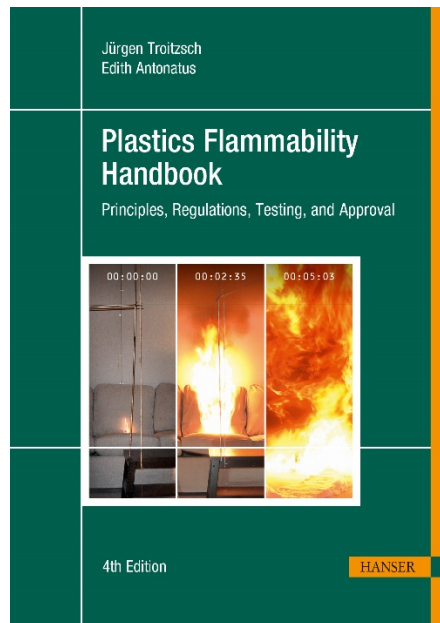


HANSER



Sample Pages

Plastics Flammability Handbook

Jürgen Troitzsch and Edith Antonatus

ISBN (Book): 978-1-56990-762-7

ISBN (E-Book): 978-1-56990-763-4

For further information and order see

www.hanserpublications.com (in the Americas)

www.hanser-fachbuch.de (outside the Americas)

© Carl Hanser Verlag, München

Preface to the Fourth Edition

In the past, none of the many publications on the reaction to fire of plastics provided a comprehensive review of the fundamentals, as well as of the relevant regulations and test methods. The *International Plastics Flammability Handbook* was first published in 1983 to fill this gap. However, in the 1980s, major changes occurred in the field of plastics fire behavior ratings on national and (increasingly) international levels. These changes made it necessary to prepare a completely revised 2nd edition of the handbook, which was published in 1990. The 1990s saw a breakthrough in the internationalization of fire testing and classification, particularly for products in buildings, electrotechnical applications, and transportation. At the same time, the perception of how to assess the main parameters governing a fire and the role of combustible materials like plastics was redefined, and led to new approaches particularly in the fields of heat release, smoke development, and toxicity of fire effluents. All these developments required a comprehensive revision and part-rewrite of the handbook, which was published in its 3rd edition in 2004.

Since then, many further changes have taken place in the fire performance requirements for construction products and rail vehicles in the European Union, the USA, and the Asia-Pacific region. In addition, the ongoing developments in the fields of electrical engineering and cables, and furniture and furnishings, as well as the ever-growing interest in smoke and toxicity of fire effluents, made it necessary to prepare a 4th edition of this handbook.

So, more than 15 years since the last edition, it was time to restructure and simplify the contents of the book, and to ask leading experts in the field to revise and to rewrite the various chapters. For this edition, Edith Antonatus agreed to join me as co-editor in order to make this major revision possible, and we want to express our gratitude to the over 30 co-authors whose expertise and commitment have made this project feasible.

The handbook consists of three parts.

Part I, “Fundamentals”, begins with an introduction to fire prevention, fires, and fire statistics, and continues with a description of the basic principles of the burning of plastics, the role of flame retardants, their mode of action, and their applica-

tion to improve the fire safety of plastics. Chapters on the burning behavior of textiles and flame-retardant textiles, smoke development, and smoke suppression follow. In the 3rd edition of this handbook, the chapters on smoke development and toxicity of fire effluents were presented as Part III “Fire effluents” at the end of the book. In this edition, they have been moved to Part I, where, after the chapter on the basics of smoke formation, the chapters on smoke development and toxicity, as well as combustion toxicology of fire effluents, now jointly describe this increasingly important topic.

It is hoped that this will facilitate the reader’s introduction to this complex subject, and also provide the background to better understand why the fire test procedures, regulations, and approval criteria covered in the second part of this handbook are necessary to provide adequate fire safety.

Part II, “National and International Fire Protection Regulations and Test Procedures”, starts with a general introduction to fire regulations and codes, and the fire test methods needed to satisfy them, followed by a comprehensive overview of international fire safety standardization, with the work of the International Standards Organization (ISO), the European Committee for Standardization (CEN), and the international electrotechnical committees as examples.

The legal provisions regarding the fire performance of plastics and other combustible products form a large part of the book, and are arranged according to a consistent scheme for a selection of countries in the three major regions (North America, Europe, Asia–Pacific). The section on each country commences with an account of the statutory regulations, and continues with a summary of the relevant test methods in the form of diagrams and tables of test specifications. Officially recognized test institutions and procedures for obtaining official product approval are enumerated under the heading “Official Approval”. Each section ends with a look at future developments in the relevant country. The reader is thus able to grasp the essentials at a glance. Further details can be taken from the original standards and regulatory documents listed in the bibliography at the end of each section.

The most extensive section of the handbook is devoted to the building sector, for which numerous fire safety regulations and test methods have been developed in all industrialized countries, and where a tremendous harmonization effort has virtually been completed in Europe. But even there, tests and classifications for specific building components such as the fire performance of façades and the external fire exposure of roofs are still not harmonized. To date, the toxicity of construction products is not part of the classification system developed by the European Commission, but subject to intense discussion. In other countries and regions of the world, particularly in Asia, great efforts have been made to improve existing smoke and toxicity regulations and test methods.

In the chapter on transportation (motor vehicles, rail vehicles, ships, and aircraft), the most important change has been the harmonization of railway fire protection standards in Europe, but there have also been many new developments in other parts of the world. Therefore, EU harmonization is covered in some detail, and sections on the USA and Canada, China, Japan, Korea, and Australia have been added. The chapter on electrical engineering has been completely reworked and simplified in light of the progress made in the international harmonization of regulations and test methods. The growing importance of the fire performance of cables is now presented in a separate comprehensive section.

The chapter on furniture and furnishings concentrates on developments of fire safety regulations and testing in the USA and the UK, and has been revised in light of trends to deregulation caused by concerns regarding the use of flame retardants. A section on measurements and model prediction of the burning rate of furniture has been added.

Part III, “Appendices”, contains various lists including a suppliers’ index for flame retardants and smoke suppressants, a list of the most common abbreviations for plastics and flame retardants, the chemical names and CAS numbers of the latter, and a choice of journals and books devoted to flame retardancy and fire protection.

It is hoped that this book will be of interest to all those concerned with plastics, flame retardancy, fire testing, and fire protection, and will help the reader to better understand this complex subject.

Jürgen Troitzsch and Edith Antonatus
Ascona and Allensbach, January 2021

Contents

Preface to the Fourth Edition	V
List of Contributors	IX
Part I	
Fundamentals	1
1 Introduction	3
1.1 Fire Prevention and Fires	3
<i>Jürgen Troitzsch</i>	
1.2 Fire Statistics	10
<i>Eric Guillaume</i>	
1.2.1 Introduction	10
1.2.2 Lessons Learned from Recent ISO Work on Fire Statistics	10
1.2.3 Current National Fire Statistics: Relevant Data on Specific Issues	12
1.2.3.1 Number of Fires	12
1.2.3.2 Number of Fire Fatalities	14
1.2.3.3 Number of Fire Injuries	17
1.2.3.4 Costs of Fire Losses	19
1.2.4 Future Developments	21
2 The Burning of Plastics	23
<i>Bernhard Schartel</i>	
2.1 Production of Volatile Fuel: Heating, Pyrolysis, Charring, Heat of Combustion	27
2.2 Decomposition of Polymers	34
2.3 Ignition and Smoldering	38
2.4 Steady Burning and Flame Spread	42

2.5	Fire Load and Fire Resistance	47
2.6	Conclusions	48
3	Flame Retardants and Flame-Retarded Plastics	53
3.1	Flame Retardants	53
	<i>Manfred Döring, Lara Greiner, and Daniela Goedderz</i>	
3.1.1	Importance, Development, and Market	53
3.1.2	Mode of Action	54
	3.1.2.1 Physical Action	55
	3.1.2.2 Chemical Action	55
3.1.3	Important Flame Retardant Classes	57
	3.1.3.1 Metal Hydroxides and Mineral Fillers	57
	3.1.3.2 Halogenated Flame Retardants	61
	3.1.3.3 Phosphorus-Containing Flame Retardants	64
	3.1.3.4 Organic Radical-Forming Agents and N-, O- and S-Containing Synergists	72
	3.1.3.5 Synergistic Flame Retardant Systems	75
	3.1.3.6 Other Flame Retardants	77
3.1.4	Greener Alternatives to Common Flame Retardants	80
3.2	Flame-Retarded Plastics	95
	<i>Rudolf Pfaendner</i>	
3.2.1	Introduction	95
3.2.2	Thermoplastics	98
	3.2.2.1 Polypropylene	98
	3.2.2.2 Polyethylene	100
	3.2.2.3 Other Polyolefins	103
	3.2.2.4 Polystyrenes	104
	3.2.2.5 Styrene Copolymers	105
	3.2.2.6 Polymethacrylates and Polyacrylates	106
	3.2.2.7 Polyoxymethylene and Polyacetals	106
	3.2.2.8 Polyamides	107
	3.2.2.9 Polyesters	109
	3.2.2.10 Polycarbonate and Polycarbonate Blends	111
	3.2.2.11 Polyurethanes	112
	3.2.2.12 Polyvinylchloride	113
	3.2.2.13 Other Halogenated Polymers	114
	3.2.2.14 High-Performance Polymers	114
3.2.3	Thermosets	115
	3.2.3.1 Epoxy Resins	115
	3.2.3.2 Polyurethanes	117

3.2.3.3	Phenolic Formaldehyde Resins	118
3.2.3.4	Unsaturated Polyesters	118
3.2.4	Elastomers	119
4	Textiles	129
	<i>A. Richard Horrocks and Baljinder K. Kandola</i>	
4.1	Introduction	129
4.1.1	Burning Behavior of Textile Fibers and Fabrics	130
4.1.2	Effect of Fabric and Yarn Structures	133
4.2	Flammability Testing of Textiles	134
4.2.1	Regulations	134
4.2.2	Test Categorization	136
4.3	Flame-Retardant Textiles	142
4.3.1	Cellulosics	143
4.3.1.1	Flame-Retardant Cottons	143
4.3.1.2	Flame-Retardant Viscose	144
4.3.1.3	Flame-Retardant Cellulosic Blends	144
4.3.2	Flame-Retardant Wool and Blends	145
4.3.3	Flame-Retardant Synthetic Fibers	146
4.4	Inherently Flame-Retardant Synthetic Fibers	147
4.5	High Heat- and Flame-Resistant Synthetic Fibers and Textiles ..	148
4.6	Intumescent Applications to Textiles	149
5	Smoke Development and Suppression	153
5.1	Smoke Development and Measurement	153
	<i>Eric Guillaume</i>	
5.1.1	Introduction	153
5.1.2	Smoke Generation	154
5.1.2.1	Definitions	154
5.1.2.2	Principles	155
5.1.2.3	Nucleation and Surface Growth	157
5.1.2.4	Coagulation and Agglomeration	159
5.1.2.5	Oxidation	160
5.1.2.6	Liquid Aerosols	160
5.1.3	Smoke Production from the Most Important Polymers ..	161
5.1.4	Smoke Measurement	162
5.1.4.1	Smoke Opacity	162
5.1.4.2	Other Smoke Parameters	166
5.1.5	Visibility Models	169
5.1.5.1	Definition of Visibility	169

5.1.5.2	Simplified Models (1950–1980)	169
5.1.5.3	Jin and Yamada Models	170
5.1.5.4	ISO 13571 Model	171
5.1.6	Fire Threat Related to Smoke	171
5.2	Smoke Suppressants	173
	<i>Rudolf Pfaendner</i>	
5.2.1	Introduction	173
5.2.2	Smoke Suppressants for PVC	174
5.2.2.1	Molybdates	175
5.2.2.2	Stannates	175
5.2.2.3	Borates	176
5.2.3	Smoke Suppressants in Combination with Halogenated Flame Retardants	177
5.2.4	Smoke Suppressants in Combination with Halogen-Free Flame Retardants	178
5.2.5	Summary and Outlook	179
6	Smoke and Toxicity from Fire Effluents	185
	<i>Eric Guillaume</i>	
6.1	Preliminary Remarks	185
6.2	Acute Effects of Fire Effluents	186
6.2.1	Asphyxiants	187
6.2.2	Irritants	188
6.3	Sub-Acute Effects of Fire Effluents	188
6.4	Chronic Effects of Fire Effluents	188
6.5	Environmental Effects of Fire Effluents	189
6.6	Quantitative Risk Assessment of Fire Effluents	190
6.6.1	Introduction	190
6.6.2	Direct and Indirect Methods	190
6.6.2.1	Direct Methods	191
6.6.2.2	Indirect Methods	192
6.7	Generation of Fire Effluents: Physical Fire Models Used for Toxicity Testing	193
6.7.1	Introduction to Physical Fire Models	193
6.7.2	What is a Physical Fire Model?	193
6.7.3	Important Characteristics to be Reproduced by the Fire Model	195
6.7.3.1	Parameters Influencing the Nature and Proportion of Gas Release	195

6.7.3.2	Combustion Conditions	195
6.7.3.3	Thermal Conditions of Degradation and Equivalence Ratio	196
6.7.3.4	Parameters Influencing the Preparation for Analysis	197
6.7.3.5	Parameters Influencing the Scale Effects	198
6.7.3.6	Parameters Influencing the Quality of the Fire Model	202
6.8	Chemical Analysis of Fire Effluents	204
6.8.1	Gases of Interest	204
6.8.2	Sampling	204
6.8.2.1	From Fire Source to Analysis	204
6.8.2.2	Probes	205
6.8.2.3	Filters	206
6.8.2.4	Sampling Line	207
6.8.2.5	Pumping System	208
6.8.2.6	Sampling Conditions	208
6.8.2.7	Gas-Solution Absorbers	208
6.8.2.8	Solid Sorption Tubes	210
6.8.2.9	Gas Bags	211
6.8.3	Selection of Analytical Methods	211
6.8.4	Validation of Analytical Methods	215
6.8.4.1	Evaluation of a Method	215
6.8.4.2	Selectivity	215
6.8.4.3	Sensitivity	215
6.8.4.4	Concentration Ranges	215
6.8.4.5	Detection and Quantification Limits	216
6.8.4.6	Accuracy of the Method	216
6.8.4.7	Repeatability and Reproducibility of the Method	217
7	Combustion Toxicology	219
	<i>Jürgen Pauluhn</i>	
7.1	Introduction	219
7.2	Toxic Hazards	221
7.2.1	Inhalation Toxicity of HCN and CO	224
7.2.2	Inhalation Toxicity of CO ₂	226
7.2.3	Respiratory Tract Irritants	229
7.3	Toxicological Risk Assessment	234
7.3.1	Definition of Uncertainty	234

