A Methodology for Global Comparison of Fire Testing Standards in Transportation Applications

by

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Author's Declaration:

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract:

In recent decades, many manufacturing industries have globalized their operations and the Canadian manufacturing sector has experienced dramatic downsizing. For a manufacturing company to succeed therefore, it is necessary for them to operate with a global perspective. In the area of fire safety, this requires understanding of, and compliance with, global regulatory requirements.

This research develops a systematic approach that can be utilized to analyze and compare the complex fire safety regulatory requirements that are stipulated for a selected topic in various countries. The approach developed is sufficiently general that it can be leveraged to compare and contrast global standards in any field or discipline. The methodology outlines six aspects of the regulatory environment that must be considered in sorting standards and then uses spreadsheets and a mind mapping program to elucidate the many relationships that exist amongst the current standards.

In this work, flammability test requirements for public transportation seating are studied, with a major emphasis on seating for railway applications. Requirements for seating in aviation, automotive (both cars and buses) and military vehicles are included in the discussion for comparative purposes.

Fire is a complex phenomenon that is difficult to characterize. The legislated testing protocols reflect this complexity with some geographic jurisdictions mandating as many as six different types of fire testing for rail seating. This work looks in depth at two of the main types of fire testing: flame spread testing and toxic effluent testing.

Flame spread testing was chosen because it is widely required, and toxic effluent testing was chosen because of the many complexities and ambiguities present amongst these standards. Eleven flame-spread tests are compared on a semi-quantitative basis, and eight fire effluent toxicity tests are discussed on a qualitative basis.

The technique developed was useful to elucidate the relationships, similarities and differences amongst the fire safety requirements for transportation seating. There are large differences in requirements among transportation sectors as well as on a geographical basis.   Using this technique, it was possible to categorize the flame spread tests into two groups and to compare the relative intensity of the tests within each of these subsets. The fire effluent toxicity tests varied so much in approach that only qualitative comparisons were possible.

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List of Abbreviations

AFAP	Allied Fire Assessment Publication
AIHA	American Industrial Hygiene Association
ASTM	American Standard Test Methods
BS	British Standard
BSI	British Standards Institution
CEFIC	European Chemical Industry Council
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CEN TS	Conditional Normative European Technical Standard
CFR	Code of the Federal Register
DIN	Deutsches Institut fur Normung
EC	European Commission
EN TS	Normative European Technical Standards
EU	European Union
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FMVSS	Federal Motor Vehicle Safety Standard
FRA	Federal Railroad Administration
FTP	Fire Test Procedure Code
IMO	International Maritime Organization
ISO	International Standardization Organization
ISO/TC 92	ISO Technical Committee on Fire Safety

NATO	North Atlantic Treaty Organization
NBS	National Bureau of Standards
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Health and Safety
NRC	National Research Council
SAE	Society of Automotive Engineers
SMS	Safety Management System
SOLAS	Safety of Life at Sea
UIC	International Union of Railways
UL	Underwriters Laboratories
USDOT	United States Department of Transportation

List of Symbols

List of Symbols	**Typical Units**	**Name**
ε	unitless	Emissivity
σ	W/m^2K^4	Stefan Boltzman constant
ARHE	kW/ m^2	Average rate of heat emission
CFE	kW/m^2	Critical flux at extinguishment
CIT	unitless	Conventional Index of Toxicity
CO	unitless	Carbon monoxide
CO_2	unitless	Carbon dioxide
D	m^2/sec	Diffusion coefficient
$D_{s\ max}$	$((b/m)m^3/m^2)$	Maximum specific optical density
F_{12}	unitless	Configuration Factor or view factor
F_s	min^{-1}	
FTIR	unitless	Fourier Transform Infra-red
HBr	unitless	Hydrogen bromide
HCl	unitless	Hydrogen chloride
HCN	unitless	Hydrogen cyanide
HF	unitless	Hydrogen fluoride
HHR_{30}	kW/ m^2	Heat release rate at 30 minutes
I_s	BTU/min^2	Radiant panel index
IDLH	ppm or mg/m^3	Immediately dangerous to life and health
IR	unitless	Infra-red
L	m	Length of flame
LC_{50}	ppm or mg/m^3	Lethal concentration 50
LD_{50}	ppm or mg/m^3	Lethal dose 50
LC_{Lo}	ppm or mg/m^3	Lethal concentration low
k	W/mK	Thermal conductivity
MARHE	kW/m^2	Maximum average rate of heat emission
n	moles	number of moles
Nox	unitless	Nitrogen oxides, primarily NO and NO_2
P	atmosphere	Pressure
Q	BTU/min or W	Rate of heat release
q"	W/m^2	Heat flux
R	m^3 atm/K mol	Universal gas constant
SO_2	unitless	Sulfur dioxide
SPR_{30}	m^2s^{-1}	Smoke production at 30 minutes
T	C or K	Temperature
V	m^3 or l	Volume
V'	m^3/sec	Volumetric flow rate

Chapter 1. Introduction

1.1 Understanding Global Flammability Regulatory Frameworks

The objective of this research is to develop a systematic approach that can be used to understand the differences in requirements for fire safety testing on a single global basis. One of the major outcomes of this research should be the development of a simplified methodology for analysis of the complex and regulated field of fire performance testing for transportation applications. The method should also be sufficiently flexible that it can be leveraged for application to other complex regulation systems spanning multiple geographies.

Research to clarify legislated fire testing requirements is important to both the University of Waterloo Fire Research Lab and to Canadian industry. There are literally thousands of flammability standards in the world. For the University of Waterloo Fire Research Lab, the ability to more efficiently identify the most important standards and to quickly understand and assess the differences between them is critical to performing the most meaningful and relevant research.

In order for Canada to have a successful manufacturing presence around the world, Canadian companies must be able to compete on a global basis. The ability to effectively analyze fire safety requirements in a global context can help advance Canadian industry by increasing quality and performance of products whilst reducing research and development cycle times, thus positioning them to be more competitive in a global marketplace. This is critical in the Canadian manufacturing sector, which has been severely challenged and has seen significant declines in recent years. Since 2000, capacity utilization has declined in 16 of 20 manufacturing industries. In the period from 1990 to 1999, the Canadian manufacturing sector averaged growth of 3.4% but from 2000 to 2006, it contracted at an average annual rate of 0.3% [1]. From 2004 to 2008, more than one of every seven manufacturing jobs in the country were lost, and in Ontario in that time frame, one in five manufacturing jobs were lost [2]. More recent statistics for the province of Ontario, indicate that this trend is continuing. In the ten-year period from January 2003 to September 2012, twenty eight percent, or 255,000 manufacturing jobs were lost [3]. Clearly then, every small gain is needed to help this struggling sector.

In applications where markets interface with public safety, fire safety, and in particular, flammability test requirements are often legislated, but there is no universal, globally recognized system for specifying the codes and standards applicable to a particular product or sector. This research develops an approach that can be applied to clarify the complexity created by the overlap of legislatively mandated technical testing requirements, common industrial practices in various geographical locations and actual technical performance criteria. To keep the scope of the research manageable, the methodology that has been developed to address this need will be demonstrated using global flammability requirements for railway passenger seating with comparison to the requirements specified for other selected modes of transportation. The approach itself is much more general, however, and could be applied to other intersections of technology and legislation, like building codes, electrical codes, use of combustibles in cable or network applications and upholstered furniture for consumer or industrial use to name a few.

In this thesis, the remainder of this chapter provides an overview and introduction to the field and some history of fire test standards. Chapter 2 documents the findings of the literature search and discusses how these results were used to define the project direction. Chapter 3 discusses the methodology used. It delineates how the selected research tools were chosen as well as discusses the methodology used to select test methods for illustration and to analyze the relationships within and between the selected methods. Chapter 4 presents and discusses the results of qualitative and quantitative analysis of flame spread and fire gas toxicity tests. Chapter 5 summarizes the conclusions of the analysis. Chapter 6 discusses further work that could expand upon this topic.

1.2 Overview of Fire Testing

Fire performance testing and flammability assessment of materials and products is very much a field in flux. There are many different organizations publishing flammability standards and, as a result, there are thousands of flammability standards globally. These outline many different approaches for measuring the same parameter, and the approaches specified, as well as results derived from different standards frequently are not readily comparable. Even within the field, there is limited work documenting correlations amongst results from different methods or evaluating the equivalency of the various methods. The work that has been done often concludes that there is no, or only very poor, correlation between methods purporting to characterize the same flammability property [4-8].

At the same time, flammability test requirements are constantly changing. Many of the standards are in a perpetual revision cycle. There are active change agents and passive change agents. Throughout history, the most consistent active change agent for fire regulations has been catastrophic accidents involving a major fire and consequent loss of life [9] and/or structural collapse. Recent examples include the 2004 Madrid train bombing or the 2001 World Trade Center collapse. After a major accident, lessons learned during the post-accident investigation are captured through changes to various standards, particularly those impacting public safety and sometimes in changes to legislation [10]. Specific examples of this are provided in Section 1.3, “Historical Overview”.

The complexity in categorizing and interpreting fire performance test standards is further increased by the fact that there are many different parameters being used to describe or characterize a fire scenario, and the performance criteria, in the different test methods. In addition, the transient nature of burning and difficulty in controlling test conditions in various fire performance tests leads to an inherently larger uncertainty in the results than is common in many other fields of measurement.

Finally, new societal demands and expectations also drive changes in flammability test requirements [5]. Other factors that have impacted fire regulations in more subtle ways are:

Demand for increased fuel efficiency,
Low cost to serve,
Diminishing inexpensive global oil reserves,
Global warming,
Sustainability (especially as third world nations raise their standard of living),
Public safety expectations,
Public convenience expectations,
Acceptable risk (and quantitative risk assessment),
Global terrorism,
Geographic trade protectionism,
Litigation and appointment of "cause",
Increased selection of polymeric materials,
Development of flame-retardants.

Some of these factors have resulted in changes to products and services that have spawned the development of new flammability test standards. Examples include the potential for ignition and fire as a result of addition of creature comfort features, like padded seating, that incorporate combustible materials or monitor screens built into new seat backs. Other factors have driven major changes with fire safety implications, such as the replacement of heavy, non-combustible metal parts with lightweight combustible polymeric materials. Digges et al [11] report that from 1960 to 1996 the weight of combustible material in a typical automobile increased tenfold (from about 9 kg to about 90 kg), and this trend continues as new polymers with improved properties are developed. Recently, composite aircraft have been built and NFPA 130 [12] discusses rail cars where the exterior surface is made of combustible composite materials.

As well as changes to the materials being used in rail applications, passengers increasingly expect a quiet atmosphere, sophisticated climate control systems, electronic control systems and connectivity during their travel, adding to the availability of both fuel and potential ignition sources. The development of very long sections of underground services, (like the train that crosses under the English Channel) have also required changes to performance criteria. And in some geographic locales, economic initiatives like the creation of the European Union as a unified economic alliance have forced harmonization of numerous technical standards that were previously mandated by individual countries. Such forces, together with all the above drivers, spawn constant revision and modification of codes and standards, making it extremely difficult for manufacturers to easily track and keep abreast of applicable fire performance requirements across product groups and around the world.

1.3 Historical Overview

Over the course of the past century, perhaps longer, initiatives related to development of fire regulations have frequently been mounted in response to major accidents [9]. As a result of some investigations, organizations were established to maintain and oversee all related future fire safety activity. The sinking of the Titanic spawned the creation of the SOLAS (Safety of Life at Sea) committee that has been defining marine passenger standards since 1914 [13]. The National Fire Protection Association (NFPA) was formed in the 1890's and the Life Safety Code was developed in 1913 in response to major industrial fires [14] and more recently has extended its mandate to cover other fire safety regulations as well. Questions that came out of these accident investigations resulted in the development of many new test methods [9].

The very first reaction-to-fire tests were developed in the early 1900's to rank performance of specialized materials like flame retarded timbers or flammable fabrics, for various applications [7]. The 1930's saw the development of standardized tests for flammability of textiles in both England and the United States and the realization that broader-ranging flammability tests were needed. The1940's saw the development of Bunsen burner tests for plastics as well as the Steiner tunnel test to characterize flame spread. The Steiner Tunnel test was developed after a series of large fires with significant loss of life and property in night clubs, hotels and hospitals in the United States in the 1940's [9]. The Steiner tunnel test became the main North American standard for determining the flammability rating of building materials and Steiner Tunnel test results have since been incorporated into the requirements of numerous standards. The Steiner Tunnel test is a large scale test and it is difficult and expensive to perform, so this created a demand for smaller scale flame spread tests. Over the next several decades a number of other tests to characterize various aspects of fire performance of materials and components were developed. Even to date, for many current standards, the testing requirements frequently reflect the testing technology that was available at the time when the standards were developed with little variation over the years. Updates to the base standard typically build on precedent via existing methods and changes to testing requirements are frequently seen as an undesirable expense by business interests. An historical listing of several major fire safety standards for various sectors related to the transportation industry is summarized in Table 1.1 [5, 12-18].

The intent of all fire safety legislations is to protect people and property from the serious threat posed by fire. Yet research in recent decades has found poor correlation between the

Table 1.1 Selected historical milestones in fire regulation initiatives [5,12-18]

Sector	**Year**	**Initiative**
Buildings	1913	NFPA 101 - Life Safety Code
Marine	1914	The SOLAS (Safety of Life at Sea) Convention
Rail	1922	UIC Standards (Union Internationale de Chemins de fer, also known as International Union of Railways)
Aviation	1967 – 78	FAR 25.853 - Requirements for Compartment Interiors: Crew and Passengers (Ref. b)
Automotive	1972	FMVSS-302 – Federal Motor Vehicle Safety Standard - Flammability of Interior Materials
Rail	1970	Federal Railway Safety Act, Section 202 (e)
Rail	1975 - 1983	NFPA 130 - Standard for Fixed Guideway Transit and Passenger Rail Systems
Rail	1999	Federal Railroad Administration, 49 CFR, Transportation, Parts 216, 223, 229, 231 and 238, Passenger Equipment Safety Standards, Final Rule, Federal Register, 64, 91, USDOT, National Archives and Records Administration, Washington DC
Rail	2009	CEN TS 45545 Parts 1 to 5 - Railway Applications - Fire Protection on Railway Vehicles

results of many of the bench scale, standard tests used in the assessment of fire performance and the actual hazard that exists from large-scale fires [5, 7, 8, 11, 19]. Therefore, in practice, many legislations mandate the use of tests that do not accurately reflect realistic fire scenarios and the resultant hazards. This, along with the other factors discussed above, combines to make the field of fire safety standards and legislation difficult to understand and navigate successfully. In recent years, there has been a renewed international effort to develop a coherent and comprehensive set of fire safety standards and guidance documents under the auspices of ISO TC92 SC3, Fire Threat to People and the Environment [20]. While this is a laudable initiative, it will undoubtedly be a very long time, before fire performance regulations are in any way harmonized on an international scale.

1.4 Summary

Fire safety regulations and fire safety test standards are complex, varied and continually evolving. There are a large number of fire properties that can be measured, and there is poor correlation between fire test methods that purport to measure the same parameters. Yet, fire safety laws and standards have a major impact on globalization of trade. The degree of standardization and cooperation varies depending upon the sector involved. In all cases, however, there are many stakeholders with special interests: countries (sometimes with national, regional and local interests), industry associations, companies and non-governmental organizations. The ability to perform globally, either in the marketplace or in the conduct of relevant fire safety research, requires the ability to determine what standards apply to any particular topic of interest.

Chapter 2. Literature Review

This research is based primarily upon the retrieval and analysis of information from a multitude of sources, augmented by experimental measurements where research or calculations did not provide the needed information. Therefore, initially, extensive Internet searching was used to gain an understanding of the field at large. First academic searches were conducted on a variety of university library technical sources (Compendex, Engineering Village etc.) and when the these searches did not yield enough satisfactory information, Google searches were also used to determine the range of standards and standards organizations and companies that exist and the professional organizations involved in order to define a framework from which to work. A listing of the key abbreviations for these different organizations and groups involved in transportation fire safety can be found in the List of Abbreviations at the start of this thesis, but more detailed information can be found in the listings contained in Appendix A – Glossaries (Tables A-1, A-2 and A-3).

After more than a hundred titles of test standards, each somehow referenced in fire testing applications for transportation interiors were identified, analysis revealed wide-ranging content. The standards vary in length from a few pages to hundreds of pages. The content can be very specific and focus on a single topic, or can be very broad ranging to include all aspects of a mode of transportation including terminals, transit route considerations, equipment and operation. Many standards rely on use of other existing standards, creating a complex, inter-connected web of information. For example, the first standard reviewed, NFPA 130 [12], referenced 54 different technical standards and the second standard, DIN 5510-2 [47], and referenced 47 other technical standards. Table 2.1 is a partial listing of the titles from the series of test standards that were identified early in the research. These were used to develop an appreciation for the field overall.

From the preliminary assessment, it quickly became clear that the standards relating to transportation fire safety are so diverse that developing an in depth understanding of them was going to be very difficult. Therefore, several possible ways to categorize them are considered in this research. One approach is to classify them via the transportation sector involved. Alternatively they can be categorized according to the legislative framework for the jurisdiction in which they apply; or by fire parameter being evaluated. Yet another approach is to undertake a direct comparison of the technical requirements stipulated in each individual standard. After an overview of standards across the key transportation sectors, the following sections provide illustrative examples and discussion on the use of each these approaches for categorization of the railway standards of interest here.

Table 2.1 Initial listing of transportation flammability test standards considered

Standard Number	**Standard Name**
14 CFR 25 App. F, Pt. 1	Airworthiness Standards: Transport Category Airplanes, Part D - Design and Construction Fire Protection
14 CFR 25 App. F, Pt. 2	Airworthiness Standards: Transport Category Airplanes, Part D - Design and Construction Fire Protection
AFAP 1	NATO Reaction to Fire Tests for Materials - Overview and Ignitability of Materials (3rd Ed.)
AFAP 2	NATO Reaction to Fire Tests for Materials - Smoke Generation (3rd Ed.)
AFAP 3	NATO Reaction to Fire Tests for Materials - Toxicity of Fire Effluents (3rd Ed.)
AFAP 4	NATO Reaction to Fire Tests for Materials - Surface Spread of Flame (3rd Ed.)
AFAP 5	NATO Reaction to Fire Tests for Materials - Heat Release Rate (3rd Ed.)
ASTM D2863	Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index)
ASTM D3675	Surface Flammability of Flexible Cellular Materials Using a Radiant Heat Energy Source
ASTM E1317	Flammability of Marine Surface Finishes
ASTM E1321	Material Ignition and Flame Spread Properties
ASTM E1354	Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Comsuption Calorimeter
ASTM E1537	Test Method for Fire Testing of Upholstered Furniture
ASTM E1590	Fire Testing of Matresses
ASTM E162	Surface Flammability of Materials Using a Radiant Heat Energy Source
ASTM E176	Standard Terminology of Fire Standards
ASTM E2061	Guide for Fire Hazard Assessment of Rail Transportation Vehicles

Standard Number	**Standard Name**
ASTM E2067	Practice for Full-Scale Oxygen Consumption Calorimetry Fire Tests
ASTM E2257	Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies
ASTM E662	Specific Optical Density of Smoke Generated by Solid Materials
ASTM E800	Standard Guide for Measurement of Gases Present or Generated During Fires
ASTM F1550	Test Method for Determination of Fire-Test-Response Characteristics of Components or Composites of Matresses or Furniture for Use in Correctional Facilities after Exposure to Vandalism by Employing a Bench Scale Oxygen Consumption Calorimetry
ASTM G125	Measuring Liquid and Solid Material Fire Limits in Gaseous Oxidants
Bombardier SMP 800-C	Toxic Gas Generation from Material Combustion
BS 5852	Assessment of the ignitability of upholstered seating by smouldering and flaming ignition sources
BS 6853 Annex B	Toxicity test
BS 6853 Annex D	Three metre cube smoke density test
BSS 7239	Test Method for Toxic Gas Generation by Materials on Combustion
C-8914, Annexure II	Schedule of Technical Requirements for Flexible Load Bearing Polyurethene Foam Cushions for Passenger Coaches
CGSB 4-GP-2, M 27.1	Canadian Standard Textile Test Vertical Burn
CGSB 4-GP-2, M 27.2	Canadian Standard Textile Test 45 Degree Burn
DIN 54341	Testing of seats in railways for public traffic - Determination of burning behaviour with a paper pillow ignition source
DIN 54837	Determination of burning behavior using a gas burner
DIN 5510-2	Preventive Fire Protection in Railway Vehicles. Part 2 - Fire behavior and fire side effects of materials and parts - Classification, requirements and test methods
DIN EN 1021-1	Furniture - Assessment of the ignitability of upholstered furniture - Part 1: Ignition source smouldering cigarette
DIN EN 1021-2	Furniture - Assessment of the ignitability of upholstered furniture - Part 2: Ignition source match flame equivalent
DIN EN 14390	Fire test - Large-scale room reference test for surface products
DIN EN 2310	Aerospace series - test method for the flame resistance rating of non-metallic materials
DIN EN 2826	Aerospace series - burning behavior of non-metallic materials under the influence of radiating heat and flames - Determination of gas components in the smoke.
EN 11925-2	Reaction to Fire Tests - Ignitability of products subject to direct impingement of flame, Pt. 2-Single flame source test
EN 13501-1	Fire classification of construction products and building elements, Pt. 1-Classification using data from reaction to fire tests
EN 13823	Reaction to fire tests for building - Conditioning procedures and general rules for selection of substrates
EN 2824	Aerospace series - Burning behaviour of non-metallic materials under the influence of radiating heat and flames - Determination of smoke density and gas components in the smoke of materials - Test equipment apparatus and media;

Standard Number	**Standard Name**
EN 2825	Aerospace series - Burning behaviour of non metallic materials under the influence of radiating heat and flames - Determination of smoke density;
EN 2826	Aerospace series - burning behavior of non-metallic materials under the influence of radiating heat and flames - Determination of gas components in the smoke.
EN ISO 1182	Reaction to fire tests for building products - Non-combustibility test
EN ISO 1716	Reaction to fire tests for building products - Determination of heat of combustion
EPA SOP 312	Cleaning of Canisters
EPA TO 14	Determination Of Volatile Organic Compounds (VOCs) In Ambient Air Using Specially Prepared Canisters With Subsequent Analysis By Gas Chromatography
EPA TO 15	Determination Of Volatile Organic Compounds (VOCs) In Air Collected In Specially-Prepared Canisters And Analyzed By Gas Chromatography/ Mass Spectrometry (GC/MS)
FAR 25.853(a) vertical	U.S. Federal Aviation Regulation – Part 25 Compartment Interiors – Part 1 – Test Criteria and Procedures for Showing Compliance with 25.853 or 25.855
FMVSS-302	Federal Motor Vehicle Safety Standard – Flammability of Interior Materials. This standard has been adopted internationally and it is technically equivalent to ISO 3795 which was published in 1989. ISO 3795 is used in Europe, Canada and Japan.
IEC 60695-7	Fire Hazard Testing – Part 7.1 – Toxicity of fire effluents, general guidance
IMO FTP Code, Part 8	International Code for Application of Fire Test Procedures, Part 8: Upholstered furniture, IMO Res.A.562(16), Fire test of upholstered furniture
IS-7888 Cl. 11	Methods of Test for Flexible Polyurethane Foam
ISO 19701	Methods for sampling and analysis of fire effluents
ISO 19702C	Toxicity testing of fire effluents – guidance for analysis of gases and vapours in fire effluents using FTIR analysis
ISO 21489	Fire Safety – Measurement of smoke gas components in cumulative tests
ISO 5658-2	Lateral flame spread
ISO 5659-2S	Plastics – Smoke Generation – Determination of optical density by a single chamber test
ISO 5660-1	Reaction-to-fire tests – Heat release, smoke production and mass loss rate, Pt. 1: Heat release rate (cone calorimeter)
ISO 5725	Accuracy of Measurements and Results Package
ISO 9705-2	Fire Tests - Full scale room test for surface products – Part 2: Technical background and guidance
ISO/CD 21489	Fire Tests – Methods of Measurement of Gases by Fourier Transform Infrared Sepectroscopy in Cumulative Smoke Test
ISO/TR 9122-3	Toxicity Testing of Fire Effluents – Part 3: Methods for the determination of gases and vapours in fire effluents.
ISO/TR 9705-2	Reaction to fire tests – Full-scale room tests for surface products – Part 2: Technical background and guidance
NCD 1409	Toxicity Index
NF X 10-702	Determination of the opacity of the fumes in an atmosphere without air renewal
NF X 70-100	Fire Tests – Analysis of Gaseous Effluents – Part 1: Methods for Analyzing Gases Stemming from Thermal Degradation; Part 2: Tubular Furnace Thermal Degradation Method

Standard Number	Standard Name
NFPA 271	Standard Method of Test for Heat and Visible Smoke Release Rate for Materials and Products using an Oxygen Consumption Calorimeter
NFPA 271	Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products using an Oxygen Consumption Calorimeter
NT fire 047	Nordtest Combustible Products: Smoke Gas Concentrations, Continuous FTIR Analysis
NT fire 055	Nordtest Matresses: Burning Behavior Full Scale Test
Pr CEN TS 45545-2	Railway Applications - Fire Protection on Railway Vehicles, Pt. 2 - Requirements for fire behavior of materials and components
Test Method I	Test Method 1 for Non-Metallic Materials for use on Railways
UIC 564-2 Annex 13	Fire resistance of seats: Toxic fume emmission
	UIC 564-2 – Regulations relating to fire safety in passenger carrying railway vehicles or assimilated vehicles used on International service
	UIC 564-2 Annex 8 Fire resistance of foam materials

2.1 Overview of Key Sectors

Initially, regulations pertaining to fire safety were developed to cover buildings, but they have expanded to cover mass transportation sectors like marine, rail and air because in all of these applications, safety of life is paramount yet egress is restricted. There have been relatively fewer mandated fire regulations for automobiles than for other sectors, because individuals have control of the vehicles and egress is usually more directly accessible, except in severe accident scenarios. In this section, a very brief overview of the current standards and global legislative environment relating to each of the key transportation sectors is provided to set the context for the following chapters. Updated information on this can be found in Appendix B.

Airline Standards

The airline fire safety standards developed by the United States have been adopted globally. The technical testing requirements are documented in the FAR Part 25 Appendix F [16] and have been updated regularly, typically in response to significant air accidents. Several manufacturers have developed standards that they require in addition to those specified in FAR Part 25.

Marine Standards

Marine fire safety standards are also international in scope and are under the jurisdiction of the International Maritime Organization (IMO). In 1996, the IMO developed the Fire Test Procedure (FTP) Code, which is comprised of nine parts [21]. In 2010, IMO released major revisions and updates to their FTP Code, changing them to performance-based codes from prescriptive codes. The new codes came into effect July 1, 2012, as planned.

Automotive Standards

There was little in the way of legislated flammability requirements for passenger compartments for many years. In response to concerns over the recurring ignition of automotive interiors due to passengers' smoking cigarettes etc. the Society of Automotive Engineers (SAE) developed and published SAE J369 – Flammability of Polymeric Interior Materials – Horizontal Test Method in 1969. In 1972 the US government published a national standard for automotive interiors, FMVSS 302 (Federal Motor Vehicle Safety Standard 302) [15] that was based on SAE J369. This test has since become an international standard. SAE J369 (Society of Automotive Engineers), ISO 3795, BS AU 169 (UK), ST 18-502 (France), DIN 75200 (Germany), JIS D 1201 (Japan) and ASTM D 5132 are all technically equivalent [11].

Rail Standards

There are many railway safety standards. In contrast to the transportation sectors discussed above, there has been limited harmonization of the standards in this sector. The countries with the most highly developed rail legislation and testing requirements are Great Britain, France, Germany and the United States, but other countries have their own standards as well. In areas where trains may frequently cross national boundaries, standards for inter-operability are necessary. To fill this need, the UIC was formed in 1922. In the early years it had fifty-some members from three continents; now, it has 197 members that originate from all five continents. In addition to interoperability standards, the UIC has also published many technical performance standards, and in this area, their requirements are most closely related to historical French standards [17]. Recent trends in rail standard development in Europe will be discussed in Section 2.2.2.

NATO Standards

NATO standards apply to military vehicles for the over two hundred countries that are members of NATO. They are not specific to a single mode of transportation but have been included here for discussion and comparison because of the wide range of their applicability in transportation systems.

2.2 Overview of Legislative Framework in Key Geographies

As discussed above, flammability requirements for some modes of transportation are globally standardized, but this is not the case for rail transportation. Railway fire safety provides an excellent example of how different jurisdictions can employ vastly different approaches to fire performance test requirements. Examples of this are illustrated in the following discussions with respect to how Canada, the United States and Europe approach the situation for civilian rail safety and as members of NATO.

2.2.1 Canada

Responsibility for fire-related regulations in Canada is spread among various bodies. NRC conducts fire research, but mainly related to buildings and building codes or military topics and not to public transportation [22]. NRC also publishes the National Building Code and the National Fire Code. Transport Canada addresses wide-ranging issues pertaining to motor vehicle, marine, air and rail transport, including all aspects of safety [23]. The National Railway Association of Canada is an industry group comprised of more than fifty freight, intercity passenger, and commuter and tourist rail operators in Canada. Their website contains links to the important legislation pertaining to rail operations in Canada [24]. Municipal public transit systems may or may not even be considered "railways" depending upon the equipment used and decisions made by the Authorities Having Jurisdiction (AHJ) [25].

In 1989 the federal Railway Safety Act of 1985 came into force [26]. The original act made individual railway companies responsible and accountable for the safety of their own operations. The Railway Safety Act was amended in 2011 to further expand the role of "companies" in rail safety, and now covers not just railway companies, but also includes manufacturers of rolling stock, among many others [26, 27]. The act requires that equipment be designed according to sound engineering principles and that professional engineers approve designs. This implies that fire performance test standards and requirements are decided by company and customer specifications. Proposed standards for major projects are submitted to the appropriate government agencies for review and approval as required. A typical approach taken in rail design is to comply with local legislative requirements and then to follow the recommendations of a highly recognized standards setting body like NFPA, APTA or ISO for example.

In 1999, Transport Canada introduced an additional compliance requirement over and above the Railway Safety Act requiring the use of a Safety Management System (SMS) to integrate safety into day-to-day requirements for all rail systems [28]. SMS was added to the Railway Safety Act as an amendment in 2001 [29]. It requires that companies submit an SMS plan initially and provide annual updates. The federal government also mandates rail safety inspection services in the interest of public safety.

The links to Canadian regulations, rules and orders provided by the Railway Association of Canada are largely concerned with operational and maintenance issues. Details of product performance, such as fire performance of rail seating are not addressed in any of the rules and regulations listed. This is consistent with the approach defined by the Railway Safety Acts of 1985 and 2011, which shifted the responsibility for design safety to rail manufacturing and operating companies. All Canadian rail systems (inter-city or commuter) must meet the safety standards mandated by Transport Canada, but the Transport Canada regulations do not specifically address fire properties of passenger seating or interior finishes. Therefore, at present in Canada, the fire safety of these systems would be highly influenced by the technical professionals designing the systems as well as the actual manufacturers of the components. In the absence of specific legal requirements, it is customary to rely on recognized technical standards such as those published by NFPA.

2.2.2 United States

In the United States, the Federal Railroad Administration (FRA) mandates passenger rail safety standards, and is under the jurisdiction of the United States Department of Transportation. Prescriptive passenger rail safety requirements are defined in the Code of the Federal Register (CFR), Title 49, Section 238 [30] and NFPA 130, which covers fire safety and fire protection for guide way transit and rail systems, and is kept consistent with the legislated requirements of the United States [12]. There may also be state or municipal requirements in addition to those imposed federally in the USA, depending upon the AHJ involved.

There has been much renewed interest in the standards and requirements for passenger rail services in the United States in recent years. Work is on going by a number of bodies to transition from the current historical prescriptive standards to performance based standards as is popular worldwide in the building industry. The Volpe Institute, Underwriters Laboratories (UL), ASTM, NFPA, the United States Fire Marshalls and the American Public Transportation Association have all been actively involved in research to define future directions in railway passenger fire safety in recent years [5, 12, 30-32]. However, since the requirements outlined in NFPA 130 are the ones currently in use, and they are consolidated into a single source document, these are used in this work for describing American requirements.

2.2.3 Europe

Rail standards in Europe are quite complex and are currently very much in flux. Historically, different countries used different regulations. Great Britain, France and Germany all had unique legislative requirements specific to passenger rail service. There also existed another set of international passenger rail standards published by the Union Internationale de Chemin de Fer (UIC) [17]. As of this writing, the UIC has a total of 197 members (active, associate and affiliate members) from all five continents. The members may be railway companies, infrastructure managers, or railway related service providers. Full membership is restricted to train operators or major infrastructure managers. North American members include VIA Rail, Amtrak, US DOT, California High Speed Authority and the Association of American Railroads (AAR) [33].

One of the drivers for the formation of the European Economic Union in 1993 was to harmonize issues that were obstructions to free trade. Conflicting fire regulations and/or fire regulations specific to each country have been identified as examples of a barrier to European economic free trade. Therefore, many fire regulations in Europe have been under review in recent years, and passenger rail safety requirements are currently in the process of being revised. More information about the current European framework can be found at the European Committee for Standardization (CEN) webpage [34] and is summarized below.

In spite of a historically high degree of rail inter-connectivity initiatives (enabled by the UIC), several large countries maintained their own sets of railway standards, most notably France, Germany and Great Britain. During European harmonization discussions, fire safety of trains was identified as a high priority topic for standardization. To address the issue of fire safety, CEN and the European Committee for Electro-technical Standardization (CENELEC) chartered a working group entitled CEN/CLC/WG FPR to develop a common strategy of Fire Protection for Railway Applications. Other groups were chartered to conduct research and make recommendations to those defining the legislation. In 2009, CEN TS-45545 was published as a collection of conditional documents open for comment by EU member states. In 2011, all member countries were to provide feedback on what changes were needed. Research to support the finalization of EN 45545-2 is still ongoing under a group called “transfeu” chartered by the European 7th RTD Framework Programme [35]. They planned to publish the revised version of EN TS-45545 late in 2012; however, as of this writing, the final documents were not publically available. Appendix B contains an update on this initiative.

This major initiative will completely revise and standardize rail requirements across all of Europe. The intent is that all CEN member states must manufacture their new rail cars to these new standards, or they cannot sell or use their new rail cars within the EU zone. Recognizing the huge economic impact of this move, a number of other countries have signed on as “affiliate” members to this initiative. Affiliate countries cannot contribute to decision-making, but can participate in the trade benefits of such an agreement to supply materials and components for new rail cars. The members of CEN and the CEN affiliates are listed in Table C-1 of Appendix C. Canada and the United States are not in this list, but both Canada and the USA are members of ISO TC 92, the International Organization for Standardization Technical Committee on Fire Safety [36], which is also heavily involved in the activities of the transfeu group.

2.2.4 NATO Countries

NATO is a multi-national political and military alliance that seeks to promote peace and stability both by diplomatic means and military intervention, as required. Canada, the United States and Europe are all members of NATO. A complete listing of the NATO members and their partners can be found in Table C-2 of Appendix C.

The military branch of NATO has defined and published fire resistance standards for the acceptance of materials for use in all NATO military vehicles. These standards are publicly available for downloading from the Internet and represent a multi-national collaboration that spans many technologies and forms of transportation. Since these standards are readily publicly available and are applicable in over two hundred countries, they have been included in the high level comparisons conducted for of this research. It is not clear to what extent NATO standards pertain to rail applications because detailed information about military practices are classified information [37], but rail infrastructure is an important asset in times of conflict. For example, Toomey discusses the impact of the recent war in Bosnia on the rail infrastructure in that country [38].

2.2.5 Synopsis

The summaries provided above illustrate the wide variability of approaches to railway fire safety that currently exists in various jurisdictions around the globe. These range from locales that have no formal legislative requirements, to country specific requirements, to multi-national agreements for single or multiple platforms. Some countries have their own requirements or use a blend of existing standards from other countries. The legislative framework is changing however, and many countries are watching the changes that are happening in Europe and the United States.

The intent of this thesis is to rank the severity of fire testing requirements for public transportation seating for a number of geographies and jurisdictions, with an emphasis on rail seating. It does not attempt to fully investigate the regulatory requirements for rail seating fire safety for every country, but when relevant technical standards containing fire performance testing were identified for a particular country, that information was included in the analysis. Therefore, technical standards for the USA [12], Europe [18, 39], NATO [40-42], Japan [43] and India [44-46] have been included in the comparison. Canada no longer has national prescriptive requirements for rail seating, but the Canadian situation has been described. China has developed national standards, which have borrowed heavily from the German standard DIN 5510 [47] and information from DIN 5510-2 has been used to comment on the general direction of Chinese requirements [48], but authoritative Chinese standards have not been found or used in this thesis. Iv [49] reports that in practice, a government may mandate test requirements, but may have difficulty implementing these requirements. Chinese experience in purchasing rail equipment has shown that equipment is often manufactured according to the standards applicable in the country of manufacture and not to the standards specified by an individual government, even for a country as large and powerful as China. In this age of increasing globalization, their experience raises questions about the effectiveness of national regulation in technical arenas. It is not unusual for equipment manufacturers to request substitution of a standard that they consider equivalent or better to the method specified. Not infrequently, multi-national companies have market capitalization larger than the GDP of many smaller countries, and they may feel that they understand the technology better than some outside group, like a national or state regulatory body. The quandary then arises as to whether the equipment provided is appropriate for use per the standards in force, or if “national” standards are a sustainable practice. Pressure for more global harmonization will continue, but resolution will not be quick because of vested political and economic factors.

