600s, HRRpeak, FIGRA, TSP) SBI and FIPEC methods can be adequate.

The toxic product yields from five commercial cables obtained from a steady state tube furnace (SSTF) method (IEC 60695-7-50, Purser furnace) were compared with results from a large-scale test[183]. The large scale uses the physical fire model in the proposed prEN50399-2-2 test and effluent gas analysis by Fourier transform infrared (FTIR) and a static tube furnace method (NF X 70-100). The yields of CO2, CO, HCl and smoke showed reasonable agreement, given the differences in the extent of burning and the accuracy of the mass-loss data available for the large-scale test.

6.4.2 Sandwich Panels

Assessment of the fire behaviour of sandwich panels has been made[184]. The fire behaviour of these panels is dependent on a combination of material characteristics, such as the nature of the core material, and the mechanical behaviour of the panels arising from joints, dilations, etc. The proposed European product standard for sandwich panels (prEN 14509) proposes the intermediate scale test method SBI (EN 13823) to certify panels. The standard uses a mounting procedure which does not fully reflect the end-use conditions of the panels.

In a previous research project conducted by Nordtest it was shown that the correlation between the SBI test method and both the ISO 9705 and ISO 13784 part 1 was poor. The SBI test method did not use the mounting from prEN 14509.

6.4.3 Polymers and Composites

In a recent report[185] six material systems (each consisting of a non-combustible insulation material and a combustible facing) were tested to demonstrate compliance with the requirements for fire-restricting interior finish materials. Two systems were tested using the ISO 9705 room/corner test, and (non-)compliance of the remaining systems was determined on the basis of Cone Calorimeter data. It was demonstrated that the Cone Calorimeter criteria appear to be a reliable indicator of ISO 9705 room/corner test performance of material systems consisting of non-combustible insulation with a combustible facing. However, further research and refinement of the performance criteria is necessary to address material systems that marginally fail the Cone Calorimeter criteria and perform satisfactorily in the room/corner test. A model of the ISO 9705 room/corner test could be used to develop criteria that allow for a trade-off between ignition and heat release rate performance.

Polymers used in electronics have also been studied.[186] The materials considered in this study gave a wide range of results for the three standard bench-scale flammability tests used to evaluate them. The ignitability, upward flame spread resistance, heat release characteristics and product yields were measured for these materials in several well-defined configurations. Although a detailed study of full-scale performance of these materials is not available, it is likely that both UL94 performance and the rate of heat release measurements are necessary to predict how these materials can be expected to react in a real fire scenario. Data from small scale tests has been used to model fires in a combustion corner[187].

The increase in fire testing is being partly driven by the worldwide shift from building codes now in place to performance based codes[188,189]. The desire is to make code decisions based solely on scientific data.

7 Fire Performance of Composites

7.1 Introduction

The evaluation and prediction of the performance of composites during and after a fire is a developing area of research. The performance of composite structures for marine applications is compared to traditional metal structures with respect to structural integrity, skin failure, and heat transfer.

7.2 Modeling Efforts

Recent work[190] focuses on and summarizes efforts to model strength parameters of sandwich composite materials subjected to fire. The softening and resultant skin failure of the material at heat fluxes up to a maximum of 50 kW/m^2 has been studied. Gibson et al[191] looked at fire testing of glass-fiber composites under load and the residual post fire strength of the composites. Previous work cited in the Gibson paper established that the load-bearing strength of composites is severely degraded by fire. This work builds upon the two-layer model discussed in papers by Mouritz & Mathys. They modeled the time a composite structure maintains its structural integrity under load in a fire. The main conclusion of the paper was that "integrity times in fire are short and that composite structures are especially prone to local compressive failure". These types of models do enable the prediction of post-fire structural strength (mechanical properties) based on bench scale testing. For example, in a study of 13 fiber-reinforced thermosets[192], the agreement between the calculated and measured post-fire residual mechanical properties was within 10%.

7.3 Performance Evaluation

Mouritz and Gardiner[193] studied the flammability characteristics and compression properties of PVC-core and phenolic-core sandwich composites. The phenolic-core material had better ignition resistance than the PVC-core composite, but the differences in the strength properties between the two composites were less significant both during and after the fire. A study of post-fire flexural properties of fiber reinforced polymer composites (polyester-, epoxy-, and phenolic-based) indicated that the phenolic-based material had increased resistance to ignition but did not show significantly better post-fire strength than the other composites[194]. This paper discussed the mechanism of strength loss of the composites. The decrease in the flexural properties of the phenolic-based composite was attributed to thermal degradation and cracking of the resin matrix. The failure of the polyester- and epoxy-based materials was attributed to combustion of the resin and formation of delamination cracks. An earlier paper[195] described similar results for glass-reinforced phenolic polymers and included a good review of early work in this area.

A 3-year, 6-nation European military project examined the fire performance of naval composite structures[196,197]. The composites included glass reinforced plastics with and without a protective phenolic resin surface treatment. Test methods ranged from small scale bench top tests up to full scale tests. The full scale tests used cellulosic fires (950°C after 60 min) and hydrocarbon fires (maximum temperature of 1100°C). This program also investigated the insulation properties, structural integrity and load-bearing performance of the composites during and after a fire. The structural integrity and load-bearing performance for the phenolic resin surface treated composite materials were better than those without the phenolic resin surface treatment. The online book "Marine Composites"[198] describes a US Navy thermo-mechanical test program. Data is presented for one composite material (Balsa-core, E-Glass/Vinyl Ester) which performed well, and other materials are briefly discussed qualitatively.