7.3.2	Analysis of Time–Dose–Response Relationships	235
7.3.2.1	Asphyxiants	235
7.3.2.2	Irritants	238
7.4	Application of the Fractional Effective Dose (FED) Model	240
7.5	Conclusions	242

Part II

National and International Fire Protection Regulations and Test Procedures 247

8 Regulations and Testing 249

Edith Antonatus and Jürgen Troitzsch

8.1	Introduction	249
8.2	Sets of Regulations and Codes	251
8.2.1	Types and Basis	251
8.2.2	Application	252
8.2.3	The Role of Standards	253
8.3	Test Methods	253
8.3.1	Laboratory-Scale Tests	254
8.3.1.1	Test Specimens	254
8.3.1.2	Ignition Sources	254
8.3.1.3	Parameters Measured	255
8.3.2	Large-Scale Tests	256

9 International Standardization 257

9.1	Introduction	257
-----	------------------------	-----

Edith Antonatus

9.1.1	International Standardization	257
9.1.2	Regional Standardization	259
9.1.3	International and Regional Fire-Related Standards for Transportation	259

9.2	International Organization for Standardization (ISO)	261
-----	--	-----

Björn Sundström

9.2.1	Introduction	261
9.2.2	Scope of ISO/TC 92 Fire-Related Activities	262
9.2.3	ISO/TC 92/SC1: Fire Initiation and Growth	264
9.2.3.1	General Use of Test Data and Fire Safety Engineering	268
9.2.3.2	Non-Combustibility	268
9.2.3.3	Ignition and Flame Spread	269

9.2.3.4	Heat Release and Smoke Production	273
9.2.3.5	Large-Scale	276
9.2.3.6	Calibration and Supporting Procedures	280
9.2.4	Future Developments	280
9.3	European Committee for Standardization (CEN)	282
	<i>Edith Antonatus</i>	
9.3.1	Introduction	282
9.3.2	Development of Standards	282
9.3.3	Fire-Related Activities in Building	284
10	Building	287
10.1	Introductory Remarks	287
	<i>Edith Antonatus</i>	
10.1.1	Classification and Testing of Fire Performance of Building Materials and Components	289
10.1.1.1	Non-Combustible Materials	289
10.1.1.2	Combustible Materials - Laboratory Tests	290
10.1.1.3	Roofs	291
10.1.1.4	Large-Scale Tests	291
10.1.2	Official Approval	292
10.1.3	Present Situation and Future Developments	292
10.2	Americas	293
	<i>Marc Janssens</i>	
10.2.1	United States of America	293
10.2.1.1	Statutory Regulations	293
10.2.1.2	Consensus Standards	297
10.2.1.3	Test Methods Referenced in U.S. Building and Fire Safety Codes	300
10.2.1.4	Summary of Small-Scale Ignition and Combustibility Tests	303
10.2.1.5	Summary of Small-Scale Reaction-to-Fire Tests	309
10.2.1.6	Summary of Intermediate and Large-Scale Reaction-to-Fire Tests	315
10.2.1.7	Summary of Fire Tests for Furnishings and Contents	325
10.2.1.8	Summary of Fire Resistance Tests	325
10.2.1.9	Summary of Exterior Fire Exposure Tests	329
10.2.1.10	Future Developments	334
10.2.2	Canada	335
10.2.2.1	Statutory Regulations	335

10.2.2.2	Testing of the Fire Performance of Building Materials and Components	336
10.2.2.3	Summary of Selected Material Flammability Tests Referenced in the NBCC	339
10.2.2.4	NBCC Fire Performance Requirements for Interior Finish Materials	345
10.2.2.5	Accredited Testing Laboratories	346
10.2.2.6	Future Developments	346
10.3	Europe	348
10.3.1	European Union	348
	<i>Björn Sundström</i>	
10.3.1.1	Introduction	348
10.3.1.2	The Euroclasses: Classification Systems and Fire Tests	350
10.3.1.3	Future Developments	376
10.3.2	National Fire Regulations and Tests	377
	<i>Edith Antonatus</i>	
10.3.2.1	Austria	378
	<i>Dieter Werner</i>	
10.3.2.2	Belgium	388
	<i>Bart Sette</i>	
10.3.2.3	France	394
	<i>Eric Guillaume</i>	
10.3.2.4	Germany	403
	<i>Edith Antonatus</i>	
10.3.2.5	Hungary	413
	<i>István Móder, Imre Juhász</i>	
10.3.2.6	Italy	417
	<i>Eleonora Anselmi</i>	
10.3.2.7	The Netherlands	428
	<i>R. J. M. (Rudolf) van Mierlo</i>	
10.3.2.8	Nordic Countries	432
	<i>Björn Sundström</i>	
10.3.2.9	Poland	435
	<i>Jadwiga Fangrat</i>	
10.3.2.10	Spain	442
	<i>Antonio Galán Penalva</i>	
10.3.2.11	Switzerland	451
	<i>Marcel Donzé</i>	
10.3.2.12	United Kingdom	465
	<i>Edith Antonatus</i>	

10.4	Asia/Pacific	479
10.4.1	China	479
	<i>Jun-Sheng Wang and Xing Jin</i>	
10.4.1.1	Statutory Regulations	479
10.4.1.2	Classification and Testing of the Fire Performance of Building Materials and Components	487
10.4.1.3	Official Approval	498
10.4.1.4	Future Developments	499
10.4.2	Japan	499
	<i>Hideki Yoshioka</i>	
10.4.2.1	Statutory Regulations	499
10.4.2.2	Classification and Testing of the Fire Performance of Building Materials and Components	500
10.4.2.3	Recent Developments of New Standard Test Methods as JIS (Japanese Industrial Standard)	504
10.4.2.4	Official Approval	509
10.4.2.5	Future Developments	510
10.4.3	Republic of Korea	512
	<i>Jungmin Choi</i>	
10.4.3.1	Statutory Regulations	512
10.4.3.2	Fire Performance Classification and Testing of Building Materials	513
10.4.3.3	Official Approval	516
10.4.3.4	Future Developments	517
10.4.4	Australia	518
	<i>Alex Webb</i>	
10.4.4.1	Statutory Regulations	518
10.4.4.2	Classification and Testing of the Fire Performance of Building Materials and Components	519
10.4.4.3	Official Approval	527
10.4.4.4	Future Developments	529
10.4.5	New Zealand	530
	<i>Peter Whiting</i>	
10.4.5.1	Statutory Regulations	530
10.4.5.2	Classification and Testing of the Fire Performance of Building Materials and Components	532
10.4.5.3	Official Approval	533

10.4.5.4	Codemark	534
10.4.5.5	Future Developments	535
11	Transportation	537
11.1	Motor Vehicles	537
	<i>Anja Hofmann and Jonas Brandt</i>	
11.1.1	Introduction	537
11.1.2	Background – Vehicle Fires	538
11.1.3	Statutory Regulations	539
11.1.4	Requirements and Tests of Interior Materials for Buses and Cars	541
11.1.5	Other Fire Safety Requirements for Vehicles	548
11.1.6	Changes in Regulations	550
11.1.7	Potential Future Changes in Regulations	552
11.2	Rail Vehicles	554
11.2.1	Introduction	554
	<i>Torben Kempers</i>	
11.2.2	Europe	556
	<i>Torben Kempers</i>	
11.2.2.1	Harmonized Railway Standard EN 45545	556
11.2.2.2	Future Developments	569
11.2.3	United States of America and Canada	570
	<i>Marc Janssens</i>	
11.2.3.1	United States of America	570
11.2.3.2	Canada	578
11.2.3.3	Future Trends	578
11.2.4	People's Republic of China	579
	<i>Shuai-Xia Tan</i>	
11.2.4.1	Statutory Regulations	579
11.2.4.2	Fire Protection Requirements, Classification, and Tests	581
11.2.4.3	Future Developments	590
11.2.5	Japan	591
	<i>Koichi Wada</i>	
11.2.5.1	Statutory Regulations	591
11.2.5.2	Classification and Testing of Materials and Components	595
11.2.5.3	Official Approval	598
11.2.5.4	Future Developments	598
11.2.6	Republic of Korea	599
	<i>Jungmin Choi</i>	

11.2.6.1	Statutory Regulations	599
11.2.6.2	Fire Hazard of Rail Vehicles	600
11.2.6.3	Fire Performance Criteria	601
11.2.6.4	Future Developments	606
11.2.7	Australia	607
	<i>Alex Webb</i>	
11.2.7.1	Statutory Regulations	607
11.2.7.2	Passenger Rolling Stock	607
11.2.7.3	Materials Fire Performance	608
11.2.7.4	Future Developments	608
11.3	Ships	609
	<i>Edith Antonatus</i>	
11.3.1	Statistics Regarding Fires on Board Passenger Ships ...	610
11.3.2	SOLAS Chapter II-2: International Regulations for Fire Safety of Ships	612
11.3.2.1	Development of SOLAS Fire Safety Regulations and Revision Activities	612
11.3.2.2	Structure of Chapter II-2 of SOLAS	613
11.3.2.3	Alternative Design and Arrangements for Fire Safety	615
11.3.3	Fire Test Procedures Code (FTP code)	616
11.3.4	Provisions for High-Speed Craft	625
11.3.5	Future Developments	626
11.4	Aircraft	627
	<i>Torben Kempers</i>	
11.4.1	Introduction	627
11.4.2	Statutory Regulations	628
11.4.3	Fire Behavior Testing	629
11.4.3.1	Bunsen Burner Flammability Testing	631
11.4.3.2	Heat Release Testing	635
11.4.3.3	Smoke Emission and Toxicity Testing	637
11.4.3.4	Additional Testing	639
11.4.3.5	Thermal/Acoustic Insulation Testing	642
11.4.4	Future Developments	644
12	Electrical Engineering and Cables	647
12.1	Electrical Engineering	647
	<i>Jun Haruhara, Mattia Ferraris, and Jürgen Troitzsch</i>	
12.1.1	International Fire Safety Requirements and Standards (IEC)	649
12.1.1.1	Objectives and Organization	649

12.1.1.2	Fire Hazard Testing, IEC TC 89	650
12.1.1.3	International Certification	675
12.1.2	Fire Safety Regulations in North America (UL, CSA) ...	676
12.1.2.1	Test and Approval Procedures of the Underwriters' Laboratories	676
12.1.2.2	CSA Test and Approval Procedures	690
12.1.3	Fire Regulations and Standards in Europe	691
12.1.3.1	European Committee for Electrotechnical Standardization (CENELEC)	691
12.1.3.2	Electrotechnical Products and EU Directives ..	692
12.1.3.3	Approval Procedures in Europe	694
12.1.4	Fire Regulations and Standards in Asia	696
12.1.5	Other Fire Safety Test Methods	698
12.1.6	Future Developments	699
12.2	Fire Hazard Assessment of Cables	705
	<i>Esther Hild</i>	
12.2.1	Small-Scale Testing	705
12.2.2	Large-Scale Testing	709
12.2.3	Side Effects of Cable Fires	719
12.2.3.1	Smoke	719
12.2.3.2	Flaming Droplets	720
12.2.3.3	Acidity	721
12.2.4	Fire Resistance Characteristics of Cables	721
12.2.5	Fire Hazard Assessment on Railway Rolling Stock Cables	725
12.2.6	Future Developments	726
13	Furniture and Furnishings	729
13.1	Introduction	729
	<i>Edith Antonatus</i>	
13.2	UK and Ireland	732
	<i>Edith Antonatus</i>	
13.2.1	Regulations and Tests for Furniture Suitable for Domestic Use	732
13.2.1.1	Test Methods Applied in the UK Regulations for Upholstered Furniture and Corresponding European Test Methods	732
13.2.1.2	Classification of Soft Upholstery in the UK ...	734
13.2.2	UK Regulations and Tests for Furniture Used in Public Areas	736

13.3	United States of America	738
	<i>Marc Janssens</i>	
13.3.1	Statutory Regulations	738
13.3.2	U.S. Smoldering Tests for Upholstered Furniture and Mattresses	740
13.3.3	U.S. Open-Flame Tests for Upholstered Furniture and Mattresses	746
13.4	Measurements and Predictions of the Burning Rate of Furniture	750
	<i>Marc Janssens</i>	
13.4.1	Measurement Methods	750
	13.4.1.1 Cone Calorimeter	750
	13.4.1.2 Furniture Calorimeter	751
	13.4.1.3 Room Calorimeter	752
13.4.2	Model Predictions	754
13.5	Conclusions and Future Developments	755
Part III		
	Appendices	761
	Appendix 1 – Suppliers of Flame Retardants and Smoke Suppressants	763
	Appendix 2 – Abbreviations for Plastics and Flame Retardants ...	769
	Appendix 3 – Flame Retardants: Chemical Names and CAS Numbers	775
	<i>Rudolf Pfaendner</i>	
	Appendix 4 – Journals and Books	779
	Authors Index	781
	Standards Index	783
	Keywords Index	791

training (origin of the fire, source of the fire, characteristics and circumstances of the fire, etc.), or for which they have insufficient time to give sound answers.