2.3 Categorization According to Fire Parameter Under Study

As an alternative approach to classification of fire performance requirements based on legislative jurisdiction, this section discusses how fire performance requirements can be classified according to the fire parameters being evaluated. In order to do this, appropriate fire parameters must first be defined and their relation to fire performance testing understood. In this respect, it must be recognized that fire itself is a multi-faceted phenomenon. The same material exposed to an identical ignition source will not burn the same way twice unless extreme measures are taken to control the many other parameters that influence fire growth and development. As such, in different fire tests, the fire performance can be characterized by any one, or a combination, of parameters that include, but are not limited to: rate of flame spread, ignition energy, ignition delay, heat production, smoke production, toxic gas evolution, weight loss, spread of fire by dripping onto a substrate, or time to self-extinction of the flames. Some test methods are designed to measure only one aspect of fire performance; in others it is required to characterize fire performance based on several flame parameters. Some tests permit variation in the experimental conditions, whilst others specify very strict bounds on ambient or other conditions that might affect the fire performance. As such, even using the same test standard, it may not be adequate to state that a certain parameter was measured by that specific method without further clarification. This will be illustrated in the following discussion on how three different jurisdictions, Japan, Europe and NATO, specify use of the same test method, the ISO 5660 - Reaction-to-fire tests: Heat release, smoke production and mass loss rate test method in evaluation of fire performance of railway components. The ISO 5660 standard consists of two parts; Part 1: Heat release rate (cone calorimeter method) and Part 2: Smoke production rate (dynamic measurement), designated as ISO 5660-1 and ISO 5660-2 respectively. Both parts of the test can be conducted on the same sample in a standard cone calorimeter, where a horizontal sample of the material is exposed to a uniform radiant heat flux from a conical heater; however, ISO 5660-1 only requires that the heat release rate profile be measured with time after ignition whereas ISO 5660-2 also requires the characterization of the smoke and combustion products generated at specified times after the initiation of combustion.

Amongst the jurisdictions of Japan, Europe and NATO, the most obvious difference in application of this standard to railway seating is that Japan and Europe both require that rail seating be tested only according to ISO 5660 -1 whereas the NATO standard AFAP 5 – NATO Reaction to Fire Tests for Materials [40], requires that the seating must be tested according to both ISO 5660-1 and ISO 5660-2 (with modifications).

More in depth investigation, however, reveals further differences as well in that Japan, the EU and NATO each specify that the ISO 5660 test be conducted in a somewhat different manner, as shown in Table 2.2.[1]

Table 2.2 ISO 5660 test conditions specified by different authorities [43,39,40]

Authority	**Test No.**	**Replicates**	**Applied Heat** (kW/m^2)	**Time** (min)	**Parameters Measured**[1]
Japan	1	3 to 6	50	10	Max. heating value (MJ/m^2), MAHRE (kW/m^2), Ignition time (sec)
Europe	1	3	25	20	MAHRE (kW/m^2)
NATO	1	3	25	22	AHRE (kW/m^2), MAHRE (kW/m^2), HHR$_{30}$ (kW/m^2), SPR$_{30}$(m^{2}s^{-1})
	2	3	50	22	

Japan [43] and Europe [39] each require that samples be tested under only one set of conditions using ISO 5660-1 protocols (heat release), though different conditions are defined even for each of these jurisdictions. In contrast, NATO AFAP 5 [40] requires that samples be tested under two sets of test conditions using both ISO 5660-1 (heat release) and ISO 5660-2 (smoke production)

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[1] Definitions for the measured parameters listed in Table 2.2 can be found in Appendix A, Table A-3, Definitions.

procedures. The tests not only differ in the intensity of heat flux applied by the cone heater to the sample, but also the length of time the tests must be conducted and the final fire performance parameters that must be calculated.

Additional variations arise because of the information contained in the fire performance test report commissioned to record the results of the above tests and certify whether a product passed the test specification for a specific country or agency. The ensuing test report might include values for only specific fire performance parameters of interest, even though a fully documented report as specified in ISO 5660, should include all of the test conditions and parameters listed in Table 2.2 and more. Additionally, some test labs tailor their reports to each client request, again possibly providing less information than outlined in the original ISO 5660 document. In either case of a truncated test report, if the actual test conditions vary from those expected under ISO 5660, different fire performance results can be obtained, and the results should not be leveraged.

By way of example of such possible differences, European passenger rail seat evaluations require a record of only the maximum average heat release emission rate (MAHRE) for each test [39], whereas the Japanese stipulate that a material exhibits "resistance to burning" by setting acceptance criteria based on a combination of parameters measured during the test. The combined acceptance criteria used in Japan are illustrated in Table 2.3 [43] and include a record of the total heat released by the sample during the test, combined with either the time to ignition or the maximum average heat release rate, depending upon the actual test values obtained. In contrast, fire performance assessment of seating for use in NATO military applications is even more complicated and requires a material exhibit acceptable values of average heat release emission at specific times ($AHRE_t$), maximum average heat release emission rate (MAHRE) and maximum rolling 30 second averages for both heat release and smoke production (HHR_{30} and SPR_{30} respectively) [40].

Table 2.3 Japanese ‘Resistance to Burning” criteria [43]

Overall heat value (MJ/m^2)	**Ignition time** (sec)	**MAHRE** (kW/m^2)
8 or less		300 or less
Exceeding 8 and 30 or less	60 or more	

Results from samples tested using the conditions specified in Japanese protocols cannot be leveraged to either European or NATO requirements because the length of the test specified across these standards is also different. Summary reports written for either European or NATO tests similarly cannot be directly leveraged, however the similarity in test conditions between these two groups may permit partial leveraging of results if the raw data is available for reanalysis. Similarly, raw data from the 50 kW/m^2 NATO test could be reworked to provide the information specified for Japan. Typically, however, test labs do not provide customers with their raw data but furnish instead only summarized reports of the test results, necessitating that manufacturers test and retest their products in order to comply with fire performance requirements in these jurisdictions.

As well as the obvious differences outlined above, these three fire performance tests are quite different from a technical point of view as well. It is not appropriate to leverage cone calorimeter test results conducted at one heat flux setting to tests specified at a different heat flux setting. Even if the total amount of heat applied is the same, a sample that is heated more intensely, but for a shorter period of time may exhibit a different heat release profile than an identical sample that is exposed to a lower heat flux for a longer period of time [6]. Therefore, a MAHRE value determined using the heat flux conditions required by Europe would not be acceptable for use in evaluating a material for use in a Japanese rail car. This is because both the thermal decomposition (pre-ignition) and burning of a material are comprised of chemical reactions subject to all the rules of chemical kinetics. For example, there may be several possible and competing thermal decomposition routes for a material. These different decomposition reactions will generally have different energies of activation, so activation with an intense radiation source (like 50 kW/m^2) can well be expected to initiate a different decomposition route than activation by a less intense energy source (like 25 kW/m^2). Taken one step further, the composition of fuel vapour formed via one route may differ from that of the other, which in turn will directly influence the combustion intensity (heat release rate) and effluents evolved after ignition of the sample.

The example given above based on test standard ISO 5660 illustrates the kind of complexity that can be encountered with fire testing standards even when assessing the use of a single specified method in different legislative environments. Even though different jurisdictions might specify characterization by a common test procedure, it is possible that the test results and actual fire performance data, even for the same material, cannot be leveraged from one jurisdiction to the next. Thus, in the few cases such as the one above where a common test method is specified, different test conditions and performance parameters may be stipulated. However, in most cases, the situation is further exacerbated since entirely different tests are required for each different jurisdiction and sector, as well as for civilian versus military purposes.

2.4 Summary

Regulations pertaining to fire safety in seating for transportation applications are not globally harmonized. Further, even if jurisdictions specify a common test, the test conditions specified may vary and this can make the test results for one jurisdiction unsuitable for use in another situation. There is variation across transportation sector, across geographical and political alignments and across technical requirements. The reasons for this are many and varied. Thus the main transportation sectors were reviewed and a synopsis of the extent of their harmonization was presented.

It became apparent from the initial literature survey that the area of fire performance standards for railway fire safety is an area of extreme complexity. Therefore, this research will outline a systematic approach to analyzing the kind of complex information involved in understanding the area and develop a new methodology that can be leveraged to organize and analyze information related to any flammability research and development initiative that involves legislatively mandated requirements. The approach documented here will be designed such that it is useful for ensuring that future research projects at the University of Waterloo, and projects done in collaboration with industry partners, are able to address global regulatory requirements, as required. Development and application of the approach may well have broader implications, however, in that it may also help to identify gaps in background knowledge and application of existing standards. This, in turn, may guide new research into fire safety by highlighting needs and identifying avenues for improvement in both the technical basis for, and universal application of, fire performance test standards around the world.

Chapter 3. Methodology

3.1 Methodology for Selection of Research Tools

Surveys of the literature and review of existing fire performance test standards discussed in Chapter 2 clearly indicate that the fire testing requirements for any public transportation service are very complex. They reflect an intricate balance between government and industrial interests, public safety and historical practices. At the same time, since fire safety science is an emerging field and fires are dynamic, multi-faceted events, there are many parameters that can be used, and that are currently acceptable for use in describing different aspects of fire performance and behavior. These include time to ignition, energy required for ignition, heat release rate, burn rate, smoke production and toxic gas production to name a few. As a result, different countries stipulate different methods for fire safety testing and many methods can be performed in more than one way whilst still being recognized as acceptable. Legislation sometimes specifies a particular method be performed, but in a modified manner, and sometimes for parameters outside of the original and intended scope of the method. Additionally, many methods are in a perennial review cycle, which promotes constant change and potential improvement, but presents a challenge in terms of implementation of a given standard within and across jurisdictions even within the same transportation sector.

In order for an industry or researcher to understand, and remain current with, the complex and ever changing legislative landscape of fire safety regulations, new methodologies and approaches are required. In particular, this research aims to develop methods that can be used to systematically analyze and understand differences in fire safety performance requirements for transportation applications. It was determined that the methods had to allow the user to search for and highlight relationships among various key topics related to the broad range of standards that may apply to a given situation. Based on the preliminary analysis outlined in Chapters 1 and 2, it became clear that the tools also had to be flexible enough to allow the user to account for, organize and conduct analysis within and across many parameters of interest including, for instance, geography, flammability property, fire performance indicator, principle of operation of a given test and severity of a given test. These requirements led to the choice of Excel®[2] spreadsheets and Freemind mind mapping software as the main tools to be used in development of the present methodology. This section discusses these two tools and how and why they were chosen as the basis for the current research.

3.1.1 Spreadsheet Software

Spreadsheets facilitate the ready organization of vast amounts of information as combined textual and numerical data. They permit a user to perform calculations, sort data and easily add, subtract and hide data. For this reason, spreadsheets were chosen as the platform by which to systematically enter and store information on the key parameters and other details pertinent to each of the fire performance tests under study. While there are many such database software packages available, Microsoft Excel® spreadsheet software is an industry standard program and also is already widely used by the Fire Research Group at the University of Waterloo. As such, it was deemed to be a somewhat universal platform for development of the present method. Further, it was chosen to permit easy collaboration amongst University of Waterloo researchers and their industrial partners – the immediate users of the tool.

3.1.2 Mind Mapping Software

Spreadsheets are useful for storing, analyzing and organizing information, but not for visualizing and highlighting relationships among various key topics. Mind mapping software was chosen as the platform through which to develop this portion of the method. The concept of Mind mapping was

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[2] Registered trademark of the Microsoft Corporation

initially popularized by Tony Buzan [50] in the 1970's and it has more recently been developed into software that promotes and facilitates visual thinking. It is useful for brainstorming, problem solving, organizing and showing relationships between ideas and topics. Figure 3.1 below is an example of a mind map that graphically depicts the range of mind mapping software that is available for various computing devices, as organized by type of device. With this map, a user can quickly identify those programs that can be used on any one of five different computing devices. Using a mind-mapping program, the same information can be quickly and effectively organized and sorted in a number of other ways as well. For example, Figure 3.2 shows the same information analyzed to highlight the five mind mapping software programs that are available in a way that the user can quickly see the compatibility of each program on a range of different devices.

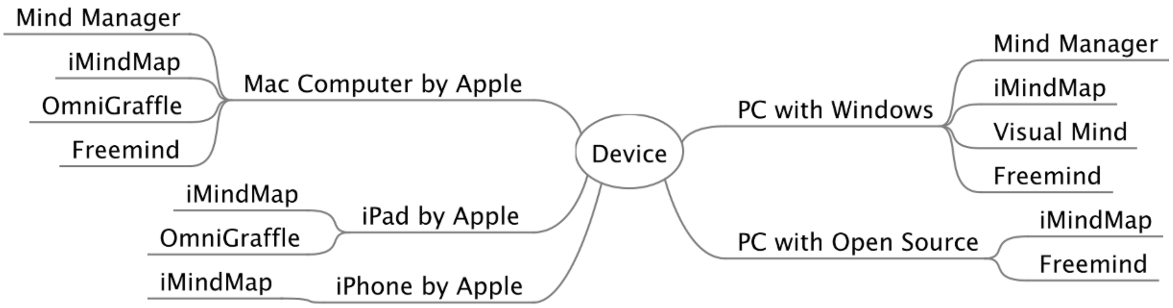

Figure 3.1 Mind-mapping software for specific devices

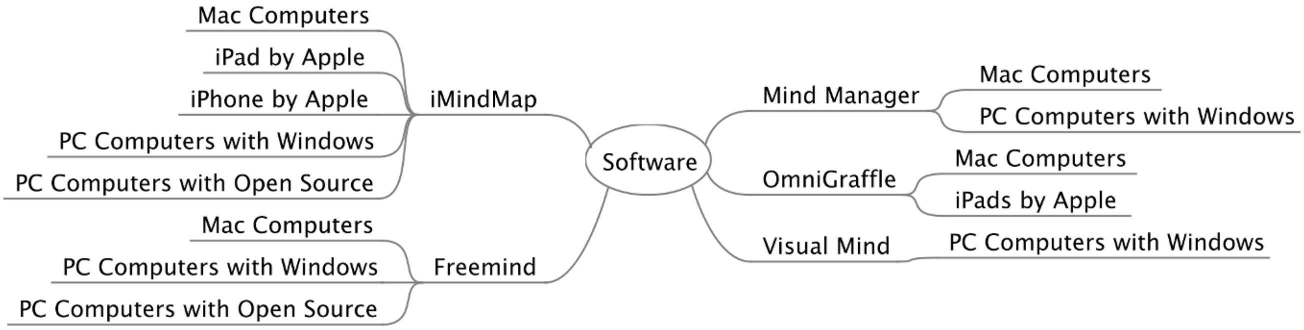

Figure 3.2 Devices supported by specific mind-mapping software program

In addition to facilitating the visual presentation of relationships, mind mapping software typically also permits expansion and contraction of any subset of information that is contained in the database so that the resulting map is tailored to suit the needs at hand. This change of view is done with a single click. Figure 3.3 shows the same mind-map as Figure 3.2, but in a collapsed view rather than in the fully expanded view.

Figure 3.3 Selected mind-mapping software choices

There are several approaches that can be used to populate mind maps and these are discussed in more detail in Appendix D.

As can be seen from Figures 3.1 through 3.3, there are many commercially available programs that can be used for mind mapping. Further investigation reveals that they each have various features, strengths and weaknesses. The following discussion defines the process used to select the mind-mapping program used in this study. It is fully recognized that since software options are continually evolving and changing, repeating this same selection process now, or at any point in the future, may lead to different results and recommendations in terms of the best choice for the present application.

In the spring of 2011, an extensive Internet search of mind mapping software was conducted to evaluate the products available at that time. The key criteria by which the available options were evaluated were: 1) software transportability in terms of the ability of the software to function on all major operating systems (Microsoft Windows, Apple and Linux), 2) output options including scalable print and output/export formats (including .pdf format), 3) the ability to annotate input and add author research notes, and 4) cost.

Table 3.1 lists the programs identified by this search and evaluated during the selection of the mind mapping software. Features that were considered during the evaluation are listed in the column titles of Table 3.1 [51-55]. Prices quoted in the table below are for single use licenses; however, some programs offer multi-user licenses and/or subscriptions with automatic updates and differing levels of technical support. Some of the commercial programs have an impressive array of powerful features, but most of these features were not deemed to be necessary for the purposes of this project. Instead, most highly ranked were the ability to operate on multiple platforms (to permit ready collaboration), to share output via the use of .pdf files and low cost. As a result, the Freemind mind mapping software was chosen because it provided these most important features at the best price.

Table 3.1 Comparison of mind mapping software programs [51-55]

Program	**Platforms**	**Scalable Printing**	**HTML Export**	**Notes**	**Exports to Other Formats**	**Cost**[3]
Mind Manager	PC, Mac	Yes	Yes	Extensive	Yes - Variable	$$$
iMindMap	PC, Mac, Linux, iPhone, iPad	Yes	Version dependent	Version dependent	Version dependent	$ to $$$
Visual Mind	PC	Yes	Version dependent	Yes	Version dependent	$$ to $$$
Omni Graffle	Mac, iPad	Yes	Yes	Extensive	Yes, Many	$ to $$
Freemind	PC, Mac, Linux	Yes	Possible	Minimal	.pdf	Free

[3] Legend: $ is < $100; $$ is between $100 to $200; $$$ is > $300

3.2 Methodology for Selection of Fire Tests

In Chapter 2, a wide range of fire safety standards applicable in the transportation industry were identified and the need to compare the specified fire test methods on a technical basis was illustrated. The section above provided the rationale for selection of tools to be used in organizing and analyzing the vast and complex information contained in the array of transportation fire safety standards that had been found. In this section, further rationale is provided in terms of the initial characterization and review of the standards and the selection of tests to review in detail. Following this, the detailed methodologies that were employed for characterization and assessment of flame spread and toxicity test standards are described. The results of these evaluations are presented in Chapter 4.

3.2.1 Preliminary Characterization and Review

During the literature review, a list of over one hundred unique standards was identified as being pertinent to fire resistance of transportation seating. The unedited list can be found in Table C.1 of Appendix E. To make sense of the large body of information collected, each standard identified was further examined from the six perspectives given below:

1. Which group defined this standard? Was it a country, an international body, a corporate entity, a professional body or a trade group?
2. To what geographies or jurisdictions does this standard apply?
3. When was the standard originally created? What is the latest release?
4. What is the primary objective of each standard?
5. What does the standard measure?
6. Is this a standard in common use that is not mandated by law?

With the number of different standards in the set, however, it proved difficult to organize the information based on this level of analysis alone. Therefore, to bring more clarity to the assessment, a higher level of categorization was conducted and the standards identified were further classified into one of four main categories: “overview” standards, “technical performance” standards, standards outlining “analytical techniques” and standards supplying “supporting information”. The present research then focused primarily on “overview” standards and “technical performance” standards in order to keep the sample set manageable in terms of developing and demonstrating use of the systematic organization and evaluation methodology that forms the basis of this research.

The list of overview and technical performance standards pertaining to air and rail seating in the jurisdictions of interest here consists of thirty-eight unique standards, not including any analytical or informational standards. The list would also be considerably longer if synonymous test titles were included. The listing of these standards can be found in Table E.2 and the list sorted by jurisdiction is contained in Figure E.1 of Appendix E.

Standards in the other two categories could of course be subjected to a similar process of evaluation in future work, but standards in these latter two categories are more concerned with details of “how to do the tests” rather than “what tests to perform”. The remaining sections of this Chapter then outline, in turn, the process by which the “overview” and “technical performance” standards were further classified and assessed.

3.2.2 Overview Standards

As mentioned in Section 3.2.1, there are many kinds of standards. Some standards have a very narrow focus, and others have a broader perspective. These latter standards frequently mandate what is to be tested and by what techniques. These kinds of standards are referred to as “overview” standards in this work. After the set of “overview standards” was identified (see Table 3.2 for examples), they were further divided by geography or jurisdiction and by the applicable

Table 3.2 Overview standards

Industry/ Applicability	Report Number	Test Name	Year	Geography
Aviation	FAR 25.853	Airworthiness Standards: Transport Category Airplanes, Part D - Design and Construction Fire Protection, Requirements for Compartment Interiors: Crew and Passengers - c) Seat Cushions	<1967	USA
Military	AFAP 1	NATO Reaction to Fire Tests for Materials - Policy for the pre-selection of materials for military applications (Ed. 3)	2010	NATO
Motor Vehicle	FMVSS 302	Federal Motor Vehicle Safety Standard - Flammability of Interior Materials	1972, 1991	USA
Rail	C-8914	Schedule of Technical Requirements for Flexible Load Bearing Polyurethene Foam Cushions for Passenger Coaches	2002	India
Rail	Pr CEN TS 45545-1	Railway Applications - Fire Protection on Railway Vehicles - Part 1 - General	2009	EU
Rail	Pr CEN TS 45545-2	Railway Applications - Fire Protection on Railway Vehicles - Part 2 - Requirements for fire behavior of materials and components	2009	EU
Rail	UIC 564-2	UIC 564-2 – Regulations relating to fire safety in passenger carrying railway vehicles or assimilated vehicles used on International service	1991	International
Rail		Technical Standard for Japanese Railway	2006	Japan
Rail	ASTM E2061	Fire Hazard Assessment for Rail Transportation Vehicles	2009	USA
Rail	NFPA 130	Standard for Fixed Guideway Transit and Passenger Rail Systems	2010	USA
Rail	49 CFR Part 216	Federal Railway Administration, Fed. Reg., Vol. 64, No. 91, pp 25539-25705, Passenger Equipment Safety Standards, Final Rule	2009	USA
Rail	DIN 5510-1	Preventive Fire Protection in Railway Vehicles. Part 1 - Levels of protection, fire protection methods and certification	2009	Germany
Rail	DIN 5510-2	Preventive Fire Protection in Railway Vehicles. Part 2 - Fire behavior and fire side effects of materials and parts - Classification, requirements and test methods	2009	Germany
Rail	BS 6853	Code of practice for fire precautions in the design and construction of passenger carrying trains	1999	UK

transportation sector, according to the perspectives listed above. It was also noted that, in contrast to technical performance standards, these “overview standards” frequently contain legally mandated requirements. The legal requirements may be country specific, or may apply to a range of countries. If an international body, like the European Union, NATO or IMO; defines the “overview standard” the mandated requirements apply to all member states. Occasionally, a country specific overview standard is adopted globally, as in the case of the airline safety standards developed by the United States. Table 3.2 summarizes the key set of the “overview” or umbrella standards that were identified for various transportation sectors with the standard title, year of issue and geographical jurisdiction in which it applies. These groups of standards are discussed further below.

As was discussed in Chapter 2, air, marine and NATO military standards are largely harmonized and have been for many years. Automotive safety standards also exhibit some degree of global harmonization; this is facilitated by the global nature of the automobile industry. At the time this research was done, performance based standards were being phased into the marine industry, but all other transportation sectors were using prescriptive standards. This work focuses on prescriptive standards. Therefore, Table 3.2 compares only representative standards relating directly to flammability requirements for seating in aviation, rail, automotive, and military applications.

It is clear from the entries in Table 3.2, that requirements for passenger rail seating are not globally harmonized to the same degree as the other modes of transportation. As such, much of the focus of the remaining discussion will revolve around fire safety for railway applications.

Within the set of railway standards listed in Table 3.2, the UIC standards are not law by any jurisdiction, but rather they are defined by railway undertakings that are members of the UIC. The UIC provides a forum for international railway entities to collaborate, and there is significant overlap between UIC standards and individual country specific legislations. For this reason and although they are listed in Table 3.2 for the sake of completeness, UIC standards will not be discussed in detail in this study.

Current European requirements are listed in Table 3.2 under the umbrella of CEN TS 45545: 2009. This is a document that is published, but is still under review. However, since it will supersede all current country specific regulations when approved and adopted, it was deemed appropriate as the basis by which to define European standards for the present work. That said, the German standard DIN 5510 is listed separately because China is an industrially important geography, and although it has its own regulatory system, current Chinese requirements are modeled after DIN 5510-2 [47].

3.2.3 Technical Standards

Once the relevant “overview” standards were identified, Freemind software was used to illustrate the “technical” standards required by the various jurisdictions. Figure 3.4 summarizes which fire tests and/or fire performance measurement parameters are specified for rail seating by several countries and jurisdictions. From Figure 3.4, it is clear that there are significant differences in how various legislative bodies look at flammability concerns in passenger rail seating. Some jurisdictions rely on providers to define appropriate technical standards (Canada), while some jurisdictions look at only two or three parameters in order to characterize flammability (the United States looks at flame spread and smoke, India looks at flame spread and toxicity of fire gases and Japan looks at flame spread, heat release and ignition tests). All other jurisdictions studied look at five or six fire characteristics and require testing on full seating units as well as small-scale tests. Due to the number and variety of methods encompassed in these requirements, the output shown in Figure 3.4 was further analyzed to assess the current state of flammability testing across all jurisdictions and thereby select which kinds of tests merited more in depth investigation initially.

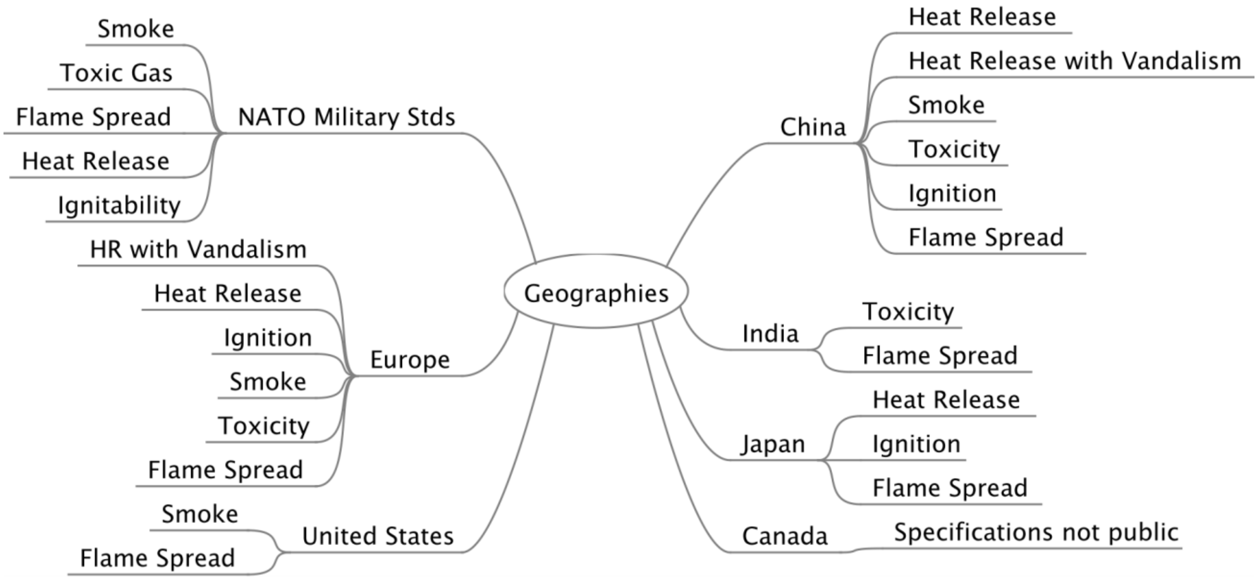

Figure 3.4 Legislatively mandated testing requirements for rail seating in selected geographies

Since some form of flame spread testing is common across all of the jurisdictions surveyed, it immediately was chosen for further evaluation. Other specified fire performance parameters and their associated test methods were then reviewed.

Heat release is currently considered the single most important measurement to predict the hazard potential of a fire [7]. At this point in time however, only three of the seven jurisdictions evaluated require direct measurement of heat release values to define fire performance. As discussed in some detail in Chapter 2, all three of the jurisdictions requiring heat release measurements use the same method and equipment, but specify that the test be conducted with different experimental conditions. Additionally, the test conditions specified in one jurisdiction are still conditional and under review, so it was felt to be premature to devote more in depth discussion to this set of tests at this point in time.

There are only two vandalism tests currently mandated, and the newest one of these is still under revision, so on that basis, seat vandalization tests were not chosen for further evaluation at this time.

Four jurisdictions currently require smoke tests, ignitability tests or toxic gas release tests. Of these three classes of test, the field of toxicity testing is the most complex and the least standardized in terms of both defining the detailed methodology for testing and setting acceptance criteria for evaluation of the true fire hazard or performance of a sample. For this reason, toxicity test methods were chosen as the second topic to subject to more detailed evaluation using the methods developed in this research.

3.2.4 Rationale for Tests Selected

Once it was determined that the flame spread and toxicity tests would be subject to more detailed review, a number of additional factors were considered whilst picking the most relevant standards for detailed consideration. First it was deemed necessary to evaluate any test currently mandated by law. Table 3.3 lists the subset of specific flame spread and toxicity tests legislatively mandated by the jurisdictions referenced in Table 3.2, each with test number and title as well as the reference legislation or overview document. A full listing of all of the tests mandated by these particular jurisdictions can be found in Figure E.1 and Table E.2 of Appendix E – Flammability Test Titles and Test Descriptions. Based on the initial criterion, the top section of Table 3.3 lists the flame-spread tests to be evaluated. These correspond well to the full list of tests identified via background research to be important to flame spread assessment. The second half of Table 3.3 lists the toxicity tests to be reviewed but, unlike the case for flame spread, this was not deemed to be a complete list of the important available tests. It was therefore decided that other tests that are in common use, but which are not legally mandated, should also be reviewed. Important tests of this nature include those developed and promoted by the major manufacturers of transportation equipment, like Bombardier

Inc. (SMP 800-C), Boeing Corporation (BSS 7239) and Airbus Industries (ABD 0031 7.4). The British toxicity test method from BS 6853 – Annex B was also included because of its historical significance, which will be highlighted in comparisons included in Chapter 4.

Table 3.3 Flame spread and toxicity tests pertaining to rail seating as per Figure 3.3

Flame Spread		**Required By**
ASTM D3675	Surface Flammability of Flexible Cellular Materials Using a Radiant Heat Energy Source	49 CFR Part 216, NFPA 130
ASTM E162	Surface Flammability of Materials Using a Radiant Heat Energy Source	49 CFR Part 216, NFPA 130
C-8914 Annexure II	Schedule of Technical Requirements for Flexible Load Bearing Polyurethane Foam Cushions for Passenger Coaches	C - 8914
DIN 54837	Determination of burning behavior using a gas burner	DIN 5510-2
FMVSS 302	Federal Motor Vehicle Safety Standard – Flammability of Interior Materials	FMVSS 302
ISO 5658-2	Reaction to fire tests -- Spread of flame -- Part 2: Lateral spread on building products in vertical configuration	CEN TS 45545-2 and AFAP 4
Japan Test Method 1	Test Method 1 for Non-Metallic Materials for use on Railways	Technical Std. for Japanese Railway
14 CFR 25 App F Part 1	Airworthiness Standards: Transport Category Airplanes, Part D - Design and Construction Fire Protection – Part 1, Vertical Test	FAR 25.853
14 CFR 25 App F Part 2	Airworthiness Standards: Transport Category Airplanes, Part D - Design and Construction Fire Protection – Part 2, Kerosene Burner for Seats Test	FAR 25.853
IS 7888 Clause 11	Methods of Test for Flexible Polyurethane Foam	C - 8914
Toxicity		
NCD 1409	Determination of Toxicity Index	C - 8914
DIN EN 54341	Testing of seats in railways for public traffic – Determination of burning behaviour with a paper pillow ignition source	DIN 5510-2
NF X 10-100	Fire Tests - Analysis of Gaseous Effluents - Part 1: Methods for Analyzing Gases Stemming from Thermal Degradation; Part 2: Tubular Furnace Thermal Degradation Method	CEN TS 45545-2 and AFAP 3
ASTM E662	Specific Optical Density of Smoke Generated by Solid Materials	FAA
ISO 5659-2	Plastics – Smoke Generation Part - 2: Determination of Optical Density by a Single Chamber Test	CEN TS 45545-2 and DIN 5510-2

While it is recognized that Boeing Corporation and Airbus Industries manufacture airplanes and not rail cars, their toxicity tests are readily available through contract laboratories, and the Boeing fire effluent test has been recommended for use in assessing fire effluent toxicity of rail car interior components [31]. The final toxicity test methods that are compared in the present thesis are listed in Table 3.4.

Table 3.4 Toxicity tests for detailed comparison

Test Number	Test Name	Year	Geography
NF X 70-100	Fire Tests - Analysis of Gaseous Effluents - Part 1: Methods for Analyzing Gases Stemming from Thermal Degradation; Part 2: Tubular Furnace Thermal Degradation Method	2006	France
ISO 5659-2 for DIN 5110-2	Plastics - Smoke Generation - Determination of optical density by a single chamber test	2009	EU
ISO 5659-2 for CEN TS 45545 Annex C	Plastics - Smoke Generation - Determination of optical density by a single chamber test	2009	EU
ISO 5659-2 for AFAP 3	Plastics - Smoke Generation - Determination of optical density by a single chamber test	2009	International
ASTM E662	Specific Optical Density of Smoke Generated by Solid Materials	2006	USA
Bombardier SMP 800-C	Toxic Gas Generation from Material Combustion	2009	Bombardier Corp.
ABD 0031 7.4	Fire test to aircraft material - Smoke toxicity test	1994	Airbus Industries
BSS 7239	Test Method for Toxic Gas Generation by Materials on Combustion	1980’s	Boeing Corp.
BS 6853 Annex B	Code of Practice for fire precautions in the design and construction of passenger carrying trains - Toxicity test	1999	UK
NCD 1409	Toxicity Index		India

Brief descriptions of all of the test methods mentioned above are included in Chapter 4 when the various methods are discussed.

3.3 Methodology for Comparison of Identified Fire Tests

Once the flame spread and toxicity tests to be included in the study had been identified, it was of interest to also develop methods by which to rank and/or compare important elements of each test (for example, severity or intensity of fire exposure) so that results from one test could be more easily compared to the results of other tests. After further investigation, however, it was determined that, due to the wide variation in tests techniques, this idea was not feasible. Instead, it was determined that a relative ranking of test intensity might be done on selected sub-sets of tests, but that in other instances, only qualitative comparisons would be possible. In Chapter 4, therefore, both toxicity tests and flame-spread tests will be compared qualitatively, but only flame-spread tests will be compared quantitatively. The methods developed for use in these comparisons are outlined in the following sections.

3.3.1 Methodology for Comparison of Toxicity Tests

Based on the initial evaluation discussed in the previous sections, further evaluation of toxicity test methods was undertaken with the intent to understand the differences in approach used in various toxicity tests rather than to rank the severity of the toxicity tests relative to a specified reference or to each another. This approach is further supported when consideration is given to the current state of the science and legislation in toxicity testing. Scientific experts have divergent opinions on which fire toxicity measurements are appropriate and / or meaningful [8, 20, 36], as well as on how to conduct such measurements, and on how well they may or may not represent what will happen in a real fire scenario. For example, some jurisdictions specify toxicity tests for interior transit components and others do not specify toxicity testing at all. Some jurisdictions focus on smoke production instead. Some major manufacturers have developed and implemented their own fire toxicity tests and standards.

3.3.1.1 Factors Affecting Toxic Effluent Production

This variation in approach is understandable when considered in the context of the complex chemical and physical processes that occur during a fire and how they affect the fire performance of a given material. In toxicity testing, this is exacerbated by difficulties incurred in trying to obtain and conduct appropriate analysis on a representative sample of gases from the burning material and relating toxicity information from a single burning material to the toxicity of the environment that might be encountered should that material be involved in a real fire. Nonetheless, there are some key factors that should be considered in developing an approach to qualitatively compare amongst toxicity test methods. Physico-chemical factors include fire ventilation conditions, scale of test, intensity of ignition source, effluent identification and choice of which effluents are measured, as well as the assigned toxicity threshold values. Combined with these are factors such as the location, method and duration of sample collection, the methods of effluent analysis and their accuracy, data normalization processes and exposure levels, models and risk indices used in interpretation of the results. These are discussed below in the context of their application to fire testing.

In fire toxicity testing it is especially difficult to compare results between different test methods because the fire effluents generated during a fire are highly dependent upon both the fire and ventilation conditions and the test design. There are a number of factors involved. Every fire goes through phases of pre-ignition, decomposition/vaporization, initiation (ignition), fire growth, steady state burning and decay. During these stages, the nature and relative amounts of combustion products can differ, so the timing and duration of sampling is important [4]. In addition, the products of combustion from a fire are dependent upon the availability of air during the course of the fire. The flame temperatures reached, influenced by both the air availability and the amount of material burning, similarly influence the decomposition and oxidation products. Figure 3.5 illustrates that the availability of air affects not only the flame temperatures attained, and thus the effluent gases produced, but also changes the total burning time over the lifecycle of an idealized, standard fire meaning that care must be taken in comparing samples taken at the same in tests where the same sample is burned subject to different ventilation conditions.

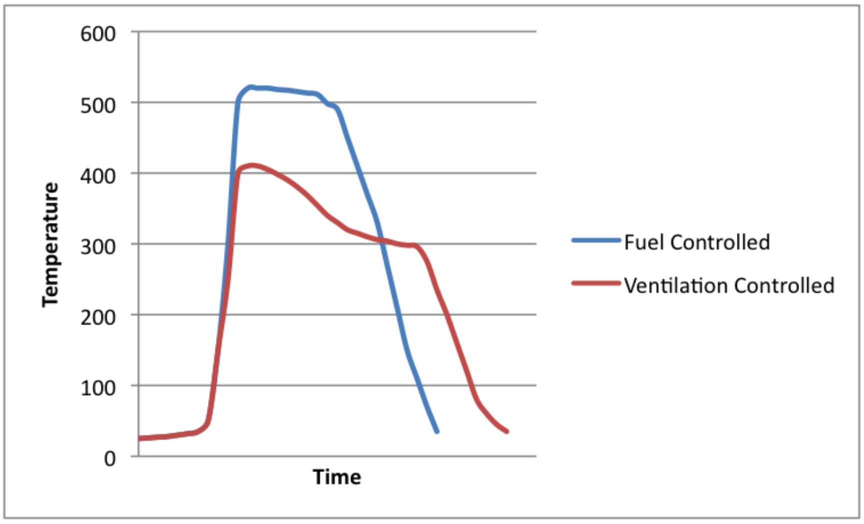

Figure 3.5 Idealized fire growth curve and typical temperatures

The factors mentioned above relate to the physico-chemical processes by which the fire effluent gases are generated and must be considered in any relative assessments of fire toxicity test methods.

Further complications in toxicity characterization can be introduced due to the methods specified for both sample collection [56] and for the analysis of the toxic elements. For example, samples can be collected at different times, either 4 or 8 minutes after ignition or at the time of maximum smoke density are common practices. None of these approaches ensures that the samples are taken when the toxic gas species are at their peak concentrations and since there is no way to know or predict when toxic gas production is at a maximum, or even representative, for any particular sample or test method, there is certainly no way to know comparability of results between tests. Added to this is the possibility that the manner in which the sample is withdrawn for analysis could upset the equilibrium of the test method since toxicity measurements are often conducted as part of another test, an approach that is frequently favoured to minimize the cost of testing. Again, all of these factors should be considered in determining relative merit of one toxicity test relative to another.