A lot of the research related to post-fire strength properties of composites has focused on tensile, compression or flexural strength testing. However, the low velocity impact resistance of sandwich composites post-fire has been investigated[199]. Significant loss of impact resistance was seen for short (<100 s) fire exposure times. For the type of sandwich composites studied, the results indicated lower density (and therefore higher insulating and lighter) core material retained less strength than high density core materials. This was attributed to the higher face sheet temperature of low density core that resulted in failure of the face sheet integrity.

Thermoplastics, such as polypropylene and polystyrene, and polyurethane foam thermosets can soften and flow at elevated temperatures. Ohlemiller and Shields[200] have investigated the flow dynamics and flammability of such materials.

Gibson et al.[201] recently presented a paper on "Effect of stress on the fire reaction properties of polymer composite laminates". They reported that stress can affect resistance to ignition and that increasing tensile stress results in an increase in heat release rate and smoke production. Compression had the opposite effect.

7.4 Heat Transfer

Inorganic fire resistive materials such as gypsum-based and silicate-based coatings, and intumescent composite coatings are used to protect steel structures from fire and heat damage.

Work by Bentz et al.[202] has focused on the use of a Slug Calorimeter to determine thermal conductivities of inorganic fire-resistive materials described in an earlier paper[203]. In the earlier paper, it was shown that the difference in thermal conductivity for four materials ranged from 30% at room temperature up to almost 100% at elevated temperatures (~ 600°C). To date, this test method has been applied to non-intumescent fire-resistant materials but it is planned to use the method to study intumescent materials.

An evaluation of intumescent coatings for marine fire protection was published in 2003[204]. Nineteen state-of-the-art intumescent coatings were evaluated using a range of tests including small scale lab tests and full scale tests on the ex-USS Shadwell. The results indicated that the water based coatings failed primarily due to thermal performance, physical problems with adherence, and fragility of the char. The solvent based coatings failed due to thermal performance and production of heavy smoke.

An intumescent coating comprised of an epoxy resin with inorganic components rated F90 (withstanding 90 min in fire) in Germany was used to evaluate heat insulation performance as determined by a bench-scale cone calorimeter and a small-scale furnace[205]. While a good correlation between the different scale test set-ups was seen, the upper temperature limit of the cone calorimeter (750°C and maximum irradiation of 75 kWm^{-2}) limited the usefulness of the cone calorimeter compared to the small-scale furnace. In particular, the authors point out that the operating range of the cone calorimeter is lower than the upper temperature ranges targeted by the highest performance intumescent coatings.

While modeling and prediction of heat transfer properties for standard, non-fire resistive materials is routine, the modeling of the heat transfer properties of composites present additional complexity due to thermal degradation. Lau et al[206] combined the use of a thermal-mechanical analysis tool (TMAT) and a temperature and mass dependant thermal model to predict the fire response behaviour of a glass/vinylester woven fabric. TMAT simulates the composite properties of a woven fabric from its constituent properties determined by small-scale testing. This model can be used to predict or assess the damage to a composite ship structure subjected to fire.

8. Recommendations

The literature reviewed in this report indicates that no one small scale fire test is applicable to all materials. However, if a single test had to be selected the cone calorimeter has the greatest utility since so many different fire parameters can be determined in a single test. It is very important to consider the configuration (and orientation) of sample within the apparatus when trying to correlate small scale fire data with the actual fire performance of a material. Factors such as sample preparation, the type of sample, ignition source, and sources of error contribute to difficulties in using the results of small scale tests to determine the performance of a material or component in an actual fire.

Most intermediate and larger scale fire tests use data from small scale fire tests to make decisions concerning the conditions to be used in the intermediate and large scale tests fire tests. This will become increasingly important as building codes become performance based.

There are no specific standards which are applicable to every material and application. Using materials which pass standard tests is the first step in the selection process from the fire and flammability perspective.

The most important aspects in fire testing are heat release rate and smoke production. This is because both directly affect survivability of persons in a fire. Flammability and flame spread are parameters that are very important in evaluating polymeric and composite materials for marine applications.

Modeling of fire continues to develop. Advances in understanding the aspects of fire have led to the development of models with improved fire prediction capabilities.

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Damage control is a priority for naval vessels. An important component of damage control is the rapid detection and extinguishment of fires. However, the risk and severity of shipboard fires can also be reduced through the selection of non metallic materials that are less susceptible to ignition, have low rates of flame spread, generate less smoke, and release less heat and toxic gases than competing products.

In this report the standards for the fire performance of non metallic materials, methods and apparatus used to evaluate the fire performance properties required by the standards, and models related to fire are reviewed. The standards include those of the International Maritime Organization (IMO) and the International Standards Organization (ISO), US military specifications (Mil Spec) and Royal Navy Defence Standards (Def Stan) and associated Naval Engineering Standards (NES). The methods include ASTM (American Society for Testing and Materials), Underwriter's Laboratories (UL), ISO, and NES fire performance standards. These standards refer to a broad range of apparatus required to perform the testing. The fire models include one and two zone and computational fluid dynamic models, and detector response, egress, and fire endurance models.

The applicability of small scale/laboratory fire testing to the evaluation of non metallic material performance in larger scale fire tests is discussed. Although there are many small scale/laboratory tests used to access the fire properties of non metallic materials, no one test or suite of tests was found whose data correlated well with large scale test results for all materials and fire scenarios. However the cone calorimeter was determined to be the most applicable due to the amount of data generated with this test.

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