As a consequence, in Canada and the People's Republic of China, nearly all fire reports are filled in by fire officers who never received training in fire investigations. In other countries, such as Kenya, the Republic of Korea, Japan, and the USA, only a small number of fire reports are filled in by fire officers who received specially adapted training.

1.2.3 Current National Fire Statistics: Relevant Data on Specific Issues

Even if current fire statistics cannot be compared from one country to another (with a few exceptions), they can still be useful to describe the global fire safety situation and trends for a group of countries, or the specific fire safety situation of a country.

1.2.3.1 Number of Fires

In many countries, the trend is to a decreasing or (more recently) an unchanged number of fires. The number of reported fires and fires per million inhabitants for selected countries (USA [4, 5], Russia [6, 7], France [6, 8], UK [6, 9], Finland [6, 10], and Switzerland [6, 11, 12]) are illustrated in Figure 1.1 and Figure 1.2.

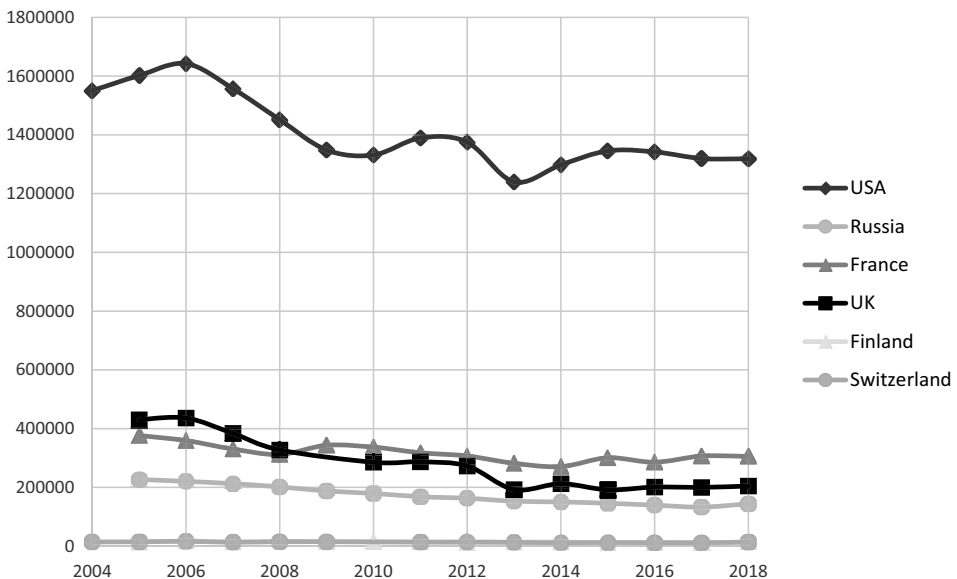


Figure 1.1 Number of fires in selected countries

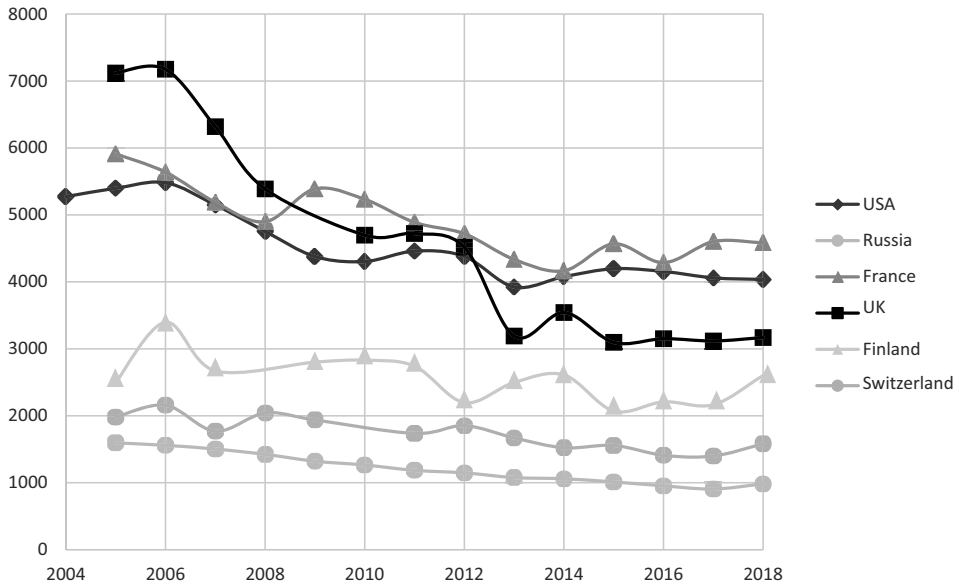


Figure 1.2 Fires per million inhabitants in selected countries

The analysis of the “World Fire Statistics” reports [6], published annually by the International Association of Fire and Rescue Service (CTIF), shows that for the 16 EU countries for which statistics were available (representing 62% of the EU population at that time), there was a decrease of 19% in the number of fires between 2006 and 2010.

Trend Uncertainties

The above statistics are called into question by recent local developments, which may reverse the global trend.

For example, in France, the last available Ministry of Interior official fire statistics [8] show an increase of 11% in the number of fires in 2015 compared to 2014. In the USA [4, 5], 1,240,000 fires were recorded in 2013, rising to 1,298,000 in 2014, representing an increase of 4.7% in one year.

In other cases, the situation seems to be unstable, with periods of increase followed by periods of decrease. An example is the number of fires in the Republic of Korea [13] from 2001 to 2009, shown in Figure 1.3.

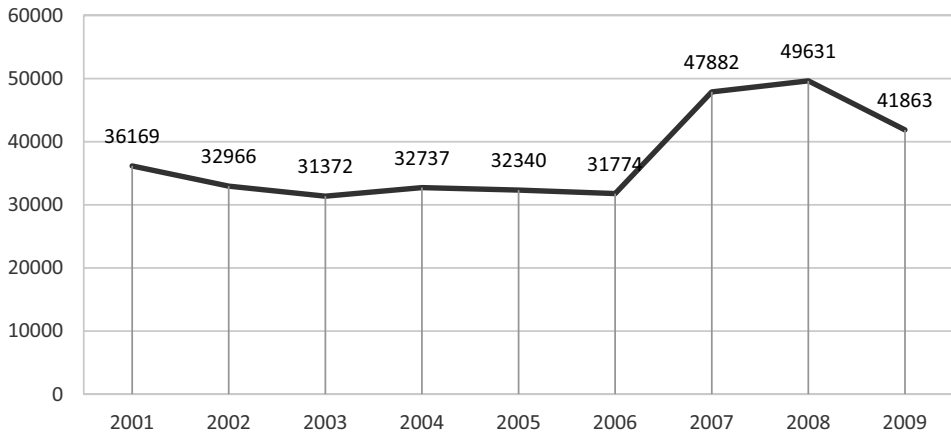


Figure 1.3 Number of fires in the Republic of Korea from 2001–2009

Local Trends to a Larger Number of Fires

As can be seen in Table 1.1, in some countries, the trend is to a larger number of fires; this may be due to an improved data collection system.

Table 1.1 Trend to a Larger Number of Fires in Selected Countries

Country	Number of reported fires					Change
	1995	2004	2006	2009	2010	
Poland [6]	72,391	–	–	159,122	–	+220%
Austria [6]	–	–	30,297	–	34,363	+13%
Ghana [6]	–	2,418	–	2,708	–	+12%

1.2.3.2 Number of Fire Fatalities

In many countries, a trend to a decreasing number of fire fatalities can be seen. However, in some countries, the situation is different and the number of fire fatalities is growing. In addition, some fire statistics show an unexpectedly high proportion of male fire fatalities, and also indicate that most fire deaths are recorded in residential building fires.

Decrease of Fire Fatalities in Many Countries

The number of fire fatalities and fire fatalities per million inhabitants for selected countries is illustrated in Figure 1.4 and Figure 1.5 (here, the curves for France are virtually covered by the UK ones).

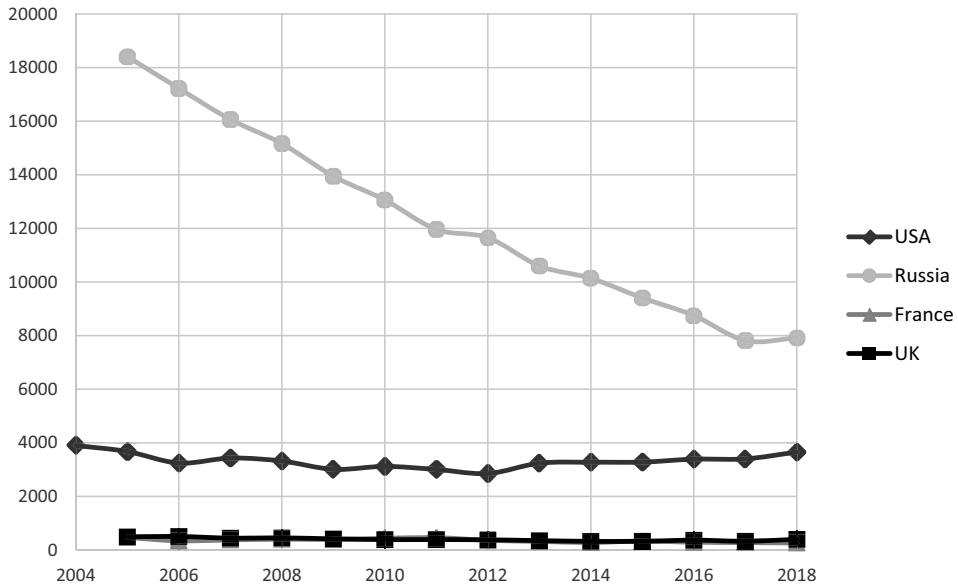


Figure 1.4 Number of fire fatalities in selected countries

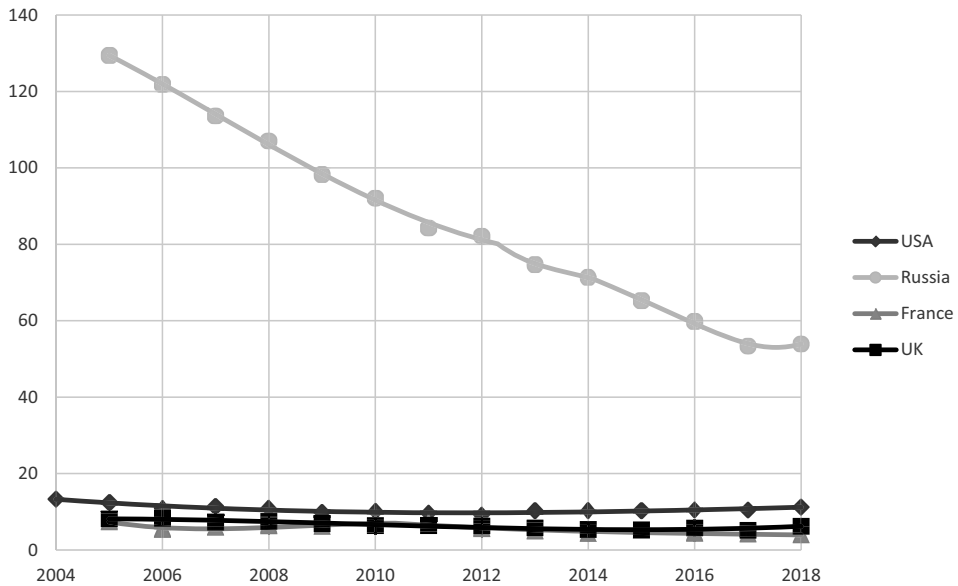


Figure 1.5 Number of fire fatalities per million inhabitants in selected countries

The “World Fire Statistics” issue no. 7 (published in 2012) covers the period 2006–2010, and shows that for the 19 EU countries for which statistical data were available (representing 74% of the EU population at that time), there was a decrease of 17% in the number of fire fatalities.

In the French official fire statistics, the number of fatalities at the location of fires (either discovered, or declared dead after unsuccessful resuscitation attempts) has decreased by 60% in the 32 years from 1982–2014, as summarized in Table 1.2.

Table 1.2 Total Number of Fire Fatalities Discovered at the Location of Fires

	Year						Difference	Change
	1982	1990	1999	2008	2012	2014		
Fatalities	702	579	460	402	362	280	422	-60%

Statistics on Japanese fire fatalities [15] show a significant proportion of suicides, and a higher-than-expected proportion of deaths of elderly people.

Trend Uncertainties

In the USA [4, 5], 2,855 fire deaths were recorded in 2012, increasing to 3,240 in 2013 and to 3,275 in 2014, representing an increase of nearly 15% in two years. In France, the Ministry of Interior’s official fire statistics [8] show an increase of 16% from the number of fire fatalities in 2014 (280) to 2015 (325).

All figures dealing with fire fatalities must be considered carefully. Indeed, the exact definition of a fire death is rarely specified in documents on fire statistics. Therefore, it is possible that a significant number of people with fire injuries died in hospital or during transport to it, and so may not have been counted in the final statement, skewing the final result.

In Ireland, the USA and Finland, the proportion of fire fatalities that were male was unexpectedly high, as shown in Table 1.3.

Table 1.3 Male Fire Fatalities in Selected Countries

Country	Year	Male fire fatalities	Female fire fatalities
Ireland [14]	2007	66%	34%
USA [4, 5]	2015	62%	38%
Finland [10]	2013	74%	26%

Fire Fatalities in Residential Buildings

Residential buildings contribute to most fire deaths because people live, cook, and sleep there.

In the official 2014 fire statistics published by the French Ministry of Interior in 2015, of the 280 fire deaths reported by the French Fire Departments, 228 fire fatalities were recorded in residential buildings, representing over 81% of all fire deaths. In a special study carried out by the Paris Police Laboratory for the three years 2012–2014, over 86% of all fire fatalities discovered at the location of fires by the Paris Fire Brigade (BSPP) were recorded in residential buildings, including one fire death in a residential high-rise building (IGH A). This is also true for some selected other countries, as shown in Table 1.4.