All of the toxicity tests listed in Table 3.4 are conducted on a relatively small scale and the relevance of small scale toxicity tests has previously come under question [31, 56, 57] since it is thought that some small scale tests might not generate enough heat to ensure that the test mirrors the full combustion that would occur in a large scale device. In full-scale fires, the high heat fluxes generated can be sufficient for burning to continue even at low oxygen concentrations (possibly as low as 5 vol. % oxygen in localized regions of large and vigourous fires [4] even though oxygen levels of 12 to 15 volume % are typically required to support combustion). In bench scale experiments, heat fluxes are not likely to be adequate to support combustion at such low oxygen concentrations and will result in different fire effluent gas profiles. Large-scale fires also generate more turbulence and mixing than is experienced during testing using smaller bench scale devices [56], suggesting differences in both mixing and ventilation conditions between the two situations. This is considered in the results contained in Chapter 4.

Finally, it must be noted that many of the tests currently specified for toxicity testing are actually tests that were designed for another primary purpose, but have been modified so that the effluents can be collected and used to assess the toxicity of the combustion products. In fact only two of the five legally mandated toxicity tests listed in Table 3.3 are designed primarily for testing toxic combustion products. The other mandated tests use gas samples taken from smoke or heat release tests. While this may be an attempt to streamline the complex and expensive requirements of fire testing by specific authorities, the lack of coordination amongst authorities renders comparison of toxicity test results on a global basis even more difficult.

3.3.1.2 Analytical Approach

Efforts have previously been made to evaluate and compare existing methods for toxicity testing. Hull [56] sought to understand which fire toxicity tests gave the most meaningful results. He analyzed how the smoke generation systems varied among various techniques and he classified these into one of four basic types, shown in Figure 3.6.

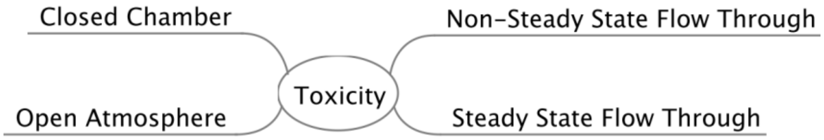

Figure 3.6 Categories of smoke generation devices in combustion toxicity tests

Hull then proceeded to compare the fire effluents measured in bench scale tests to those measured in large scale testing. In all, he analyzed twenty-seven bench scale toxicity test methods to determine how the smoke was generated, what fire stages were attained and most importantly how the toxic gases measured in each test compared to toxicity data obtained for the same materials tested at larger scales. He also identified if the toxicity measurement employed traditional analytical techniques or animal response indicators. Hull compared results from two open chamber devices; thirteen closed chamber methods, five non-steady state flow through and seven steady state flow through designs. An overview of the methods analyzed is shown in Figure 3.7.

Small-scale or bench-scale test designs in which the concentration of key effluent gases followed similar trends to those generated from an ISO room fire test were deemed to give the best results, based on the premise that the large scale test is the best predictor of what happens in the real fire situation. By comparing results from the various designs listed above, it was found that only steady state flow through test chamber designs gave results that aligned well with large-scale tests in ISO rooms through all stages of a fire. These potential limitations notwithstanding and with due consideration of the factors discussed above, more detailed comparisons are drawn amongst existing toxicity test methods for transportation applications in Chapter 4.

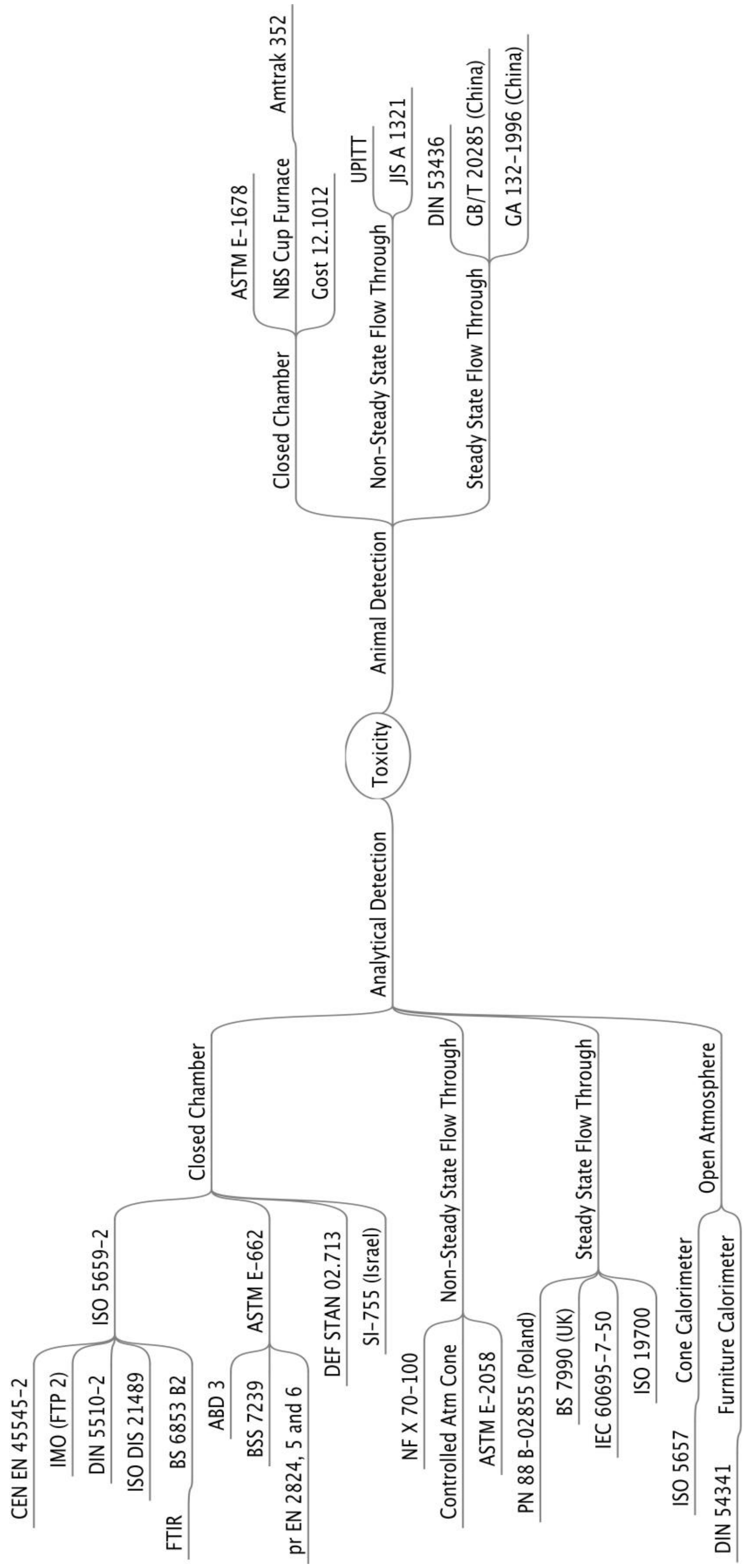

Figure 3.7. Comparison of smoke toxicity test by experimental design features

3.3.2 Methodology for Comparison of Flame Spread Testing

The second important class of tests to be considered here is the flame spread tests. Flame spread testing typically consists of monitoring the rate of burning across the surface of a specimen that is oriented vertically, horizontally or at a specified angle to the ignition source. Ignition may be facilitated by direct flame contact or as a result of an indirect radiative heat flux applied to the sample surface. Some methods use a combination of the two. The decision of what constitutes a flame-spread test versus some other sort of flammability test is somewhat arbitrary. Some pairs of flame spread methods and ignitability test methods are more closely aligned than some pairs of flame spread methods. In this work, the decision of which tests to include for comparison was based upon how the method was formally named and the parameters being measured, not the similarity of the techniques or tools used. Table 3.5 lists the flame-spread methods referenced in Table 3.3.

Table 3.5 Flame spread tests compared for energy intensity

Test Number	**Test Name**	**Radiation**	**Direct Flame**
AFAP 4	NATO Reaction to Fire Tests for Materials - Surface Spread of Flame (3rd Ed.)	Y	Y
ASTM D3675	Surface Flammability of Flexible Cellular Materials Using a Radiant Heat Energy Source	Y	Y
ASTM E162	Surface Flammability of Materials Using a Radiant Heat Energy Source	Y	Y
ISO 5658-2	Reaction to fire tests -- Spread of flame -- Part 2: Lateral spread on building products in vertical configuration	Y	Y
14 CFR 25 App F, Part 1	Airworthiness Standards:Transport Category Airplanes, Part D - Design and Construction Fire Protection - Part 1, Vertical Test	N	Y
14 CFR 25 App F, Part 2	Airworthiness Standards:Transport Category Airplanes, Part D - Design and Construction Fire Protection - Part 2, Kerosene Burner for Seats Test	N	Y
C-8914 Annexure II	Schedule of Technical Requirements for Flexible Load Bearing Polyurethene Foam Cushions for Passenger Coaches	N	Y
DIN 54837	Determination of burning behavior using a gas burner	N	Y
FMVSS 302	Federal Motor Vehicle Safety Standard - Flammability of Interior Materials. (Equivalent to ISO 3795)	N	Y
IS 7888 Clause II	Methods of Test for Flexible Polyurethane Foam	N	Y
ISO 3795	Road vehicles, and tractors and machinery for agriculture and forestry -- Determination of burning behaviour of interior materials	N	Y
Japan Test Method 1	Test Method 1 for Non-Metallic Materials for use on Railways	N	Y

Table 3.5 also indicates whether ignition is carried out via a radiant panel, a direct flame or a combination of both. From the Table it can be seen that all of the tests have a direct flame as some part of their ignition protocol, with one third also utilizing a radiant heat source. Therefore characterization of both will be considered here for use in comparisons amongst the various test methods outlined in Chapter 4.

3.3.2.1 Energy Intensity of Selected Flame Spread Methods

One important factor in determining the outcome and severity of the various flame spread test methods is the intensity of energy applied to ignite the test sample in each case [4]. The energy to which a sample is exposed in any test is the sum of any applied conductive, convective and radiant heat energy. Therefore, the energy of the ignition source(s) used in each test method was analyzed to determine which of each of these forms of heat transfer applies, and then the energy input due to each applicable mode of heat transfer was estimated and compared. This was done based on theoretical considerations as discussed below.

Theory of Energy Transfer

The total energy that is incident on a sample is the sum of the energy from all sources. For example, in a radiant panel test like ASTM D3675, which employs both a radiant panel and a pilot flame for ignition of a sample, the heat flux applied to the sample would be as described in Equation 3-1 [58].

$$Q''_{F} = Q''_{Fpanel} + Q''_{Fflame} \qquad \text{Eq. 3-1}$$

where Q''_{F} = total rate of heat application to the sample (W or kW); Q''_{Fpanel} = total rate of heat application from the radiant panel (W or kW); and Q''_{Fflame} = total rate of heat application via the pilot flame (W or kW).

Both the flame and the panel can potentially contribute energy to the sample via radiation, conduction and convection, such that:

$$Q''_F = q'''_{\text{panel radiant}} + q'''_{\text{panel conduction}} + q'''_{\text{panel convection}} + q'''_{\text{flame conduction}} + q'''_{\text{flame convection}} + q'''_{\text{flame radiation}} \qquad \text{Eq. 3-2}$$

The heat by conduction from the radiant panel, $q'''_{\text{panel conduction}}$, is 0 since there is no direct contact between the panel and the sample and $q'''_{\text{panel convection}}$, the heat by convection from the radiant panel, is generally considered negligible in comparison to the radiation contribution, $q'''_{\text{panel radiant}}$. The same assumptions cannot be made about the contributions from the pilot flame. In the majority of these tests, the pilot flame should impinge on the sample surface in the region of the most intense radiation.

3.3.2.2 Estimation of Energy Input from Radiant Sources

The radiant heat flux at a point distant from a fire or radiation source can be estimated using the equation 3-3 [58]:

$$\dot{q} = \varepsilon\sigma T_2^4 F_{12} \qquad \text{Eq. 3-3}$$

Where:

$\dot{q}$= heat flux to the sample (W/m^2)

ε = emissivity (unitless)

σ = Stefan Boltzman constant = 5.67 x 10 $^{-8}$ W/m^{2}K^4

T_2 = source (flame) temperature (K)

F_{12}= configuration factor or view factor between the radiant source and the sample (unitless)

The configuration factor, F_{12}, considers the size of both the radiating source and the receiver (or sample for a flammability test), the distance of the source from the sample and the geometric relationship between the two. Techniques do exist to evaluate F_{12} and in some situations, good estimates can be calculated. For some common, frequently occurring geometric configurations, reasonable estimates can be made from charts or published literature. To obtain accurate estimates for complex geometries that are not common, the use of complex mathematical modeling is required, and even that cannot always provide accurate predictions, depending upon the exact configuration of the test situation.

The geometries specified in ASTM D3675, ASTM E162, ISO 5658-2 and AFAP 5 are complex and configuration factors are not easily estimated. Additionally, the test methods are written in such a way that it is not easy to compare the intensity of radiation used in the two ASTM methods to the intensity used in the two ISO based methods and no literature studies attempting to calculate this were found. The ASTM methods provide a single flame equivalency temperature for the centre point of the panel and the ISO based methods provide desired heat flux values for a range of positions along a calibration board. Other researchers, when faced with evaluating this problem [31, 59] have measured the incident radiation at varying locations along the inclined sample in the ASTM tests, so as to permit comparison with the ISO 5658-2. Therefore, the result of this previous work is used in Chapter 4 for comparing the energy intensity of the methods, instead of calculations.

3.3.2.3 Estimation of Energy Inputs from Flames

For all of the tests listed in Table 3.5, it was necessary to estimate the energy input to a sample for various methods of direct flame ignition. Calculation of the actual energy that might be input to a sample from a flaming source can be a mathematically challenging task, but relative rankings can be made by multiplying the net heat of combustion of the fuel by the rate of fuel consumption and the duration of the flame exposure to obtain an estimate of the total energy input. This method was used when a test method indicated the fuel and flow rate for the fuel to be used in a flaming ignition system.

On the other hand, when a method specified a laminar flame of a specific length be established on a burner of a particular diameter, the volumetric flow rate was estimated using Equation 3-4 [58]:

$$L = V' / (2\pi D) \qquad \text{Eq. 3-4}$$

Where:

L = length of flame (m)

V' = volumetric flow rate of fuel (m^3/sec)

D = diffusion constant (m^2/sec)

Exactly how the calculation was done depended upon the fuel specified and the exact information available. Details of three different calculation approaches are described in Chapter 4 in the sections describing Laminar Flame Calculations.

Finally, in the case when a test method did not specify a flow rate, but instead specified the use of a Bunsen burner with a specific flame length, the flow rate was estimated using the charts published by Lewis and von Elbe [60].

Two test methods specified burning a known volume of ethanol in a metal cup of a specific size. It was not known how long these flames would burn, if the flames would be long enough to contact the sample or what the average energy intensity of the flame would be, so for this case, timed experiments were conducted using conventional and infrared cameras and an average flame intensity was calculated.

The results of these analyses for both radiant panel methods and direct flame only methods are presented and discussed further as each technique is examined in Chapter 4.

3.4 Summary

In summary, fire standards pertaining to mass transportation were identified and sorted according to the criteria described in Section 3.2.1. Excel® and Freemind mind mapping software were used to analyze the test titles collected. Overview standards were identified and studied to determine which tests are legally mandated. The legally mandated tests were organized by geography or authority and compared using mind-mapping software. The frequency of test types, in combination with other factors like pending revision cycles, legislative changes and the complexities of the field were considered in the final selection of tests to analyze in detail. Fire spread tests and fire effluent toxicity tests were selected for in depth analysis. Once the test methods for detailed evaluation were identified, the methodology that would be employed to analyze each class of test was discussed.

The production of fire effluents is highly influenced by the fire conditions and varies over the course of any particular fire. The factors that influence fire effluents were discussed. There are many ways to approach the characterization of a field as complex as fire effluent characterization. Hull [56] had conducted a particularly thorough and meaningful series of studies comparing bench scale fire effluent tests to large scale fire effluent testing. His approach was analyzed using mind maps and was selected as the basis for further analysis of the fire effluent toxicity tests used in transportation applications.

Flame spread tests were reviewed as to the type of ignition sources employed (radiant panels, open flames or both). The theory of energy transfer was reviewed, and a summary of how the energy input of both the radiation sources and the open flames were estimated was provided.

Chapter 4 – Results and Discussion

The fire effluent toxicity tests and the flame-spread tests identified in Chapter 3 are further discussed and compared in this chapter. Due to the considerations outlined in Chapter 3, tests to determine the toxicity of fire effluent are discussed in a qualitative manner while flame spread tests are discussed both qualitatively and quantitatively, to the extent possible. The methods used throughout this Chapter were presented in Chapter 3, with key details of any calculations contained in Chapter 4, Section 4.2.1.2.

4.1 Analysis of Fire Toxicity Tests

Detailed information on all of the smoke toxicity tests included in Table 3.4, which are the fire effluent toxicity methods relevant to mass transit applications, were analyzed according to the methodology used by Hull [56] and described in Chapter 3.

Before continuing with the analysis, it should again be noted that there are situations for which it is very difficult to obtain all of the information required to understand the details of a particular toxicity test method. For example, China has modeled their railway fire standards on the German DIN 5510-2 [47] system. The current DIN 5510-2 smoke toxicity test requirements are significantly different than the smoke toxicity tests stipulated in the Chinese building code requirements, namely GB/T 20285 and GA 132-1996 described by Hull [56]. Therefore, toxicity tests from China were dropped from discussion. Other examples where information is difficult to source are the corporate test standards since these are not available for purchase. It was deemed important to keep them in the analysis so, in these cases, as many details as possible were gleaned from textbooks and secondary, public sources, like the websites of commercial testing labs [56, 61]. Independent of the methodologies developed in the course of this research, such ambiguities and deficiencies in information will continue to plague any analysis of worldwide standards. Thus, decisions regarding the set of standards to include in a given analysis must be made on a case-by-case basis.

With this in mind, Table 4.1 shows the results of the preliminary analysis of the tests identified in Table 3.4, considering the chamber configuration and the kind of detection system used. Details of the analytical detection techniques allowed for each test will be explored in more detail in section 4.1.2 since many methods permit and sometimes require the use of multiple detection schemes, either within the specific standard or as mandated in the appropriate overview standard.

Table 4.1 Comparison of toxicity test methods specified in mass transportation standards

Test Name	**Configuration**	**Detection**
ABD 0031 – 7.4	Closed Chamber	Analytical
ASTM E662	Closed Chamber	Analytical
Bombardier SMP 800C	Closed Chamber	Analytical
BSS 7239	Closed Chamber	Analytical
DIN 54341	Open Chamber	Analytical
ISO 5659-2	Closed Chamber	Analytical
NCD 1409	Closed Chamber	Analytical
NF X 70-100	Non-steady State Flow Through	Analytical

From Table 4.1, it can be seen that all of the smoke toxicity tests used in mass transport applications currently use analytical methods for measurement of toxic gas concentration, rather than the alternate, animal response toxicity measurement methods identified in the review by Hull [56]. Similarly, none of the current methods use steady state flow through designs for combustion gas generation, even though this latter was found by Hull to give the best correlation with large-scale test results [56]. Other issues with both the test configuration, methods of detection and reporting will be further outlined and discussed in more detail in following sections.

4.1.1 Fire Effluent Toxicity Tests – Effluent Generation Chamber

As discussed in Chapter 3, fire is a dynamic event and, therefore very difficult to characterize. As such, great care must be exercised to control as many parameters as possible in any fire test in order to obtain consistent results over time. Consequently, the choice of experimental configuration is expected to have a large impact on the combustion gases produced during a fire toxicity test. To better understand the range of methods specified in the various standards listed in Table 4.1 Freemind mind mapping software was used to illustrate relationships among existing effluent toxicity methods based on soke chamber design. The results are shown in Figure 4.1.

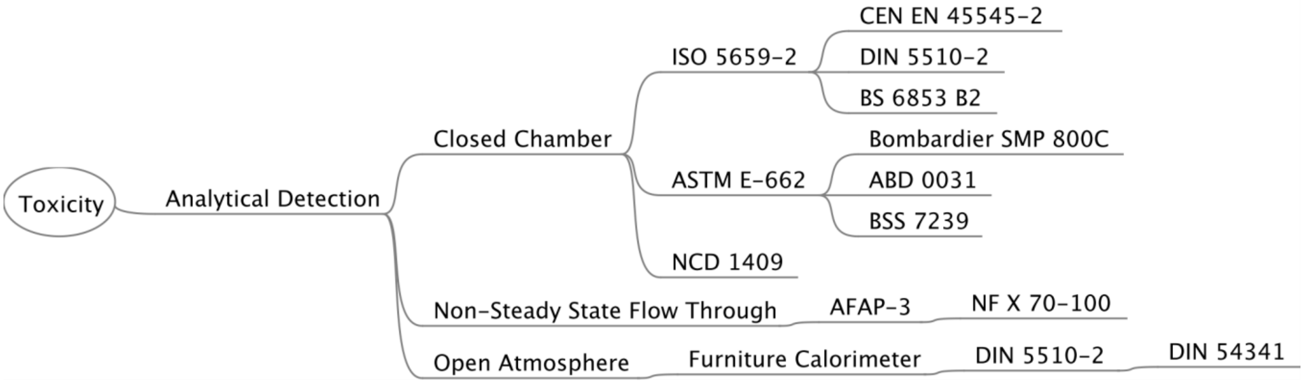

Figure 4.1 Selected fire toxicity test designs by smoke effluent chamber type

As can be seen from the Figure, most of the smoke toxicity test methods specified for use in transportation applications use a closed chamber technique of some kind and none uses the steady state flow through design for combustion gas generation that was found to best mirror results obtained in larger-scale tests, specifically the ISO room fire test [56]. The only transportation-related directive that does not specify a closed chamber technique is the military AFAP 3. In most of the tests, the sample is ignited inside the closed chamber and samples of the effluents are withdrawn from the chamber into the detection system. Two tests are based on slightly different configurations, however. One is a small bench scale test, NF X 70-100, which employs a non-steady state flow chamber design. In this test, the sample is heated to one of several pre-determined temperatures for a set period of time and the effluent gases are collected and analyzed. In contrast, DIN 5510-2, permits the use of data from a larger scale test apparatus, an open furniture calorimeter (like DIN EN 14390), instead of that specified in ISO 5659-2; however, this test is not a requirement, but a permissible alternative. Under the guidance of DIN 5510-2, it is further permitted to characterize the effluents using stack FTIR during burning of entire seats in the furniture calorimeter, provided the stack gases are analyzed at intervals of not more than one minute and that the data is in accordance with DIN 54341 protocols for the analysis of rail components. Since differences in test chamber design, analytical detection methods and sample size will all have an impact on the results, all of these tests are discussed in more detail in the following sections and compared further with respect to these and other key considerations.

4.1.2 Fire Effluent Toxicity Tests - Methods of Detection

In addition to differences in test chamber design, Hull identified two significantly different approaches used for detection of toxicity of the effluents generated in fire performance tests [56]. These are the determination of lethal dose via animal exposure and detection by analytical techniques with comparison to threshold levels, usually either LD_{50} or IDLH values for common products of combustion. Since existing results from animal exposure studies often factor into the definition of the LD_{50} or IDLH values used as threshold criteria for toxicity, below is a brief discussion on the use of animal versus analytical detection.

At one time, there was a belief that animal testing was preferable over analytical characterization of fire effluents. Factors that favoured animal testing included the fact that analytical test methods were expensive and often inaccessible and that there might be synergistic effects that would increase the overall toxicity of the fire environment from a mixture of fire effluent species that might not be measured through analytical determination of concentrations of individual species. There was also a potential for the production of unknown, but highly toxic compounds or "supertoxicants" during combustion that would not even be assessed by the analytical detection schemes in use at that time [5, 62, 63]. Factors against animal testing have mounted in recent times and include the issues that it is difficult to regulate and that there are ethical questions concerning the use of live animals in toxicity testing. Further, while it is relatively easy to quantitate acute LC_{50} values for animals, it has been found over time that there is no reliable way to correlate these values to human LC_{50} values or to other detrimental effects such as incapacitation for decision-making through exposure to a given toxin.

Over the past several decades, the advancement of analytical science, the development of fire toxicity models and the increased concern over unnecessary animal testing have all contributed to the increased use of analytical testing techniques for fire effluents. Much of the migration from animal based detection to analytical detection occurred in the 1990's as research to better understand toxicity was conducted, a body of knowledge on fire effluent effects evolved and mathematical models to predict the additive, synergistic and antagonistic effects of common fire effluent gases was done [62]. It is now well known that there are interactions between some of the common fire effluent species and much is understood in terms of how they affect living beings. These interactions can be additive, synergistic or antagonistic. Some of these effects exhibit themselves immediately while others present days to weeks after exposure. Over time, it has come to be understood that most deaths due to fire effluents are known to be due to the fast acting and ubiquitous carbon monoxide [64], although deaths primarily due to HCN have been on the rise [65]. Some species (particularly CO_2 and HCN) can increase the respiratory rate. This can increase the toxic effect of other combustion products. Additionally, in fire situations, there is also often a reduction in the available oxygen concentration, which in itself leads to toxic effects and which frequently impairs motor coordination and judgment. Time has also shown that very few materials form "supertoxicants". In fact, only two have been identified in the past thirty years of testing; polytetrafluoroethylene (PTFE) and trimethylol propane phosphate (TMPP) [5, 62, 63].

Further, models have been developed to estimate the relative toxic effects of combinations of fire effluent gases based upon determination of the concentration of individual fire gases [62, 66]. Stec and Hull compare two of these methods and discuss the strengths and weaknesses of both approaches [66]. Because of these advances, there has been a move away from the use of animal testing for fire gas toxicity in recent years.

From the third column of Table 4.1, it can be seen that none of the tests mandated by law or developed by major transportation equipment manufacturers uses animal testing. The remainder of the discussion on toxicity in this thesis, then, is concerned only with assessment of analytical detection of fire effluent gases.

4.1.2.1 Analytical Detection Techniques

All of the fire effluent toxicity tests for transportation may specify analytical detection techniques, but there is significant variation in the range of techniques permitted. There are also significant differences in the effectiveness and efficiency of the various analytical techniques that are specified for determination of effluent toxicity in fire testing. Through application of the Freemind software, Figure 4.2 more clearly illustrates which techniques are permitted by each of the fire toxicity test methods discussed above.

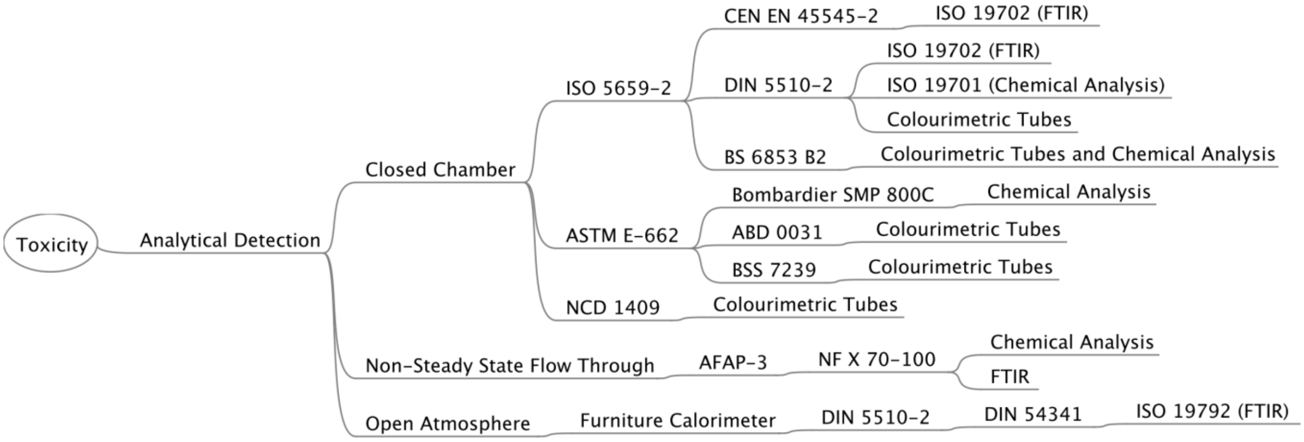

Figure 4.2. Key features of selected fire toxicity test designs

Referring to Figure 4.2, it can be seen that several fire test methods permit the use of only one kind of analytical measurement (CEN EN 45545-2: 2009, BS 6853 B2, NCD 1409, furniture calorimeter for DIN 5510-2). Some methods specify several different techniques, with some of those methods specific to a single toxic gas of interest (AFAP 3 and DIN 2826 as per BS 6853 B2). Others permit the use of any one of several analytical techniques across all toxic gases of interest (Bombardier SMP 800C, NF X 70-100 and ISO 5659-2 for DIN 5510-2). Some tests expressly prohibit the use of colourimetric tubes for measuring fire effluent gases. DIN 5510-2 is even more complex. It permits the use of several techniques if the sample is collected using ISO 5659-2 unless measured values of the effluent gases are nearing the permissible toxicity thresholds in which case, colourimetric tubes are not allowed and additional and more stringent techniques must be employed to determine concentration levels.

Across all tests shown in Figure 4.2, however, one of three categories of fire effluent analysis is specified: colourimetric tubes, FTIR spectroscopic analysis or a complex suite of analytical chemistry techniques. In each case, the method is employed to detect at least one main toxic species and determine whether the concentration of that species is above or below a listed threshold value for toxicity. Commonly detected species include carbon dioxide, carbon monoxide, hydrogen fluoride, hydrogen chloride, hydrogen bromide, hydrogen cyanide, nitrogen and nitrous oxides, and sulfur dioxide. For detection and quantification of these species, each of the techniques specified in current transportation standards has specific pros and cons, which directly affect the accuracy and reliability of the test results. These form the basis for qualitative comparison of the various methods, so are summarized in Table 4.2 and discussed briefly below.

Table 4.2 Advantages and disadvantages of selected detection techniques

Pros	**Cons**
Colourimetric Tubes	
Inexpensive	Can have interferences
Easy to use	Are not highly accurate
Results available quickly	
FTIR Analysis	
Accurate and precise	Moderately expensive
One instrument can determine many species	Requires skilled operator for set up and operation
Results available relatively quickly	Requires on-going maintenance
Spectra can be stored for later reference	
Analytical Chemical Methods	
Accurate and precise	Requires a lab
	Requires highly skilled operators with multiple skill sets
	Expensive to operate and maintain
	Requires multiple types of analysis
	Results not ready quickly
	Sample may need to be stabilized and stored before analysis; sample may deteriorate or adhere to sampler

Colourimetric Tubes

Historically, colourimetric tubes are frequently specified for detection of toxic gas effluents from fires. A different tube is utilized for detection and analysis of each gas of interest and tubes must be pre-calibrated for the concentration of gas expected in a given effluent stream. Many of the tubes come in multiple concentration ranges, and the measurable concentration range can also sometimes be modified by the number of pump strokes performed. Colourimetric tubes are the least expensive and easiest to use of the methods currently specified. While they can provide accurate results for single known chemicals, the results are frequently less accurate for fire effluent gases since fires produce complex mixtures of gases and many tubes are prone to interferences from other possible components. They can also experience plugging or entrapment from the soot and other particulate matter generated during fire testing.

The Draeger Corporation is a major provider of colourimetric tubes, and they publish extensive documentation on the proper use of their products. Table 4.3 [67] summarizes some of the constraints and interferences relevant to their products for the 8 main fire effluent gases covered in the test methods shown in Figure 4.2.

Some of the gas species of interest, such as CO_2, HCl, HF, SO_2 and nitrous fumes, can be analyzed by more than one kind of colourimetric tube, and so are listed more than once in Table 4.3 if the interferences for the tubes differ. In addition, there are no known tubes for some important fire effluent gases such as hydrogen bromide, HBr. In these instances, one must use the closest matching tube and develop appropriate methods by which to correct the results. In the case of HBr, the closest colourimetric tube on the market is one for chlorine, which will also respond to bromine with similar sensitivity, but with less accuracy (standard deviation of 25 to 30% reported for bromine verses 10 to 15% for chlorine) [67]. The results detected by that tube must be re-calculated as results for HBr, which weighs much less. If results for bromine are inadvertently substituted as results for hydrogen bromide, artificially high toxicity values will be calculated and acceptable materials may fail the toxicity test. Chlorine, chlorine dioxide and nitrogen dioxide are all known to show some reaction on this tube as well so if present will contribute to inaccuracy of measured concentration values [67]. Despite their low cost and relative ease of use, therefore, this example serves to indicate that

Table 4.3 Common interferences for selected Draeger™ tubes [67]

Analyte	Tube	Possible Interferences
CO_2	CO_2	For 0.5 to 10 vol%: Hydrogen sulfide in the TLV range does not interfere. In a range comparable to the calibrated range for carbon dioxide, sulfur dioxide is indicated. The sulfur dioxide sensitivity is approximately 1/3 (e.g. 3 vol. % sulfur dioxide gives an indication of 1 vol. %).
CO	CO	Acetylene is also indicated, however, with less sensitivity. Petroleum hydrocarbons, benzene, halogenated hydrocarbons and hydrogen sulfide are retained in the pre-layer. In the case of higher concentrations of interfering hydrocarbons, use should be made of a carbon pre-tube. Higher concentrations of easily cleavable halogenated hydrocarbons (e.g. trichloroethylene) are liable to form chromyl chloride in the pre-layer, which changes the indicating layer to a yellowish-brown. CO determination is impossible in the case of high olefin concentrations.
HCN	Cyanide	Free hydrogen cyanide is indicated already before breaking the ampoule. Acid gases are indicated with different sensitivities. A certain portion of the cyanide can have reacted with the CO2 in the air through hydrolysis. It is impossible to measure cyanide in the presence of phosphine.
HF	HF 10 – 90 ppm	Other mineral acids, e.g. hydrochloric acid or nitric acid, are indicated. Alkaline gases, e.g. ammonia, cause minus results or prevents an indication.
HF	HF 1.5 to 15 ppm	In the presence of higher humidity (> 9 mg H2O / L), hydrogen fluoride mist is generated, which cannot be quantitatively indicated by the detector tube (i.e. the indication is too low). Other halogenated hydrocarbons in the TLV range do not interfere.
HCl	Hydrochloric acid 500 – 5000 ppm	Hydrogen sulfide and sulfur dioxide do not interfere in the TLV range. It is impossible to measure hydrochloric acid in the presence of other mineral acids. Chlorine and nitrogen dioxide are indicated, but with different sensitivities.
HBr	Chlorine 50-500 ppm	Bromine is indicated with the same sensitivity, but with a higher standard deviation of about 25 to 30 %. Chlorine dioxide and nitrogen dioxide are indicated as well, but with different sensitivities.
NOx	NO_2	Chlorine and ozone are also indicated, but with different sensitivities. Nitrogen monoxide is not indicated.
NOx	Nitrous Fumes 200 – 2000 ppm	Chlorine and ozone are also indicated, but with different sensitivities.
SO_2	SO_2	Hydrogen sulfide is indicated, with the same sensitivity. It is impossible to measure sulfur dioxide in the presence of hydrogen sulfide. Nitrogen dioxide will shorten the reading.
	SO_2	Hydrochloric acid is indicated in high concentrations. 10,000 ppm Hydrochloric acid corresponds to an indication of 150 ppm sulfur dioxide. No interference by: 500 ppm nitrogen monoxide 100 ppm nitrogen dioxide
	Acid Test	This tube indicates various acid gases with differing sensitivities and colors ranging from yellow to pink. It is impossible to differentiate them.

colourometric tubes can suffer from some serious drawbacks in terms of toxicity testing in fires. This has prompted some organizations to limit their use to detection of gas concentrations only well below threshold values or even to prohibit their use in fire gas toxicity testing all together.

FTIR Spectroscopy

FTIR or Fourier Transform Infrared Spectroscopy is a spectrally based analysis method in which a single instrument can be used to detect and measure many species, including the eight gases of most interest in fire effluent studies. The spectra from any test can be archived and reanalyzed again at a later date, which can be a major advantage as well. While able to provide data for a wide range of gases, FTIR systems are moderately expensive to obtain and need on-going calibration and maintenance. FTIR can provide accurate and precise measurements; however, soot interference can be an issue and a skilled operator is required to set up and run the analysis, as well as interpret the final results.

Other Analytical Techniques

Before FTIR became widely available as a real time, “in situ”, affordable analytical technique for effluent toxicity analysis, independent chemical tests were performed to measure each effluent gas of interest. Table 4.4 lists the main effluent gases and corresponding analytical test methods recommended for each in traditional analytical detection schemes. Since this strategy requires multiple analyses to be conducted on specialized laboratory equipment usually only found in analytical chemistry laboratories, the equipment required is expensive to operate and maintain and requires use of very skilled operators. Although chemical analysis is accurate and precise, it is clearly a much more complex analytical regimen than either FTIR or colourimetric tubes. All of the analytes listed below can be measured directly by FTIR.

Table 4.4 Permitted measurement techniques for fire effluents

Analyte	**Permissible Techniques**
Carbon dioxide	Non-dispersive infrared spectrometry (NDIR)
Carbon monoxide	Non-dispersive infrared spectrometry (NDIR)
Hydrogen fluoride	Spectrophotometry OR Specific electrode ionometry
Hydrogen chloride	Titrimitry using a silver electrode OR Ion chromatography
Hydrogen bromide	Titrimetry using a silver electrode OR Ion chromatography
Hydrogen cyanide	Spectrophotometry OR Ion chromatography
Nitrogen dioxide	Ion chromatography
NO, NOx	Chemiluminescence
Sulfur dioxide	Ion chromatography

The methods listed in Table 4.4 align with the recommendations in DIN 5510-2, AFAP 3 and DIN EN 2826. In reality, there are even more ways that these gases can be measured including gas chromatography, gas chromatography coupled with mass spectrometry and electrochemical cells to name a few. Frequently, to perform the analyses listed above, a sample of the effluent gas needs to be captured and sometimes stored before analysis. When this is the case, the sample collection techniques can become quite complex in and of themselves. The four most common approaches are to route the sample directly into an instrument (possible with NDIR or FTIR) or collect the sample in an evacuated gas-sampling bag, or to capture and stabilize the gases in a liquid solution or on a solid substrate. In this latter situation, the nature of the solution or substrate will need to be specific to the component of interest. More detail on this and on the possible interferences for these species of interest can be found in Fardell and Guillaume [68].

As was discussed in Section 4.1.1 above, the ISO 5659-2 method was originally written as a test to measure the smoke density generated from materials when exposed to a constant radiant heat flux; however, some major overview standards now use the test as a means of generating the gas samples necessary for flame toxicity evaluations. Most notably this is the case for DIN 5510-2 and CEN

45545-2: 2009. In both of these directives, samples of smoke are collected from the smoke density chamber at 4 minutes and 8 minutes into the test and the smoke is analyzed for the eight gases listed above, namely CO_2, CO, HF, HCl, HBr, HCN, NOx, and SO_2. DIN 5510-2 permits quantification of the gases by IR, analytical chemistry methods or colourimetric tubes. If colourimetric tubes are used and the measured concentration of a gas is greater than or equal to 80% of the toxicity threshold limit, then the concentration of that gas must also be measured using another method (like FTIR). As of 2011, the CEN 45445-2 protocol stipulated that the gas concentrations should be measured by FTIR, and if other methods were used, documentation of the equivalency of results from these other methods to FTIR results had to be included in the report. In either case, these directives demonstrate flexible application of the available analysis methods in determination of gas effluents during fire toxicity testing.

Summary

In summary, use of Excel spreadsheets and mind mapping software has allowed comparison of the multitude of test apparatus, analysis and detection methods that are currently outlined in toxicity test methods for public mass transit applications. Use of the methods developed here, with additional background research targeted towards the content of the appropriate standards, leads to some key observations. Animal testing can prove a comparative ranking of acute toxicity effects of a mixture of gases for animals of a specific species, but it cannot provide meaningful correlation to human incapacitation or human toxicity thresholds. Species-specific relationships have been well documented in the literature. Recent trends are towards the use of analytical testing for characterization of fire gas toxicity.

There is significant variation in the accuracy, ease of application and operator skill levels associated with the methods currently specified for detection and analysis of effluents from fire tests. Detection and measurement of fire effluent gases is typically done one of three ways: by FTIR, by a suite of traditional analytical chemistry techniques or by colourimetric tubes. FTIR can give near real-time data and requires the least effort once properly set up. Both FTIR and the traditional chemical analysis can give good and accurate results. Colourimetric tubes are the easiest to use, but they are less accurate and are prone to interferences. As such, some of the current test methods permit their use but require a retest if the results attain eighty percent of a threshold value.

4.1.3 Sample Size and Normalization Methods

Further investigation of existing test methods indicates that once the sample of fire effluent gas has been generated, collected and analyzed, the results can be normalized either with respect to the mass of fuel tested (i.e., on a weight basis) or with respect to the surface area of the sample tested (i.e., on an area basis). In bench scale tests where only a very small sample, usually one gram or less, is used for testing, results are generally normalized based on sample weight. Examples are NF X 70 - 100 [56] and NCD 1409 [46] toxicity test methods. On the other hand, when the test is conducted using a larger sample, usually 75-100 mm x 75-100 mm or even a full-scale item, the results are more often normalized on the basis of sample area and particular calculation techniques specified for each test method. For example, BS 6853 B2 [56] is a method that uses a 75 mm x 75 mm sample, and it stipulates that the calculations for normalization are to be based upon area, according to the guidelines set out in pr EN 2826 [56]. While results for different materials tested using the same method of normalization may be comparable, the use of different methods of normalization can lead to different issues when test results must be interpreted or scaled to realistic fire scenarios. Therefore, this important consideration is discussed in the following paragraphs.

The sample size for the bench scale toxicity tests listed in Figure 4.1 (NF X 100 and NCD 1409) is typically 1 gram, but may be as low as 0.1 gram for low-density materials. While such tests are economical to perform and can provide a consistent relative ranking of some aspects of effluent toxicity from different materials, the output data is normalized based on mass of sample tested which leads to several potential issues in interpretation of the results. First, for many manufactured items, it is difficult to produce a one-gram sample that is representative of the product, especially when considering multi-layered composite seat constructions. Further, the sample is so small that it will not necessarily be exposed to representative heat fluxes before decomposition or ignition and, in turn, the combustion products produced may not be indicative of what would have been formed in a real situation. Early research in this field found a much higher level of toxicity in the hot gases evolved during real fires than would be expected from the results of bench scale tests of the same materials as those involved in a particular fire [69], signaling that it is necessary to exercise caution in scaling and applying bench-scale test data to the real situation.

In contrast to the bench-scale tests, most of the current transportation tests involve the use of intermediate sample sizes of dimensions 75 mm on a side and 25 mm thick with an exposed area of 65 mm square. The samples are either tested in a closed chamber as described in ASTM E662 with testing conducted as described in NFPA 130, Bombardier SMP 800C, ABD 0031 or BSS 7239; or in a closed chamber as described in ISO 5659-2 with testing conducted as described in CEN EN 45545-2: 2009, DIN 5510-2 or BS 6853 B2, or tested as full-scale seat units and conducted in a furniture calorimeter (i.e. DIN EN 14390 as per conditions described in DIN 5510-2). In all these tests, the toxicity data are normalized based on at least the area of the sample that burned; some also consider the depth of material that burned. In general, intermediate scale tests are more costly to run than their bench-scale counterparts, and tests using full seats are more expensive again. While either type may provide consistent relative rankings of material toxicity, just as with the bench-scale tests discussed above, their applicability to full fire scenarios is the subject of on-going debate. First, for many tests there has been little or no direct comparison of test results with data from representative transportation fires. In some comparative studies with respect to full-scale room fire scenarios, it was found that neither of these test configurations correlated well with large scale testing performed in ISO fire test rooms [56]. In other studies, correlation was found for some, but not all parameters between intermediate scale and full-scale flash over type fires [8]. In contrast, Borgeson [31] found a good correlation between the effluents measured from intermediate scale tests and those obtained during the first five minutes of the room scale fire tests. Based on the latter study, if it can be assumed that people will escape within 5 minutes of the fire initiation in a mass transportation fire intermediate scale tests might be deemed to provide appropriate toxicity information. On the other hand, for longer escape times of up to thirty minutes, results of the intermediate scale tests may not provide a good prediction of conditions that could develop during a real fire situation.

Summary

It is clear from the results and discussion presented above that the use of mind mapping software has allowed a high-level, systematic investigation into both the technical details and methodologies specified by the many smoke toxicity test methods included in Table 3.4. Results of this high level analysis have highlighted that in addition to differences with respect to the methods used for generation of effluents, the sample size tested and the normalization methods specified, the detection method chosen also plays a significant role in characterization and measurement of toxicity of fire effluents. To probe further into differences and similarities amongst the various tests, it is necessary to examine and compare the tests in even more detail. Summary descriptions of the tests of interest to this study are presented in the next section.

4.1.4 Description of Fire Effluent Toxicity Tests

The major experimental configurations of specified tests were described in Section 4.1.1 and the types of detection and measurement schemes used in the tests have been described in Section 4.1.2. This next section describes in more detail each test currently required or permitted by the major jurisdictions reviewed here. For this purpose, tests are sorted as mass-based tests or area-based tests depending on the size of sample and normalization procedure specified in each method.

4.1.4.1 Mass Based Tests

Mass based tests are bench-scale tests conducted on a small sample, typically one gram with results expressed in terms of the amount of toxic species produced per weight of material burned. Amongst the fire effluent toxicity tests specified in the transportation sectors considered, there are two mass based tests, the Indian standard NCD 1409 and the military standard AFAP 3. Each will be discussed in turn.

NCD 1409

The Indian NCD 1409 test employs an airtight chamber of at least $0.7m^3$. The chamber has a hinged door and the sample is exposed to a Bunsen burner with externally supplied air and operating at a temperature of 1150°C. There is only one test condition specified – that the sample is to be completely engulfed in flame during the test and is expected to burn completely. The sample is suspended over the flame on a non-combustible mesh in a non-combustible support flame. The test is performed three times. The test employs the open burner flame burning inside of the closed test chamber, so the device must be calibrated to compensate for the production of carbon dioxide, carbon monoxide and nitrogen oxides from the burner flame as well.

The test uses colourimetric tubes for detection. The sample size must be chosen so that the effluent gases of interest will be “in range” in terms of the detectable concentration for the colourimetric detection tubes employed. For this, typically about 1 gram of sample is used. If the sample is of low density, or is known to be highly fluorinated, the test sample may weigh as little as 0.1 gram, or possibly less.

As a method, NCD 1409 has both strengths and weaknesses. In terms of detection method, it relies on colourimetric tubes with the limitations discussed previously. Also, while the colourimetric tubes are situated in ports directly in the combustion chamber, so there is no loss of analytes in sample lines, there is the potential for soot and particulates to clog the inlets of the analyzer tubes which could further degrade measurement accuracy. On the other hand, because the test flame is at 1150°C promoting complete combustion, rather than thermal degradation, of the sample and that the test is performed three times for each sample, the significance of these effects should be reduced. In fact, because the test flame is at 1150°C using a burner with externally supplied air; the test is tailored to examine effluent gas evolution from only one phase of a fire (flaming combustion).

AFAP 3

The military standard, AFAP 3 [42], similarly specifies testing of only one gram of sample, using the analytical test device specified in the French Test NFX 70-100. A schematic of the test device can be found in Figure 4.3. In this test, the sample is placed in a quartz boat in a stream of hot flowing air (2L/min) for a specified period of time and is weighed before and after the test, so complete combustion is not a given.

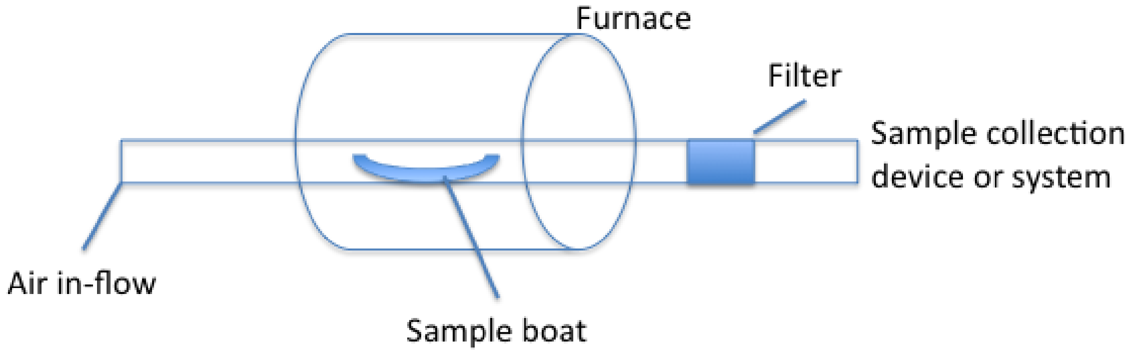

Figure 4.3 Schematic of the NF X 70-100 Fire Effluent Toxicity Tester

In fact, the French test specifies that samples be tested at three temperatures (400, 600 and 800°C, chosen to correspond to oxidatively pyrolytic, well ventilated and under ventilated conditions) [56]. In contrast, the military specification stipulates that each sample is to be tested in duplicate at only two different temperatures (350 and 800 °C), corresponding to oxidative thermal decomposition and combustion conditions.

AFAP 3 requires the determination of 11 different fire effluent gases quantified by rigorous analytical methods. The effluent gases may be directed to either FTIR or NDIR gas analysis systems, or may be collected in bubblers, on solid substrates or in gas sample bags for later analysis. A wide range of possible analytical techniques is permitted; however the use of colourimetric detection tubes is prohibited.

Both of the above tests base all of their results on burning just one gram of sample, and they stipulate dramatically different burning conditions, so the results of these two tests cannot be expected to be comparable to each other. Additionally, due to the use of colourometric tubes in the Indian standard, the results of these tests will be less reliable and less accurate than results determined using the AFAP 3 methods. Both the NATO AFAP 3 and the Indian rail standards are the only jurisdictions that permit the use of such small sample tests for seating. In contrast, most overview standards only permit the use of one-gram samples for evaluating the combustion toxicity of small parts, and not major components that will be used in the interior of a rail car. This difference exemplifies the on-going debate into what is an appropriate sample size for the conduct of fire performance testing. Protagonists for methods based on one gram of sample may argue that these tests provide a quick, easy and economical screening tool for comparing fire effluent toxicity amongst candidate materials. Antagonists would argue that tests done at this small scale would not yield realistic combustion products. To seek answers to such key questions, globally coordinated research in this field is actively being pursued for the transportation sector [35].

4.1.4.2 Area Based Tests

The seven other fire effluent toxicity tests referenced in transportation requirements and listed in Figure 4.1 are area based methods. The mass based tests just discussed were designed specifically to measure fire effluent gases, but these other tests were not. Six of these seven methods use the NBS smoke chamber, configured either as described in ASTM E662 [70] or ISO 5659-2 [71]. A picture of the NBS smoke chamber, in ISO 5659-2 test configuration, is shown in Figure 4.4.

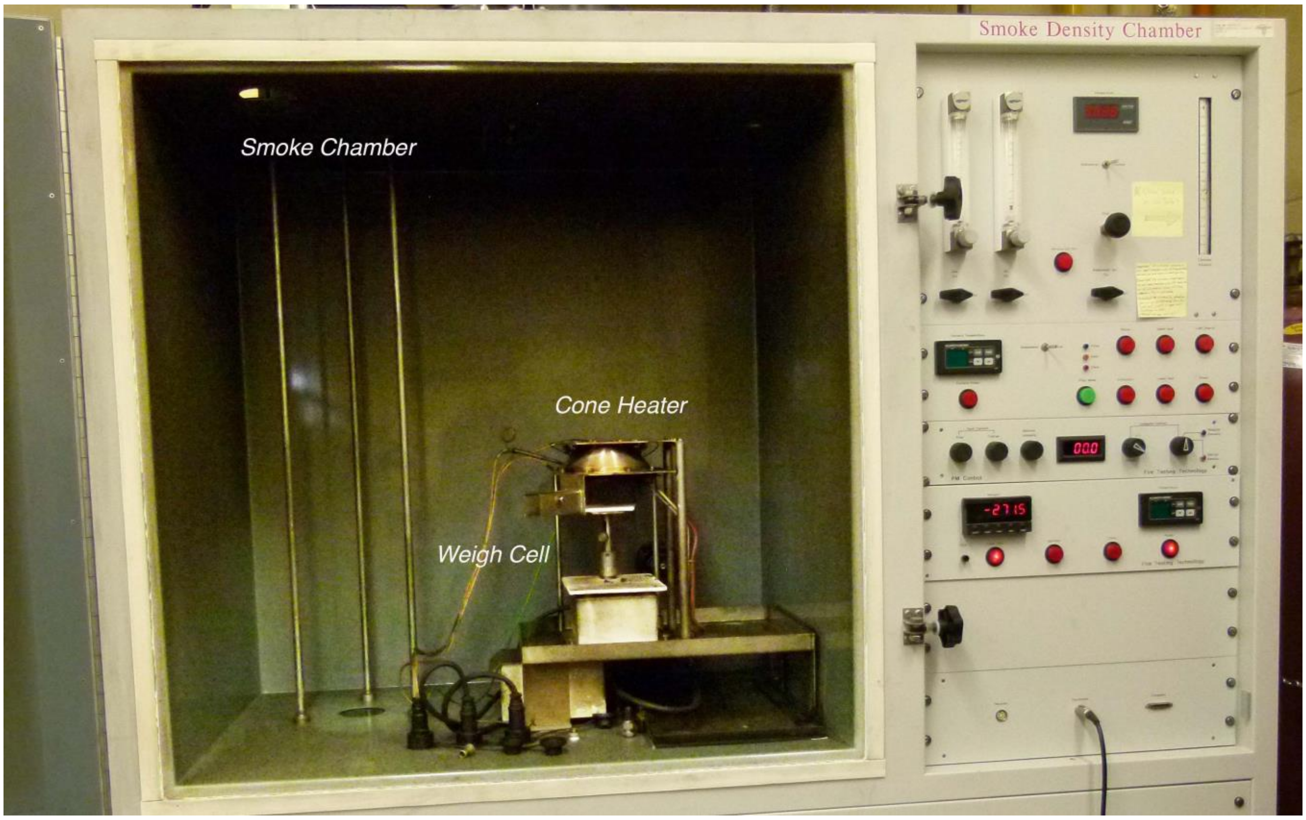

Figure 4.4 NBS smoke chamber configured for ISO 5659-2 testing

ASTM E662 [70] and ISO 5659-2 [71] were not designed to measure fire effluent toxicity. They are closed chamber smoke density tests that have been adapted to permit collection and analysis of fire effluent gases. Since they are conducted in a closed test chamber, they are thought to mimic burning conditions most similar to those that would be encountered in under-ventilated fire situations. These two tests have many similarities, but also some key differences. Their main similarities and differences are summarized in Table 4.5 and outlined below.

Table 4.5 Comparison of ASTM E662 method and ISO 5659-2 method

<table>
<tr><th colspan="9">SMOKE TEST CONFIGURATIONS</th></tr>
<tr><th>Chamber Used</th><th>Conditions Tested</th><th>Replicates</th><th>Sample Orientation</th><th>Radiant Source</th><th>Radiation Intensity</th><th>Fuel</th><th>Sample Size</th><th>Test Duration</th></tr>
<tr><td>mm</td><td></td><td></td><td></td><td></td><td>kW/m^2</td><td></td><td>mm</td><td>min</td></tr>
<tr><td colspan="9">ASTM E662</td></tr>
<tr><td>914x610x914</td><td>Flaming</td><td>3</td><td>Vertical</td><td rowspan="2">Vertical 3 in circle window</td><td>25</td><td>Propane</td><td>76x76x25</td><td>20</td></tr>
<tr><td>914x610x914</td><td>Non-flaming</td><td>3</td><td>Vertical</td><td>25</td><td>None</td><td>76x76x25</td><td>20</td></tr>
<tr><td colspan="9">ISO 5659-2</td></tr>
<tr><td>914x610x914</td><td>Flaming</td><td>3</td><td>Horizontal</td><td>Cone</td><td>25</td><td>Propane</td><td>76x76x25</td><td>10</td></tr>
<tr><td>914x610x914</td><td>Non-flaming</td><td>3</td><td>Horizontal</td><td>Cone</td><td>25</td><td>None</td><td>76x76x25</td><td>10</td></tr>
<tr><td>914x610x914</td><td>Flaming</td><td>3</td><td>Horizontal</td><td>Cone</td><td>50</td><td>Propane</td><td>76x76x25</td><td>10</td></tr>
<tr><td>914x610x914</td><td>Non-flaming</td><td>3</td><td>Horizontal</td><td>Cone</td><td>50</td><td>None</td><td>76x76x25</td><td>10</td></tr>
</table>

Both ASTM E662 and ISO 5659-2 employ the same smoke chamber as pictured in Figure 4.4 and they both use samples that are 75x75x25 mm in size, with a sample surface area of 65 x 65 mm exposed to an incident radiant heat flux comparable to that used in a cone calorimeter. The ASTM test, however, specifies that both the sample and the radiant heat source be placed in a vertical orientation, whereas the sample in the ISO 5659-2 test is oriented in a horizontal position with a radiant cone heater (comparable to that in a cone calorimeter) located directly above the sample. Both original smoke tests require samples to be tested in triplicate in both a flaming and a non-flaming mode. A full characterization by ASTM E662 would test 6 samples, whereas the full characterization by ISO 5659-2 would test 12 samples because ASTM E662 only requires testing at a single irradiance intensity of 25 kW/m^2 whereas ISO 5659-2 requires testing at both 25 and 50 kW/m^2. In the flaming mode, both tests use a propane flame, but the ASTM flame consists of 6 small "flamelets" applied through a manifold across the bottom of the sample for a total energy input of 76 W while the ISO 5659-2 test employs a single propane pilot flame of 30 mm in length located horizontally above the sample and below the irradiating cone to ignite off-gases as they are generated.

As written, ASTM E662 and ISO 5659-2 are both smoke density tests, not toxicity effluent tests. Therefore, each of the six identified toxicity effluent tests under discussion here uses one of these two methods as a basis, but incorporates further differences specifically related to toxicity measurement protocols. Table 4.6 highlights some of these differences as gleaned through use of the mind mapping methods developed in this work.

Table 4.6 Attributes of closed chamber fire effluent toxicity tests

Test Name	Test Configuration	Conditions Tested	Replicates	Detection Methods	Sampling Times
SMP 800C	E662	25 kW/m^2 Flaming	1	Analytical	4 to 20
		25 kW/ m^2 Non-Flaming	1	Analytical	4 to 20
ABD 0031	E662	25 kW/ m^2 Flaming	3	Colourimetric Tubes	4
		25 kW/ m^2 Non-Flaming	3	Colourimetric Tubes	4
BSS 7239	E662	25 kW/ m^2 Flaming	3	Colourimetric Tubes	4
CEN TS 45545-2: 2009	5659-2	50 kW/ m^2 Non-Flaming	3	FTIR	4 and 8
DIN 5510-2	5659-2	25 kW/ m^2 Flaming	3	Various	4 and 8
BS 6853 B2	5659-2	25 kW/ m^2 Flaming	1	DIN EN 2826	85% of peak smoke or 20 minutes

The duration of each of the tests was examined but has not been included in Table 4.6 because the duration of a given test would be influenced by whether the experimentalist was using a single test to measure both smoke and toxicity results, or was seeking to evaluate toxicity data alone. The times specified for collecting the samples for toxicity testing is indicated instead.

Methods Based on ASTM E662

Methods SMP 800C, ABD 0031 and BSS 7239 are all based upon the ASTM E662 test protocol. All three of these tests require that the sample be tested using an incident radiant flux of 25 kW/m^2, but they differ in the method of detection used, the number of replicates required, the acceptable threshold values referenced, the number of gas species monitored, the sample timing and whether or not pilot flames are used.

SMP 800C specifies testing of a single sample in each of flaming and non-flaming modes and analyzes for the 8 most common combustion effluent gases using analytical chemical techniques. The use of colourimetric tubes is prohibited. The effluent sample is collected as per DIN EN 2826 (1995) over a 16 minute period from 4 to 20 minutes into testing [72].

ABD 00301 measures only 6 common combustion effluent gases (CO_2 and HBr are not measured) and measurement is exclusively by colourimetric tubes. The test is conducted in both flaming and non-flaming modes [73]. The sample is taken at 4 minutes into the test [74]; however, the available information sources do not make it clear how many replicates are required.

In BSS 7239, each sample is tested in triplicate but in flaming mode only. The same 6 combustion effluent gases as specified in ABD 00301 are measured using colourimetric tubes [61]. The sample is taken at 85% of the peak smoke density or at 20 minutes if the smoke density has not peaked.

Methods Based on ISO 5659-2

Methods CEN EN 44554-2, DIN 5510-2 and BS 6853 B2 are all based on the test configuration specified in ISO 5659-2, however there are again a number of differences in how each test is run.

CEN EN 44554-2 requires that the fire effluent test be run in triplicate at an irradiance of 50 kW/m^2 and without a pilot flame. Eight common combustion products are to be measured at 4 minutes and 8 minutes after the test is initiated and the analysis is to be performed using FTIR. The permissible exposure guidelines are completely aligned with the NIOSH IDLH values.

In contrast, DIN 5510-2 requires that the fire effluent test be run in triplicate at an irradiance of 25 kW/m^2 and with a pilot flame. Eight common combustion products are measured at 4 minutes and 8 minutes after the test is initiated and the measurements are to be performed by FTIR, analytical chemical methods or colourimetric tubes. If colourimetric tubes are used, and the test results measure 80% of a threshold value or higher, then the test must be repeated using a more stringent analytical technique. The permissible exposure guidelines are completely aligned with the NIOSH IDLH values.

BS 6853 B2 tests a single sample at an irradiance of 25 kW/m^2 with a pilot flame. Eight common combustion products are to be measured at 85% of the peak smoke density or at 20 minutes if the smoke density has not peaked by the end of the specified test time of 20 minutes. The tests are to be performed according to ISO 2826, which employs a combination of colourimetric tubes and potentiometric titrations for characterization of the fire effluent gases. The permissible exposure guidelines are completely aligned with the NIOSH IDLH values.

Open Test Configuration Method

The only area-based test under consideration in this research that does not use the closed NBS smoke test chamber, is the permissible alternative collection and testing of fire effluent gases from full scale testing of entire train seat units, permitted in DIN 5510-2. When this approach is used, the fire effluent gases are collected from the furniture calorimeter (operated according to DIN 14390) and are analyzed using FTIR with samples taken at least once per minute for the entire time the seating is burning. Since these tests are performed in an open configuration as provided in the cone or the furniture calorimeters, they may best model well-ventilated fires and, as such, may provide results that are quite different than those obtained for the same material in the other area based tests discussed in this section.

Summary

Toxicity tests are typically performed in one of four kinds of test configuration (open, closed, non-steady state flow through or steady state flow through). Toxicity tests for transportation seating all use one of the first three configurations, but based on assessments in the literature only the fourth configuration gives results that are expected to correlate well with large-scale fires. The results from toxicity tests are reported on a weight basis or an area basis. The weight-based results are generated by tests that use a small sample (typically one gram). Many jurisdictions require these kinds of tests for small items, but few use them for large items like seats. Indian passenger service and NATO military applications are two notable exceptions, all other jurisdictions reviewed use medium to large scale, area based toxicity tests to characterize seating.

At present then, fire regulators struggle to find a balance between test chamber sizes and designs that are economically feasible and practical to use and those that would provide the ultimate, most correct information with respect to toxicity of various materials during a fire. There are no easy solutions, only compromises. Additionally, all of these factors must be considered in concert with toxicity thresholds specified in each standard when interpreting the results of fire effluent tests for mass transportation applications. Toxicity threshold values are discussed in the next section of this report.

4.1.5 Fire Effluent Toxicity Testing - Interpreting Fire Effluent Test Results

There is great variation in the measurement techniques used to detect and analyze the toxicity of fire effluents, but there is also significant variation in terms of what concentration of a given toxicant constitutes an acceptable exposure and an acceptable level of risk. In terms of specific products measured, most methods look at eight common combustion products, while some methods look at more combustion products (AFAP 3, NCD 1409) and some look at fewer combustion products (BSS 7239 and ABD 00317-4).

Across the public transportation standards of interest in this research, there are vastly differing interpretations of what level of exposure poses an acceptable risk. Some methods use LD_{50} values, based on concentration levels and exposures consistent with an expectation that fifty per cent of the people would survive a thirty-minute exposure to the concentration of each common combustion gas on the specified list. Other methods use IDLH or “Immediately Dangerous to Life or Health” values and determine acceptable levels of exposure consistent with a 30-minute exposure to IDLH values for a defined list of common combustion gases. The first approach assumes a passenger will escape with their life, the second that they will escape with no permanent long-term damage to their health. Table 4.7 lists the combustion effluent gases that are measured and their respective toxicity threshold values as specified in the toxicity test methods selected for this research. Since most of the fire effluent test methods identified and reviewed in this work state that they use NIOSH values, the current and historical IDLH values published by NIOSH [75] are also listed in Table 4.7. NIOSH presents an excellent, peer-reviewed summary of toxicity data for public use.

In 1995, however, NIOSH published major revisions to the IDLH values for a large number of chemical species. On their webpage [75], extensive discussion is provided on the rationale for the changes made. Table 4.7 therefore includes both the older NIOSH values as well as any revised NIOSH values for all fire toxicity effluent gases mentioned in the methods studied in this research. In Table 4.7 and the discussions following, all toxicity threshold values are expressed as ppm for ease of comparison as well.

Table 4.7. Comparison of toxic gases and toxicity thresholds

	AFAP 3	NCD 1409	SMP 800C	BSS 7239	ABD 0031	DIN 5510-2	CEN TS 45545	BS 6853	NIOSH IDLH	NIOSH IDLH
Year	2010		2009	2008	2009	2009	2009	1999	1994	1995
Unit	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Carbon Dioxide	100,000	100,000	90,000			39,500	40,000	50,000	50,000	40,000
Carbon Monoxide	4,000	4,000	3,500	3,500	1,000	1,180	1,180	1,200	1,500	1,200
Oxides of Nitrogen	100	250	100	100	100	20	20	20	100 NO 50 NO_2	100 NO 50 NO_2
Sulfur Dioxide	400	400	100	100	100	97	97	100	100	100
Hydrogen Fluoride	50	100	100	200	100	30	30	30	30	30
Hydrogen Bromide	150	150	100			30	30	30	50	30
Hydrogen Chloride	500	500	500	500	150	50	50	50	100	50
Hydrogen Cyanide	90	150	100	150	150	50	50	50	50	50
Phenol	250	250							250	250
Formal-dehyde	500	500							30	20
Acrolein	5								5	2
Hydrogen Sulfide		750							300	100
Ammonia		750							500	300
Acrylo-nitrile		400							500	85
Phosgene		25							2	2

Examination of Table 4.7 indicates that there are some significant discrepancies amongst the threshold toxicity values used in the various standards across most of the gases that are measured.

Results of additional analysis done to research possible reasons for this are highlighted in the discussions below. They point to numerous issues and inconsistencies that can creep into standards through revisions and over time. The methods developed in this work allowed identification and assessment of such hidden issues.

Since NIOSH guidelines do change over time, the year of publication of each standard is listed in Table 4.7 (where known) and reflects the version of the standard used in this analysis, not the date of original publication. The British standard BS 6853 was included in this comparison because it was published in 1999, and shows that some jurisdictions embraced the use of the corrected NIOSH IDLH values early on. Other jurisdictions have never fully aligned with them. It also serves to illustrate that while some standards reference others in their documentation, the standards and their references may not be really consistent with one another. In this instance, SMP 800-C makes reference to BS 6853 as a source document of choice for fire effluent gases to monitor; however the actual threshold values employed in SMP 800-C are not the same as those specified in BS 6853.

From Table 4.7, it can be seen that the European based standards for civilian use (CEN TS 45545-2: 2009, DIN 5510-2, BS 6853) are aligned with 30-minute NIOSH IDLH guidelines, but industry based and military based guidelines specify limits that exceed the NIOSH values, as do the requirements in India. In 2008 the U.S. National Association of State Fire Marshalls published a set of recommendations rail service for the U.S. Department of Transportation Federal Transit Administration [31]. They recommended the use of the BSS 7239 toxicity test in combination with ASTM E662 smoke test sampled at four minutes as an acceptable toxic gas emission test. BSS 7239 has the least stringent toxicity thresholds of any of the major manufacturers' test standards. As mentioned earlier, however, these legislative changes in the U.S. have not been made.

Most of the methods reviewed in this work state that they use NIOSH values, which should align with the excellent, reviewed NIOSH summary of toxicity data for public use [75]. In this summary, the supporting data used to guide their selection of IDLH values is also outlined. Even if the test method is of current issue (recently reviewed and approved); however, the NIOSH data used by the method is not necessarily the current NIOSH data. In fact, review of the data given in Table 4.7 shows that the actual thresholds employed in specific methods do not align well with NIOSH IDLH values, historic or current. Instead, some of the thresholds listed in specific methods align with certain NIOSH data, but not with published NIOSH IDLH values. Consider the case of the threshold values for Carbon Dioxide specified across various test standards.

The NIOSH IDLH values for carbon dioxide were set as 50,000 ppm in 1994 and were reduced to 40,000 ppm in1995. Most of the toxicity test methods publish threshold values that are consistent with the current NIOSH IDLH values, but three specify threshold levels that are significantly higher than these (100,000 ppm or 90,000 ppm). The supporting data section of the NIOSH webpage publishes historical data that do align with each of these higher threshold values, even though these values are not currently endorsed by NIOSH for thirty-minute exposures. It is clear, then, that these standards have not kept up-to-date as new research and exposure data drove changes in recommended toxicity threshold values for carbon dioxide.

The threshold values specified for carbon dioxide in the standards of interest to this research are not the only examples of questionable interpretation of NIOSH data as applied to toxicity threshold values in fire tests for mass transportation applications. Due to the importance of the toxicity threshold values specified in the various fire test standards for transportation applications, a detailed listing of examples of possibly questionable use of NIOSH data with possible reference sources was compiled during the present analysis and is summarized in Table 4.8 [75] below:

Table 4.8 Comparison of questionable threshold values to selected NIOSH data [75]

Carbon Dioxide
Questionable Threshold Values: 100,000 ppm; 90,000 ppm
AIHA [1971] reported that 100,000 ppm is the atmospheric concentration immediately dangerous to life. In addition, Hunter [1975] noted that exposure to 100,000 ppm for only a few minutes can cause loss of consciousness. A 1933 study in "Tab Biol Per" (in German) published an LC_{lo} indicating human lethality after a 5 minute exposure to 90,000 ppm.
Carbon Monoxide
Questionable Threshold Values: 4000 ppm, 3500 ppm
In 1968, there was human data published by R. Lefaux (Practical toxicology of plastics. Cleveland, OH: Chemical Rubber Co.) that indicated an LC_{lo} value of 4000 ppm for a 30 minute exposure. In 1970, Rose et al. published toxicity data based on Rat data and calculated an LC_{50} value of 3568 ppm for a 30 minute exposure (Rose CS, Jones RA, Jenkins LJ Jr, Siegel J [1970] -The acute hyperbaric toxicity of carbon monoxide. Toxicol Appl Pharmacol 17:752-760).
Oxides of Nitrogen
Questionable Threshold Values: 250 ppm, 100 ppm
For the compound nitric oxide (NO), CAS No. 10102–43–9, NIOSH states, "Based on acute inhalation toxicity data in humans [Sax 1975], the original IDLH for nitric oxide (100 ppm) is not being revised at this time." For the compound nitrogen dioxide (NO_2), CAS No. 10102–44–0, NIOSH lists an IDLH of 20 ppm
Sulfur Dioxide
Questionable Threshold Values: 400 ppm
The maximum concentration for exposures of 0.5 to 1 hour is considered to be 50 to 100 ppm [Henderson and Haggard 1943]. It has been reported that 400 to 500 ppm is considered dangerous for even short periods of exposure [Henderson and Haggard 1943]. Reference quoted is: Henderson Y, Haggard HW [1943] - Noxious gases. 2nd ed. New York, NY: Reinhold Publishing Corporation, p. 131.
Hydrogen Fluoride
Questionable Threshold Values: 200 ppm, 100 ppm, 50 ppm
The NIOSH assessment is based upon a combination of human and animal data. The report that has human data states "It has been stated that 50 ppm may be fatal when inhaled for 30 to 60 minutes." [Deichmann and Gerarde 1969, Hydrofluoric acid (hydrogen fluoride, HF). In: Toxicology of drugs and chemicals. New York, NY: Academic Press, Inc., pp. 317-318.]. The NIOSH summary of data does not mention any human studies with a value of 100 or 200 ppm, but does have some calculated LC_{50} estimates based on animal data in the range of 117 to 307 ppm for 30 minutes.
Hydrogen Bromide
Questionable Threshold Values: 150 ppm, 100 ppm
NIOSH assessment based on bromine and hydrogen chloride due to lack of data on HBr. Back et al calculated an LC_{50} value of 102 ppm HBr for a 30 minute mouse exposure – Reference: Back KC, Thomas AA, MacEwen JD [1972]. Reclassification of materials listed as transportation health hazards. Wright-Patterson Air Force Base, OH: 6570th Aerospace Medical Research Laboratory, Report No. TSA-20-72-3, pp. A-216 to A-217.
Hydrogen Chloride
Questionable Threshold Values: 500 ppm, 150 ppm
The NIOSH data is based on statements in Patty about the conditions under which humans can function, but there is human data from the German reference Tab Biol Per [1933]; 3:231 that indicates that exposure to 500 ppm for 30 minutes would be lethal.
Hydrogen Cyanide
Questionable Threshold Values: 150 ppm, 100 ppm, 90 ppm
It has been reported that 45 to 54 ppm can be tolerated for 0.5 to 1 hour without immediate or delayed effects while 110 to 135 ppm may be fatal after 0.5 to 1 hour or later, or dangerous to life [Flury and Zernik 1931, Schädliche gase dämpfe, nebel, rauch- und staubarten. Berlin, Germany: Verlag von Julius Springer, p. 404 (in German).].

Phenol
Questionable Threshold Values: Not Applicable
The NIOSH determination for phenol states: The chosen IDLH is based on an analogy with cresol that has an IDLH of 250 ppm.
Formaldehyde
Questionable Threshold Values: 500 ppm
The NIOSH decision on formaldehyde is based on irritation and avoidance of permanent health effects. There is a paper that looks at lethal effects with animal data that calculates an LC$_{50}$ value of 533 ppm for 30 minutes [Izmerov NF, Sanotsky IV, Sidorov KK [1982]. Toxicometric parameters of industrial toxic chemicals under single exposure. Moscow, Russia: Centre of International Projects, GKNT, p. 69.]
Acrolein
Questionable Threshold Values: 5 ppm
There is human data for acrolein: It has been reported that 5.5 ppm results in intense irritation and marked lacrimation after 60 seconds [Henderson and Haggard 1943]. Exposures to 1.8 ppm result in slight eye irritation after 1 minute and profuse lacrimation after 4 minutes [NRC 1981]. In volunteers exposed for 5 minutes, concentrations of 2 to 2.3 ppm produced severe irritation [Darley et al. 1960]. A 10-minute exposure at 8 ppm and a 5-minute exposure at 1.2 ppm elicited extreme irritation described as "only just tolerable" [Sim and Pattle 1957].
Hydrogen Sulfide
Questionable Threshold Values: 750 ppm
It has been reported that 170 to 300 ppm is the maximum concentration that can be endured for 1 hour without serious consequences [Henderson and Haggard 1943] and that olfactory fatigue occurs at 100 ppm [Poda 1966]. It has also been reported that 50 to 100 ppm causes mild conjunctivitis and respiratory irritation after 1 hour; 500 to 700 ppm may be dangerous in 0.5 to 1 hour; 700 to 1,000 ppm results in rapid unconsciousness, cessation of respiration, and death; and 1,000 to 2,000 ppm results in unconsciousness, cessation of respiration, and death in a few minutes [Yant 1930].
Ammonia
Questionable Threshold Values: 750 ppm
The maximum short exposure tolerance has been reported as being 300 to 500 ppm for 0.5 to 1 hour [Henderson and Haggard 1943]. A change in respiration rate and moderate to severe irritation has been reported in 7 subjects exposed to 500 ppm for 30 minutes [Silverman et al. 1946].
Acrylonitrile
Questionable Threshold Values: 400 ppm
An LC$_{Lo}$ value for humans of 455 ppm was published in Schwanecke R [1966]. Safety hazards in the handling of acrylonitrile and methacrylonitrile. Zentralbl Arbeitsmed Arbeitsschutz 16(1):1-3 (in German). The NIOSH values consider the carcinogenicity of acrylonitrile and its irritant properties as well.
Phosgene
Questionable Threshold Values: 25 ppm
"The NIOSH position on phosgene is "the chosen IDLH is based on the statement by Jacobs [1967] that 1 part in 200,000 (5 ppm) is probably lethal for exposures of 30 minutes.” Gross et al. [1965] indicated that concentrations as low as 0.5 ppm for 2 hours caused definite pathological changes in the lungs of rats sacrificed 96 hours post exposure; the investigators believed some abnormalities were present 3 months after rats had been exposed at 2 ppm for 80 minutes. An IDLH of 2 ppm is used for phosgene to prevent irreversible adverse health effects."" NIOSH does also indicate an LC$_{Lo}$ value of 50 ppm for humans from the reference: Tab Biol Per .[1933]; 3:231 (in German) Henderson and Haggard (1943) stated that 25 ppm for 30 to 60 minutes is dangerous and exposure to 50 ppm may be rapidly fatal.