Table 1.4 Residential Fire Fatalities in Some Selected Countries

Country	Year	Proportion of residential fire fatalities vs total number of fire fatalities
Korea [13]	2010	65%
England [9]	2016/2017	82%
Finland [10]	2013	94%

1.2.3.3 Number of Fire Injuries

The term fire injuries is very difficult to define, and the differences between “minor injury”, “moderate injury” and “severe injury” are numerous between countries – indeed, much more so than for “fire death”. In some countries, there are even additional classifications – for example, in France, injuries are divided into “UR” (*Urgence Relative* = relative emergency) and “UA” (*Urgence Absolue* = absolute emergency).

Having highlighted these caveats, the current fire statistics show important differences in trends between countries. Figure 1.6 and Figure 1.7 summarize the number of fire injuries and fire injuries per million inhabitants for the USA [4, 5], Russia [6, 7], France [6, 8], and the UK [6, 9]. Here again, as for fire fatalities, we can note an unexpectedly high proportion of male fire injuries in some countries, and Table 1.5 shows the statistics for Spain [16] and the USA.

2.10(b) shows a computer simulation of such a non-flaming dripping V-0 behavior in a UL 94 test [63]. The simulated temperature demonstrates that in the UL 94 setup, the flame-retardant mode of action can be understood as an efficient cooling effect. The hot dripping removes enough energy so that the remaining slab extinguishes. In other tests, the effect is described as retreating from the ignition source. It is not only thermoplastics that show a large influence by melt flow and dripping at temperatures above their glass, melting, and decomposition temperatures, but also thermosets. For these, after a small delay, the pyrolysis products reach equilibrium above the decomposition temperature, yielding molten materials that behave quite similarly to thermoplastics.

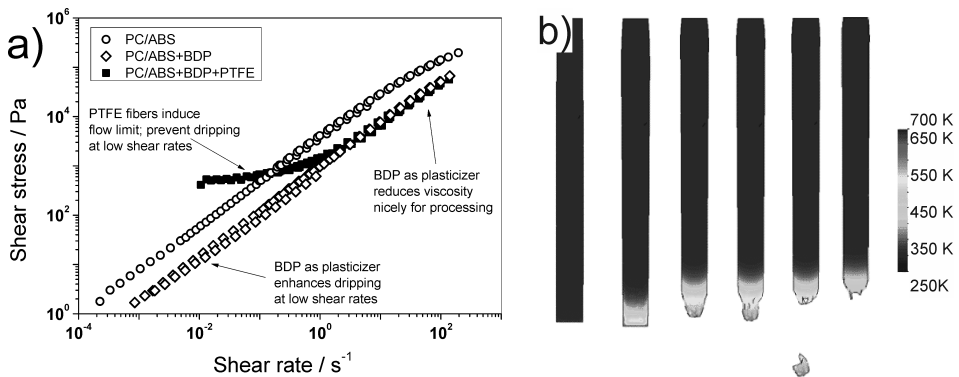


Figure 2.10 (a) Shear stress versus shear rate master curves (523 K) of PC/ABS (open circles), PC/ABS+BDP (open diamonds), and PC/ABS+BDP+PTFE (filled squares); (b) images of the PFEM simulation for extinction (V-0) of PP through non-flaming dripping

■ 2.4 Steady Burning and Flame Spread

Combustion is the exothermic process in which a fuel is rapidly oxidized, thereby consuming oxygen and producing heat and light. If the fuel is thoroughly mixed with air, and the amount of oxygen is constant, the ensuing combustion is complete; this is referred to as a “premixed flame”. In common fire scenarios, however, the amount of oxygen that can reach the fuel is limited by the laws of diffusion, hence the term “diffusion flame” [64]. A diffusion flame is characterized by its incandescent soot of a yellow-orange color, a result of incomplete combustion, as well as the lack of a clear flame front. Due to the dominating diffusion laws, the oxygen concentration from the periphery of the flame to its center is described by a gradient: the interfacial region at the material surface decomposes under anaerobic, pyrolytic conditions, while the flame zone above is characterized by thermo-oxida-

tive reactions. In all cases, the high amount of thermal energy causes the bulk material to decompose and volatilize, causing a flux of mass \dot{m}'' into the gas phase. The material flux is related to the combustion in the flame zone by the resulting effective heat flux \dot{q}_{eff}'' used for pyrolysis [3]:

$$\dot{m}'' \cdot L_g = \dot{q}_{eff}'' \quad (2.8)$$

The conditions needed to produce a flux of fuel into the flame are dependent on the underlying decomposition reactions, which are inherently specific to the material's composition and its properties (heat capacity, heat conductivity, ratio of mass to surface area, etc.). The pyrolysis of the polymer results in the release of volatile fuel into the gas phase; covalent bonds of these fuel molecules are immediately broken further (bond scission) in the flame zone. This homolytic cleavage leads to the formation of two free-radical moieties, which is the first step in a vast series of chain reactions and is referred to as the initiation reaction (Figure 2.11). The reaction of a hydrogen radical with molecular oxygen is further known as the branching reaction, as both the resulting hydroxyl and oxygen radicals make a crucial contribution to the resulting radical chain reactions. The hydroxyl radical may interact with various combustion products, such as carbon monoxide, hydrogen, or hydrocarbons to form new free radicals, thus propagating the decomposition mechanism (Figure 2.11). Termination of the free-radical chain reaction occurs when two free radicals react with one another, as is the case when a hydroxyl and a hydrogen radical, or two hydrogen free radicals, interact to form water or molecular hydrogen, respectively (Figure 2.11).

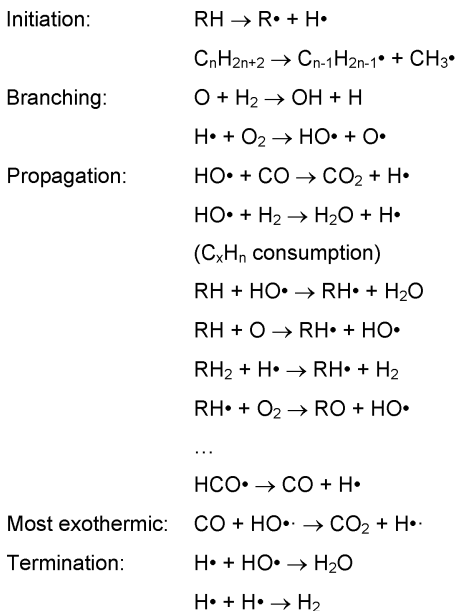


Figure 2.11

Scheme of oxidative chain reaction in the flame

Of the abundant and complex free-radical reactions taking place in a fire scenario, the formation of carbon dioxide (and a hydrogen radical) from the reaction of hydroxy free radicals with carbon monoxide is the most exothermic reaction and is the largest contributor to the heat released in a fire scenario.

The sum of all exothermic reactions in a fire scenario is known as the total heat released (THR); it is the integral of the heat release rate (HRR) curve over time. The HRR is most commonly determined by measuring oxygen consumption, and the equation used to calculate the HRR considers the material's behavior under fire conditions and the heat fluxes working upon it. When ignition is continuous and the burning rate is constant, the HRR of the material is equal to the product of the combustion efficiency χ , the heat of complete combustion of fuel gases h_c and the mass flux \dot{m}'' , which, according to Eq. (2.9), is related to the net heat flux \dot{q}_{net}'' via the enthalpy of gasification L_g [1]:

$$\text{HRR} = \chi \cdot h_c \cdot \dot{m}'' = \chi \frac{h_c}{L_g} \dot{q}_{net}''$$

$$\dot{q}_{net}'' = \dot{q}_{ext}'' + \dot{q}_{flame}'' - \dot{q}_{rerad}'' - \dot{q}_{loss}'' \quad (2.9)$$

The combustion efficiency χ is the ratio between the measured effective heat of combustion (HOC) and the heat of complete combustion h_c ; its values range from $\chi = 1$ for complete and $\chi < 1$ for incomplete oxidization. It depends somewhat on the material burning, but also on the ventilation of the fire scenario. Flame inhibition, one of the most important modes of action used in flame-retarded polymers, reduces the combustion efficiency considerably. The net heat flux used for pyrolysis can be written as the sum of the heat fluxes in steady flaming combustion (Eq. (2.5), Eq. (2.9), Figure 2.1, Figure 2.8), where \dot{q}_{ext}'' is the external heat flux working upon the material per unit area, \dot{q}_{flame}'' is the heat flux of the flame, \dot{q}_{rerad}'' is the heat flux caused by reradiation of the hot surface to the environment, and \dot{q}_{loss}'' is the loss of heat into the specimen and surrounding environment, such as the specimen holder. The product of combustion efficiency and the ratio of heat of complete combustion of the fuel gases to enthalpy of gasification is known as the heat release parameter HRP [1]:

$$\text{HRP} = \chi \cdot \frac{h_c}{L_g} = \chi \cdot (1 - \mu) \cdot \frac{h_c}{h_g} \quad (2.10)$$

A time dependent factor ($\theta(t)$) between 0 and 1 may be introduced for the influence of the protective residual layer formed during burning. When these factors are combined, the resulting equation describes the dependency of the HRR on the heat release parameter, the protective layer, and the net heat flux (Eq. (2.11)).

$$\text{HRR}(t) = \chi \cdot \theta(t) \cdot (1 - \mu) \cdot \frac{h_c}{h_g} \cdot (\dot{q}_{ext}'' + \dot{q}_{flame}'' - \dot{q}_{rerad}'' - \dot{q}_{loss}'') \quad (2.11)$$

HRR is believed to be the most important fire property to assess the fire hazard of materials [65]. Therefore, Eq. (2.11) is highlighted as the most important statement of this chapter. Apart from the parameter of heat absorption, which is set to 1 and thus neglected, it combines all of the important characteristics controlling fire behavior, including char yield, combustion efficiency, heat of combustion of the volatiles, and heat of gasification. The empirical factor $\theta(t)$ is added arbitrarily to account for the changing protective layer properties of the fire residue during burning, which results in HRR changing as a function of t . This may be superfluous if h_g is used as $h_g(t)$ to account for the impact of the residual protective layer, for instance, or if Eq. (2.11) is used to describe a constant, steady state HRR. Thus, in all relevant sources [1–3], Eq. (2.11) is always given without $\theta(t)$; thus, $\theta(t)$ may be ignored or added as an empirical contribution after the fact.

However, it must not escape our notice that without $\theta(t)$, Eq. (2.11) also covers the greatest effect of residual protective layers: the heat shielding effect. In contrast to the effects of absorption in depth and heat reflection mentioned at the beginning of this chapter, heat shielding is not connected to reduced heat absorption or increased heat reflection but is based on increased reradiation of the hot surface \dot{q}''_{rerad} . The heat shielding effect has been reported as the most important flame-retardant mode of action in layered silicate nanocomposites of non-charring polymers, for instance; in some systems, it may be the only relevant one [38]. The key to understanding this is to apply Eq. (2.1) and quantify the role (to the fourth power) of the surface temperature T in \dot{q}''_{rerad} of Eq. (2.11). The surface temperature of non-charring polymers equals their pyrolysis temperature, whereas the carbonaceous, inorganic-carbonaceous, or inorganic residual layer can heat up to much higher temperatures. Thus, jumping from a pyrolysis temperature of 420 °C to a residue surface temperature of 720 °C entails an increase in \dot{q}''_{rerad} from 10 kW/m² to 50 kW/m², compensating for the feedback from a flame or the external heat flux in a cone calorimeter experiment.

Once a material is successfully ignited, the flame is stable and starts expanding, known as flame spread. This can happen in air, along surfaces, or through porous solids [66]. It means that the affected area always offers enough combustible material to supply the flame. With respect to the quality of the fuel, an adequate amount of fuel must be provided over time. The phenomenon can be regarded as many small fuel elements igniting one after the other. The velocity of the flame spread depends on how fast the nearby fuel elements are heated up to the ignition temperature (T_{ig}). The heat flux can be provided by the burning material or other external sources. If the current element is not burning intensively or long enough to ignite the next one, the flame extinguishes [67]. Flame spread is the most important fire hazard in developing fire, but must not be confused with fire spread. Fire spread means the advancing of a fire front and thus can be flaming or smoldering [66].

For a thermally thick specimen:

$$v = \frac{\delta_f}{t_{ig}} = \frac{(\dot{q}_{flame}'')^2 \cdot \delta_f}{\pi \cdot \rho \cdot k \cdot c_p \cdot (T_{ig} - T_0)^2} \quad (2.13)$$

■ 2.5 Fire Load and Fire Resistance

In a fully developed fire, all combustible materials are believed to be on fire, and therefore this state is characterized by extreme high heat fluxes and temperatures. The fire safety objectives have changed. Ignitability, flammability, reaction to fire, and burning behavior are no longer substantial; the point is to gain time for evacuation and firefighting before the collapse of the construction and to prevent the fire from spreading further. The crucial fire properties in a fully developed fire scenario are fire load and fire resistance. Fire load is the quantity of heat that can be released during the complete combustion of all the combustible materials involved (ISO 13943). To assess the fire load of certain materials, measurements in the bomb calorimeter, cone calorimeter, or micro combustion calorimeter (MCC or pyrolysis combustion flow calorimeter, PCFC) are used [1]. In the bomb calorimeter, the specimen is combusted completely under a pure oxygen atmosphere. The result is the net heat of combustion per mass of the specimen, which can be used to calculate the worst-case fire load. More realistically, the total heat evolved (THE) in the pyrolysis of polymeric materials, along with their distinct char yields, is determined by integrating the heat release rate measured in the cone calorimeter or the MCC. Thus, the cone calorimeter delivers the HOC for a real specimen in a well-ventilated fire, and the MCC the h_c for the complete combustion of the volatiles as discussed earlier. Along with the mass of the products or components, the fire load can be assessed. Apart from the calorimetric assessment, non-combustibility tests are performed, such as ISO 1182 on construction products of the highest classification in Europe. The cylindrical specimen is placed in a preheated electric furnace, and the mass loss and temperature rise caused by the specimen are monitored within the high-temperature furnace. Since these tests also focus on complete combustion, all polymeric materials, which are generally combustible, usually fail such tests.