Careful comparison of required toxicity data and threshold values listed as acceptable in the fire performance tests under study reveals a significant divergence of opinion on what might be considered acceptable effluent gas generation levels in the event of a rail accident with a thirty-minute evacuation time. All fire toxicity standards reviewed claim to base their specified threshold values on NIOSH IDLH values, but in reality there are large differences in the acceptable exposure levels listed. Some of these differences arise from the use of different assumed escape times (fifteen minutes versus thirty minutes) and others depend upon whether the criterion of 'escape with your life' or 'escape without permanent injury or damage' is applied in determination of the threshold values. In this regard, the European rail passenger standards specify the most stringent fire effluent requirements of any existing transportation seating standard. In order to put all of the other standards listed in Table 3.4 into further context, however, the next section of the thesis will compile and compare a wide range of relevant factors in an attempt to rank the overall severity of the tests considered here.

4.1.6 Comparison of Toxicity Tests

Through the use of the methods developed in this research, the major variables inherent in toxicity effluent testing were identified and examined as summarized in the preceding sections. Each method specified for fire effluent toxicity testing has inherent strengths and weaknesses, however, because of the degree of variation in approach, it is difficult to rank the full set of tests. Nevertheless, tests with similar design elements can be compared. There are four main design elements that have emerged as important during the course of the present research. These are: the chamber design, the detection method, the threshold values specified and test species monitored. Again based on the analysis possible through use of excel spreadsheets and Freemind software, Table 4.9 illustrates a cross comparison of the specified design elements for each of the tests under study.

Table 4.9 Analysis of for toxicity test methods by design criteria

ELEMENT	CRITERION	CEN TS 45545-2: 2009	DIN 5510-2	BS 6853 B2	ABD 0031	SMP 800C	BSS 7239	Furniture Cal (5510-2)	AFAP 3	NCD 1409
Design	ISO 5659-2, non-flaming	X								
Design	ISO 5659-2, flaming		X	X						
Design	ASTM E662, flaming and non-flaming				X	X				
Design	ASTM E662 flaming only						X			
Design	Furniture calorimeter							X		
Design	Area based test design	X	X	X	X	X	X	X		
Design	Mass based test design							X	X	X
Detection	Analytical or FTIR	X	X			X		X	X	
Detection	EN 2826			X						
Detection	Colourimetric tubes				X		X			X
Limits	NIOSH IDLH	X	X	X				X		
Limits	IDLH for CO, some LC_{50}				X					
Limits	NIOSH LC_{50} limits for CO					X	X			
Limits	> NIOSH LC_{50} limits for CO								X	X
Replicates	3 or more	X	X		?		X			X
Replicates	2								X	
Replicates	1			X		X		X		
Analytes	> 8								X	X
Analytes	8	X	X	X		X		X		
Analytes	< 8				X		X			

Smoke density methods ISO 5659-2 and ASTM E662 were compared in Table 4.5, but when these tests are used for fire effluent toxicity, additional differences are incorporated, to the extent that all of the tests cannot necessarily be compared.

There are three fire effluent toxicity tests based on ISO 5659-2, however, and it is reasonable to compare these three methods (CEN EN 45545-2: 2009, DIN 5510-2 and BS 6853 B2). All three of these methods specify the use of only one test condition (albeit different across tests), look for the same analytes and employ the same toxicity thresholds. The test condition employed in CEN EN 45545-2, 50 kW/m^2 of incident radiant heat without a pilot flame, will likely lead to a wider variety of toxic or irritating gases than the lower incident radiant heat flux (25 kW/m^2) coupled with a pilot flame that is used in the other two tests. There are two reasons for this; decomposition of most materials used in transportation seating will proceed more rapidly at the higher heat flux [76, 77], and combustible decomposition products produced at the lower heat flux can be ignited via the pilot flame and thus have a greater chance of being oxidized to a smaller number of other species, such as CO and CO_2, or to be redistributed to a more limited set of nitrogen compounds, such as both HCN and NOx species. While the latter situation should not change the FED (Fractional Effective Dose) calculation, it could mask an excursion past a specific toxicity threshold value for a highly toxic decomposition product. An example of this could be the formation of acrolein (C_3H_4O) during decomposition. Acrolein has a NIOSH IDLH of 2 ppm, and combustion via the pilot flame would convert it to CO_2 and CO, which have NIOSH IDLH values of 40,000 ppm and 1200 ppm respectively. Further, CEN EN 45545-2: 2009 requires analytical detection by FTIR, a rigourous, accurate technique that analyses the gases immediately, removing the potential for sample deterioration that can plague the techniques specified in other test methods. DIN 5510-2 on the other hand recognizes that fire effluent testing is an expensive and time consuming overhead cost for industry and permits the use of a number of different testing options, all of which have merit. Fire effluent testing as per DIN 5510-2 could be done in a number of ways, of varying degrees of rigour, but if the FED calculated comes to 80% of the threshold limit values, then the materials must be retested with effluents analyzed using some of the more rigourous techniques permitted in their analysis scheme. BS 6853 B2, the oldest of these three methods, requires the testing of only one sample specimen, rather than the three specimens required in the other two methods. It also indicates that the analytes be measured according to DIN EN 2826. In recent years, DIN EN 2826 was withdrawn and has recently been re-issued. The newest version of DIN EN 2826 permits the use of colourimetric tubes for many analytes, recommends titrimetry for HCl and requires the use of titrimetry for HF. The results measured by titrimetry can be very accurate, but the bulk of the measurements are by colourimetric tubes, and their limitations have been discussed in Section 4.1.2.1. Of these three techniques, CEN EN 45545-2: 2009 is the most rigourous, then DIN EN 5510-2 and lastly BS 6853 B2.

Similarly, the three closed chamber test methods based upon ASTM E662 (ABD 0031, SMP 800C and BSS 7239) can be compared and ranked. All three of these tests are conducted using an incident radiation intensity of 25 kW/m^2, however, ABD 0031 and SMP 800 C require that the samples be tested in both flaming and non-flaming modes while BSS 7239 only requires testing in the flaming mode. SMP 800 C measures only a single sample but requires testing of the effluent gases by rigourous analytical techniques, while ABD 0031 and BSS 7239 test the samples in triplicate, but allow use of the less accurate colourimetric detection tubes for analysis. SMP 800 C tests for 8 common combustion products while ABD 0031 and BSS 7239 only test for 6 combustion products, omitting tests for CO_2 and HBr. Clearly this presents a limitation in the results since the popularity of brominated flame retardants makes HBr a problematic species to omit from scrutiny. Each of these methods defines their own unique set of acceptable threshold values, all of which are less stringent than the published NIOSH IDLH values. ABD 0031 is the only method that employs IDLH values for carbon monoxide, which is the most common cause of death from fires. All things considered, ABD 0031 is the most rigourous of these three tests because of the use of the low CO threshold, with SMP 800 C next and BSS 7239 being the least stringent.

Finally, the two mass-based fire effluent toxicity methods (AFAP 3 and NCD 1409) can be compared. These two methods use comparable sample sizes, each analyze for more than 8 gas species and each specify threshold values that exceed the NIOSH LC_{50} values for carbon monoxide, but are very different in all other aspects. AFAP 3 requires testing of two samples at two different temperature conditions (350 and 800°C) in a non-steady state flow through chamber to simulate smouldering and flaming combustion conditions. Further it requires analysis of the fire gas effluents by rigourous analytical techniques. NCD 1409, on the other hand, requires triplicate samples to be tested in a closed chamber under highly oxidative conditions (open flame at 1150°C) requiring the sample to be completely consumed during the test. The effluent gases are analyzed directly by colourimetric tubes. While the threshold values for carbon monoxide in both methods are greater than the LC_{50} for carbon monoxide, the limits are not the same for both methods. In general, limits specified in AFAP 3 are more stringent than for NCD 1409. Both methods characterize more than the standard eight combustion gases. In addition to the standard eight combustion gases AFAP 3 also measures phenol, formaldehyde and acrolein; while NCE 1409 monitors phenol, formaldehyde, hydrogen sulfide, ammonia, acrylonitrile and phosgene. In terms of determination of the potential toxicity of the fire gas effluents, AFAP 3 would be more rigourous than NCD 1409.

The final test configuration is based on the furniture calorimeter test with FTIR analysis done every minute for the duration of the test. This fire toxicity test method is in a class by itself and cannot be compared to the other methods, particularly in the absence of a known body of supporting data to support such comparisons. Further comparisons are not pursued, therefore, since during the course of this research, no such data was unearthed.

4.1.7 Fire Effluent Toxicity Testing in Summary

There are four basic configurations of test chambers that are presently used for fire effluent toxicity testing. Only one type gives results that have been found to correlate well with the results from ISO room fires across a wide range of conditions; however none of the tests used for toxicity testing of seating for public transportation (either rail or air) specify the use of this test device. Instead the tests stipulated are generally based on methods that have historical precedents. There is a European group currently doing research to develop a new test method that builds on the use of existing equipment and that is both realistic and cost effective. They expect to publish their findings in late 2012 and this may lead to significant changes in the testing of seating for mass transportation applications [35]. Details on the current status of transfeu activities can be found in Appendix B.

The results from toxicity tests are reported on a weight basis or an area basis. The weight-based results are generated by tests that use very small sample sizes (typically one gram). Many jurisdictions require these tests for small items, but not for large items like seats, where it is believed that at least intermediate scale testing is required. India, with possibly the largest rail network in the world, is a notable exception on this point, as is the NATO military standard AFAP 3. All other jurisdictions reviewed require that the toxic gas effluent concentrations be normalized based on the area of the samples under test.

Effluent detection and analysis is typically done in one of three ways: by FTIR, by a suite of traditional chemical analytical techniques (see Table 4.3) or by colourimetric tubes. FTIR can give near real-time data and requires less effort than other chemical analysis methods once properly set up. Both FTIR and the traditional chemical analysis can provide accurate results. The colourimetric tubes are the easiest to use, but they are less accurate and are prone to interferences. Some methods permit their use but require a retest if the results attain eighty percent of a threshold value.

All standards reviewed define exposure threshold values based on NIOSH IDLH values, but there are still significant differences across standards in terms of the acceptable exposures allowed. The chief differences in interpretation arise from the assumed escape times used (fifteen minutes versus thirty minutes) and differing philosophies regarding whether an occupant should escape with life or escape without permanent injury or damage. In this regard, the European rail passenger standards are the most stringent of any transportation seating standard, including the current manufacturers' standards for either air or rail that were considered in part of this research. This does not reflect a recent change of policy. Instead, the most recent European exposure guidelines specified in CEN TS 45545-2: 2009 (not yet finalized) [39], are identical to the British standard BS 6853-B2 [56] that was first published in 1999, reflecting a consistent and stringent standard over the past several decades.

Most fire effluent toxicity tests measure eight key gases (CO_2, CO, HF, HCl, HBr, NOx, SO_2, HCN). There are variations, however. Airbus Industries and Boeing Corp. monitor only six components while the Indian standard monitors fourteen different analytes. Since the Indian standard specifies use of colourimetric tubes for detection, it can be expected that there are more possible interferences and greater inaccuracies in the measured data, potentially making this test more difficult to pass in spite of its use relatively higher toxicity threshold values.

In general, the EU rail passenger standards are the most stringent of any in the world. They are also undertaking research to develop a realistic, cost effective test for predicting toxic fire effluents. If successful, the use of this test may also be expanded for use in fire safety assessment in other modes of transportation. The United States has not yet taken a formal position on fire effluent toxicity testing.

The three test methods developed by transportation equipment manufacturers are consistent in the type of test device specified, but differ in their definitions of acceptable exposure thresholds. Acceptable Airbus Industries exposure limits are more stringent than those of Bombardier Inc. and both of these are more stringent than the limits defined by Boeing Corporation. The US. Fire

Marshalls' Office did propose adoption of the Boeing toxicity test standard for use in the rail industry; however, this proposal has yet to find its way into legislation [31].

Finally, it is clear from the above analysis and results that the combined Excel spreadsheets and mind mapping methods developed and applied in this work have facilitated systematic categorization and comparison of similarities and differences amongst various attributes of the wide range of fire toxicity test methods specified around the world in the transportation sector. After initial high level analysis across all tests, four key criteria for evaluation were identified. The analysis then focused towards more detailed context and technically based comparisons of the tests. With detailed test specifications summarized via spreadsheets and mind maps, particular technical attributes within and across a set of tests were further qualitatively compared to facilitate more in depth understanding of all of the key elements embodied within various fire toxicity test methods. Finally, other characteristics, such as the relative severity of the tests, could be assigned based on an integrated evaluation of all aspects of the tests, rather than through cursory examination of only one key indicator, for example the specified toxicity threshold criterion.

4.2 Analysis of Flame Spread Test Methods

The large set of fire performance tests pertaining to public transportation seating was initially identified and discussed in Chapter 3 was also screened using combined Excel spreadsheets and mind mapping to determine those that focused on examination of material performance through use of various flame spread tests. These flame spread test methods form the subject of discussion in this section. Background and choice of the tests under consideration was discussed in Chapter 3 and flame spread tests of interest were listed in Table 3.5. The analysis methods used through the remainder of this section were also presented briefly in Chapter 3, with key details of any calculations included in Section 4.2.1.2 of this Chapter. Like the discussion of toxicity tests in

Section 4.1, the discussion in this section initially uses spreadsheets and mind maps to systematically categorize and draw similarities amongst various attributes of the flame spread methods. Then the analysis switches focus towards more detailed context and technically based comparisons of the various fire spread tests listed in Table 3.5 from both a qualitative and, where possible, a more quantitative perspective. As such, the discussion in this section is intended to illustrate that, once the initial categorization and sorting of tests has been accomplished and their detailed specifications summarized via spreadsheets and mind maps, calculation methods can also be developed and applied to characterize particular technical attributes within and across a set of tests to facilitate more in depth comparison of the key physical processes embodied within various fire performance test methods.

To put flame spread tests into context, it must be recognized that many of the most devastating fires throughout history have involved the rapid growth of fire. As a result, many of the early fire test methods were flame-spread tests that were developed in response to fires involving significant flame spread in building interiors. Since many of the most devastating fires have involved such rapid growth of fire, it is not surprising that every jurisdiction reviewed in the present analysis employs some variation of a flame-spread test. Unfortunately however, current research also indicates that flame spread tests are not necessarily the best predictors of a fire outcome [5, 7, 78] especially in applications not related to building fires.

In reality, it has been shown in practice that some existing transportation fire safety regulations do not provide appropriate protection for the fire risks currently at play in transportation scenarios, especially with respect to cars and buses [76, 77, 79]. In fact, some authorities have chosen to develop their own standards for bus seating because of the low fire safety standards mandated by law [79, 80]. It is possible that at one time the current standards may have been adequate, but recent accident history indicates that they do not always provide appropriate protection in modern systems [79]. However most of the existing fire safety regulations have been around for a long time and changes to fire safety regulations are both expensive and slow. This means that flame spread tests will remain important for fire performance assessment into the foreseeable future. In this light, the next section discusses and compares the flame spread tests that are currently specified for seating in the mass transportation industry.

All flame spread test methods involve ignition of the material under test and then observation of how the flame front develops and spreads from the area first ignited. Ignition can be accomplished by direct flame impingement using an open flame burner system or by radiant heating, generally via a radiant cone or panel and frequently coupled with a pilot flame. In the transportation standards reviewed here, there are seven flame spread tests based on open flame ignition sources alone and four flame-spread tests that employ radiant panels with pilot ignition sources, as shown in Figure 4.5.

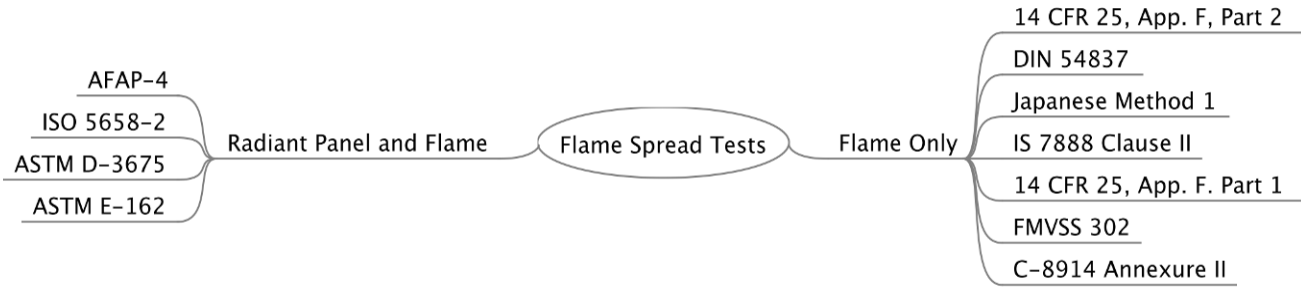

Figure 4.5 Heat input sources in reviewed flame spread test methods

Each of these broad categories of test (flame only or radiant panel with pilot flame) will be discussed in turn below, beginning with a brief description of each test, followed by an estimation of the intensity of the flame sources used to initiate the flame spread, comparison of the intensity of the radiant panel tests, and a qualitative discussion of other factors that influence the severity of a flame spread test. Finally, ordered rankings of the intensity of each kind of flame spread test (flame only or hybrid with radiant source and flame) are presented.

4.2.1 Direct Flame Contact Tests

There are seven flame spread methods identified in transportation standards that employ solely a direct flaming source for ignition and an additional four that employ both radiant panel and a flaming ignition source as shown in Figure 4.5. The key characteristics of each of the tests that use direct flame for ignition are summarized in Table 4.10. The two angles listed in Table 4.10 indicate degrees of inclination of the sample and the burner from vertical as noted. Each of these tests will be described briefly, in turn as they are listed, before conducting any test-to-test comparison of ignition intensity across tests.

Table 4.10 Key characteristics of flame only flame spread tests

Test	**Flame Angle from Vertical**	**Fuel**	**Flame Type**	**Sample Angle from Vertical**	**Sample Size** (mm)
C-8914 Annexure II	0	Methane	Bunsen burner, 10 mm I.D., 40 mm long	45	50 x 150 x13
FMVSS 302	0	Methane	Bunsen burner, 10 mm I.D, 38 mm (1.5 inches) long.	90	102 x 356 x 13
DIN 54837	45	Propane	A flat, fan shaped gas flame 45 mm wide at base	0	190 x 500
Japan Method 1	0	Ethanol	0.5 cc fuel in a metal cup	45	182 x 257
IS 7888 Cl. 11	0	Ethanol	0.3 cc fuel in a metal cup	45	100 x 100 x 50
14 CFR 25 App F, Pt 1	0	Methane	Bunsen burner, 10 mm I.D, flame 38 mm (1.5 inches) long.	0	50 x 203 x 13
	0	Methane	Bunsen burner, 10 mm I.D, flame 38 mm (1.5 inches) long.	90	50 x 203 x 13
	0	Methane	Bunsen burner, 10 mm I.D, flame 38 mm (1.5 inches) long.	45	203 x 203 x 13
	60	Methane	Bunsen burner, 10 mm I.D, 76 mm (3 inches) long.	30	Wire or cable
14 CFR 25 App F, Pt 2	90	Kerosene	Burner cone 152 mm (6 inches) high and 280 mm (11 inches wide).	0, 90	457 x 508 x 102

4.2.1.1 Test Descriptions

C-8914, Annexure II

Test standard C-8914 Annexure II from India defines the technical requirements that must be demonstrated by flexible load bearing polyurethane cushions for rail passenger coach applications. It uses a Bunsen burner flame (40 mm long with a tube diameter of 10 mm I.D.), applied at the bottom centre of a longitudinal sample inclined at a 45-degree angle. The sample is 50 mm wide, 150 mm long and 13 mm thick. The sample holder and Bunsen burner are not in an enclosed chamber. This flame is on for 30 seconds, off for 30 seconds and on for an additional 30 seconds. If the sample is ignited, it should not burn for more than 15 seconds after the flame is removed.

FMVSS 302

FMVSS 302 [15] tests are conducted in an enclosed but vented chamber. FMVSS 302 uses a Bunsen burner with air intake closed and a 38 mm (1.5 inch) flame. The sample is 356 mm (14 inches) long, 102 mm (4 inches) wide and 13 mm (½ inch) thick and held in a metal frame, with an exposed surface of 330 mm (13 inches) by 50 mm (2 inches). The sample is oriented horizontally. If there is directional variation in the sample, burn tests are conducted both longitudinally and transversely. The flame is applied to the sample for 15 seconds and is then removed. The material is permitted to burn. When the flame reaches a point 38 mm (1.5 inches) from the edge of the sample that was ignited, timing of the flame spread is started. If the material stops burning within one minute from the start of timing, and if the flames do not spread more than 51 mm (2 inches) along the sample in that minute, then the material passes the test. This test is quite widely used and therefore goes by multiple names, including ISO 3975, SAE J369, BS AU 169, DIN 75200, JIS D 1201, ST 18-502, and ASTM D5132 [81].

DIN 54837

The DIN 54837 test [97] is conducted in a burn box equipped with thermocouples and a light measuring system. The test sample is 190 x 500 mm by the thickness used in the actual application. The flame used in this test is located at the centre front of the sample, inclined at a 45 deg angle, and the burner is aimed to impinge on the vertical sample surface at 50 mm up from bottom of sample. The flame is 42 to 44 mm wide, and is in direct contact with the sample. The flame is applied to the sample for three minutes and flame spread on the sample is monitored for an additional two minutes. The test evaluates the time of ignition and the length of flame spread, as well as smoke and dripping behaviour of the material under test.

Japanese Method 1

The test called Method 1 in the Japanese Railway guidelines is conducted in an open atmosphere and uses 0.5 cc of pure ethyl alcohol as an ignition source. A sample that measures 182 x 257 mm is suspended at a 45 degree angle above the alcohol flame which is placed underneath the center of the sample and 25 mm (1 inch) from the underside of the sample, and is permitted to fully burn during the test. The steel container used to hold the alcohol is circular with dimensions 17.4 mm diameter by 7.1 mm high with walls that are 0.08 mm thick. It sits on a holder that is made of cork or other material with a similar low thermal conductivity.

IS : 7888

The Indian standard, IS 7888, is specific for evaluating flexible urethane foam used in seating applications. It uses an experimental configuration very similar to the Japanese Method 1 flame test, but with sample dimensions of 100 x 100 x 50 mm thick. The fuel used for ignition is 0.3 cc absolute ethanol, held in a preheated sample holder that is the same shape and size as that used in the Japanese test, 17.5 mm wide (external) and 7.3 mm high, but with 1 mm thick sides versus the 0.08

mm side thickness for the Japanese cup. Since the fuel holder in this test is to be pre-heated immediately before the test (within 90 +/- 15 seconds), heat losses from the fuel holder should be minimal.

14CFR 25 Appendix F, Parts I and II

Appendix F of 14 CFR 25 describes the fire tests required for airplane interior components. It consists of seven parts and describes a number of tests pertaining to a variety of different flammability evaluations. Part I defines the classes of materials used in airplanes and describes four screening tests for flame spread. Part II describes tests required for entire seat assemblies. The other five parts of this document do not pertain to flame spread in seating and will not be discussed further in this work.

An overview of the main material classes outlined in Part 1, including those for interior occupied spaces, non-occupied cargo spaces and electrical systems, is provided in Figure 4.6, along with the subcategories of materials in each class.

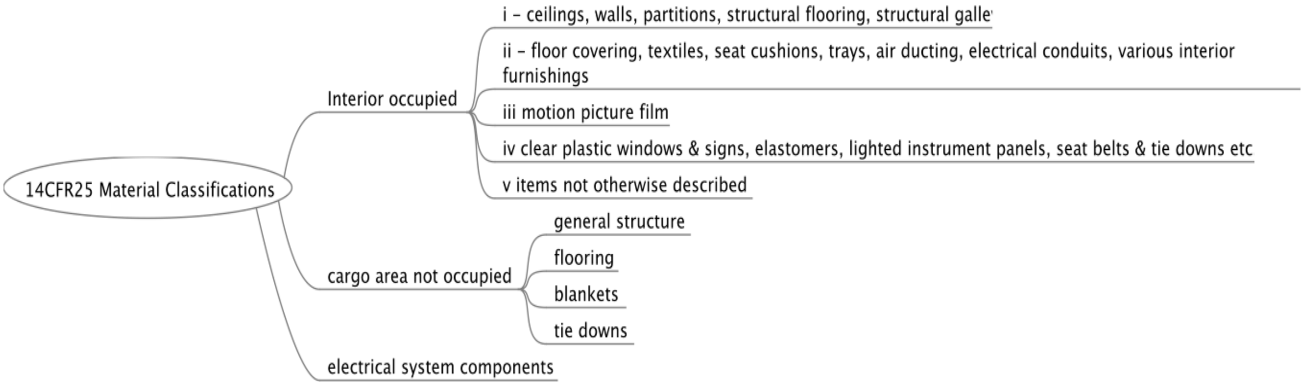

Figure 4.6 Summary of material classifications from 14 CFR 25 Appendix F, Part 1

Specific flame spread screening tests are linked to the material classes using the mindmap shown in Figure 4.7. Each of the screening tests uses a laminar methane flame as the ignition source, but in the different tests the sample sizes and the intensity of the ignition flames vary, as do the geometric configurations and length of time of application of the flames. Table 4.10 summarizes the key parameters that define the four flame spread screening tests used on these materials classes as specified in 14 CFR 25 Appendix F Part 1.

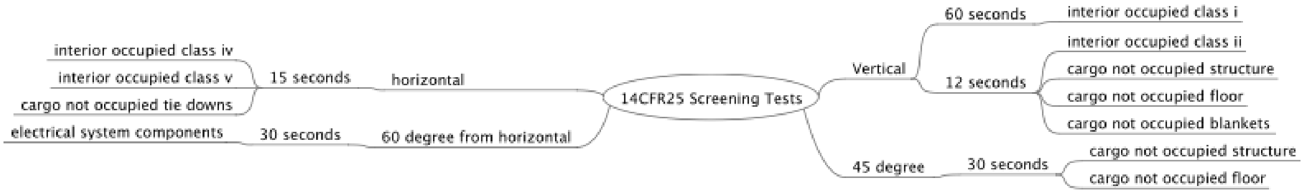

Figure 4.7 Summary of flame spread screening tests from 14 CFR 25 Appendix F, Part 1

Airplane seat cushions are included in the grouping called “interior occupied class ii”, so the only one of these screening tests that applies to airplane seating is the one for which the sample is mounted in a vertical orientation (0° in Table 4.10). This is commonly called the “vertical test”. For seat cushion samples, the laminar flame specified in the vertical test is allowed to impinge on the sample for 12 seconds, whereas it may be held for 60 seconds for some other components. Samples taken from airplane seat cushions are to be cut to a size of 305 mm (12 inches) by 51 mm (2 inches) and are to be no more than 13 mm (1/2 inch) thick. For a seat cushion material to pass this test, it must self-extinguish within 15 seconds if ignited, and any dripping materials must self-extinguish within an average of five seconds.

The Part II test of 14 CFR 25 Appendix F (Figure 4.10) is specific to airline seating and requires that a simulated, full-scale seat be subjected to an intense kerosene burner flame. The kerosene burner is applied horizontally to the middle of the edge of the horizontal seat pan for two minutes and is permitted to burn for an additional five minutes before extinguishment. To pass this test, the flame travel cannot be more than 432 mm (17 inches) across the bottom of the seat, and the weight loss of the seat before flame extinguishment cannot be more than 10 percent.

Hybrid Flame Spread Test Methods

In addition to the seven flame spread methods that employ only flames as ignition sources, and are described above, there are an additional four flame spread methods that employ a combination of a radiant panel and a pilot flame for ignition of the sample. These include AFAP 4 [41], ASTM E162 [82], ASTM D3675 [83] and ISO 5658-2 [84]. All four use the radiant panel IMO LIFT apparatus with a pilot flame, but they do not use the device in the same configuration or with the same test conditions. For purposes of analysis in this section, only the pilot flames used in the four tests are considered in order to draw comparisons with those tests that use only a flame for ignition of the sample; other details of the tests and test configurations are described and compared in later sections of Chapter 4.

4.2.1.2 Flame Intensity Estimations

The initial heat input to the sample from any flaming ignition source is a very important characteristic in terms of flame spread in that material. Therefore, it is key to properly evaluate this parameter in comparing the flame spread tests outlined above, especially since the flames applied to ignite the samples differ considerably across the various tests. To accommodate variations in the descriptions of the flaming ignition sources specified, the ignition flames themselves were sorted into categories and a number of different techniques were developed to estimate the heat intensities of the various flames. Table 4.11 summarizes the category, and the corresponding calculation technique, used to determine the intensity of the ignition flame utilized in each of the eleven flame spread methods under consideration, beginning with those methods which employ a hybrid panel and flame for ignition.

It can be seen from Table 4.11 that there are three main categories of flames used in ignition sources across all of the tests. These are ignition flames with a specified (known) fuel feed rate, laminar flames of known height but fuelled by various gases, and liquid flames using a known quantity of fuel. The overall methods used for calculation of the flame source intensities for each category have been described in Section 3.3.2.3 and typical calculations are contained in Section 4.2.1.2. More details related to application of each method to the particular flaming sources used in the tests outlined in Table 4.11 will be presented in turn below.

Table 4.11 Key characteristics of flame spread tests

Test Number	Flame Calculation Technique Used	Direct Flame	Radia-tion
AFAP 4	Known Fuel Feed Rate - Volumetric	Y	Y
ASTM D3675	Known Fuel Feed Rate - Volumetric	Y	Y
ASTM E162	Laminar Flame of Known Height – Other Fuel	Y	Y
ISO 5658-2	Known Fuel Feed Rate - Volumetric	Y	Y
14CFR 25 App. F Pt 1	Laminar Methane Flames of Known Height	Y	N
14 CFR 25 App. F Pt 2	Known Fuel Feed Rate - Gravimetric	Y	N
C 8914 Annexure II	Laminar Methane Flames of Known Height	Y	N
DIN 54837	Known Fuel Feed Rate - Volumetric	Y	N
FMVSS 302	Laminar Methane Flames of Known Height	Y	N
IS 7888 Clause II	Burning Liquid of Known Volume or Weight	Y	N
Japan Test Method 1	Burning Liquid of Known Volume or Weight	Y	N

In order to conduct the calculations required, it is necessary first to determine appropriate values for the important thermo-physical properties of the various fuels used in the flaming ignition sources above. Values were found in the literature and are summarized in Table 4.12 [10]

Table 4.12 Physical property values for fuel calculations

Fuel	**Mol. Wt.**	**Sp. Grav.**	**ΔH_{vap}**	**Heat of Combustion**	**Boiling Point**	**Flash Point**
	g/mole	kg/L	kJ/Kg	MJ/kg	°C	°C
Acetylene	26	0.621		48.2	-83.9	Not. Appl.
Methane	16		509.2	59	-161.7	Not. Appl.
Propane	44.1	0.508	425.5	46.3	-42.2	Not. Appl.
Ethanol	46.07	0.789	836.8	26.81	78.5	13
No. 1 Kerosene	154	0.825	290.8	43.1	250	57
Butane	58.1	0.584	385.8	45.7	-0.5	Not. Appl.

Calculation of Flame Intensity for Flame Spread Tests Utilizing Ignition Flames With Known Fuel Feed Rate – Gravimetric or Volumetric

Five of the eleven methods describe the flame ignition source by identifying the fuel and specifying a fuel feed rate. These are AFAP 4, ASTM D3675, ISO 5658-2, 14 CFR App. F Part 2 and DIN 54837. When the fuel feed rate is specified, the flame intensity calculation is fairly straightforward. Further, when the fuel feed rate is described on a weight basis (gravimetrically), the calculation reduces to the product of the fuel feed rate times the net heat of combustion of the fuel. The total energy release during the method then becomes the product of the intensity of the flame and the length of time over which the fuel burns. Of the tests listed above, only 14 CFR 25 Appendix F, Part 2 defines the fuel feed rate gravimetrically, while DIN 54837 describes the fuel flow rate both gravimetrically and volumetrically. The fuel, fuel feed rates and calculated energy outputs from the ignition sources specified in these two tests are listed in Table 4.13.

Table 4.13 Gravimetric fuel feed calculations

Method	**Fuel**	**ΔH Combustion**	**Feed Rate**	**Energy Output**
		MJ/kg		W
14 CFR 25 App. F, Part 2	Kerosene	43.3	252 mL/min (2.0 gal/hr)	84,500
DIN 54837	Propane	46.3	1000 mg/min	770

More typically, the fuel feed rate for flame spread tests is described volumetrically. This is the case for the ASTM D3675, AFAP 4, ISO 5658-2 and DIN 54837 tests. In these cases the Ideal Gas law (Equation 4-1) was used to estimate the number of moles of fuel consumed per second, and the number of moles was used to estimate the energy release rate of the ignition source which, combined with time of flame contact, leads to estimation of total energy output. An example of such a calculation for the energy of the acetylene flame from ASTM D3675 is provided below, and calculated results for all of these methods are summarized in Table 4.14.

Applying the Ideal Gas Law to the acetylene flame specified in ASTM D3675, the number of moles of acetylene, at 25 degrees C and atmospheric pressure, that are burned in one second can be determined using Equation 4-1:

$n = PV/RT$ Eq. 4-1

Where:

n = number of moles

P = pressure in pascals

V = volume in m^3 (as taken from the volumetric flow rate)

R = universal gas constant (8.314 m^3Pa/K mol)

T = temperature in degrees Kelvin

$$n = \frac{1.5199\ (m^3\ Pa/sec)}{2477.6\ (m^3\ PaK/K\ mol)}$$

$n = 6.13 \times 10^{-4}$ moles which since the volume is based on the volume flow rate of fuel would be a 6.13×10^{-4} moles/second.

Using this information in combination with the molecular weight of acetylene permits the estimation of how many grams of acetylene are being consumed per second.

6.13×10^{-4} moles/sec x 26 gm/mole of C_2H_2 = X Eq. 4-2

X = 0.01595 g/sec of acetylene

Multiplying the gravimetric flow rate of acetylene by the net heat of combustion of acetylene gives:

Energy release = 48.52 kJ/g x 0.01595 g/sec = 774 Watts Eq. 4-3

The fuel, fuel feed rates and calculated energy output from the ignition sources specified in all of the methods that describe the fuel flow rate volumetrically are summarized in Table 4.14.

Table 4.14 Calculations for methods with flames described by volumetric flow rate

Method	**Fuel**	**ΔH Combustion**	**Flow Rate**	**Moles per second**	**Fuel Consumption**	**Energy Release**
		kJ/kg	m^3/sec	Moles/sec	g/sec	W
ASTM D3675	Acetylene	48.52	1.5×10^{-5}	6.13×10^{-4}	0.0159	774
ISO 5658-2	Propane	46.3	6.7×10^{-6}	2.73×10^{-4}	0.0120	557
AFAP 4	Propane	46.3	6.7×10^{-6}	2.73×10^{-4}	0.0120	557
DIN 54837	Propane	46.3	8.3×10^{-6}	3.72×10^{-4}	0.0164	760

Calculation of Flame Intensity for Flame Spread Tests Utilizing Laminar Methane Ignition Flames with Known Flame Heights

Three methods that use methane as a fuel describe the ignition flame strictly by the length of flame. These methods are C 8914 Annexure II, FMVSS 302 and 14 CFR App. F Part 1. For laminar flames with relatively low fuel feed rates, the flame height is proportional to the fuel feed rate and is independent of the diameter of the tube supporting the flame [58, 60]. Lewis and von Elbe [60] published graphs documenting the flame heights for various methane feed rates. If a method specified methane as fuel and if the flame height specified in a method corresponded to the height of a flame having a feed rate documented by Lewis and von Elbe, their published value of fuel feed rate was used directly. For example, 40 mm (1.5 inch) methane flames are specified for C 8914 Annexure II, FMVSS 302, and three of the four test configurations in 14 CFR Appendix F, Part 1 (horizontal, vertical and 45 degree tests). In Lewis and von Elbe [60], a 40 mm (1.5-inch) long methane flame corresponds to a flow rate of 1 cc/min. This fuel feed rate, the molecular weight of methane and the volume of a mole of methane gas at 298K and atmospheric pressure were used to estimate an intensity of 38 W for these flames, using the approach described by Equations 4-1 to 4-3 discussed earlier in this section.

Calculation of Flame Intensity for Flame Spread Tests Utilizing Laminar Ignition Flames of Known Height – Other Fuels

When the flame height was specified, but the fuel was not methane, as in the case of method ASTM E162 a different approach was used. ASTM E162 uses the same equipment and fuel (acetylene) as ASTM D3675. In this case, the fuel feed rate of acetylene calculated for ASTM D3675 was used in conjunction with the specified flame height Equation 4-4 (also discussed in Chapter 3 as Eq. 3-4) to estimate D, the thermal diffusivity of the fuel air mixture. Then the feed rate required to generate a 76 mm (3-inch) flame could be estimated, as shown below:

$$L = \frac{V'}{2\pi D} \qquad \text{Eq. 4-4}$$

where:

L = length of flame (m)

V′ = Volumetric flow rate (m^3/sec)

D = Diffusion coefficient (m^2/sec)

This approach estimates the diffusion coefficient for acetylene in the burner used in these two methods to be 1.548×10^{-5} m^2/sec. Using this diffusion coefficient, the volumetric flow rate of the 76 mm (three inch) acetylene flame in ASTM E-162 is estimated to be 0.00000796 m^3/sec. Using the relationship described in Equations 4-1, 4-2 and 4-3, the pilot flame for ASTM E162 is estimated to be 410 Watts.

Calculation of Flame Intensity for Flame Spread Tests Using Solid or Liquid Fuels of Known Weight

The total energy release of a flame is simply the net heat of combustion multiplied by the weight of fuel burned when the quantity of fuel is specified. If the fuel is not completely consumed by the fire, the remaining sample needs to be weighed and the calculation adjusted accordingly. To calculate the flame intensity, typical burning times for the known amount of fuel are required. When that information was not provided, such as in Japan Method 1 and IS 7888, experiments were set up in the lab to simulate the burner configuration and flaming ignition source that was specified in the corresponding standard. Measurements of the flame heights and burning duration were made using cameras (regular and infrared) and stopwatches. The results of these experimental tests are presented below as they form the basis for estimation of flame intensity used in the Japan Method 1 and IS 7888 tests.

Experimental:

Japan Method 1 and IS 7888 use very similar test designs. The sample dimensions differ, but the geometries and the fuel holders are essentially the same. The Japanese method burns 5 mL of ethanol while the Indian method burns 3mL of ethanol. The experimental set-up was simulated using non-combustible components and both of these tests were described in detail in Section 4.2.1.1. A schematic of the required geometry is shown in Figure 4.8.

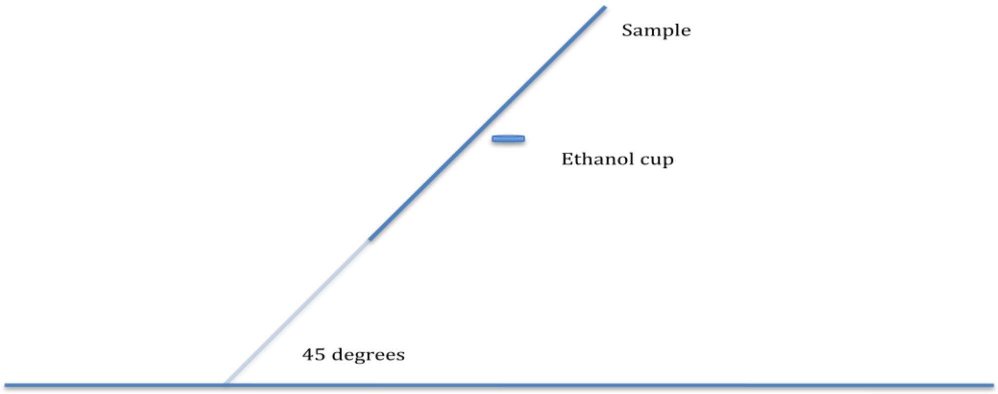

Figure 4.8 Geometric configuration of sample and fuel source for Japan Method 1

A small brass cup of appropriate dimensions was sourced from a hardware store (19 mm cap pulls) and analytical grade ethanol was used as fuel. The cup specifications for the two methods are summarized in Table 4.15 and are compared to the cups actually used for the measurements.

Table 4.15 Comparison of metal cup specifications used in simulations of alcohol burning tests

Method	Japan Method 1	IS 7888	Brass Cap Pull Used
Cup O.D. (mm)	17.5	17.5	19.69
Cup I.D. (mm)	17.4	16.5	18.71 (top), 15.50 (bottom)
Wall Thickness (mm)	0.08	1	0.5
Height of Cup (mm)	7.1	7.3	7.85
Cup Material	Steel	Metal	Brass

The Japanese method specifies that the test device be built of lightweight materials that will create minimal heat loss to the test apparatus. In contrast, the Indian method addresses the issue of heat loss to the device by indicating that trial runs should be conducted until the test device is warmed up and that no more than 45 seconds should elapse from the end of one test to the start of the next measurement. The technique described in the Indian standard was used in these experiments to ensure good data quality while simplifying the design of the test apparatus and permitting the use of heavier, non-combustible materials found around the lab. Photo of the experimental set up used is shown in Figure 4. 9.

Figure 4.9 Photograph of ethanol flame test

The test flame was measured with and without a sample board in place to understand if the presence of a sample altered the flame behaviour of the flaming ignition source for the fuel volumes specified in each test. Each measurement was conducted in triplicate and recorded using a stopwatch and a video camera, sampling at 29 frames/sec and 9256 kbps. The start and stop times were logged to determine the length of burning time of the ethanol, and the videotapes were analyzed by measuring flame heights on a computer screen to compare the effect of having a board in place on the experiment. The results of all of the measurements are summarized in Table 4.16. In Table 4.16, below, the measured heights refer to the height of the image as measured directly from the computer screen during data analysis. It was determined that an artifact that measured 22 mm on the computer screen corresponded to an actual measurement of 74.6 mm. The columns labeled as calculated heights therefore indicate the values of flame height as converted from screen measurements made during the experiments.

Table 4.16 Experimental measurements to estimate flame parameters

IS 7888 Without Board				**IS 7888 With Board**			
0.3 mL				0.3 mL			
Run No.	Time	Height Measured	Height Calculated	Run No.	Time	Height Measured	Height Calculated
	sec	mm	mm		sec	mm	mm
1	41	25	85	7	39	22	75
2	38	32	109	8	36	30	102
3	42	30	102	9	35	30	102
Average	40.3	29	98.7	Average	36.7	27.3	93
Std. Dev.	2.08	3.61	12.3	Std. Dev.	2.08	4.62	15.6
Japan Method 1 Without Board				**Japan Method 1 With Board**			
0.5 mL				0.5 mL			
Run No.	Time	Height Measured	Height Calculated	Run No.	Time	Height Measured	Height Calculated
4	59	30	102	10	50	35	119
5	58	38	129	11	48	30	102
6	55	35	119	12	48	30	102
Average	57	34	117	Average	49	32	108
Std. Dev.	2.08	4.04	13.7	Std. Dev.	1.15	2.89	9.92

With a non-combustible board in place where a sample would be, the flame burned more quickly and usually the flame height was less, than for the case without a sample board. From these experiments it was concluded that the presence of a sample board definitely affects the flame height and shape. In a real test, it is anticipated that the initial effect of a combustible sample board would likely be similar to what was observed during the tests with a non-combustible board in place, but would result in vastly different final flame heights as the sample ignited and burned.

In addition to the measurements of flame height, the average flame duration for each test was measured and the resulting values were used to calculate the average flame intensities for each test considering the weight of ethanol burned in the test and the net heat of combustion of ethanol. The results of these calculations are included in Table 4.17 with data on the relative flame intensities of the flame sources specified for all eleven flame spread tests under consideration.

Table 4.17 Energy estimates for test flames for all flame spread methods

Methods with Only Flames						
Method Name	**Sample Angle from Vertical**	**Fuel**	**Flame Angle**	**Flame Intensity**	**Duration of Flame**	**Total Flame Energy for Test**
	degrees		degrees	W	sec	J
14 CFR 25, App. F, Pt 2	0 and 90	kerosene	90	84,500	120	10,140,000
DIN 54837	0	propane	45	760	180	136,800
Japan Method 1	45	ethanol	0	350	49	17,150
Indian IS 7888	45	ethanol	0	275	37	10,175
Indian C-8914	45	methane	0	38	30+30	2,280
FMVSS 302	90	methane	0	38	15	570
14 CFR 25, App. F, Pt. 1	0	methane	0	38	12	486
Methods with Radiant Sources and Pilot Flames						
ASTM D3675	30	acetylene	hor. 15	774	900	700,000
ASTM E162	30	acetylene	hor. 15	410	900	370,000
ISO 5658-2	0	propane	0	557	1800	1,002,000
AFAP 4	0	propane	0	557	2400	1,337,000

It is possible to compare the flaming ignition sources from all tests on a qualitative basis using either the intensity of the energy supplied per unit time of exposure of the sample to the flame or using the total amount of energy delivered to the sample in a particular test. The total amount of energy delivered is determined by multiplying the intensity of the test by the total length of time for which the flame is applied. Figure 4.10 shows a mind map of the relative ranking of the seven flame spread

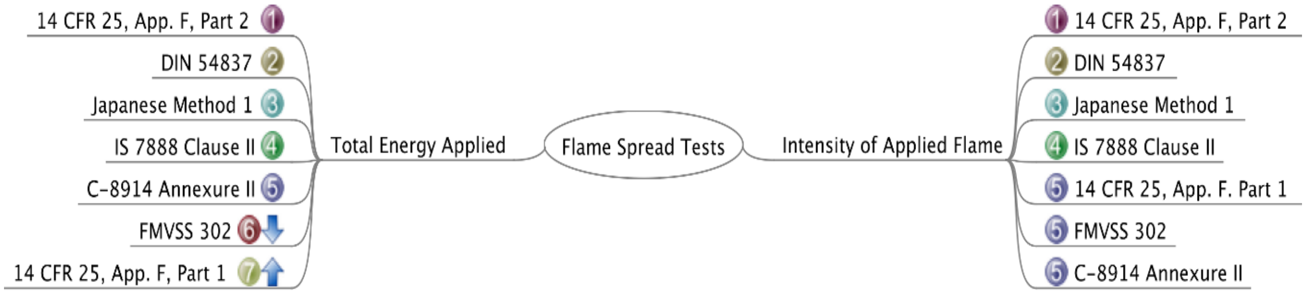

Figure 4.10 Qualitative comparison of intensity of flame only flame spread tests commonly required in transportation applications

tests that employ only direct flaming ignition sources based on each of these criterion. Figure 4.11 shows the ranked severity of all of the methods based on the relative intensities of the open flames applied to the samples in each of the tests.

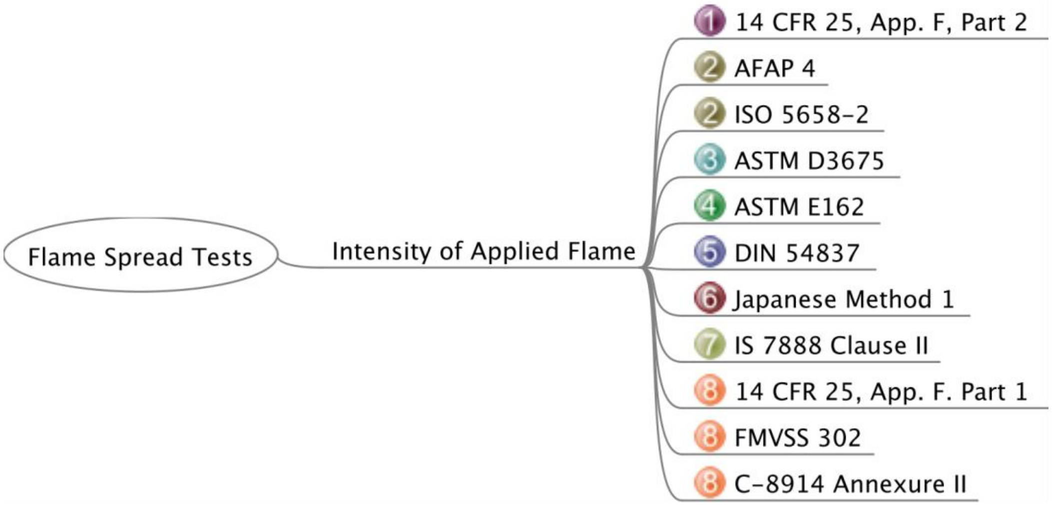

Figure 4.11 Qualitative comparison of flame intensity in all flame spread tests reviewed

The rationale used to arrive at these rankings is based only on amount of energy applied during the test and does not include geometric effects. While the intensity of the flame is a very important characteristic in a flame-spread test, it is not the only factor that contributes to the severity of the test conditions. Before final analysis of the flaming ignition source intensities, therefore, other major factors that would potentially influence the ignition severity are discussed.

4.2.1.3 Factors Influencing Direct Flame Contact Flame Spread Tests

In addition to flame intensity, test ventilation conditions, sample size and thickness, angle of orientation of the sample, flame angle and response of the material to an open flame are also important factors in determining the severity of a given flame spread test. In terms of ventilation conditions, most of the direct flame contact flame spread tests reviewed are conducted in the open air or in vented cabinets (FMVSS 302 is conducted in a closed, but well vented chamber and DIN 54837 is conducted in a large, vented burning cabinet suitable for performing smoke evaluations), so the tests are typically conducted under well-ventilated conditions.

Thickness of the sample plays a role because flame spreads somewhat differently on thermally thin and thermally thick materials. However, since this review pertains to transportation seating applications, only the thermally thick scenario needs to be considered. The geometric arrangement of the sample and the flame can have a significant impact on the rate of flame spread. Both the flame and the sample can be oriented horizontally, vertically or at some intermediate angle to a reference plane, as well as with respect to each other. The flame can also be positioned above or below the sample, or in some tests impinges directly on the side of the sample. Drysdale [58] indicates, that if all other variables are held constant, for a thermally thick material the angle of the sample influences the rate of flame spread in the following ways. For a burning sample with the flame at the top of the sample (i.e. downward propagation, either vertical or angled), the flame spread is counter current to the natural airflow patterns and spreads more slowly. For a horizontal (or close to horizontal) sample (up to +/- 15 or 20 degrees inclination), the flame spread is also counter current and relatively slow. Quintiere [85] indicates that the lateral or downward flame spread on thick solids is typically on the order of magnitude of 1×10^{-1} cm/second. For flames impinging on the bottom of a sample with an upward slope of 25 degrees or more, the flame spread becomes co-current with the natural airflow and flame spread accelerates. Quintiere indicates that the upward flame spread on thermally thick solids is typically in the range of 1 to 100 cm/sec, ten to a thousand times faster than for downward spread [85].

All of the direct flame only flame spread methods mandated for transportation seating except FMVSS 302 require an upward inclined or vertical sample configuration with flames directed towards the half-way mark or lower on the sample panel, thus providing geometries that will experience faster flame spread due to co-current airflow. FMVSS 302 is used to evaluate flame spread on samples only in the horizontal position, a sample configuration known to promote slower flame spread due to counter current airflow.

Finally, the physical properties of the sample and its response to direct flame heating are also important factors. If the material melts, the fuel will flow and may drip increasing the potential fire spread. Depending upon the flame spread test design, this factor may not be appropriately reflected in the results. Some older designs of tests especially, could provide artificially good test results indicating that the fire would not spread by this mechanism, when in fact the sample had melted and the fuel source may have moved to a location well away from a flaming ignition source. Such artificially good test results could lead to catastrophic results in a real scenario, depending on where the molten, flammable material flowed in the real fire. For this reason, methods DIN 54837, Japanese Method 1, IS 7888, 25 CFR Appendix F Part 1 require reporting of dripping and flaming material and some even include pass/fail criteria related to dripping of material during the test. In contrast, FMVSS 302, Indian Standard C 8914 and 25 CFR Appendix F Part 2 do not require any investigation into the potential for dripping of the fuel during the flame spread test.

4.2.1.4 Comparison of Flame Only Test Intensities

Considering the factors described above and the calculations of flame intensity outlined in Section 4.2.1.2, the seven flame-spread tests that use only a flaming ignition source were ranked according to intensity. Key test parameters, as well as the total flame energy output for each test, are presented in Table 4.18 along with a final relative ranking of test severity for each test.

Table 4.18 Relative severity of flame spread tests using only a flaming ignition source

Method Name	**Sample Angle from Vertical**	**Flame Angle**	**Flame Intensity**	**Relative Flame Intensity**	**Duration of Flame**	**Total Flame Energy for Test**	**Relative Test Intensity**
	degrees	degrees	W		Seconds	Joules	
14 CFR 25, App. F Part 2	0 and 90	90	75,100	1	120	10,140,000	1
DIN 54837	0	45	760	2	180	136,800	2
Japan Method 1	45	0	350	3	49	17,150	3
Indian IS 7888	45	0	275	4	37	10,175	4
Indian C-8914	45	0	38	5	30+30	2,280	5
14 CFR App. 1 Part 1	0	0	38	5	12	456	6
FMVSS 302	90	0	38	5	15	570	7

Test method CFR 25 Appendix F Part 2, the airplane full seat test using a large kerosene burner, is by far the most intense flame spread test currently in use. In this test, the flame is almost two orders of magnitude more intense than the next most intense flame, and the seat configuration used incorporates a horizontal burning surface and vertical side wall joined at a right angle. This particular geometry has been demonstrated to increase the rate of flame spread [58]. From this case, the severity of the other flame spread tests continues to decrease in the following order: DIN 54837 followed by Japan Method 1, IS 7888, then the Indian Standard C-8914. These rankings are based primarily on the flame intensity used, since all of these methods use geometries that promote co-current flow. The next three tests, Indian test C-8914, 14 CFR25 Part 1 and FMVSS 302 all use the same intensity of flame. For these tests, the duration of flame exposure as well as the geometry of the test was considered. The long duration of flame exposure for Indian test C 8914 placed it as the fifth most intense test, since the geometry promotes co-current flow. 14 CFR 25 Part 1 uses a vertical flame coupled with a vertical sample, which provides co-current flow, so this test was ranked as more severe than FMVSS 302, even though the flame is applied for slightly less time. The horizontal flame spread tests of FMVSS 302 results in a lower rate of flame spread on the order of 10 to 1000 fold, so it was felt that the geometric considerations of the FMVSS 302 would render it the least stringent of all tests in this group, in spite of the slightly longer duration of flame application.

There were two flame spread test methods located for rail passenger seating in India. It is assumed that the less stringent Indian test (C-8914 – Annexure II), has been superseded by the more rigourous IS 7888 Clause II, but definitive documentation supporting this assumption has not been located. It should be noted that the rankings shown previously in Figure 4.10 differ from the results summarized in Table 4.18 because of geometric effects. The arrows included in Figure 4.10 highlights where these differences occur.

Results such as those summarized in Table 4.18 serve to illustrate another application of the methods developed in the course of this research. Flame spread tests were initially categorized and sorted, and their detailed specifications were summarized via spreadsheets and mind maps. Based on the requirements of the various tests, calculation methods were developed and applied to characterize the intensity of the flaming ignition sources for each test. These values, combined with information on how other key features of the test methods impacted the physics of the flame spread processes, facilitated development of a preliminary ranking of the relative intensity across those flame spread tests that specify use of a flaming ignition source. A similar methodology will now be applied to rank the intensities of the hybrid flame spread tests, i.e., those that use a combination of radiant panel and flame for ignition of the sample. The results are presented and discussed in Section 4.2.2 below.

4.2.2 Radiant Panel Tests

It has long been known that incident radiation, even without direct flame contact, is an important physical mechanism in the spread of fires [58]. Many factors influence ignition by radiation without the presence of a pilot flame. These factors include surface absorption or reflection of the radiation, wavelength of radiation, chemical kinetics of the decomposition reactions in the substrate, external air currents, and geometry of the sample and the radiant source. Not only does geometry have an effect on the speed of flame spread (as was discussed in Section 4.2.1.3), but it also has an effect on the radiative heat flux from a source that will reach the surface of a sample under test. Therefore, several important factors that impact ignition by non-flaming radiation sources are reviewed here, before radiant panel flame spread tests specified for transportation seating applications are discussed.

Ignition by Flame versus Radiation

The likelihood of ignition of any material due to exposure to equivalent energy sources that are open flames versus radiant sources is not the same [86]. If the heat to the sample is provided solely by a radiant panel, the pyrolysis reactions within the sample must create a localized concentration of combustible gases and the net exothermic heat release driven by the kinetics of both the pyrolysis reactions and oxidation of these gases must be sufficient to increase the temperature of the gases above the critical temperature for ignition and therefore, these reactions form the driving force to initiate ignition. If there is an open flame in the vicinity, either acting as a source of incident radiation to the sample or as an ignition pilot flame, creation and sustenance of only a critical mass flow rate of pyrolysis gases from the sample is necessary to maintain a flammable concentration in the region of the pilot flame and thereby promote ignition. Tsai [87] and Kashiwagi [88] have shown that a radiant heat source (without an open flame) would need to input more energy into a sample to effect ignition than would an equivalent open flame of equivalent intensity.

Absorption of Radiation at Sample Surface

The decomposition path of a combustible material also has a huge impact on the how a material responds in any fire-spread test, particularly when that sample is ignited via radiant flux incident on the surface. Kashiwagi studied PMMA polymer and red oak and experimentally measured how the surface properties of different samples affect the ignition delay time for those materials [89]. Both PMMA and red oak decompose by direct gasification, without melting; however, each material absorbs different wavelengths of radiation and to varying depths, and this was found to impact the temperature rise in the top layer of the material, and hence the ease of ignition of the materials. Furthermore, Kashiwagi demonstrated that absorption of incident external radiation by decomposed material that deposits on the sample surface by the decomposition reactions themselves could also act to preferentially heat the surface of a sample. Ohlemiller and Shields [90] studied absorption of incident radiant flux into samples of polyethylene, polystyrene and several polyurethane polymers. The first two of these materials are thermoplastic polymers that melt before decomposition and vapourization occur, giving rise to pools of liquid on the surface of the sample. Such melting is always an endothermic or heat absorbing process. In contrast, the polyurethane is a thermoset polymer that does not melt but which does thermally decompose, again forming pools of liquid on the surface of the sample. These decomposition reactions can be either endothermic or exothermic depending on the material under test. In the case of polyurethanes, in addition to the influence of decomposition, a layer of char is also typically formed over the surface, helping to block air from reaching the decomposed polymer and further altering the portion of incident radiant flux seen at deeper levels into the sample. In all of the cases above, therefore the radiation seen at the surface of a sample is not strictly just a function of the incident radiant energy applied to the surface, but is also a function of how the specific sample interacts with the applied energy.

It is even difficult to compare radiant heat sources of the same intensity, because the geometric shape of the heat source makes a difference when determining the radiant flux from a source that reaches a given sample. For example, Ohlemiller and Shields [90] show that the heat flux emanating from a cone shaped radiation source to a sample depends on both the angle of incidence of the radiation onto the sample surface and depth into the material below the irradiated surface. Radiation striking a sample at a 45-degree angle was found to penetrate the sample less deeply than radiation striking the same sample at a 90-degree angle.

Girod [91] shows that samples exposed to radiation of the same nominal intensity generated by different kinds of sources (radiant conical heaters versus tungsten lamps) underwent different decomposition reactions leading to variation in flame spread results. This is due to the different wavelengths of radiation provided by the different sources in combination with variations in the way the different wavelengths interact with the sample at the surface.

The above discussions are provided to highlight several important factors that impact ignition by non-flaming radiation. The interactions outlined serve to illustrate that flame spread testing is a complex and challenging field and to provide some insight as to why tests performed by different methods often do not compare well with each other, even though they at first appear to be based on similar test configurations and protocols. With this in mind, the four flame spread test methods that employ radiant panels for ignition are described and compared in the next section.

4.2.2.1 Test Descriptions

The four hybrid flame-spread methods identified in rail standards that employ a radiant panel for ignition are ASTM E162 [82], ASTM D3675 [83], ISO 5658-2 [84] and AFAP 4 [41]. They all use the IMO LIFT apparatus with a pilot flame, but they do not use the device in the same configuration or with the same test conditions. In addition to the radiant panel ignition source, all four of these tests employ a pilot flame to ensure initial ignition of the sample. If the sample ignites, the flame front then advances along the sample from a region of higher radiant heat flux to a region of lower heat flux with the intent of determining a value of the critical heat flux at which a flame no longer propagates along the length of the sample.

Figure 4.12 Photograph of IMO LIFT device radiant heater and sample holder

Figure 4.12 contains photographs showing the radiant heater and the sample holder of an IMO LIFT device with the sample in the horizontal configuration, as would be used in the ISO 5658-2 test. The relative arrangement of these components for each of the methods is outlined in the paragraphs below, followed by discussion and comparison of ignition source intensity and relative severity of these flame spread tests.

ASTM E162 versus ASTM D3675

The ASTM E162 and ASTM D3675 tests use the same physical configuration, the same calibration settings for the radiant panel and apply heat for the same length of time, but different sizes of acetylene-air pilot flames are used for the respective tests. The geometrical layout of the sample, the radiant panel, and the pilot burner for the two ASTM methods is illustrated schematically in Figure 4.13. With this configuration, flame propagation will be downwards, or counter current to prevailing airflows. ASTM D3675 is intended specifically for the testing of flexible cellular materials whilst ASTM E162 is to be used for other materials. ASTM D3675 employs a larger pilot flame than ASTM E162, and ASTM E162 can be conducted with or without the pilot flame. Neither method is intended for use as a basis of measurement for building code purposes.

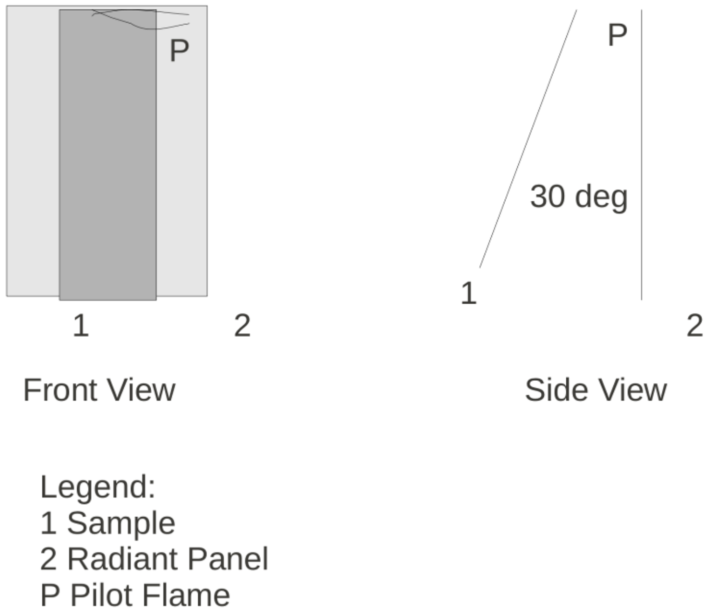

Figure 4.13 Geometry of ASTM E162 and ASTM D3675 test configuration

For each of these tests, the radiating surface is 305 mm by 460 mm (12 x 18 inches) and is oriented vertically, with the short dimension being horizontal and the long dimension being vertical. The panel can operate at temperatures of up to 815°C (1500°F). The sample panel is to be 152 x 460 x 25 mm (6 x 18 x 1 inches) and is oriented in the same way as the radiant panel, but inclined at a 30-degree angle from vertical. In both cases, if the sample material is thicker than 25 mm, it is to be cut to that thickness. If the material is innately thinner than 25 mm, it should be tested at the supplied thickness and the actual thickness of the sample should be noted. The chief difference in the physical configuration between the two methods, then, is the size and flow rate of the pilot burner.

ASTM D3675 employs an acetylene-air pilot flame that is 203 to 230 mm (6 to 7 inches) long. Within the 230 mm long flame, fuel and airflow is adjusted such that an inner blue cone of 25 mm in length is formed. The flame is oriented horizontally and angled at between 15 to 20 degrees towards the sample, such that it impinges directly on the upper central surface of the sample within 13 mm of the top of the support frame.

ASTM E162 also employs an acetylene-air pilot flame, but this flame is specified to be only 50 to 75 mm (2 to 3 inches) in length. Like ASTM D3675, the flame is oriented in a horizontal position and with a slight angle towards the upper central surface of the sample near the support frame. Normally, the pilot flame would not be touching the sample, but would be within 13 mm of the sample surface. If the sample has a tendency to shrink, then the pilot is positioned so as to touch the surface at the start of the test. While ASTM E162 normally uses a pilot flame, the test can be configured so that the pilot burner can be moved out of the area if it is not in use.

ISO 5658-2 versus AFAP 4

The ISO 5658-2 and AFAP 4 flame spread test methods are also based on use of the IMO LIFT apparatus and, while they use the same physical configuration and heat input as one another, they differ significantly from the ASTM tests.

In contrast to the ASTM methods, for these tests the radiant panel and the sample are mounted in a vertical position oriented so that the short side of the panel and sample are parallel to the vertical axis and the long side parallel to the horizontal axis. The geometrical relation between the sample, the pilot flame and the radiant panel is shown schematically in Figure 4.14. The radiant panel is positioned at a 15-degree angle out from the sample, such that the intensity of radiation impinging on the sample varies along the horizontal length of the sample (highest at the left hand side and decreasing to the right in Figure 4.14).

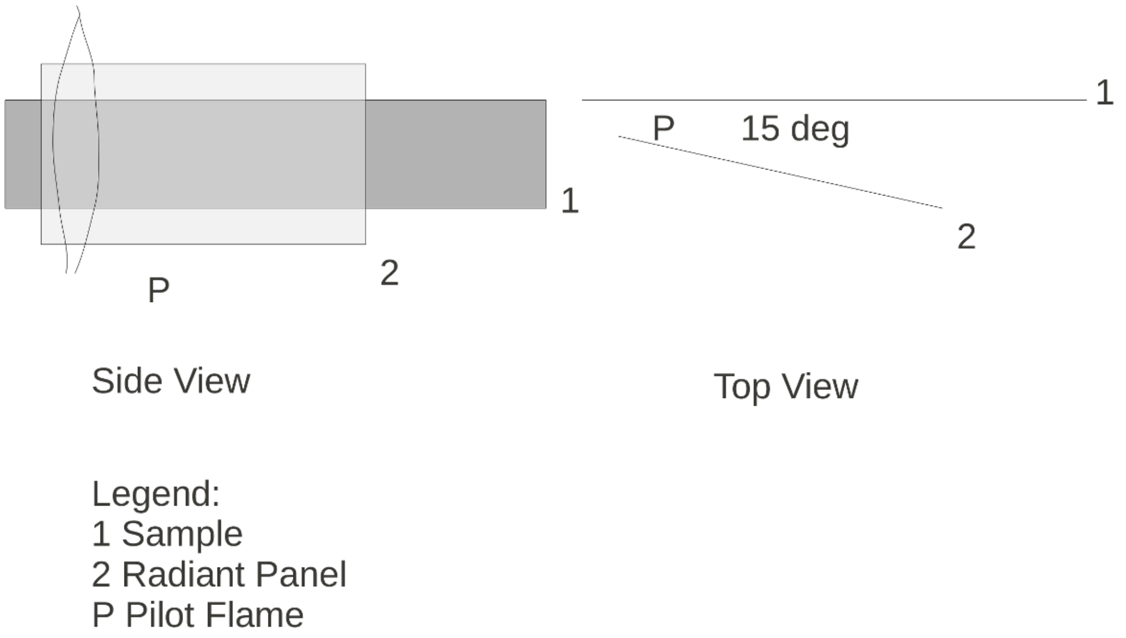

Figure 4.14 Geometry of radiant panel flame and sample in ISO 5658-2 and AFAP 4

The size of the radiant panel is 480 x 280 mm, and that of the sample is 800 x 155 mm, so the sample is almost twice as long as the sample employed in either ASTM method. Both ISO 5658-2 and AFAP 4 employ a pilot flame, fuelled by propane, with gas flows adjusted to give a flame length of 230 +/- 20 mm. The pilot flame is aimed slightly towards the upper edge of the sample frame, and may directly impinge on the surface of the sample. It is situated close to the hotter end of the specimen (Figure 4.12) and extends beyond the height of the sample, both above and below, to ignite any volatile gases issuing from the surface or any combustibles that may melt and flow from the sample at the start of the test. In this configuration, flame spread is in the horizontal direction along a vertically oriented sample.

One key difference between the ISO, the AFAP and both ASTM tests is that the AFAP 4 test apparatus includes an exhaust stack and instrumentation that is used for the estimation of heat release rate from the sample during the test. In other respects, the AFAP test report includes the same information as an ISO 5658-2 report, with additional information relating to these heat release measurements.

4.2.2.2 Radiation Intensity

The incident radiant heat input to the sample is identical for the ASTM E162 and ASTM D3675 flame spread tests. Similarly, the incident radiant heat input to the sample is identical for ISO 5658-2 and AFAP 4 flame spread tests. Therefore, only ASTM E162 and ISO 5658-2 tests are included in the following comparisons of radiation heat flux intensity for the hybrid flame spread tests.

Differences in the way that the experimental set up and calibration procedures are described in the ASTM and ISO [82-84] render it extremely difficult to directly compare the intensity of the heat flux emitted by the radiant panel and incident on the sample in the two tests. Researchers at Underwriters Laboratories conducted experiments to permit comparison of the intensity of the radiation incident on a sample from each radiant panel test as calibrated for both ASTM E162 and ISO 5658-2 [31]. A comparison of experimentally determined heat flux intensity incident on a sample (kW/m^2) relative to the distance from the hot end of the sample (starting at the position 50 mm from the end of the sample) for the two methods is shown in Figure 4.15.

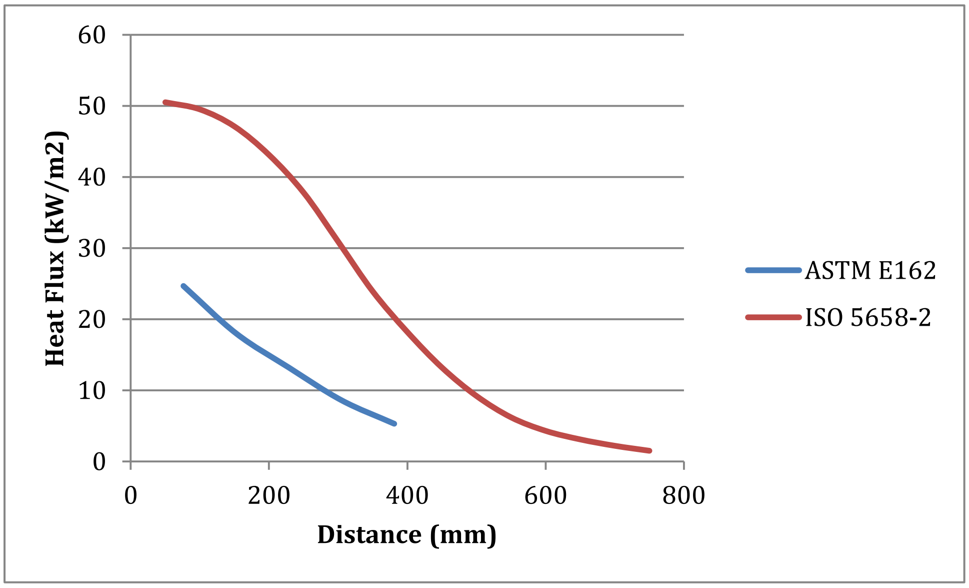

Figure 4.15 Comparison of radiant panel heat flux for ASTM E162 and ISO 5658-2

The work by Underwriters Laboratories indicates that at the hottest location, the ISO method delivers about twice the radiant heat to the sample that the ASTM methods do. The ISO test values of incident radiant heat flux range from 50 kW/m^2, at a distance of 50 mm from the hottest edge of the sample, to a flux of 1.5 kW/m^2 at a distance of 750 mm along the sample. In comparison, the ASTM method uses a shorter sample (457 mm) and measured radiant flux intensities range from 25 kW/m^2 at 50 mm from the hottest edge to 3 kW/m^2 near the cooler edge of a sample.

From the information presented above, it is possible to rank the relative amount of radiant energy at the sample surface for the four radiant panel tests specified in rail transportation seating. The AFAP 4 test is conducted for forty minutes while the ISO 5658-2 test is conducted for thirty minutes, so from the perspective of radiant heat flux, the AFAP 4 is the most intense of the four tests, ISO 5658-2 is the next intense and the two ASTM methods have the lowest and identical heat flux profiles. In the next section, ignition by the combination of radiation and open flames actually used in the hybrid flame spread will be discussed in concert with the other factors that influence the radiant heat flux at the surface of the sample, reviewed at the start of Section 4.2.2.

4.2.2.3 Comparison of the Radiant Panel Tests

Sections 4.2.2.1 and 4.2.2.2 described the four radiant panel tests specified for flame spread in transportation seating applications. There is a high degree of similarity among the tests opposite some variables. Table 4.19 summarizes many of the key physical attributes that characterize these four tests.

Table 4.19 Summary of the physical attributes of radiant panel flame spread tests

	ASTM D3675	**ASTM E162**	**ISO 5658-2**	**AFAP 4**
Sample size (mm)	152 x 457	152 x 457	800 x 155	800 x 155
Sample angle (from vertical) (degrees)	30	30	0	0
Angle between panel and sample (degrees)	15	15	30	30
Radiant panel size (mm)	300 x 460	300 x 460	480 x 280	480 x 280
Radiant panel energy (kW/m^2)	25 to 5	25 to 5	50.5 to 1.5	50.5 to 1.5
Test duration (min)	15	15	30	40
Pilot location	Top	Top	Bottom to top	Bottom to top
Orientation of pilot flame	Counter current downwards	Counter current downwards	Co-current horizontal	Co-current horizontal
Fuel	acetylene/air	acetylene/air	propane/air	propane/air
Flame length (mm)	150 to 180	50 to 75	230	230
Pilot flame intensity (W)	774	410	557	557
Pilot flame energy input (J)	696,600	369,000	1,002,000	1,337,000

Not all of the variables listed above need to be considered in a comparison of the relative severity of these four tests, but a number of them do. The key parameters selected to compare the severity of these tests are listed in Table 4.20. All of these factors have been discussed at various points in the previous discussion, but will be reviewed together in the particular context of the hybrid test methods here.