Fire resistance is the ability of a test specimen to withstand fire or give protection from it for a period of time (ISO 13943). Fire resistance is usually a property of a component rather than a material. Fire resistance properties are relevant only for polymeric materials used in fire-resistant components, systems, and structures. Common criteria are fire stability, thermal insulation, or functioning as a barrier for heat, fire, and smoke for a certain time. Fire resistance is often tested in nearly

■ 7.3 Toxicological Risk Assessment

7.3.1 Definition of Uncertainty

In combustion toxicology, an exposure dose is defined as any pre-specified amount of toxic substances exposed to over a specified duration eliciting a certain, well-defined response (binary) or effect (continuous). A response algorithm can be judged as a binary simplification of a continuous relationship. Inhalation toxicology defines the response to a given dose " $C \times t$ " as the quantification of a biologically relevant effect and as such it is subject to random variation. The traditional interpretation of dose-response information is to accept the existence of a threshold level of dose that must be inhaled to produce the toxic effect. Thus, a threshold or POD exists if there is no effect below a certain exposure level, but above that level the effect is certain to occur. The POD is defined as the point on a toxicological dose-response/effect curve established from experimental data generally corresponding to an estimated low (adverse) effect level or no (adverse) effect level. As exemplified, not all effects we see are necessarily adverse. This applies especially to sensory irritants and their psychophysical sequelae. This threshold marks the beginning of extrapolation to toxicological reference concentration values that can be calculated by dividing the POD with corresponding uncertainty or adjustment factors as illustrated earlier. These factors are used to address the differences between the experimental data and the specific human situation of interest, considering the following major uncertainties in the extrapolation procedure: inter- and intraspecies differences, differences in duration of exposure of data from bioassays and targeted human exposure, issues related to dose-response, and quality of whole database.

There is a consensus amongst toxicologists and risk assessors that uncertainty factors have to be accommodated when applying PODs from animal studies to a specific population at risk. However, in the case of fire accidents, the scope is to minimize failure of an escape event experienced once in a lifetime. There is likely to be considerable variability in the escape responses of different individuals affected by such an incident. Similarly, the concentrations of toxic fire gases released over time may change dramatically with great variability from one location to another. Many of the available toxicity data are not usually adequate for predicting precise dose-time-response/effect relationships. Smoke obscuration and heat may readily become a greater threat than that originating from toxicants. Thus, the prediction of effective cumulative exposure doses for a given scenario is more complex than the concept of a fractional effective dose (FED) used as a tool to assess the toxicity-related impact on the impairment of escape as defined by the International Standard ISO 13571 [7]. This standard defines an FED (for asphyxiants) and

an FEC (for irritants) value of 1.0 as the median value of a lognormal distribution of the ability to perform an escape response within a defined time window. Any failure to perform this task would inevitably result in fire-related fatalities. Post-exposure deaths or irreversible outcomes may not entirely be prevented by this standard. An FED or FEC of 0.1 translates to a $\approx 1\%$ population response. More recently suggested modifications of this standard are detailed elsewhere [2, 3].

The wealth of physiological and toxicological information available on rats reduces the uncertainty when extrapolating findings from this species to humans. Harmonized guidance has been published for applying inter- and intraspecies uncertainty factors to adjust inhaled doses and for applying findings from this species to humans. To the contrary, data from non-human primates cannot rely upon a strong database and the species-specific inhalation methodology is less standardized and is subject to laboratory-specific outcomes. Therefore, such unique studies can only be judged as supplemental rather than core evidence. For most of the asphyxiant toxicants, similar modes of action in animals and humans can be assumed with no interspecies factor required. Dosimetrically, the rats' respiratory ventilation is high and conservative enough to omit the variability in human activity-related differences in ventilation. However, as exemplified for ammonia, for respiratory tract irritants, it appears to be indispensable to consider in detail concentration-, modes of action-, and species-specific response-based dosimetric adjustments.

7.3.2 Analysis of Time–Dose–Response Relationships

7.3.2.1 Asphyxiants

Published analyses on the time-scaling of data from acute inhalation studies on rats used the ten Berge algorithm " $C^n \times t = k$ (constant effect)" [2, 47, 58]. By introducing the toxic load exponent (n), multiple inhalation studies with variable exposure concentrations (C) and exposure times (t) can be combined to calculate the LC_{50} and LC_{01} from the entire matrix of data. The exponential weighing factor was incorporated to better describe the relative contribution of C and t mathematically; however, for practicability, either the toxic load " n " or the toxic load " k " is a combination of both. For HCN and CO, the calculated " n " was 1.64 and 1.77, respectively. The related toxic load constants for the non-lethal threshold " $k(LCt_{01})$ " were 0.109×10^6 and 0.498×10^8 [ppm ^{n} \times min], respectively. The median lethal concentrations " $k(LCt_{50})$ " were 0.294×10^6 and 1.21×10^8 [ppm ^{n} \times min], respectively (Figure 7.7). This parameterization was derived from published nose-only inhalation studies in rats and is valid for exposure durations up to 60 min [2, 47–49].

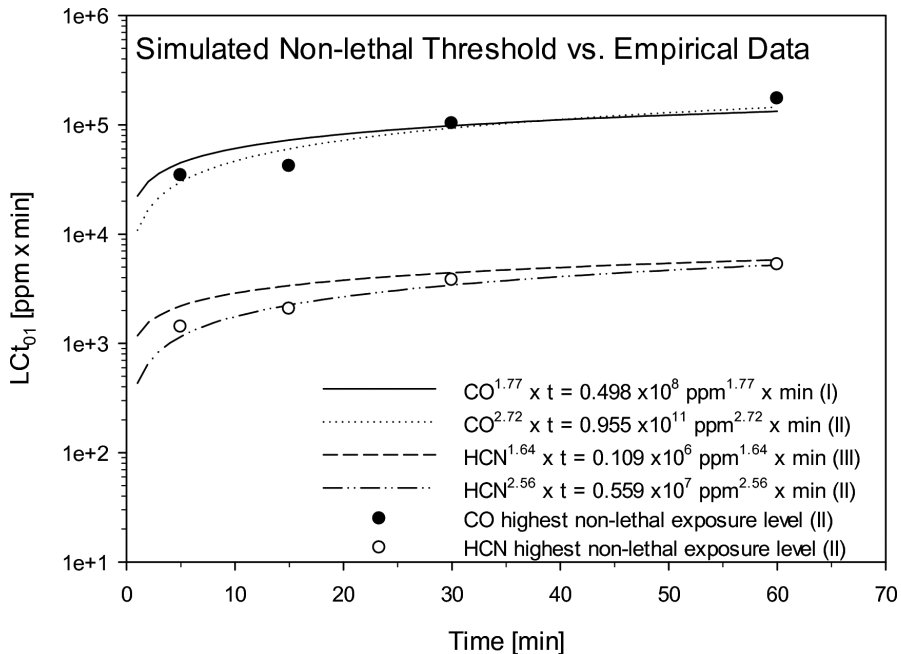


Figure 7.7 Toxic load model with $C^n \times t = \text{const.}$ effect. The non-lethal threshold (LC_{01}) values of CO and HCN were calculated based on the multiple $C \times t$ relationships of nose-only exposed rats as detailed elsewhere [2] (figure reproduced from Pauluhn, 2016 [2])

Despite the different modes of exposure (nose-only vs. whole-body) and the applied technical standards, the calculated LC_{01} of both studies were similar at 30 and 60 min exposure durations (Figure 7.7). Differences between modes of exposure may occur due to the restraint-related higher ventilation in nose-only exposed animals. Recent OECD testing guidelines consider nose-only studies superior to whole body studies as technical mishaps are less likely to occur [4, 5]. The comparison given in Figure 7.7 illustrates that the “toxic load model” provides a versatile means to calculate the cornerstones of acute inhalation toxicity LC_{50} and LC_{01} from the entire $C \times t$ matrix examined. Therefore, the comprehensive data sets from rats were given preference to isolated data using non-standardized approaches. Concurrent with the rationale given earlier, the $1/3 \times LC_{01}$ relationship was taken as a threshold below which no impairment of escape is expected to occur [2]. As illustrated in Figure 7.8, the $C^n \times t = k$ relationship is suitable to calculate any time-adjusted LC_{01} from any set of mortality data with multiple exposure durations. It appears to be reasonable to expand this equation to also calculate the incapacitation threshold (IC_{01}) with $IC_{01} = LC_{01} \times 1/3$ as shown below.

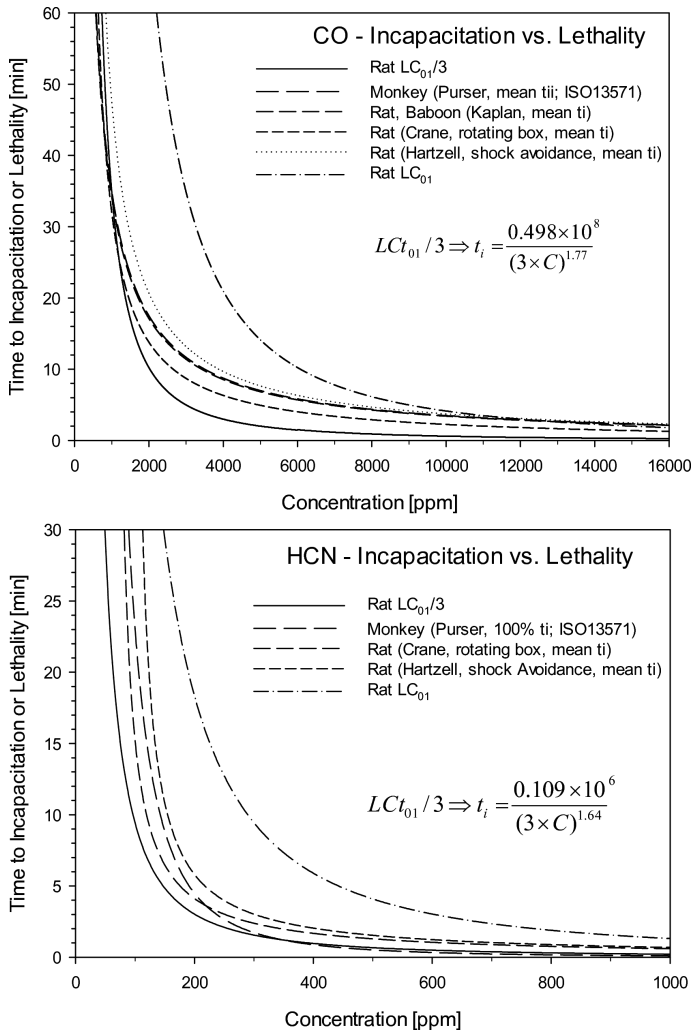


Figure 7.8 Comparison of the time-to-incapacitation in rats and non-human primates using four different endpoints to characterize incapacitation. Data were from Sweeney [48–50], Purser [51, 52], Crane [18], Kaplan [53], and Hartzell [19] as summarized by Speitel (1995) [32] (figures reproduced from Pauluhn [2])

Thus, despite their underlying different endpoints, the empirical $C \times t$ relationships support the $1/3 \times LC_{01}$ approach as sufficiently conservative. As long as this threshold is not exceeded, “impairment of escape” and post-exposure lethality will not occur. Thus, the statistically derived descriptor of toxicity POD_1 (lethality) can suitably serve as a starting point for calculating the POD_2 (incapacitation). Lethal and non-lethal POD from standardized, testing guideline-compliant acute inhalation studies on rats commonly serve as the most important cornerstones for deriving such guidance levels for chemical emergencies [8].

Mortality-based data commonly serve a broader range of exposure concentrations and durations than studies aiming solely at t_{inc} , the time to attain incapacitation. They also follow more rigid and internationally harmonized testing protocols using sufficient number of rats instead of few non-human primates with limited baseline data and benchmark validations [4, 5]. This facilitates enormously their use for hazard analysis and comparisons across different laboratories. The resultant broader and more consistent database outweighs the conceived advantage of duplicating a more “human-like” incapacitation paradigm. The surrogate endpoints used in animal bioassays for defining t_{inc} often require conditioned animals for the applied performance tests and used titration towards incapacitation. High inter-animal variability occurs at subtoxic exposure levels and either dichotomous or continuous endpoints are used. Accordingly, extrapolation errors appear to be less likely to occur when starting with a unequivocal binary endpoint to be determined simultaneously in equally exposed animals in the absence of superimposed methods of detection. These aspects give preference to the $IC_{01} = 1/3 \times LC_{01}$ approach as compared to laboratory-specific, fine-tuned, and highly specialized neurobehavioral testing batteries [2]. Titration of t_{inc} in single larger animals can hardly serve the purpose of probabilistic assessments due to animal- and method-specific variabilities.

7.3.2.2 Irritants

As referred to above, airborne chemical sensory irritants are known to evoke a burning sensation in the eyes, nose, and throat, thereby causing “impairment of escape” in an exposed individual. At high concentrations, exposure can be both incapacitating and life-threatening. Animal models were developed using the decrease in respiratory rate in mice or rats as an index of sensory irritation. Based on the concentration–response relationships, the RD_{50} , defined as the concentration causing a 50% decrease in respiratory rate, was shown to have a predictable relationship with sensory irritation in men [54–57]. The interrelationship of the RD_{50} and other descriptors of acute toxicity is compared for hydrogen hydrochloride (HCl) in Figure 7.9. Although sensory irritation occurs concentration-dependently, its severity is better described as a $C^n \times t$ dependent response [8–10]. As exemplified for HCl, the lethality-based $LC_{01}/30$ and SLOT-dangerous toxic load (DTL)/10 values correspond favorably to the AEGL-2 to AEGL-3 range (see Figure 7.9). Taken as a whole, these findings suggest that defined fractions of the LC_{01} and SLOT values are suited to serve as a basis for the estimation of threshold $C^n \times t$ values below which incapacitation can be excluded with reasonable probability.