Table 4.20 Quantitative comparison of radiant panel tests

Test Number	Test Length	Radiant Panel Energy	Angle Between Panel and Sample	Direction of Flame Travel	Pilot Flame Intensity	Energy Input by Pilot Flame
	min	kW/m^2	degrees		W	J
ASTM D3675	15	25 to 5	30	Counter-current downwards	774	696,600
ASTM E162	15	25 to 5	30	Counter-current downwards	410	369,000
ISO 5658-2	30	50.5 to 1.5	15	Co-current horizontal	557	1,002,000
AFAP 4	40	50.5 to 1.5	15	Co-current horizontal	557	1,337,000

The most important factors that influence the intensity of the radiant panel flame spread tests include: intensity of panel radiation, intensity of pilot flame, angle of radiant panel with respect to sample, geometry and direction of flame travel and test duration. Values for each of the most important factors are shown in Table 4.20, and each was ranked numerically relative to each other, as shown in Table 4.21. A ranking of 1 was considered the most intense in each case. Sample angle from horizontal was not used in the rankings because both tests employ a sample angle that is greater than 25 degrees from the horizontal. The pilot flame length was also not used for the rankings because the flame intensity was deemed to be related to the flame length and was demonstrated to be more important in comparisons of the flame spread tests that employed open flame ignition sources (Section 4.1). In this case, also, the total energy output of the pilot flame was not used in the rankings because that value is influenced by the test duration, and in these comparisons the test duration is ranked separately as it impacts the energy delivered by both the radiant panel and the pilot flame. Finally, the location of the pilot flame was not considered in the rankings because in all tests, it is located near the site of most intense radiation from the panel. The results of the qualitative ranking for each parameter as well as the overall relative rankings of the severity of the various hybrid flame spread test methods are presented in Table 4.21.

Table 4.21 Qualitative comparison of radiant panel tests from most severe to least severe

Test Number	**Test Duration**	**Radiant Panel Energy**	**Angle Between Panel and Sample**	**Direction of Flame Travel**	**Pilot Flame Intensity**	**Energy Input by Pilot Flame**	**Overall Relative Ranking**
AFAP 4	1	1	1	1	2	NC	1
ISO 5658-2	2	1	1	1	2	NC	2
ASTM D3675	3	2	2	2	1	NC	3
ASTM E162	3	2	2	2	3	NC	4

This analysis of the radiant panel tests indicates that AFAP 4 is the most intense of the tests, followed closely by ISO 5658-2. ASTM D3675 is the next less intense and ASTM E162 is the least intense of all of the four radiant panel tests evaluated. The ratings assigned to rank test duration, the radiant panel energy and the pilot flame intensity are strictly a numerical ranking based on the severity of the values listed or calculated and included in Table 4.20. The severity ratings given for the angle between the panel and sample and the direction of flame travel are more qualitative and are based on information contained in previous discussions. In Section 4.2.1.3 the effect of flame travel direction on the rate of flame spread was discussed. Since flames that travel down an inclined surface (counter current flow as in ASTM D3675 and ASTM E162) are known to travel more slowly than flames that travel across a surface with co-current flow on a vertically oriented sample (as in AFAP 4 and ISO 5658-2) [58, 85], the ASTM tests were assigned a lower severity ranking than the other two methods. In Section 4.2.2 it was discussed that the angle of incidence of radiant energy as it contacts the sample influences how much radiation is absorbed or reflected. The larger the angle between the radiation source and the sample, the more radiation is reflected rather than being absorbed [90]. The angle between the radiant panel and the sample for the two ASTM tests is larger than for the ISO 5658-2 based tests, so the ISO based tests were ranked as more severe in terms of this parameter. In summary then, from the data presented in Table 4.19 and the rankings presented in Table 4.20 it can be seen that the full analysis of the hybrid radiant panel and pilot flame spread tests indicates that the AFAP 4 flame spread test method is the most intense of the tests, followed closely by the ISO 5658-2 method. ASTM D3675 is the next less intense and ASTM E162 is the least intense of the four hybrid radiant panel flame spread tests evaluated. It must also be noted, however, that the rating values assigned in Table 4.21 reflect only a relative order of the severity of the various test methods. There has been no weighting of any of the parameters in terms of their relative significance on the test results and therefore the numerical totals have no meaning other than as input to a qualitative ranking tool.

4.2.3 Discussion of Energy Intensity of Flame Spread Methods

The relative intensities of the open flame ignition source flame spread methods and those of the hybrid methods employing both radiant panels and pilot flames have been evaluated and ranked. It is straightforward to compare the energy intensity of the various flame spread methods that use open flame ignitions sources only, and to compare the energy intensity of the various tests that are based on the IMO LIFT apparatus, but it is not feasible to compare the energy intensity of the two groups of tests to one another. In part this is due to the significant differences in energy transfer from the various ignition sources to the samples, but is also due to the fact that the energy outputs for the flame ignition tests are expressed in watts of energy available in the burner flame (W), while the energy outputs for the radiant panel tests are expressed as flux from the radiant panel (kW/m^2) and total energy from the pilot flame (W), so that actual energy input to the sample in the two tests cannot be readily compared.

On the other hand, the ignition source energy levels for each test method discussed above can be compared to energy levels for known fire sources that are documented in the literature in order to gain a better understanding of the flame spread test ignitions source intensity relative to real fire scenarios. Fire intensity values for different real world scenarios, in terms of average power and incident heat flux, are listed in Tables 4.22 [31, 58, 92-95] and 4.23 [31, 58, 96] respectively, to facilitate comparison with values summarized in Tables 4.17 and 4.20.

Table 4.22 Average power output of various flame sources [31,58,92-95]

Flame Source	**Average Power** W	**Approx. Scale of Fire**
Cigarette butt	< 22	2 mm (.1 in)
Match	40 - 80	35 mm (1.4 in)
Butane flame	290	145 mm (5.7 in)
Butane flame	630	240 mm (9.5 in)
BS 5852 Wood Crib 7 (126 gm) 62.5 mm tall	3400	280 mm (11 in)
Waste paper basket	40,000	1 m (3 to 4 feet)
Steiner tunnel test flame	88,000	1.5 m (4.5 feet)
Cushioned office chair	160,000	2.4 m (8 feet)

Table 4.23 Typical radiant heat flux values for various scenarios [31,58,96]

Flame Source	**Flame Intensity** kW/m^2
Human tenability	2.5
Heat flux at room floor at flashover	20
Small fire	25 – 35
Medium fire	50
Full scale room fire at flash over	80

Tables 4.17 and 4.21 compare and rank the intensity of the various flame spread methods currently mandated for transportation seating. Comparison of the intensity of the sources listed in Tables 4.17 and 4.22 indicates that there is a wide variation in the intensity of flames employed in the flame spread tests, which employ a flaming ignition source. In fact, these values span almost the full range of values listed in Table 4.22. The 14CFR 25 Appendix F Part 2 test is by far the most intense flame spread test (75 kW), with the German test DIN 54837 a distant second (760 W), the Japanese and Indian IS 7888 tests being the next most severe in terms of ignition source intensity (around 300 W) and the remaining tests employing flames comparable to those produced by a match or a cigarette lighter. The airplane seat test simulates the exposure to the seat that would occur in a fiery crash, and safeguards that the seats will not make the situation dramatically worse in the short term,

allowing for passengers to escape. The other flame spread tests all mimic what happens in the case of a small, accidental fire caused by trash or cigarettes or a combination of the two.

The hybrid test methods employ pilot flames to ensure that the sample under test catches on fire and then they monitor the radiant heat flux at which the flame self extinguishes. The ignition sources in these tests therefore vary significantly in intensity but since they are there to ensure initial ignition of the samples, they should not have a significant impact on determining the critical heat flux at extinguishment of the material. Instead it is the energy of the radiant panel that is important in the hybrid flame spread tests. Comparison of Tables 4.20 and 4.23 reveals that the energy supplied by the radiant panel in the flame spread tests considered here mimics either a small fire (25 kW/m^2) (ASTM E162 and ASTM D3675) or a medium fire (50 kW/m^2) (ISO 5658-2 and AFAP 4) and are similar to incident flux levels generally assigned during cone calorimeter testing as well. Both of these flame intensities could also be considered comparable to differing stages of a developing fire. It must also be remembered, however, that the different geometries used have a significant impact on the intensity of the tests.

Review of the literature did not locate any studies in which the order of the severity of various flame spread tests was ranked, but there were a number of studies in which attempts were made to correlate the results of various flame-spread tests to larger scale tests or data from real fires as is discussed in the next paragraph. In every study reviewed, the results were consistent with the rankings proposed herein.

In the literature, it has been found that some of the flame-spread tests correlate well to large scale tests, but some are not conservative when compared with large scale testing and analyses of a number of real transportation fires [11, 31, 77, 79, 80]. For comparison to the present rankings, these studies are summarized in the following paragraphs.

Underwriters Laboratories was commissioned by the U.S. government and the U.S. Fire Marshalls to conduct studies to determine and recommend changes to the testing requirements to improve the fire safety of passenger trains [31]. Amongst other things, their report [31] compared test duration to assumed escape times and concluded that the exposure and test durations specified in current flame spread tests are reflective of the assumed evaluation time needed or available in real transportation situations. The airplane seat test is conducted for a total of 5 minutes and assumes 2 minutes for evacuation and the two ASTM flame spread standards referenced for rail are conducted for 15 minutes. In comparison, building escape time is assumed to be 15 minutes in Room Corner tests and it was postulated that train evacuation should be quicker than building evacuation so a 15-minute exposure was deemed very appropriate [31]. In contrast, the European rail flame spread test is conducted for 30 minutes and the military vehicle test for 40 minutes, reflecting that these jurisdictions make different assumptions for passenger egress.

The Underwriters report [31] also included an extensive comparison of the ASTM E162 and the ISO 5658-2 flame spread tests and correlated the test results from both test methods to time to flashover test results from NFPA 286, a full-scale corner room test. The report indicated interesting correlations between NFPA 286 and flame spread test results generated by the ISO 5658-2 method but did not observe the same kinds of correlation with the ASTM E162 test results. Unfortunately, none of these results were reported in sufficient detail to draw in depth conclusions; instead, a recommendation for further study was made. Nonetheless, this study indicates that perhaps the ISO 5658-2 test method is a better predictor of large scale fire behavior than the ASTM E162 method, which is consistent with the results presented in Table 4.21 and analysis presented.

In a separate study, Hofmann [79] tested three kinds of seating; a bus seat, a train seat and an automobile seat using the suite of small scale tests defined in CEN TS 45545: 2009 for European trains. Large-scale paper cushion flame spread tests as described in DIN 5510-2 were also performed for all of the bus and train seat simulations. The paper cushion test described uses a paper cushion made of 100 grams of plain newsprint where the outer covering is a single sheet of newsprint, and the "stuffing" is comprised of crumpled balls of newsprint. All of the seats tested were commercially available seats approved for their respective uses in Germany. The test data was used to model the expected flame spread in a both a simulated bus and simulated train interior. The simulation scenario was designed to recreate the conditions involved in a tragic bus fire in Hanover Germany in 2008 that resulted in twenty fatalities and numerous injuries. After 66 seconds, the fire in the simulated train interior had self-extinguished while predictions for the simulated bus interior indicated rapid flame spread along the ceiling of the bus. Based on these results, it was recommended that changes be made to fire safety standards for bus interiors. The results also indicate, however, that the flame spread criteria required by CEN TS 45545-2: 2009 (based on ISO 5658-2) provide a higher standard of fire performance for transportation seating than those specified in the FMVSS 302 flame spread test.

This conclusion is supported by independent work related to fire statistics in the transportation sector published in the U.S. [98] for the time period of 1980 to 2005. The statistics indicate a decrease in transportation fire accidents over time, however automobile fires are consistently among the largest causes of fire death in the United States (about 500 annually). As a result, there is concern in the transportation industry that FMVSS 302 does not provide adequate protection against flame spread in the case of fire [80, 81]. Digges et al. [81] published an analysis of what would be required to improve the life safety for passengers involved in automobile crash scenarios from a fire perspective.

In the 1980’s, the U.S. National Conference on School Transportation adopted a more stringent test than FMVSS 302 that used a paper bag filled with newspaper as an ignition source, and many U.S. and Canadian school bus authorities use this standard, although the law does not mandate its use [80]. More recently, some ASTM E05 fire standards committee members felt that a paper bag filled with newspaper was not a reliable, reproducible source of ignition so a new standard, ASTM E2574 - Standard Test Method for Fire Testing of School Bus Seat Assemblies was developed. This new standard was first published in 2011 but is still in the ASTM review and approval process.

Svebrant [77] indicates in his research that in full-scale automotive tests, temperatures of 700 to 800°C were attained within 3 minutes of ignition, and all of the exposed materials passed the FMVSS 302 flame spread tests. He performed cone calorimetry heat release tests (ISO 5660) to study the heat release rates of eleven different materials that passed the FMVSS 302 flame spread test and evaluated the results in comparison to the heat release and time to ignition criteria required by a number of test standard requirements in other transportation sectors including trains (CEN TS 45545: 2009 requirements), high speed craft and submarines. Only one of the eleven materials passed any of the heat release and time to ignition tests specified by the other sectors, and even that material obtained only a partial pass on a test specified for trains that was conducted with a relatively low incident flux of 25 kW/m^2. This study did not compare the results or severity of the FMVSS 302 to other flame spread test methods, but did compare FMVSS 302 results to results obtained in cone calorimetry studies that have been demonstrated to correlate with large scale flame tests. Through such comparisons, it was found that the results provided by the FMVSS 302 test method are not conservative. The poor performance of materials tested using FMVSS 302 is consistent with the severity rankings obtained in the present analysis.

While it has not been possible to develop a rigourous quantitative comparison of the severity of the various flame spread tests employed in the major transportation sectors, comparative rankings of flame only and of hybrid radiant panel and flame tests have been made. Of the eleven flame spread tests reviewed in detail, four of them use radiation with a pilot flame and the others use direct flame contact as a heat source. The airplane seat kerosene burner tests delivers 75kW for two minutes and is the only flame spread test that delivers the magnitude of heat that would come from a fully developed fire. The four radiant panel tests are the next most intense tests and they deliver lower amounts of heat over a longer period of time, as might be experienced with a small to medium sized fire. All of the other tests deliver significantly less energy to the sample with several of them delivering energy only equivalent to the input from a match or a cigarette. The suggestion that the flame-spread tests are not conservative is borne out by analyses of several real transportation fires.

Comparison of the final rankings presented in Table 4.17 to the previous rankings presented in Table 4.16 indicates that it is not just the intensity of the flame that is important in determining severity rankings across flame spread tests. In the case of the FMVSS 302 test method, it is the geometry of the test in combination with the intensity of the flame that renders it the least severe of all of the tests considered.

4.3 Risk Analysis in Railway Fire Safety Standards

A recent trend, in general, in fire safety regulation is to move from prescriptive to performance-based standards for design. This trend has started in the transportation sector as well, with the IMO transitioning from prescriptive to performance based standards in 2012 [21]. Due to the importance of such changes in terms of application and interpretation of fire performance test methods and results in the future, this next section compares how Europe and the Unites States are incorporating risk assessment into their rail standards.

The latest European rail standard incorporates a performance based approach through the use of a mixture of prescriptive and performance criteria that are mandated across all European countries. The performance-based element defines different operation categories and design categories for trains. Operational categories consider factors like: time spent in tunnels or on elevated structures, length of train relative to the tunnel or elevated sections and egress scenarios for the passengers and staff of the rail service. Design categories consider whether the train is automatic and operating without trained emergency staff on board, whether it has sleeping cars or double-decked cars, or whether it contains just standard coaches. For each service level of train, prescriptive safety requirements are described in a series of risk matrices that define different necessary fire test performance levels, as measured through fire tests involving five different possible flame sources. The necessary fire performance tests, and flame types employed, are matched to rail services of different categories, car types and hazard degrees. This approach is relatively easy for an end user to follow in that they just need to identify, from a matrix of possible types of train service, which kind of rail service they are evaluating and the requirements that must be met are pre-defined. For the two fire test methods from this standard that have been evaluated in depth in the present research, the European technical requirements are found to be quite rigourous.

The American approach to the use of risk assessment in rail transportation is quite different. The legislated requirements have not changed significantly in decades, but an ASTM standard has been developed that describes how to conduct a risk assessment for a rail service. The standard is entitled "ASTM E2061 – 09a Standard Guide for Fire Hazard Assessment of Rail Transportation Vehicles" [99] and it promotes a performance-based approach to fire safety design of railway cars. This methodology is very comprehensive, but the approach is quite different from that seen in Europe. There is less focus on the category of rail service for which the train is being designed and more on the specific train scenario being evaluated. In all, ASTM E2061 requires that the evaluation consider the entire rail car opposite the thirteen different fire scenarios that are shown in Figure 4.16.

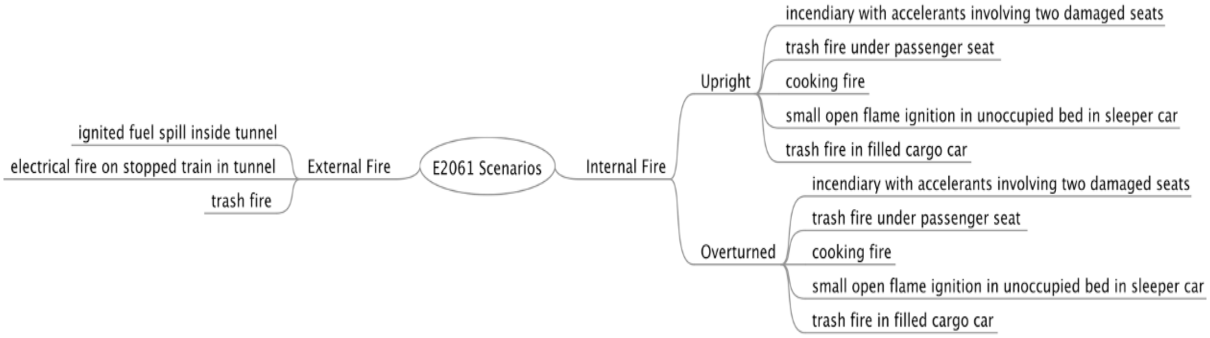

Figure 4.16 ASTM E-2016 risk scenarios for evaluation

For each scenario considered, the evaluation is to consider a “worst case” scenario involving a train operating at capacity and including passengers of varying capability for a the scenario of “least accessibility”. The standard does not state which calculations, fire tests or evaluations are to be used to assess performance of the train design, but does provide a comprehensive list of possible tools that could be used in the assessment with explanatory background and notes. In general, the ASTM guide is aligned with the existing American legislative requirements, but in some respects it is more aligned with thought patterns seen in the recent European work than any other North American based requirement to date. Examples of this shift are the strong emphasis on use of heat release test results rather than the existing flame spread tests discussed above and also the requirement for evaluation of a scenario involving vandalization to a pair of adjacent seats exposed to a fire source. In any case, the desired outcome from these comprehensive risk assessments is to decide if a newly designed rail car provides better, equivalent, inferior or different protection to rail passengers than presently accepted designs. If a finding of “different” is found, evaluators must demonstrate that the different approach provides protection at least equivalent to existing systems.

4.4 Summary

This Chapter of the thesis looks critically and in depth at fire effluent toxicity testing and flame spread testing for rail transit seating. There are many historical, economic and political reasons why the standards have evolved to their current state. The present analysis has shown that most of the transportation standards, particularly the land based transportation standards are weak on a technical basis. A number of geographies only address a few aspects of fire safety testing in their rail safety requirements (notably the U.S.A., India, Canada, Japan). Similarly, on a transportation sector basis, the various aspects of fire are not uniformly covered either. The new European rail requirements and the NATO military requirements cover the broadest range of possible fire hazards. Global aviation requirements do not mandate fire effluent toxicity testing, but the major manufacturers in these fields have developed their own tests. The requirements for automotive seating (including requirements for buses) have the narrowest range of required testing and the least stringent performance standards of any field reviewed.

There is a growing body of work that supports the idea that the single most important predictor of a fire outcome are the total heat release and heat release rate [5, 7]. Fire heat release is primarily measured by cone calorimeters, furniture calorimeters or room scale tests. ISO 5859-2 with a stack can also measure heat release, as is specified in the AFAP-4 fire performance test method.

Some, but certainly not most, jurisdictions require heat release rate testing of transportation seats. Of those jurisdictions that require heat release testing, the cone calorimeter is most frequently required with incident radiant heat flux that is equivalent to small or medium size fires as opposed to fires approaching flashover conditions (25 or 50 kW/m^2 cone setting versus 80 to 90 kW/m^2 for many realistic fire scenarios) [6]. The choice of heat flux for cone calorimeter experiments is chosen to simulate a developing fire, rather than the conditions from a fully developed fire. That is useful in studies to select materials that will be less prone to catch fire readily, but less useful in the event of intentionally set fire using accelerants, which has also been demonstrated to be a realistic fire scenario several times in public transportation scenarios in the past decade (for example: 2004 Madrid train incident, 2005 London transit incidents, 2009 Detroit airplane incident). Current thinking suggests that the total heat release combined with the heat release rate is the best indicator of the damage potential of a fire. Some jurisdictions currently include these measures in their fire performance test requirements or are actively moving in that direction. Risk assessment and the use of computational models are also being used. Some recently revised legislation initiatives are actively including risk analysis in their regulations.

The use of computational fluid dynamic models is not currently mandated in any jurisdiction, but has been a practice in many places globally for a decade or more now. The development of these methods permits the development of performance based standards, which is a growing trend across the entire field of fire safety.

Fire safety testing for mass transit is a mature field that has been in existence for over one hundred years. In spite of this, it is still a field in flux. Some sectors are highly standardized globally (air, marine and military). Other sectors, like rail, are largely not standardized in spite of international efforts to do this since the 1920's.

Chapter 5 – Conclusions

The objective of this research was to develop a systematic way to identify, evaluate and compare regulated fire safety requirements in a given field. A methodology was developed and it was demonstrated in the analysis of two very different sub-sets of fire testing.

The process illustrated in this research is as follows:

Determine if there are legislated requirements for a given application,
Identify which groups define the legislations,
Determine if there are additional requirements that are not legislated,
Ensure the most recent versions are being considered,
Identify the technical requirements,
Compare, and if possible, rank the relative severity of the relevant topics or tests.

Basic spreadsheet programs are excellent tools for collecting information, but a different kind of tool is needed to help visualize differences and relationships that exist within a body of information. Mind-mapping software has been demonstrated to be a suitable tool for visualization of complex, information rich bodies of knowledge, like jurisdictional fire regulations.

In this work, mind-mapping software has been successfully used to describe the required testing frameworks across various geographies and types of flammability testing. It has also been successfully used to elucidate the differences between test specifications in two very different areas of flammability testing, namely toxicity of fire effluents and flame spread tests.

Using the tools and analyses developed here, it has been determined that in this instance, an absolute ranking of the severity of fire effluent toxicity and flame spread test requirements for public transportation by sector cannot be defined because there are many aspects to fire testing and the various jurisdictions do not necessarily consider the same fire hazards. Rankings can however be made for specific aspects of fire testing.

5.1 Fire Effluent Toxicity Testing

In summary, for fire effluent toxicity testing, there are four basic configurations of test devices used. Historical precedence is a significant factor in the choice of tests mandated. Only one type gives results that correlate well with the results from larger scale ISO room fires across a wide range of conditions, but none of the tests used in seating for public transportation use this kind of test device. Some of the test configurations used do correlate reasonably with portions of the ISO room fires and if the correlation is good for the length of time required for escape, this may be considered acceptable.

The results from toxicity tests are reported on a weight basis or an area basis. The weight-based results are generated by tests that use a small sample (typically one gram). Many jurisdictions require these kinds of tests for small items, but few use them for large items like seats. Indian passenger service and NATO military applications are two notable exceptions. The other seven of the nine toxicity tests use area based tests, which use larger samples that can provide a more representative burning. Most of these tests also employ the use of radiant heat sources to initiate thermal decomposition of the products, but they vary in their use of pilot flames, which can have a marked effect on the balance of toxic products produced.

Detection and measurement of fire effluent gases is typically done one of three ways: by FTIR, by a suite of traditional analytical chemistry techniques or by colourimetric tubes. FTIR can give near real-time data and requires the least effort once properly set up. Both FTIR and the traditional chemical analysis can give good and accurate results. The colourimetric tubes are the easiest to use, but they are less accurate and are prone to interferences. Some methods permit their use but require a retest if the results attain eighty percent of a threshold value.

All fire toxicity standards reviewed claim to use NIOSH IDLH values for threshold values, but there are still significant differences in what are deemed to be acceptable exposures. The chief differences in interpretation arise from the assumed escape times (fifteen minutes versus thirty minutes) and whether the criterion of ‘escape with your life’ or ‘escape without permanent injury or damage’ is applied when threshold exposure values are determined. In this regard, the European rail passenger standards are the most stringent of any transportation seating standard.

Most fire effluent toxicity tests measure eight key components, but there are some exceptions. Airbus Industries monitors only six components while the NATO military test AFAP 3 monitors eleven analytes and the Indian standard monitors fourteen different analytes. Airbus Industries exposure limits are more stringent than those of Bombardier Inc. and both of these are more stringent than the limits used by Boeing. The US. Fire Marshalls’ Office was proposing the adoption of the Boeing toxicity test standard for use in the rail industry.

The EU is conducting research to develop a realistic, cost effective test for predicting toxic fire effluents, and if successful, wish to expand the use of this test to other modes of transportation. The United States has not yet taken a formal position on fire effluent toxicity testing for land transportation systems (rail or vehicular).

5.2 Flame Spread Testing

The flame-spread tests legislatively mandated may employ either a radiant panel with a pilot flame for initiation of flame spread, or employ direct contact with an open flame. Radiant heat without a pilot flame requires more energy to initiate a fire than direct flame contact for reasons discussed in depth in Chapter 4. Severity of methods using radiant heat sources cannot be directly compared to those based on open contact flaming ignition sources, but semi-quantitative estimates can be made to permit the ranking of the relative intensities of all of the flame-spread tests mandated. These rankings have been made successfully.

Of the eleven flame spread tests reviewed in detail, four of them use radiation with a pilot flame and the others use direct flame contact as a heat source. The airplane seat kerosene burner tests delivers 75kW for two minutes and is the only flame spread test that delivers the magnitude of heat that would come from a fully developed fire. The three radiant panel tests deliver lower amounts of heat over a longer period of time, as might be experienced with a small to medium sized fire (25 to 50 kW/m^2). The rest of the flame spread tests use smaller fires, several using fires as small as the energy input from a match or a cigarette. The suggestion that the flame-spread tests are not conservative is borne out by analyses of several real transportation fires.

Fire safety testing for mass transit is a mature field that has been in existence for over one hundred years. In spite of this, it is still a field in flux. Some sectors are highly standardized globally (air, marine and military). Other sectors, like rail, are largely not standardized in spite of international efforts to do this since the 1920’s.

Chapter 6 – Future Work

This work developed a methodology for analyzing complex systems of fire regulations and demonstrated the use of the new approach in the assessment of two kinds of fire testing in mass transit applications. To gain a complete understanding of fire testing of mass transit rail seating, similar analyses should also be completed for heat release tests, smoke tests, ignition delay tests and full scale seat vandalization tests per the tests summarized in Figure C.1. Future work on the heat release tests should include the optional HHR tests that are permitted in the USA as alternates to the flame spread and smoke tests that are currently prescribed. Further evaluation of seat vandalization testing should be postponed until after the EU finalizes EN TS 45545 in late 2012. The only jurisdictions mandating seat vandalization tests are the EU, Germany, and possibly China. If the German standard DIN 5510-2 is retired once EN TS-45545 is finalized and adopted, EN TS-45545 would be the only seat vandalization standard remaining unless China has and maintains one similar to DIN 5510-2. Although not a mandatory requirement, the recently published ASTM E2061 also includes evaluation of vandalized seats that should be considered.

Other possible future work in this area could include the development of mind maps that evaluate significant applications for each of the major pieces of equipment in the University of Waterloo, Fire Research Lab. Examples of his for the IMO LIFT device currently housed at the labs are shown in Figures 6.1 and 6.2.

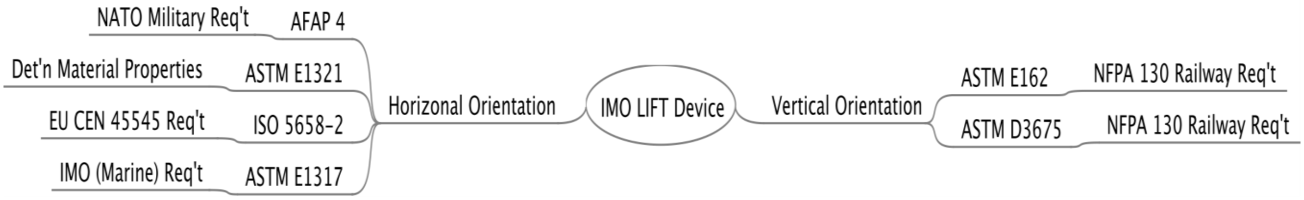

Figure 6.1 Major applications for IMO LIFT Device by test configuration

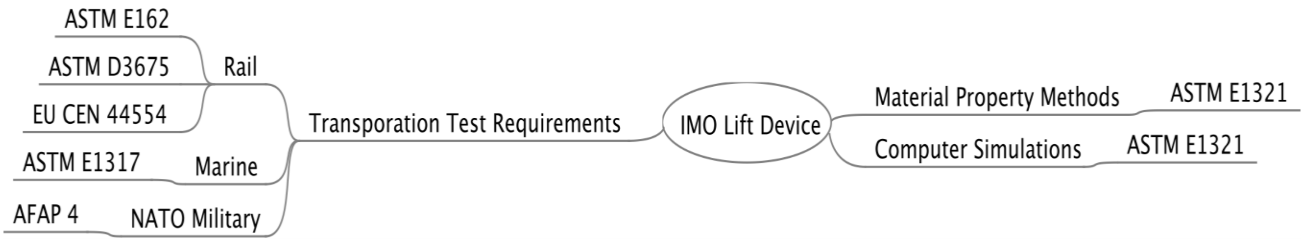

Figure 6.2 Major applications for IMO LIFT Device by Desired Output

Figures 6.1 shows in a single glance the major fire performance test methods that the instrument can be used for, as well as what physical configuration is required for performing each of these tests. Figure 6.2 shows some major areas of flammability research, and illustrates which methods this instrument can provide in these fields of research. Figures 6.1 and 6.2 are incomplete as presented, but they could be expanded as more projects using the instrument are undertaken, and as more systems of legislative requirement are investigated.

A library of such mind maps for all of the major fire test equipment available at UW could expedite the definition of research projects and choice of experimental equipment to use for testing, could speed the learning curve of students new to the field and could be an effective marketing tool for the lab, helping to attract new projects, as potential partners could more easily understand the capabilities of the lab.

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Appendix A – Glossaries

Table A.1 Abbreviations for key global organizations

Abbreviation	**Proper Name**	**Affiliation**	**Comments**
AFAP	Allied Fire Assessment Publication	International	AFAP documents are sponsored and published by the Defence Investment Division of NATO
AIHA	American Industrial Hygiene Association	U.S.A.	
ASTM	American Standard Test Methods	U.S.A./Int'l	
BS	British Standard	Great Britain	
BSI	British Standards Institution	Great Britain	Publishes standards with the BS numbering system
CEFIC	European Chemical Industry Council	European	
CEN	European Committee for Standardization	European	Non-profit, established under Belgian law and has 31 member states. Encompasses all things mechanical and chemical. Publishes standards with the EN numbering system.
CENELEC	European Committee for Electrotechnical Standardization	European	
CEN TS	Conditional Normative European Technical Standard	European	
CFR	Code of the Federal Register	U.S.A.	
DIN	Deutsches Institut fur Normung	Germany	Publishes standards with the DIN numbering system
EC	European Commission	European	
EN TS	Normative European Technical Standards	European	EN are also national standards in the member countries of the CEN.
EU	European Union	European	
FAA	Federal Aviation Administration	U.S.A.	
FAR	Federal Aviation Regulations	U.S.A & International	Developed by the US FAA with guidance from US Aerospace Industries Association, US Air Transport Association, International Civil Aviation Organization and the International Air Transport Association.

Abbreviation	Proper Name	Affiliation	Comments
FMVSS	Federal Motor Vehicle Safety Standard	U.S.A	
FRA	Federal Railroad Administration	U.S.A.	
FTP	Fire Test Procedure Code	International	Developed in 1996 by the IMO, it contains fire test methods for flammability, smoke and toxicity for materials and components used on ships. There are 9 parts to this collection of procedures.
IMO	International Maritime Organization	International	
ISO	International Standardization Organization	International	Based Switzerland
ISO/TC 92	ISO Technical Committee on Fire Safety	International	Historically focussed on fire safety in buildings, but in 1995, its scope was expanded to fire safety in general.
NATO	North Atlantic Treaty Organization	International	A political and military alliance consisting of 28 member countries and a number of affiliates. The goal is maintaining peace through diplomatic and military action as required.
NBS	National Bureau of Standards	U.S.A	
NFPA	National Fire Protection Association	U.S.A./Int'l	
NIOSH	National Institute for Occupational Health and Safety	U.S.A.	
NRC	National Research Council	Canadian	In Canada, fire related regulations that impact the safety of the general public are under the jurisdiction of either NRC, Department of Consumer and Corporate Affairs or Ministry of Transport (motor vehicles, marine, air and rail transport).
SAE	Society of Automotive Engineers	International	
SMS	Safety Management System	Canadian	Canadian regulatory requirement for rail operators.
SOLAS	Safety of Life at Sea	International	International convention concerning the safety of merchant ships under the International Maritime Organization.
UIC	International Union of Railways	Int'l / France	Union Internationale de Chemins de fer

Abbreviation	Proper Name	Affiliation	Comments
UL	Underwriters Laboratories	International	Global, independent safety science company
USDOT	United States Department of Transportation	U.S.A	

Table A.2 Symbols

Symbol	**Typical Units**	**Name**
LC_{50}	ppm or mg/m^3	Lethal concentration 50
LD_{50}	ppm or mg/m^3	Lethal dose 50
LC_{Lo}	ppm or mg/m^3	Lethal concentration low
IDLH	ppm or mg/m^3	Immediately dangerous to life and health
CIT	unitless	Conventional Index of Toxicity
MARHE	kW/m^2	Maximum average rate of heat emission
CFE	kW/m^2	Critical flux at extinguishment
$D_{s\ max}$	((b/m)m^3/m^2)	Maximum specific optical density
I_s	BTU/min^2	Radiant panel index
F_s	min^{-1}	
Q	BTU/min or W	Rate of heat release
IR	unitless	Infra-red
FTIR	unitless	Fourier Transform Infra-red
CO	unitless	Carbon monoxide
CO_2	unitless	Carbon dioxide
HF	unitless	Hydrogen fluoride
HCl	unitless	Hydrogen chloride
HBr	unitless	Hydrogen bromide
HCN	unitless	Hydrogen cyanide
Nox	unitless	Nitrogen oxides, primarily NO and NO_2
SO_2	unitless	Sulfur dioxide
L	m	Length of flame
V'	m^3/sec	Volumetric flow rate
D	m^2/sec	Diffusion coefficient
P	atmosphere	Pressure
V	m^3 or l	Volume
n	moles	number of moles
R	m^3 atm/K mol	Universal gas constant
T	C or K	Temperature
q"	W/m^2	Heat flux
k	W/mK	Thermal conductivity
F_{12}	unitless	Configuration Factor or view factor
ε	unitless	Emissivity
σ	W/m^2K^4	Stefan Boltzman constant
ARHE	kW/ m^2	Average rate of heat emission
HHR_{30}	kW/ m^2	Heat release rate at 30 minutes
SPR_{30}	m^2s^{-1}	Smoke production at 30 minutes

Table A.3 Definitions

Name	**Definition**
LC_{50}	LC_{50} is a measurement of acute lethal toxicity by inhalation. It is the concentration of a chemical in air at which 50% of a suitably large test population will die within a specified time span (frequently 30 minutes).
LCt_{50}	Median lethal concentration per minute which is the product of the concentration of a toxic component and and the exposure time causing lethality in 50% of test animals.
LC_{lo}	The lowest lethal concentration of a material in air reported to have caused death in a human or an animal.
LD_{50}	LD_{50} is a measurement of acute lethal toxicity by ingestion. It is the concentration of a chemical which when ingested will kill 50% of a suitable large test population within a specified time span.
IDLH	Immediately dangerous to life or health - Any condition that poses an immediate or delayed threat to life or that would cause irreversible adverse health effects or that would interfere with an individual's ability to escape unaided from a permit space. Note: Some materials--hydrogen fluoride gas and cadmium vapor, for example--may produce immediate transient effects that, even if severe, may pass without medical attention, but are followed by sudden, possibly fatal collapse 12-72 hours after exposure. The victim "feels normal" from recovery from transient effects until collapse. Such materials in hazardous quantities are considered to be "immediately dangerous to life or health." [29 CFR 1910.146]
C_f	Toxicity Concentration - Concentration of the gas considered fatal to mass for a 30 minute exposure time (ppm)
CIT	Conventional Index of Toxicity - equals a scaling factor multiplied by the sum of the measured concentration divided by the Toxicity concentration for all of the measured toxic combustion products. Dimensionless.
FED	Fractional Effective Dose (as defined in DIN 5510-2)
LIFT	Lateral Ignition and Flame Spread Test. This test device was developed initially for the maritime industry, but is now widely used for flame spread evaluations in other jurisdictions. The device is still sometimes called the IMO LIFT apparatus.

Appendix B – Recent Changes and Updates

A number of significant changes have occurred since this work was initiated and researched from the autumn of 2010 to the spring of 2012. The most important of these are the legislative changes.

When this work was initiated, the IMO performance based Fire Test Procedures were still in the development stage, with an expected implementation date of July 1, 2012. The IMO website indicates that these new codes were implemented on July 1, 2012 as originally planned [100].

The European train regulations CEN TS 45545 were under development while this research was being conducted and the comments included herein on this topic are all based on the draft document that was published in 2009. This series of draft documents was open for comment by member countries while this research was being conducted, and multi-national groups with diverse stakeholders continued to research topics throughout this time frame. The originally published time line indicated that member countries would have the opportunity to comment on the draft documents of CEN TS 45545 in 2011 and that the final, revised version would be published and become law in 2012, with an appropriate phase in period. CEN was to have voted on EN TS 45545-2 on November 10, 2012 [101]. In reality, this timeline was extended by a few months. In June, 2013, the newer version, EN TS 45545-2:2013 was released, and must be available for purchase in member states by the end of September 2013. Member states have until the end of March 2016 to withdraw any currently existing standards that conflict with EN TS 45545-2:2013. Users of this work will need to revisit the newly released version of EN TS 45545-2 to determine if there have been significant changes to the technical requirements.