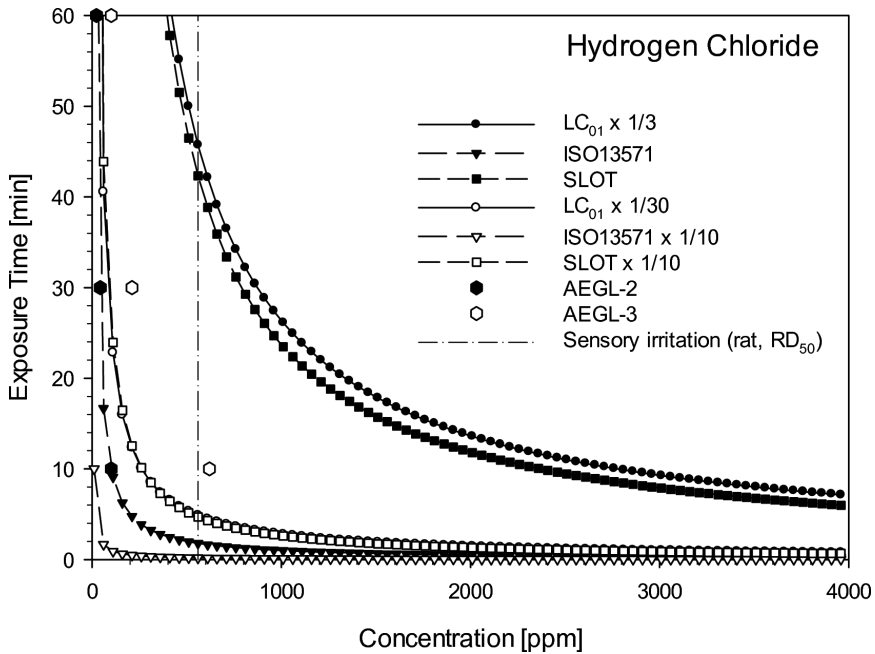


Figure 7.9 Concentration \times exposure time comparisons of the irritant gas HCl. The toxic load $C^n \times t = \text{const.}$ effect model used the published parameterization of SLOT-DTLs [10] for the general population. The $1/30 \times LC_{01}$ from rats exposed to HCl was taken as a reference to demonstrate the implicit conservatism of the course taken

It is interesting to note that the SLOT (DTL) principle [10] arrives at the same conclusion for both asphyxiant and irritant chemicals by using the toxic load model but different rationales for the same uncertainty factor to account for variability of the human population (Figure 7.9) [10]. When looking at the SLOT criteria, they reflect exposure conditions just on the verge of causing a low percentage of deaths in the exposed general population. It takes around 1% mortality in animals (LC_{01}) as being representative of SLOT conditions. They are used to provide estimates of the extent (i.e., hazard ranges and widths) and severity (i.e., how many people are affected, including the numbers of fatalities) of the consequences of each identified major accident hazard [10, 11]. The comparison of the SLOT-DTL/10 with the $LC_0/30$ relationships given in Figure 7.9 supports the notion that SLOT-DTL/10 appears to be a defensible estimate for assessing the irritation-related threshold for incapacitation.

- Better control of building materials and products
- Continued maintenance of buildings and relevant parts and components.

Regarding full-scale tests for façades, the European Commission is currently trying to develop a harmonized full-scale test method, but an international discussion has started as well. In a number of countries, regulations for high-rise buildings are under review or have been reviewed, and the international scientific community is focusing on the topic of fire safety of façades.

Another discussion relates to toxicity of combustion gases from construction products. While in Europe, Australia, and the USA (except New York) this topic is currently not considered as relevant for fire safety, some Asian countries have introduced toxicity requirements for construction products. Most countries rely on the approach that it is key to prevent people from exposure to smoke, because smoke is always toxic. The European Commission has commissioned a study confirming this approach [2]. But the discussion is ongoing, and further requirements for combustible building products may come up in the future.

References for Section 10.1

- [1] Regulation (EU) No. 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC.
- [2] Study to evaluate the need to regulate within the Framework of Regulation (EU) 305/2011 on the toxicity of smoke produced by construction products in fires, European Commission, 2017.

10.2 Americas

Marc Janssens

10.2.1 United States of America

10.2.1.1 Statutory Regulations

An acceptable level of fire safety is accomplished for new or substantially renovated construction through compliance with local regulations. These regulations are based on national model building codes. Additional regulations based on a national model fire prevention code ensure that this level of fire safety is maintained during the lifespan of the building. The U.S. model codes are largely prescriptive. Acceptance criteria for construction materials, products, and assembly designs are generally based on performance in standardized fire tests. The following sub-sections provide a brief overview of the model code system in the USA.

For a more comprehensive review, the reader is referred to the book by Diamantes [1].

U.S. Model Codes

There are two model building and fire prevention code organizations in the United States; the International Code Council (ICC) [2] and the National Fire Protection Association (NFPA) [3].

ICC was formed in 1994 as an umbrella organization consisting of representatives of three older model code organizations: Building Officials and Code Administrators International (BOCA), International Conference of Building Officials (ICBO) and Southern Building Code Congress International (SBCCI). The purpose of ICC was to facilitate the development of a single set of model codes to replace the codes maintained by BOCA, ICBO and SBCCI, i. e., the National, Uniform, and Standard codes respectively. The BOCA, ICBO and SBCCI codes served for many years as the basis for local fire safety regulations in Northeastern, Southern, and Western regions of the country. Although the ICC member groups agreed to discontinue their individual codes in 2000, many local jurisdictions did not immediately transition and continued to rely on the older documents for several years. At the time of this writing, the older regional codes have been superseded by national ICC and NFPA codes throughout the U.S.

ICC promulgates the International Building Code (IBC) and the International Fire Code (IFC). The IBC and IFC are supplemented with a series of model code documents that provide more detail and additional requirements for specific types of buildings (e.g., one- and two-family dwellings) and specific building systems and components (e.g., plumbing), or to achieve specific objectives (e.g., mitigate risks to life and property from wildfires). Collectively, the IBC, IFC, and supplemental documents are referred to as the International Codes[®], or I-Codes[®]. New editions of the I-Codes are published every three years. The I-Codes can be viewed online for free [4]. The free access is referred to as publicACCESS[™]. A subscription to premiumACCESS[™] is required for users who want to print sections of a code, search and annotate the document, or need other advanced features. In the District of Columbia and the states of Arizona, Kansas, and Nevada the I-Codes are adopted by jurisdictions at the local level. In the remaining states, the I-Codes are adopted statewide, although local jurisdictions in some states are allowed to amend the state code and include more stringent requirements.

In 2003, NFPA published the first version of its model building code, NFPA 5000. A new edition is published in the same year as the IBC. In addition, NFPA promulgates a fire prevention code and the *NFPA 101: Life Safety Code*[®]. The latter is widely used throughout the country but is primarily concerned with occupant safety in specific types of buildings and does not address all building construction and fire prevention issues. NFPA also maintains codes that are included in the I-Codes by

reference. The most noteworthy of these is the *NFPA 70: National Electrical Code*[®]. At this time NFPA 5000 has not yet been adopted by a local jurisdiction. NFPA codes and standards can also be viewed online for free [5].

Demonstrating Compliance with Building Code Fire Safety Requirements

Fire protection of buildings addresses all aspects of fire safety and consists of a combination of active and passive measures. Active fire protection devices such as sprinkler, smoke control, and detection and alarm systems require manual, mechanical, or electrical power for their operation. Testing of active fire protection devices is beyond the scope of this handbook. Passive fire protection does not require any external power. There are essentially two types of passive fire protection measures that involve fire testing of construction products, structural elements, and assemblies.

The objective of the first type of measures is to reduce the likelihood of ignition and limit the rate of fire growth to the critical stage of flashover in the compartment of fire origin. A slow-growing fire leaves more time for safe egress of building occupants, and generally results in reduced property damage at the time of manual or automatic suppression. This can be accomplished by using interior finishes and furnishings with specific ignition, flame spread, and heat release characteristics. These characteristics are determined based on performance in standardized tests that expose a specimen to the thermal environment representative of the initial stages of a fire. Standardized tests are also used to control ignition of and flame spread over exterior façade and roof surfaces. A secondary objective of the first type of measures is to control the quantities of particulate matter (which affects visibility) and of toxic products of combustion that can cause human casualties and excessive damage to equipment. The city of New York is the only jurisdiction in the U.S. that specifies a smoke toxicity requirement for construction products in its building code¹.

Despite the first type of measures, fires do grow to full involvement of the room of origin. When this happens, the focus shifts to containing the fire within a limited area, at least for a certain time. Thus, fire spread to other parts of the building or adjacent buildings is delayed or prevented. This containment process is referred to as compartmentation. It is accomplished by providing fire-resistive floor, wall, and ceiling assemblies and by protecting openings and penetrations through room boundaries. Compartmentation also involves protecting structural elements and assemblies to avoid or delay partial or total collapse in the event of fire.

¹⁾ § 803.5 of the New York City Building Code[®] [6] requires that interior wall or ceiling finishes, other than textiles, upon exposure to fire, shall not produce products of decomposition or combustion that are more toxic than those given off by wood or paper when decomposing or burning under comparable conditions as tested in accordance with NFPA 269: *Standard test method for developing toxic potency data for use in fire hazard modeling*.

To demonstrate compliance with fire safety requirements in the code, the architect or builder typically needs to present a report from an accredited laboratory to the code official that confirms that the product, structural element, or assembly was tested according to the applicable standard method and meets the acceptance criteria specified in the code. Most accredited fire testing laboratories publish a directory of tested products. These directories facilitate the code official's job to verify compliance and determine which variations from the tested product, element, or assembly are acceptable (e.g., acceptable range of thicknesses, substrates, and adhesives, etc.)

Generally, there is no requirement that tested products be listed, labeled, and subject to periodic follow-up plant inspections and verification testing, although there are exceptions. For example, the IBC requires that fiber-reinforced polymers delivered to the job site shall bear the label of an approved agency showing the manufacturer's name, product listing, product identification and information sufficient to determine that the end use will comply with the code requirements.

Product manufacturers sometimes develop a new product or identify a new application for an existing product that does not meet the established building code requirements. In 2003, the ICC created a technical evaluation service (ICC-ES) [7], which determines whether such a product or application meets the intent of the building code. If that is found to be the case, ICC-ES identifies a test method or develops a calculation method to evaluate the product, and establishes acceptance criteria. The results of the technical evaluation are published in a report. Presentation of the evaluation report to the code official serves as an alternative approach to demonstrate building code compliance. Testing in support of an evaluation report shall be performed by an accredited laboratory. New acceptance criteria developed as part of a technical evaluation are published in a separate document, which facilitates future evaluations of the same type of product or application requested by other manufacturers (or later by the same manufacturer). In recent years several accredited fire testing laboratories, third-party quality assurance agencies, and fire consulting engineering firms have developed competing evaluation services.

Testing Laboratory and Third-Party Quality Assurance Agency Accreditation

Testing in support of building code compliance can only be performed by accredited laboratories. There are two independent organizations in the U.S. that provide this type of accreditation service for fire testing laboratories: the American Association for Laboratory Accreditation (A2LA) [8] and the International Accreditation Service (IAS) [9]. Both use the requirements and criteria described in ISO/IEC 17025 [10]. As a result, a laboratory has to demonstrate an internationally recognized level of competence to be accredited. A2LA and IAS accreditations only cover specific standard test procedures. The test methods for which a laboratory is accredited are listed on the certificate, which can be printed from the A2LA and IAS

websites. Both A2LA and IAS also accredit agencies that offer a listing, labeling, and follow-up inspection program for products that (in accordance with the code) require third-party quality assurance (QA). In this case, the agencies are periodically assessed according to the guidelines and criteria in ISO/IEC 17020 [11]. Table 10.1 provides a list of the fire testing laboratories in the U.S. that are accredited by IAS. The table also indicates for each laboratory whether it has an accredited third-party QA program and can perform some of the most common standardized fire test methods referenced in the IBC. A complete list of tests can be found on the IAS certificate. Only the laboratories that offer QA services have a directory of tested products.

Table 10.1 IAS-Accredited Fire Testing Laboratories Located in the U.S.

Fire testing laboratory	QA	ASTM standards				NFPA standards	
		E84	E108	E119	E136	285	286
Architectural Testing [12]	✓	✓	✓	✓	✓	✓	✓
FM Approvals [13]	✓	✓	✓	✓			
Intertek Testing Services [14]	✓	✓	✓	✓	✓	✓	✓
NGC Testing Services [15]		✓	✓		✓		
QAI Laboratories [16]	✓	✓	✓		✓		
Southwest Research Institute [17]	✓	✓	✓	✓	✓	✓	✓
Underwriters' Laboratories [18]	✓	✓	✓	✓	✓	✓	✓
Western Fire Center [19]			✓	✓			

10.2.1.2 Consensus Standards

In general, the building code fire safety requirements for products, structural elements, and assemblies are based on performance in a standardized test developed according to a consensus process. The primary consensus-based organizations in the U.S. developing and maintaining fire test standards are ASTM International (previously the American Society for Testing and Materials) [20] and the National Fire Protection Association (NFPA) [3]. Several fire testing laboratories in the U.S., such as Underwriters' Laboratories (UL) [18] and FM Approvals [13], have established a consensus process that meets the requirements of the American National Standards Institute (ANSI) so that they are permitted to develop and publish American National Standards [21].

- **LGAI Technological Center, S.A. (Applus)**

Campus de la U.A.B. Ronda de la Font del Carme, s/n 08193 – Bellaterra
(Barcelona)

Phone: 935 672 000

Email: info@appluslaboratories.com

Web: www.applus.com

10.3.2.10.4 Future Developments

Currently (January 2020), the regulation for industrial facilities is under revision, but there is no public document available so far.