Some of the original time targets for implementation of this work were met; others were not. The current plan is to publish EN TS 45545, Edition 1 in 2013 with a second edition to be published at a later date when certain, difficult technical issues have been more fully investigated [102]. One of the technical issues causing delay is agreement on a suitable toxicity of fire effluent test. The currently proposed test is not felt to be sufficiently robust.

Two of the groups actively involved in continuing this work over the past several years were ISO TC-92 and a group called “transfeu”. Transfeu was formed with the goal of developing a holistic approach of fire safety performance-based design methodology able to efficiently support European surface transport standardization. The bulk of their work was published by November 2012, but work continues on two topics: development of a dynamic measure of toxicity and the use FSE and simulation as a possible alternative to current Fire safety regulation and standard (TSI and TS 45545). Their early work included the development of a large body of fire test results on materials used in train interiors, and this database is to be used as a resource to assist in the development of their performance-based recommendations.

Transfeu released many reports on a wide variety of fire safety topics pertaining to transportation in recent months [100]. At least eight of these reports were released from 2011 to the present, including one on toxicity testing released on November 15, 2012 [103]. This report summarizes a wider range of recent European legislations on toxicity test requirements in more detail than was explored in this thesis. While, their results are consistent with this work in that no legislative requirements for fire effluent toxicity tests in airplanes were identified, there was not complete overlap in the airline test standards, identified, reviewed and discussed. Both studies looked at the fire effluent standards of Airbus and Boeing, but the Transfeu group included information on Fokker Airplanes (that went out of business in 1996), but not those of Bombardier. Their comparison of the toxicity tests employed by Airbus, Boeing and Fokker concluded that Airbus was the most severe test of these three. This work found the Airbus fire effluent toxicity test to be the most severe of Airbus, Boeing and Bombardier.

Also, since this work was initiated, the version of the Technical Standard for Japanese Railways that was available on line [43] was the 2006 version of this document. The 2010 version of this document, now entitled "Technical Regulatory Standards on Japanese Railways" was posted to the link quoted on March 31, 2012. This update did not make any substantive changes to the sections of this standard quoted in this body of work.

Appendix C – Geographic and Legislative Background

Table C.1 Members and affiliates of CEN (European Committee for Standardization)

CEN Members		CEN Affiliates
Austria		Albania
Belgium		Armenia
Bulgaria		Azerbaijan
Cyprus		Belarus
Czech Republic		Boznia & Herzegovina
Denmark		Croatia
Estonia		Egypt
Finland		Macedonia
France		Georgia
Germany		Israel
Greece		Jordan
Hungary		Lebanon
Iceland		Libya
Ireland		Moldova
Italy		Montenegro
Latvia		Morocco
Lithuania		Serbia
Luxembourg		Tunisia
Malta		Turkey
Netherlands		Ukraine
Norway		
Poland		
Portugal		
Romania		
Slovakia		
Slovenia		
Spain		
Sweden		
Switzerland		
United Kingdom		

Table C.2 NATO members and affiliate countries

NATO Member Countries		**Partner Countries**	**NATO Affiliation**
Albania		Armenia	EAPC
Belgium		Austria	EAPC
Bulgaria		Azerbaijan	EAPC
Canada		Belarus	EAPC
Croatia		Bosnia and Herzegovina	EAPC
Czech Republic		Finland	EAPC
Denmark		Macedonia	EAPC
Estonia		Georgia	EAPC
France		Ireland	EAPC
Germany		Kazakhstan	EAPC
Greece		Malta	EAPC
Hungary		Moldova	EAPC
Iceland		Montenegro	EAPC
Italy		Russia	EAPC
Latvia		Serbia	EAPC
Lithuania		Sweden	EAPC
Luxembourg		Switzerland	EAPC
Netherlands		Tajikistan	EAPC
Norway		Turkmenistan	EAPC
Poland		Ukraine	EAPC
Portugal		Uzbekistan	EAPC
Romania		Algeria	Mediterranean Dialogue
Slovakia		Egypt	Mediterranean Dialogue
Slovenia		Israel	Mediterranean Dialogue
Spain		Jordan	Mediterranean Dialogue
Turkey		Mauritania	Mediterranean Dialogue
United Kingdom		Morocco	Mediterranean Dialogue
United States		Tunisia	Mediterranean Dialogue
		Bahrain	ICI
		Qatar	ICI
		Kuwait	ICI
		United Arab Emirates	ICI
		Australia	Contact Countries
		Japan	Contact Countries
		Korea	Contact Countries
		New Zealand	Contact Countries

Appendix D – Population of Mind Maps

There are many different ways to populate mind mapping software, depending upon the problem at hand and the desired outcome. Several different approaches to their population were used during the course of this body of work and are described below. An additional approach, not used in this particular body of work, is also described.

Introduction to a Complex and Poorly Understood Field

At the start of this project, the author knew very little about the different fire tests for transportation seating. A body of standards was collected and key information was extracted and entered into a spreadsheet. The spreadsheet had columns for the name, the reference number, the original date of publication, the most current issue, the jurisdiction, the kind of test, the parameters measured, the sample size, the flame angles, the flame intensities, the fuel, the use of a radiant panel, the radiation intensity, the duration of testing, the values measured or calculated and a column for comments. The spreadsheet became very large, with some columns well populated and most columns sparsely populated. The sorting functions in Excel were used to analyze the data to understand the tests in various ways. The product of this first initiative was the framework of the mind map shown in Figure D.1. The map shown in Figure D.1 also shows some of the annotations and icons used in the refining of the test selections and the ranking of the flame intensity calculations. This really helped understand the different kinds of fire testing involved in the field, and what their primary purpose was, but it did not help understand the testing required in each jurisdiction. This leads to another way mind maps can be used, and that is to answer a specific question.

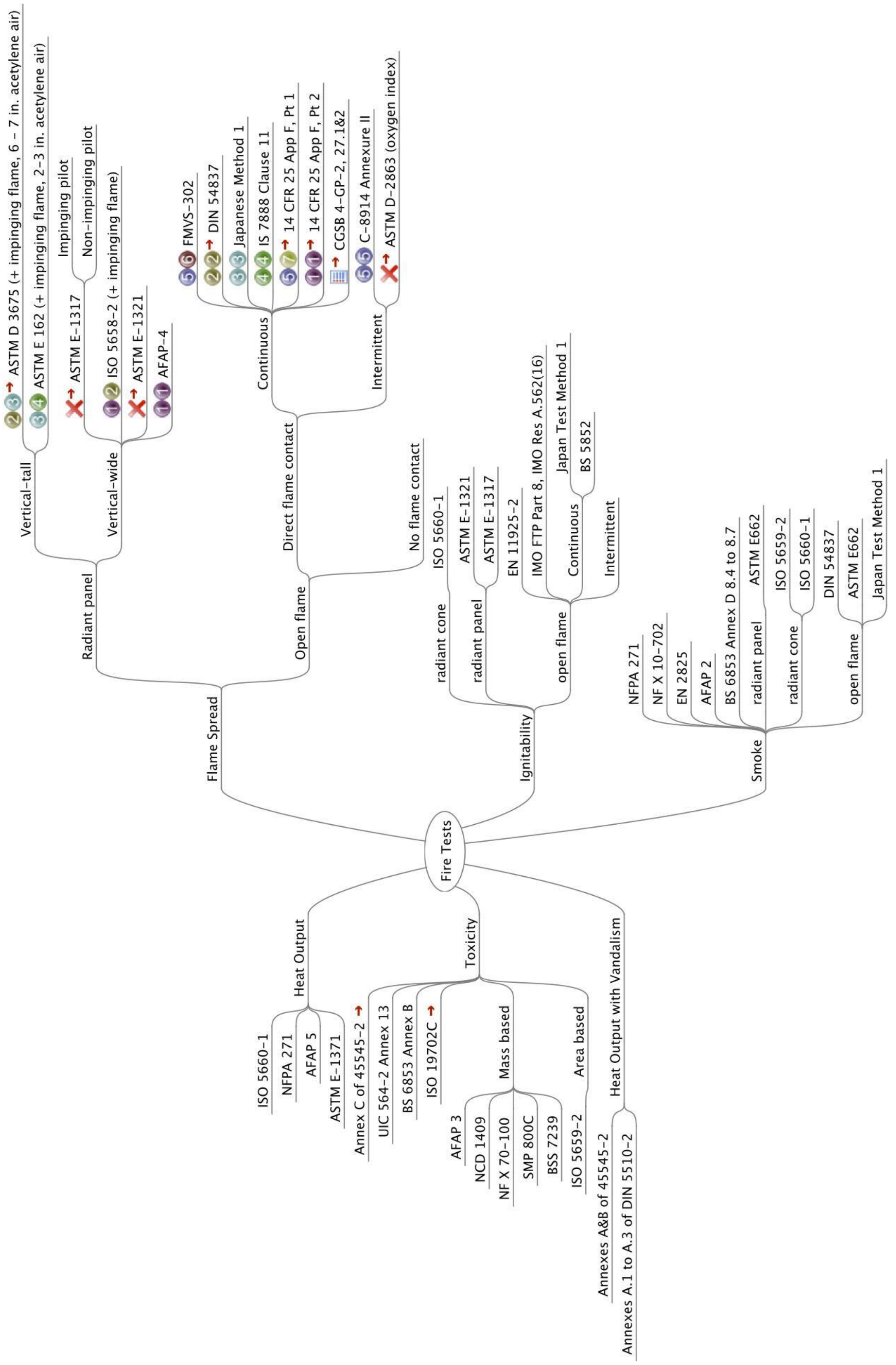

Figure D.1 Mind map of fire tests by type

To Answer a Specific Question

The large Excel workbook was sorted so as to identify which tests were associated with each jurisdiction. This information was used to create the mind map shown in Figure 3.4. Definitive information was not available for China, but several resources indicated that China modeled their regulations closely after DIN 5510-2 from Germany. In order to complete the mind map that became Figure 3.4, it would be necessary to understand the requirements of DIN 5510-2, a fifty-six-page document.

Analysis of a Complex Technical Document or Standard

It is not necessary to create a spreadsheet to analyze a complex document or technical standard. One just needs to study the index of the document to determine the sections of relevance to the question at hand, and then to analyze the contents of the sections of relevance, and build the mind map accordingly, adding points of interest on branches within each section, if and as desired. Figure D.2 illustrates what was found for DIN 5510-2 when this analysis was done.

Similarly, other complex but well organized bodies of information can be analyzed and summarized on a single page of information directly. An example of this is Figure 3.7, the analysis of the research on fire effluent toxicity testing by Hull [56]. Hull wrote a descriptive summary for each of the twenty-seven methods he reviewed. The salient design features were used as the main branches of the diagram and information from each test was populated accordingly. There were two ways to draw the basic diagram, with either four main branches corresponding to each chamber design, or two main branches corresponding to the main detection classes. Both approaches were used, and the mind map that was visually simplest was chosen for use.

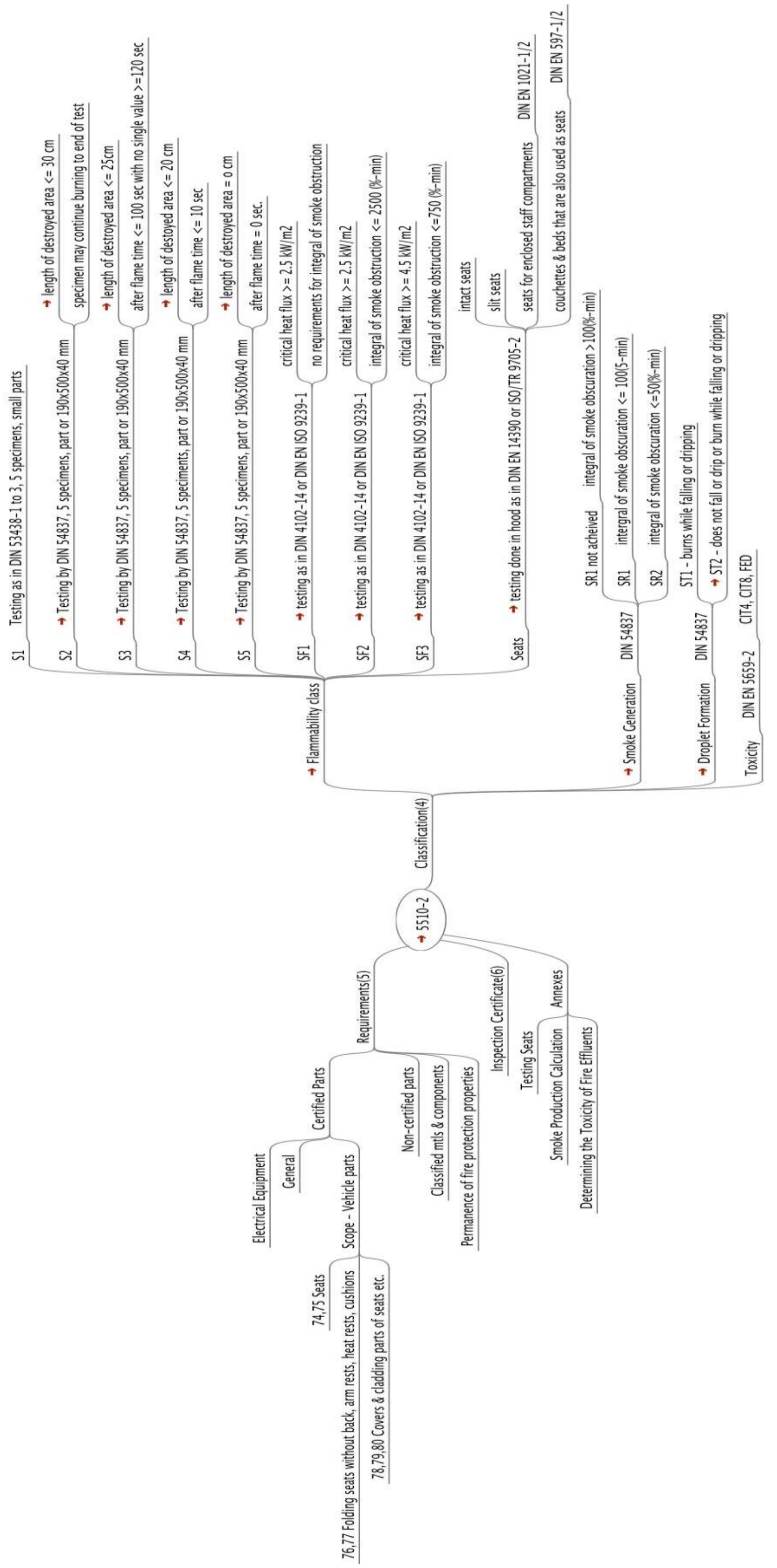

Figure D.2 Mind map of organization and testing requirements in DIN 5510-2

To Summarize Complex Relationships Efficiently

Mind maps can summarize a large amount of complex information in a single graphic, while simultaneously illustrating the relationships that exist among the information. In addition to showing a series of parent/child relationships, arrows can be drawn between different branches of the map, and hyperlinks, symbols and emoticons can be added to each node. Some commercial programs have even more functionality added.

To Brainstorm a Problem Via a Shared Computer Screen

If a group of people is trying to solve a complex problem, and they are at different locations, but sharing a common computer view through an electronic meeting software program, mind mapping programs can be an effective brainstorming tool. The meeting moderator can capture peoples' ideas as nodes on a mind map during brainstorming, and because each node can be pulled around and moved, without retyping, the moderator can move all the nodes around at the direction of the various participants to create a group understanding reflecting the combined insights of all of the specialists involved in the discussion, reaching a better understanding than might be possible otherwise because the solution is so visual.

Mind mapping software is a flexible and powerful tool that can be used in a variety of ways, some of which have been summarized above.

Appendix E – Flammability Test Titles

Chapter 3 provided detailed information on the selection of flame spread and toxicity tests to be discussed. The full list of test titles originally considered is shown in Table E.1 below.

Table E.1 Flammability test titles by type, name, year and jurisdiction

Test Type	Test Number	Test Name	Geography
Flame Spread	DIN EN 2310	Aerospace series - test method for the flame resistance rating of non-metallic materials	Germany
Flame Spread	AFAP 4	NATO Reaction to Fire Tests for Materials - Surface Spread of Flame (3rd Ed.)	NATO
Heat release	AFAP 5	NATO Reaction to Fire Tests for Materials - Heat Release Rate (3rd Ed.)	NATO
Ignitability	BS 5852	Assessment of the ignitability of upholstered seating by smouldering and flaming ignition sources	UK
Ignitability	AFAP 1	NATO Reaction to Fire Tests for Materials - Overview and Ignitability of Materials (3rd Ed.)	NATO
Ignitability	IMO FTP Code, Part 8	International Code for Application of Fire Test Procedures, Part 8: Upholstered furniture, IMO Res.A.562(16), Fire test of upholstered furniture	International Marine Organization
Smoke	AFAP 2	NATO Reaction to Fire Tests for Materials - Smoke Generation (3rd Ed.)	NATO
Smoke	NF X 10-702	Determination of the opacity of the fumes in an atmosphere without air renewal	France
Toxic Gas	ISO 19702C	Toxicity testing of fire effluents - guidance for analysis of gases and vapours in fire effluents using FTIR analysis	International
Toxic Gas	AFAP 3	NATO Reaction to Fire Tests for Materials - Toxicity of Fire Effluents (3rd Ed.)	NATO
Toxic Gas	ISO 19701	Methods for sampling and analysis of fire effluents	International

Test Type	Test Number	Test Name	Geography
Smoke, Toxic Gases	ISO-5659-2S	Plastics - Smoke Generation - Determination of optical density by a single chamber test	EU
Toxic Gas	NF X 70-100	Fire Tests - Analysis of Gaseous Effluents - Part 1: Methods for Analysing Gases Stemming from Thermal Degradation; Part 2: Tubular Furnace Thermal Degradation Method	France
Flame Spread	ASTM E162	Surface Flammability of Materials Using a Radiant Heat Energy Source	USA
Flame Spread	ASTM D3675	Surface Flammability of Flexible Cellular Materials Using a Radiant Heat Energy Source	USA
Smoke	ASTM E662	Specific Optical Density of Smoke Generated by Solid Materials	USA
Heat release	Pr CEN TS 45545-2	Annex A&B Seat vandalization and heat release test	EU
Toxic Gas	Pr CEN TS 45545-2	Annex C Toxicity test	EU
Various	Pr CEN TS 45545-2	Railway Applications - Fire Protection on Railway Vehicles - Part 2 - Requirements for fire behavior of materials and components	EU
Flame Spread	ISO 5658-2	Lateral flame spread	EU
Heat, Smoke & Mass Loss	ISO 5660-1	Reaction-to-fire tests -- Heat release, smoke production and mass loss rate -- Part 1: Heat release rate (cone calorimeter method)	EU, Japan
Foam Properties	IS-7888 Cl. 11	Methods of Test for Flexible Polyurethane Foam	India
Testing Mandate +	C-8914, Annexure II	Schedule of Technical Requirements for Flexible Load Bearing Polyurethene Foam Cushions for Passenger Coaches	India
Toxic Gas	NCD 1409	Toxicity Index	India
Ignition, Smoke & Flame	Test Method I	Test Method 1 for Non-Metallic Materials for use on Railways	Japan
Flame Spread	FAR 25.853(a) vertical	Airworthiness Standards:Transport Category Airplanes, Part D - Design and Construction Fire Protection	USA

Test Type	Test Number	Test Name	Geography
Flame Spread	14 CFR 25 Appendix F, Part 1 (vertical test)	Airworthiness Standards:Transport Category Airplanes, Part D - Design and Construction Fire Protection	USA
Flame Spread	14 CFR 25 Appendix F, Part 2	Airworthiness Standards:Transport Category Airplanes, Part D - Design and Construction Fire Protection	USA
Smoke	BS 6853 Annex D, 8.4 to 8.7	Three metre cube smoke density test	UK
Smoke	EN 2825	Aerospace series - Burning behaviour of non metallic materials under the influence of radiating heat and flames - Determination of smoke density;	EU
Test Equipment	EN 2824	Aerospace series - Burning behaviour of non-metallic materials under the influence of radiating heat and flames - Determination of smoke density and gas components in the smoke of materials - Test equipment apparatus and media;	EU
Toxic Gas	BS 6853 Annex B	Toxicity test	UK
Toxic Gas	EN 2826	Aerospace series - burning behavior of non-metallic materials under the influence of radiating heat and flames - Determination of gas components in the smoke.	EU
Burning Behavior	DIN 54341	Testing of seats in railways for public traffic - Determination of burning behaviour with a paper pillow ignition source	Germany, China
	DIN EN 14390	Fire test - Large-scale room reference test for surface products	EU
Ignitability	DIN EN 1021-1	Furniture - Assessment of the ignitability of upholstered furniture - Part 1: Ignition source smouldering cigarette	EU
Ignitability	DIN EN 1021-2	Furniture - Assessment of the ignitability of upholstered furniture - Part 2: Ignition source match flame equivalent	EU
Burning Behavior	ISO/TR 9705-2	Reaction to fire tests - Full-scale room tests for surface products - Part 2: Technical background and guidance	EU

Test Type	Test Number	Test Name	Geography
Flame Spread	CGSB 4-GP-2,Method 27.1	Canadian Standard Textile Test Vertical Burn	Canada
Flame Spread	CGSB 4-GP-2,Method 27.2	Canadian Standard Textile Test 45 Degree Burn	Canada
Flame Spread	DIN 54837	Determination of burning behavior using a gas burner	Germany, China
Flame Spread, Toxic Gas, Smoke and Dripping	DIN 5510-2	Preventive Fire Protection in Railway Vehicles. Part 2 - Fire behavior and fire side effects of materials and parts - Classification, requirements and test methods	Germany, China
Heat, Smoke and Weight Loss	NFPA 271	Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products using an Oxygen Consumption Calorimeter	USA
Ignitability	EN 11925-2	Ignitability test	EU
Risk Assessment	ASTM E2061	Guide for Fire Hazard Assessment of Rail Transportation Vehicles	USA
Toxic Gas	Bombardier SMP 800-C	Toxic Gas Generation from Material Combustion	Bombardier Corp.
Toxic Gas	BSS 7239	Test Method for Toxic Gas Generation by Materials on Combustion	Boeing Corp.
Toxic Gas	UIC 564-2 Annex 13	Fire resistance of seats: Toxic fume emmission	EU
Rail	UIC 564-2	UIC 564-2 – Regulations relating to fire safety in passenger carrying railway vehicles or assimilated vehicles used on International service	EU
Rail	UIC 564-2 Annex 8	Fire resistance of foam materials	EU
Rail	C-8914	Schedule of Technical Requirements for Flexible Load Bearing Polyurethene Foam Cushions for Passenger Coaches	India
Aviation	FAR 25.853	Requirements for Compartment Interiors: Crew and Passengers - c) Seat Cushions	USA
Rail	Pr CEN TS 45545-1	Railway Applications - Fire Protection on Railway Vehicles - Part 1 - General	EU

Test Type	**Test Number**	**Test Name**	**Geography**
Rail	Pr CEN TS 45545-2	Railway Applications - Fire Protection on Railway Vehicles - Part 2 - Requirements for fire behavior of materials and components	EU
Rail	UIC 564-2	UIC 564-2 – Regulations relating to fire safety in passenger carrying railway vehicles or assimilated vehicles used on International service	International
Motor Vehicle	FMVS-302	Federal Motor Vehicle Safety Standard - Flammability of Interior Materials	USA/ International
Rail		Technical Standard for Japanese Railway	Japan
Rail	ASTM E2061	Fire Hazard Assessment for Rail Transportation Vehicles	USA
Rail	NFPA 130	Standard for Fixed Guideway Transit and Passenger Rail Systems	USA
Rail	49 CFR Part 216	Federal Railway Administration, Fed. Reg., Vol. 64, No. 91, pp 25539-25705, Passenger Equipment Safety Standards, Final Rule	USA
Military	AFAP 1	NATO Reaction to Fire Tests for Materials - Policy for the pre-selection of materials for military applications (Ed. 3)	NATO
Rail	DIN 5510-2	Preventive Fire Protection in Railway Vehicles. Part 2 - Fire behavior and fire side effects of materials and parts - Classification, requirements and test methods	Germany, China
Rail	DIN 5510-1	Preventive Fire Protection in Railway Vehicles. Part 1 - Levels of protection, fire protection methods and certification	Germany, China
Rail	BS 6853	Code of practice for fire precautions in the design and construction of passenger carrying trains	UK
Furniture	ASTM E1537	Fire Testing of Upholstered Furniture	USA
Mattresses	ASTM E1590	Fire Testing of Matresses	USA
Heat, Smoke and Weight Loss	ASTM E1354	Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Comsuption Calorimeter	USA
Measurement selection	ASTM E800	Standard Guide for Measurement of Gases Present or Generated During Fires	USA

Test Type	Test Number	Test Name	Geography
Toxic Gas	BSS 7239	Test Method for Toxic Gas Generation by Materials on Combustion	USA/ International
Ignitability	EN 11925-2	Reaction to Fire Tests - Ignitability of products subject to direct impingement of flame - Part 2 - Single flame source test	EU
Flame Spread	FMVSS-302	Federal Motor Vehicle Safety Standard - Flammability of Interior Materials. This standard has been adopted internationally and it is technically equivalent to ISO 3795 which was published in 1989. ISO 3795 is used in Europe, Canada and Japan.	USA/ International
Flame Spread	ASTM E1317	Flammability of Marine Surface Finishes	USA
Ignitability, Flame Spread	ASTM E1321	Material Ignition and Flame Spread Properties	USA
Measurement selection	ASTM G125	Measuring Liquid and Solid Material Fire Limits in Gaseous Oxidants	USA
Oxygen Index	ASTM D2863	Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index)	USA
Analytical	NT fire 047	Nordtest Combustible Products: Smoke Gas Concentrations, Continuous FTIR Analysis	Norweigan
Mattresses	NT fire 055	Nordtest Matresses: Burning Behavior Full Scale Test	Norweigan
Analytical support	EPA SOP 312	Cleaning of Canisters	USA
Analytical	EPA TO 14	Determination Of Volatile Organic Compounds (VOCs) In Ambient Air Using Specially Prepared Canisters With Subsequent Analysis By Gas Chromatography	USA
Analytical	EPA TO 15	Determination Of Volatile Organic Compounds (VOCs) In Air Collected In Specially-Prepared Canisters And Analyzed By Gas Chromatography/ Mass Spectrometry (GC/MS)	USA
Burning Behavior	ASTM E2067	Practice for Full-Scale Oxygen Consumption Calorimetry Fire Tests	USA
Building Materials	ASTM E2257	Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies	USA

Test Type	Test Number	Test Name	Geography
Furniture	ASTM F1550	Test Method for Determination of Fire-Test-Response Characteristics of Components or Composites of Matresses or Furniture for Use in Correctional Facilities after Exposure to Vandalism by Employing a Bench Scale Oxygen Consumption Calorimetry	USA
Furniture	ASTM E1537	Test Method for Fire Testing of Upholstered Furniture	USA
Analytical	ISO 19701	Methods for sampling and analysis of fire effluents	International
Analytical	ISO 19702	Toxicity testing of fire effluents - Guidance for analysis of gases and vapours in fire effluents using FTIR gas analysis	International
Burning Behavior	ISO 9705-2	Fire Tests - Full scale room test for surface products - Part 2: Technical background and guidance	International
Analytical	ISO 21489	Fire Safety - Measurement of smoke gas components in cumulative tests	International
Analytical	ISO/TR 9122-3	Toxicity Testing of Fire Effluents - Part 3: Methods for the determination of gases and vapours in fire effluents.	International
Analytical	ISO/CD 21489	Fire Tests - Methods of Measurement of Gases by Fourier Transform Infrared Sepectroscopy (FTIR)in Cumulative Smoke Test	International
Toxic Gas	IEC 60695-7	Fire Hazard Testing - Part 7.1 - Toxicity of fire effluents, general guidance	International
Building Materials	EN 13823	Reaction to fire tests for building - Conditioning procedures and general rules for selection of substrates	EU
Analytical	ISO 5725	Accuracy of Measurements and Results Package	International
Heat, Smoke and Weight Loss	NFPA 271	Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption	USA
Terminology	ASTM E176	Standard Terminology of Fire Standards	USA
Building Materials	EN 13501-1	Fire classification of construction products and building elements - Part 1: Classification using data from reaction to fire tests	EU

Test Type	Test Number	Test Name	Geography
Aviation	EN 2824	Aerospace series - Burning behaviour of non-metallic materials under the influence of radiating heat and flames - Determination of smoke density and gas components in the smoke of materials - Test equipment apparatus and media;	EU
Smoke	EN 2825	Aerospace series - Burning behaviour of non metallic materials under the influence of radiating heat and flames - Determination of smoke density;	EU
Building Materials	EN ISO 1182	Reaction to fire tests for building products - Non-combustibility test	EU
Building Materials	EN ISO 1716	Reaction to fire tests for building products - Determination of heat of combustion	EU
Aviation	BSS 7239	Test Method for Toxic Gas Generation by Materials on Combustion	UK
Aviation	DIN EN 2826	Aerospace series - burning behavior of non-metallic materials under the influence of radiating heat and flames - Determination of gas components in the smoke.	Germany

As was discussed in Chapter 3, the list in Table E.1 was further refined several times. Figure D.1 and Table E.2 below present the full range of tests mandated in the geographies of interest.

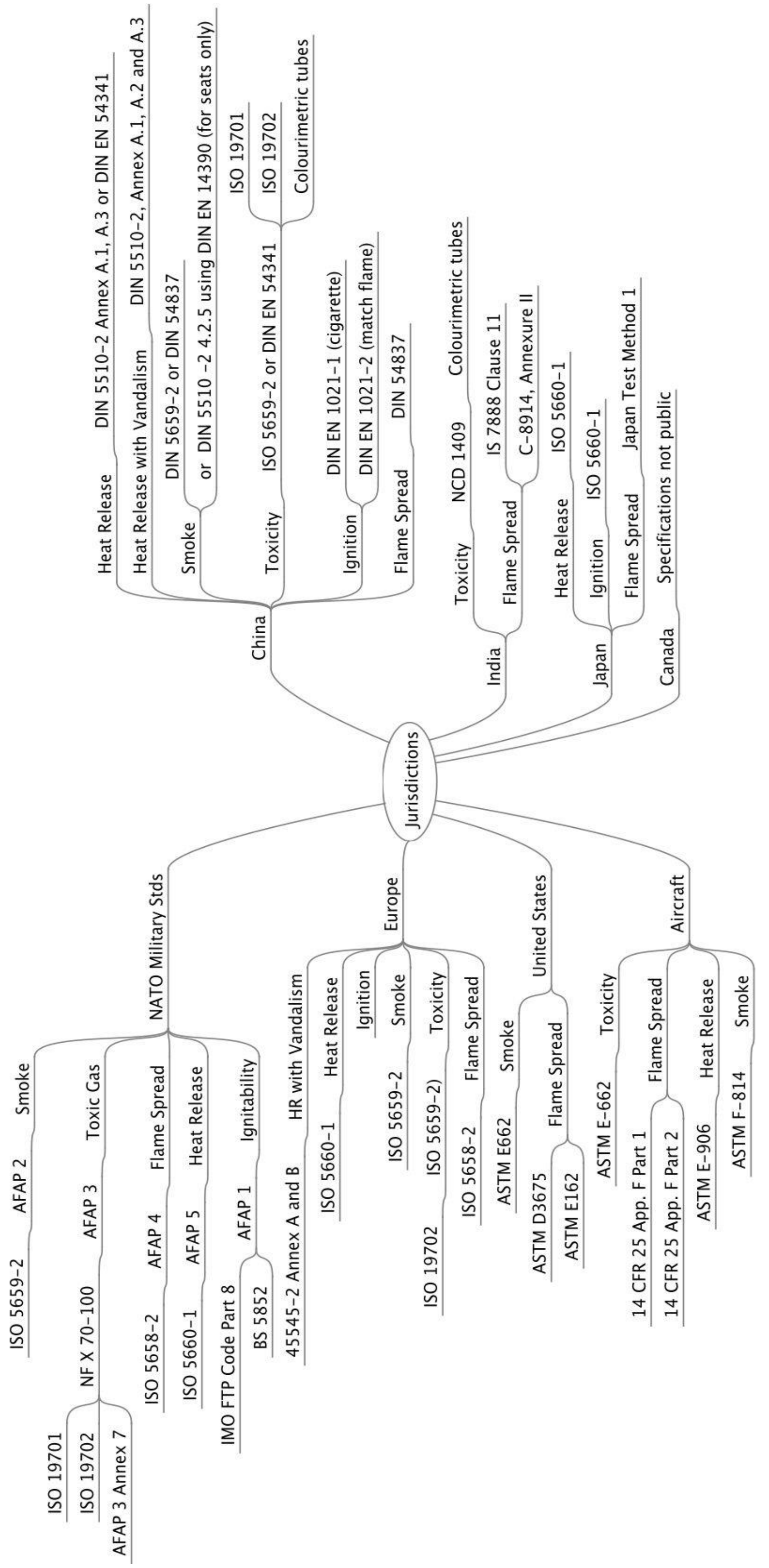

Figure E.1 Flammability tests for rail and air seating mandated by selected geographies

Table E.2 Titles of flammability tests for rail and air seating tests in Figure D.1

Flame Spread	
ASTM D3675	Surface Flammability of Flexible Cellular Materials Using a Radiant Heat Energy Source
ASTM E162	Surface Flammability of Materials Using a Radiant Heat Energy Source
C-8914 Annexure II	Schedule of Technical Requirements for Flexible Load Bearing Polyurethene Foam Cushions for Passenger Coaches
DIN 54837	Determination of burning behavior using a gas burner
ISO 5658-2	Reaction to fire tests -- Spread of flame -- Part 2: Lateral spread on building products in vertical configuration
Japan Test Method 1	Test Method 1 for Non-Metallic Materials for use on Railways
14 CFR 25 App F Part 1	Airworthiness Standards: Transport Category Airplanes, Part D - Design and Construction Fire Protection – Part 1, Vertical Test
14 CFR 25 App F, Part 2	Airworthiness Standards: Transport Category Airplanes, Part D - Design and Construction Fire Protection – Part 2, Kerosene Burner for Seats Test
AFAP 4	NATO Reaction to Fire Tests for Materials - Surface Spread of Flame (3rd Ed.)
IS 7888 Clause 11	Methods of Test for Flexible Polyurethane Foam
Heat Release	
ISO 5660-1	Reaction-to-fire tests -- Heat release, smoke production and mass loss rate -- Part 1: Heat release rate (cone calorimeter method)
DIN EN 54341	Testing of seats in railways for public traffic – Determination of burning behavior with a paper pillow ignition source
DIN EN 14390	Fire test – Large scale room reference test for surface products
AFAP 5	NATO Reaction to Fire Tests for Materials - Heat Release Rate (3rd Ed.) References ISO 5660-1 and 5660-2.
ASTM E-905	Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using a Thermopile Method
Ignitability	
BS 5852	Assessment of the ignitability of upholstered seating by smouldering and flaming ignition sources
Japan Test Method 1	Test Method 1 for Non-Metallic Materials for use on Railways
ISO 5660-1	Reaction-to-fire tests -- Heat release, smoke production and mass loss rate -- Part 1: Heat release rate (cone calorimeter method)
EN 11925-2	Reaction to fire tests -- Ignitability of products subjected to direct impingement of flame -- Part 2: Single-flame source test
DIN EN 1021-1 and -2	Furniture – Assessment of the ignitability of upholstered furniture – Part 1: Ignition source smouldering cigarette, Part 2: Ignition source match flame equivalent
IMO FTP Part 8	International Code for Application of Fire Test Procedures, Part 8: Upholstered furniture, IMO Res.A.562(16), Fire test of upholstered furniture

Toxicity	
NCD 1409	Determination of Toxicity Index
Annex C 45545-2	Railway Applications - Fire Protection on Railway Vehicles - Part 2 - Requirements for fire behavior of materials and components – Annex C – Toxicity Test
ISO 5658-2	Reaction to fire tests -- Spread of flame -- Part 2: Lateral spread on building products in vertical configuration
ISO 19702C	Toxicity testing of fire effluents - guidance for analysis of gases and vapours in fire effluents using FTIR analysis
AFAP 3	NATO Reaction to Fire Tests for Materials - Toxicity of Fire Effluents (3rd Ed.)
ISO 5659-2	Plastics - Smoke Generation - Determination of optical density by a single chamber test
DIN EN 54341	Testing of seats in railways for public traffic – Determination of burning behaviour with a paper pillow ignition source
NF X 10-100	Fire Tests - Analysis of Gaseous Effluents - Part 1: Methods for Analyzing Gases Stemming from Thermal Degradation; Part 2: Tubular Furnace Thermal Degradation Method
Smoke	
ASTM E662	Specific Optical Density of Smoke Generated by Solid Materials
ISO 5659-2	Plastics - Smoke Generation - Determination of optical density by a single chamber test
Japan Test Method 1	Test Method 1 for Non-Metallic Materials for use on Railways
DIN 54837	Determination of burning behaviour using a gas burner
DIN EN 54341	Testing of seats in railways for public traffic – Determination of burning behaviour with a paper pillow ignition source
DIN 5510-2 4.2.5	Preventive Fire Protection in Railway Vehicles. Part 2 - Fire behavior and fire side effects of materials and parts - Classification, requirements and test methods
AFAP 2	NATO Reaction to Fire Tests for Materials - Smoke Generation (3rd Ed.)
Heat Output with Vandalism	
Annexes A&B of 45545-2	Railway Applications - Fire Protection on Railway Vehicles - Part 2 - Requirements for fire behavior of materials and components - Annex A&B Seat vandalization and heat release test
Annex A.1-.3 of DIN 5510-2	Preventive Fire Protection in Railway Vehicles. Part 2 - Fire behavior and fire side effects of materials and parts - Classification, requirements and test methods – Annex A. Testing Seats