References for Section 10.3.2.10

- [1] Código Técnico de la Edificación. Documento Básico Seguridad en caso de incendio. (CTE DB SI). December 2019.
- [2] Real Decreto 2267/2004, de 3 de diciembre, por el que se aprueba el Reglamento de seguridad contra incendios en los establecimientos industriales.
- [3] Corrección de errores y erratas del Real Decreto 2267/2004, 3 de diciembre, por el que se aprueba el Reglamento de seguridad contra incendios en los establecimientos industriales.
- [4] Real Decreto 842/2002, de 2 de agosto, por el que se aprueba el Reglamento electrotécnico para baja tensión, Published on 18/09/2002.
- [5] Ley 38/1999, de 5 de noviembre, de Ordenación de la Edificación, 06/11/1999.
- [6] Real Decreto 314/2006 de 17 de marzo, por el que se aprueba el Código Técnico de la Edificación.
- [7] Real Decreto 732/2019, de 20 de diciembre, por el que se modifica el Código Técnico de la Edificación, aprobado por el Real Decreto 314, de 17 de marzo.
- [8] Nota aclaratoria sobre la aplicación al Reglamento de Seguridad Contra Incendios en los Establecimientos Industriales (Real Decreto 2267/2004) del Reglamento Delegado 2016/364, que establece las clases posibles de reacción al fuego de los cables eléctricos (3 abril 2017).
- [9] Garcia Alba, S. Section 10.15 Spain in *Plastics Flammability Handbook: Principles, Regulations, Testing, and Approval* (3rd Edition), Troitzsch, J. (Ed.), Hanser, 2004.
- [10] ENAC website (www.enac.es) (accessed January 2020).

10.3.2.11 Switzerland

Marcel Donzé

10.3.2.11.1 Statutory Regulations

According to the federal constitution of Switzerland, the 26 cantons are responsible for matters regarding the public fire authorities, and they enact their own laws. Regarding the “Agreement between all cantons to remove technical barriers to trade” [1], in their laws the cantons have to adopt the fire protection regulation issued by the VKF (Vereinigung Kantonaler Feuerversicherungen, Association of Cantonal Fire Insurances). The intended purpose of this regulation is the safety of people and property in the event of fires and explosions. The regulation consists of

the VKF fire protection standard 1-15 [2] and the VKF fire protection guidelines. The fire protection standard specifies the basic principles. Requirements and measures are listed in the guidelines, thematically divided into 19 documents.

10.3.2.11.2 Classification of Reaction to Fire of Building Materials

Within the VKF fire protection regulations, all materials and construction components in buildings with requirements regarding reaction to fire are referred to as building materials. The important criteria for reaction to fire are the burning behavior, smoke production, flaming droplets, and (for cables) corrosivity. Classification is possible according to EN 13501 or a test according to the national VKF guidance “Building material and construction components, part B: Testing regulations” [3].

Classification According to EN 13501

Construction products are classified according to EN 13501. In addition to the reaction-to-fire classification according to EN 13501-1, classifications for roof coverings (according to EN 13501-5) and cables (according to EN 13501-6) apply. In addition, the rules for a “classification without further testing” (CWFT) can also be applied. Details of the tests, the classification procedures and the “CWFT” are described in Section 10.3.1.

Classification According to the National VKF Guidance [3]

The reaction to fire is assessed according to the burning behavior, the degree of smoke development, and the presence of flaming droplets, and is classified by a fire coding. The fire coding is established by standardized tests.

Burning behavior

In the sense used in this assessment, the burning behavior of a material is defined by its flammability and the burning rate, and is substantiated by testing. The classification of building materials is based on combustibility grades 3 to 6. Materials of combustibility grades 1 and 2 are not approved as building materials. Details are shown in Table 10.83.

Table 10.83 Combustibility Grades 1 to 6

Combustibility grade	Burning behavior	Example
1	<i>Extremely easy to ignite and extremely fast burning</i>	Nitrocellulose
2	<i>Easy to ignite and fast burning</i>	Celluloid
3	<i>High combustibility</i> Building materials with high combustibility: burn spontaneously and fast without additional heat supply.	Plastic foams without flame retardants
4	<i>Average combustibility</i> Building materials with average combustibility: continue to burn spontaneously for a longer period of time without additional heat supply.	Conditioned white wood
5	<i>Low combustibility</i> Building materials with low combustibility: continue to burn slowly or carbonize only with additional heat supply. After removal of the heat source, the flames must go out within a short time interval and afterglowing must cease.	Plastics containing flame retardants
5 (200 °C)	<i>Low combustibility at 200 °C</i> Building materials fulfilling the requirements of combustibility grade 5 even under the effect of an elevated ambient temperature of 200 °C.	Rigid PVC
6q	<i>Quasi non-combustible</i> Building materials containing a low content of combustible components, which are classified as non-flammable for non-combustible application purposes.	Several mineral wool products
6	<i>Non-combustible</i> Building materials without combustible components, which do not ignite, carbonize or incinerate.	Concrete

Determination of combustibility grade

The application of the combustibility grade test described below is normal practice. Special regulations exist for certain materials such as flooring and textile materials.

The test is conducted using a standardized test apparatus shown in Figure 10.42. The test criteria are summarized in Table 10.84.

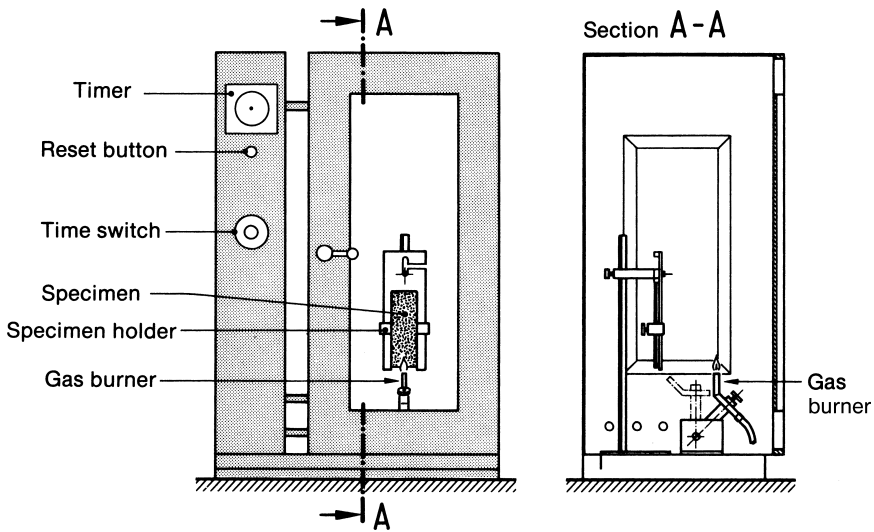


Figure 10.42 Combustibility test apparatus

Table 10.84 Combustibility Test Criteria

Specimens	Six specimens: <ul style="list-style-type: none"> ▪ Compact materials: 160 mm × 60 mm × 4 mm ▪ Foams: 160 mm × 60 mm × 6 mm
Specimen position	Vertical
Ignition source	Propane-operated displaceable burner, flame tip temperature approx. 900 °C, flame length 20 mm, inclined at 45° to horizontal
Test duration	Flame application 15 s on lower front edge until the flame has reached the upper part of the specimen holder or until extinction
Conclusion	According to test result, classification into combustibility classes 3–5 as specified below

Test procedure at room temperature

A minimum of three tests is conducted. If these three tests do not result in the same classification, the number of tests is increased to six, always deleting the highest and the lowest results. The remaining worst result is the one that determines the classification.

A conditioned specimen of the building material is mounted in a vertical position on the test rig, and a standardized ignition source is applied in the center of the lower front edge.

Test procedure at an ambient temperature of 200 °C

In the test apparatus, which can be heated, the temperature is increased to 200 °C until constant conditions have been reached. The specimen is clamped into the

specimen holder. After the specimen has been heated up for 5 min, the tests are conducted as described above.

Classification: The decisive criterion for the classification is the time elapsed from the start of the flame application until the tip of the flame reaches the upper part of the specimen holder (150 mm from the lower edge of the specimen) (referred to as “time”) or until the flame extinguishes (referred to as “burning time”).

If rising of the tip of the flame to the upper part of the specimen holder is not unambiguously observed, a cotton thread according to the SN 198 898 standard must be tensioned at this level, and the time taken to burn it measured. For classification purposes, the test using the cotton thread has priority over a visual observation. Details of classification and requirements are summarized in Table 10.85.

Table 10.85 Classification of Building Materials Based on Combustibility Test Requirements

Classification	Requirements
Combustibility grade 3	<ul style="list-style-type: none"> Time to reach upper part of the specimen holder: 5–20 s
Combustibility grade 4	<ul style="list-style-type: none"> Time to reach upper part of the specimen holder: > 20 s Burning time: > 20 s
Combustibility grade 5	<ul style="list-style-type: none"> The flame does not reach the upper part of the specimen holder (150 mm) Burning time: ≤ 20 s
Combustibility grade 5 (200 °C)	<ul style="list-style-type: none"> The flame does not reach the upper part of the specimen holder (150 mm) Burning time at temperature of 200 °C: ≤ 20 s
Combustibility grades 6q and 6	<ul style="list-style-type: none"> No ignition, incineration, or carbonizing and non-combustibility test

Non-combustibility test

Non-combustibility is tested according to DIN 4102-1 (version 1998), Chapter 5. For details, see Section 10.9.2.1 in the 3rd edition of this Handbook [4].

Classification: The decisive criteria for classification are flame duration, temperature increase in the non-combustibility furnace, and/or level of lower calorific value of the tested building material. Details are shown in Table 10.86.

Table 10.86 Classification of Non-Combustible Building Materials

Classification	Requirements
Combustibility grade 6q	Flaming: ≤ 20 s and Temperature increase (ΔT): ≤ 50 K <i>or</i> Calorific value, lower (LHV): ≤ 4200 kJ/kg
Combustibility grade 6	No flaming and Temperature increase (ΔT): ≤ 50 K

Radiant panel test for floor coverings

The combustibility of floor coverings is tested with the radiant panel test. Test apparatus and specifications are based on DIN 4102-14 (version 1990), and are shown in Section 10.9.2.1 in the 3rd edition of this Handbook [4].

The test chamber has a temperature of 18 ± 5 °C. The air throughput rate of the chamber is approx. 170 m³/h. The incident heat flow radiated from the following distances by the radiant panel onto the plane of the specimen must range between:

- at 200 mm: 0.87 to 0.95 W/cm²
- at 400 mm: 0.48 to 0.52 W/cm²
- at 600 mm: 0.22 to 0.26 W/cm².

All values from 100 to 900 mm measured for the heat flow – plotted as a function of the distance – result in the heat flow profile required for the assignment of heat flow densities (W/cm²).

Classification: To specimens which do not ignite (or burn to a width of < 10 cm), a heat flow density of > 1.1 W/cm² is assigned.

Specimens burning to a width of more than 90 cm have a lower heat flow density compared to the calibration value at 90 cm. In all other cases, a heat flow density corresponding to the burning distance is assigned to the specimens on the basis of the heat flow density profile.

The value critical for classification is found by averaging the heat flow densities of three specimens (1050 × 250 mm). The classification criteria are summarized in Table 10.87.

Table 10.87 Classification Criteria for Floor Coverings

Classification	Requirements
Combustibility grade 3	Heat flow density: < 0.25 W/cm ²
Combustibility grade 4	Heat flow density: 0.25–0.49 W/cm ²
Combustibility grade 5	Heat flow density: ≥ 0.5 W/cm ²

Smoke-developing behavior

The test is conducted in a standardized test box based on the American XP2 chamber to ASTM D2843. Test apparatus and specifications are described in Section 10.2.1.5. Six specimens are tested, with the required dimensions listed in Table 10.88.

Table 10.88 Dimensions of Test Specimens for Smoke Test (in mm, $\pm 10\%$ tolerance)

	Compact materials	Foams	Composite flooring materials
Length	30	60	30
Width	30	60	30
Thickness	4	25	Original thickness

Three tests are conducted. The specimen is placed on a defined wire netting and is burnt by means of a flame of 150 mm length. Any melting material is exposed to a flame in a metal sheet cup according to DIN 4102-1, item 5.1.2.2 (version 1977). Flame exposure is continued until complete combustion of the specimen.

Classification: The decisive criterion for classification is the maximum light absorption. The requirements are shown in Table 10.89.

Table 10.89 Classification Criteria for Smoke-Developing Behavior

Classification	Requirements
Smoke grade 1	Maximum light absorption: > 90%
Smoke grade 2	Maximum light absorption: > 50 to 90%
Smoke grade 3	Maximum light absorption: 0 to 50%

Fire coding

The combustibility and smoke grades established on the basis of the test results are expressed as “fire coding”, which is a combination of the combustibility and the smoke-developing classification.

For example, a fire coding of 4.1 means that the building material has an average combustibility (grade 4) and develops heavy smoke when burnt (grade 1).

Flaming droplets

A filter paper is placed at the bottom of the test apparatus for the combustibility test. If the filter paper is ignited during the test by a flaming droplet, the product receives the additional assessment “Building material with flaming droplets”.

Reaction to Fire Groups

Based on the reaction-to-fire classification according to EN 13501 or the national VKF guidance, building materials are divided into four reaction to fire groups [acronym = RF (from the French “réaction au feu”)]:

- RF1 (no contribution to fire)
- RF2 (low contribution to fire)
- RF3 (acceptable contribution to fire)
- RF4 (unacceptable contribution to fire).

ences EN 45545-2 as main source – again underlining the importance of this new fire safety standard. It is expected that national developments will be in line with further developments of the EN 45545 series of standards.

11.2.2 Europe

Torben Kempers

For many years, most countries in Europe had their own national railway standards, describing the requirements with respect to fire safety for each country. In these standards, reference was made to the actual application in the railway rolling stock, as well as the operation mode of the train itself. Such standards differentiated between (for instance) commuter trains, high-speed intercity trains, and trains running underground or in tunnels.

With the formation of the European Community and the fact that an increasing number of trains actually cross several borders within Europe, the need for a harmonized railway standard became clear. In 1991, the European Committee for Standardization (Comité Européen de Normalisation, CEN) and the European Committee for Electrotechnical Standardization (CENELEC) joined forces to develop a single series of harmonized European railway standards. This resulted in the publication of the EN 45545 series, “Railway applications – Fire protection on railway vehicles” [1].

The former national standards dealing with the fire protection of railway vehicles have now mostly been withdrawn or are only used for very limited applications within the specific countries (for example refurbishment of old trains or local transportation networks). Therefore, they are no longer dealt with in this section. For the most important countries in Europe (United Kingdom, Germany, France, and others) the national standards can be viewed in the 3rd edition of this book under Section 11.2 [2].

In the following sections, the harmonized EN 45545 series and related standards will be dealt with in more detail.

11.2.2.1 Harmonized Railway Standard EN 45545

Since 1991, the European Committee for Standardization (CEN) has worked on the development of a single harmonized railway standard for Europe. The aim was to replace all existing national standards by one single standard, covering all aspects related to the fire protection on railways. The underlying thought was that such a harmonized standard would support the free trade within the European Union, and become a means to improve the interlinking and interoperability of the national rail networks.

In the following sections, we will explain the development process, the general structure of the standard, the details of the two most important parts, the listed products and requirements, and finally the next steps that are being undertaken.

11.2.2.1.1 Development Process

The actual work to develop the harmonized railway standard has been undertaken within technical committees CEN/TC 256 “Railway applications” and CLC/TC 9X “Electrical and electronic applications for railways”, through the creation of a Joint Working Group (JWG). In this JWG various experts from industry, railway operators, and testing institutes joined forces to define the proper test methods and corresponding specification limits.

In parallel, supporting research work was done in projects funded by the European Commission, such as the FIRESTARR (“Fire Standardisation Research in Railways”) research project on the reaction-to-fire performance of products in European trains (funded in 1997), and the TRANSFEU project, focusing on the development of a fire safety-performance based design methodology (funded in 2009).

Because of the complexity of the project, it was not until 2009 that CEN/CENELEC decided to publish the harmonized standard, initially as a technical specification, to gather feedback from industry and rail operators. This harmonized set of specifications was the CEN/TS 45545 series, consisting of seven parts.

In April 2010 the draft standard prEN 45545 series was published, for review and comments from the CEN/CENELEC member countries. In total, more than 500 comments were received, which were all addressed by the JWG in a period of 9 months. This resulted in the publishing of the Final Draft FprEN 45545 series in 2012.

Finally, in March 2013 the final version of the EN 45545 series of standards [1] was published. The so-called “date of withdrawal” was set at 3 years, meaning that EN 45545 would become official in March 2016, at the same time replacing all existing national standards.

Amendments to parts 2 and 5 of the series were published in 2015, comprising some minor editorial and technical modifications or clarifications, without changing the overall requirements as listed in the original 2013 editions.

Technical Specification for Interoperability

The EN 45545 is a *voluntary* series of standards. Only after it is referenced in one of the Technical Specifications for Interoperability (TSIs) it becomes mandatory. These TSIs are law in Europe.

The TSI active from 2014, “rolling stock – locomotives and passenger rolling stock” (“TSI-LOC&PAS”) [3], referred to EN 45545-2 (from 2013) in the clause regarding “Measures to prevent fire” and the corresponding Appendix J-1 index 58 (material requirements) and 59 (flammable liquids).

This TSI-LOC&PAS also had a clause (7.1.1.5) on “Transitional measure for fire safety requirement”. This clause stipulated that during a transitional period ending three years after the date of publication of this TSI (i. e., ending 31 December 2017), it was permitted to still refer to the former regional railway standards – even though they became obsolete with the publication of EN 45545-2. As of 1 January 2018, this transitional measure for fire safety requirement was no longer valid. As of that date, materials for all new projects plus refurbishments (e. g., new parts, designs, or systems) needed to comply with the EN 45545-2 requirements.

The new version of the TSI-LOC&PAS, published in 2019 [4], only allows the application of current EN 45545-2:2013+A1:2015.

11.2.2.1.2 Structure of EN 45545-1 and -2

As mentioned before, the EN 45545 series consists of seven parts:

- Part 1: General
- Part 2: Requirements for fire behaviour of materials and components
- Part 3: Fire resistance requirements for fire barriers
- Part 4: Fire safety requirements for railway rolling stock design
- Part 5: Fire safety requirements for electrical equipment including that of trolley buses, track guided buses and magnetic levitation vehicles
- Part 6: Fire control and management systems
- Part 7: Fire safety requirements for flammable liquid and flammable gas installations.

Of this series, Parts 1 and 2 are the most relevant to plastics in general and their fire behavior in particular, since they describe (amongst others) measures to minimize the possibility of ignition of materials installed on railway vehicles due to accidents or vandalism.

EN 45545-1

Part 1 covers the principal definitions used throughout the whole series, the Operation Categories and Design Categories, the fire safety objectives, and the general requirements for fire protection measures.

Railway vehicles are classified according to four Operation Categories:

- Operation Category 1: Vehicles for operation on infrastructure where railway vehicles may be stopped with minimum delay, and where a safe area can always be reached immediately (example: urban rail)
- Operation Category 2: Vehicles for operation on underground sections, tunnels and/or elevated structures, with side evacuation available, and where there are

stations or rescue stations that offer a place of safety to passengers, reachable within a short running time

- Operation Category 3: Vehicles for operation on underground sections, tunnels and/or elevated structures, with side evacuation available, and where there are stations or rescue stations that offer a place of safety to passengers, reachable within a long running time
- Operation Category 4: Vehicles for operation on underground sections, tunnels and/or elevated structures, without side evacuation available, and where there are stations (example: London Underground).

Note: the boundary between short and long running times is 4 min.

Additionally, railway vehicles are classified under the following Design Categories:

- A: Vehicles forming part of an automatic train having no emergency-trained staff on board
- D: Double-decked vehicles
- S: Sleeping and couchette vehicles
- N: All other vehicles (standard vehicles).

Clause 4 states that the objectives of EN 45545 are to minimize the probability of a fire starting, to control the rate and extent of fire development, and through this, to minimize the impact of the combustion products on passengers and staff. Here the standard distinguishes between fires resulting from accidental ignition or arson, fires resulting from technical defects, and fires resulting from larger ignition models.

Further, EN 45545-1 defines that when vehicles are being maintained and/or repaired, all items replaced shall either comply with the requirements of the EN 45545 series or shall, as a minimum, be of equivalent performance to the item replaced; all parts and components replaced during refurbishment shall comply with the requirements of the EN 45545 series.

EN 45545-2

In EN 45545-2, Hazard Levels (HL1 to HL3) are determined according to Table 11.8, using the definitions on Operation Categories and Design Categories, as given in Part 1.

Table 11.8 Hazard Level Classification

Operation Category	Design Category			
	N	A	D	S
1	HL1	HL1	HL1	HL2
2	HL2	HL2	HL2	HL2
3	HL2	HL2	HL2	HL3
4	HL3	HL3	HL3	HL3

In practice, around 70–90% of the commercial market is covered by HL2.

In EN 45545-2, the essential fire safety requirements are described as follows: “the design of rolling stock and the products used shall incorporate the aim of limiting fire development should an ignition event occur so that an acceptable level of safety is achieved”. The reaction-to-fire performance of materials and components depends on the nature of the base material, but also on the location of the products, their shape and layout, the surface exposed, and the mass plus thickness of the materials. For that reason, all known applications in railway rolling stock have been listed in the table called “Requirements of listed products”, which also includes the corresponding set of requirements that these products need to fulfill. In this table the listed products have been classified and differentiated into sub-groups, depending on their general location (interior or exterior) and specific use (e.g. furniture, electrotechnical equipment, mechanical equipment).

For those products that have not been listed in the table “Requirements of listed products” in the standard, one either has to follow the so-called “grouping rules”, or refer to Table 11.9.

Table 11.9 Requirements for Non-Listed Products According to the Exposed Area and Location in The Vehicle

Exposed area	Location	Requirement set
> 0.20 m ²	Interior	R1
	Exterior	R7
≤ 0.20 m ²	Interior	R22
	Exterior	R23

In EN 45545-2, some general principles are also given. Specifications apply for (as examples) cables, multilayer laminates, coatings, etc. Noteworthy in this respect is the following principle: *A test which qualifies any product or surface shall also qualify any product or surface which differs in color and/or pattern.*

This principle is different from the one given in the previous national railway standards. In the past the qualification had to be done on each material + color + thickness combination, making the amount of test work very large. This is now no longer required.

In EN 45545-2, the normative Annexes A through D play an important role. For seats, Annex A describes the standard vandalism test for seat coverings, and Annex B is devoted to the fire test method for complete seats.

Annex C describes in detail the test methods for determination of toxic gases from railway products, and Annex D gives the protocol how to prepare the test specimen for the various tests. These Annexes are an integral part of the 2013 version of EN 45545-2, including its Amendment A1 of 2015.

11.2.2.1.3 Requirements

As mentioned before, EN 45545-2 lists a large number of known applications (products) plus their corresponding sets of requirements. In the following section a selection of products and their requirement sets is described.

Wall Claddings, Ceilings, Partition Walls

Products with a relatively large surface area, such as wall claddings and partition walls (IN1A – Interior vertical surfaces) and ceilings (IN1B – Interior horizontal downward-facing surfaces) are linked to the **R1** set of requirements – which is the most stringent requirement set of this standard. Table 11.10 lists the tests that need to be performed and the classification limits for **R1**.

Table 11.10 R1 Set of Requirements

Reference	Test	Standard	Parameter	Test criteria	HL1	HL2	HL3
T02	Spread of Flame	ISO 5658-2	CFE [kW/m ²]	Minimum	20	20	20
T03.01	Heat Release	ISO 5660-1 at 50 kW/m ²	$MARHE$ [kW/m ²]	Maximum	–	90	60
T10.01	Smoke Density	ISO 5659-2 at 50 kW/m ²	$D_{s,4}$ [-]	Maximum	600	300	150
T10.02			VOF_4 [min]	Maximum	1200	600	300
T11.01	Toxicity		CIT_G [-]	Maximum	1.2	0.9	0.75

For these large surfaces both the spread of flame (according to ISO 5658-2 [5]) and the heat release (according to ISO 5660-1 [6]) performance are critical, as are the smoke density and toxicity (both according to ISO 5659-2 [7]).

Strips

When smaller strips of material (IN3A – Strips) are mounted on the walls, the spread of flame performance of the material can still be considered as critical, but the heat release performance no longer is. This is reflected in the **R3** set of requirements, listed in Table 11.11, which does not mention any heat-release requirements.

Table 11.11 R3 Set of Requirements

Reference	Test	Standard	Parameter	Test criteria	HL1	HL2	HL3
T02	Spread of Flame	ISO 5658-2	CFE [kW/m ²]	Minimum	13	13	13
T03.01	Heat Release	ISO 5660-1 at 50 kW/m ²	$MARHE$ [kW/m ²]	Maximum	–	–	–
T10.01	Smoke Density	ISO 5659-2 at 50 kW/m ²	$D_{s,4}$ [-]	Maximum	–	480	240
T10.02			VOF_4 [min]	Maximum	–	960	480
T11.01	Toxicity		CIT_G [-]	Maximum	1.2	0.9	0.75

Seat Shells

When one considers seat shells (F1C – Passenger seat shell – Base, and F1D – Passenger seat shell – Back), it becomes clear that heat release is a critical parameter, but the spread of flame is not. This is because the individual seats are not likely to be able to spread the fire easily. Table 11.12 covers the corresponding **R6** set of requirements, which does not list any spread-of-flame requirements.

Table 11.12 R6 Set of Requirements

Reference	Test	Standard	Parameter	Test criteria	HL1	HL2	HL3
T02	Spread of Flame	ISO 5658-2	CFE [kW/m ²]	Minimum	–	–	–
T03.01	Heat Release	ISO 5660-1 at 50 kW/m ²	$MARHE$ [kW/m ²]	Maximum	90	90	60
T10.01	Smoke Density	ISO 5659-2 at 50 kW/m ²	$D_{s,4}$ [-]	Maximum	600	300	150
T10.02			VOF_4 [min]	Maximum	1200	600	300
T11.01	Toxicity		CIT_G [-]	Maximum	1.2	0.9	0.75

Electrotechnical Equipment

For most electrotechnical equipment, including connectors, the dimensions and weights are relatively small. Therefore, it does not make sense to focus on spread of flame and/or heat release performance. Instead, for this class of products a different set of requirements has been defined – **R22**. Table 11.13 lists the requirements for **R22**.

Table 11.13 R22 Set of Requirements

Reference	Test	Standard	Parameter	Test criteria	HL1	HL2	HL3
T01	Oxygen Index	ISO 4589-2	OI [%]	Minimum	28	28	32
T10.03	Smoke Density	ISO 5659-2 at 25 kW/m ²	$D_{s,max}$ [-]	Maximum	600	300	150
T12	Toxicity	NF X 70-100 at 600 °C	CIT_{NLP} [-]	Maximum	1.2	0.9	0.75

In this set of requirements, the Oxygen Index – measured according to ISO 4589-2 [8] – has been listed to characterize the flammability performance of the used material. Spread of flame and heat release are not taken into account.

In this case, the toxicity performance of the material is determined using the French tube furnace test methods NF X 70-100-1 [9] and NF X 70-100-2 [10].

Keywords Index

- 1,2-bis(tetrabromophthalimide)ethane 63
- 1,3,5-tris(2,3-dibromopropyl) isocyanurate 101
- 1 kW nominal premixed-flame test, IEC 60695-11-2 662
- 3 m cube test 375
- 4,6-tris(2,4,6-tribromophenoxy)-1,3,5-triazine 104
- 9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide 62, 65, 106, 116
- 50 W horizontal flame test method, IEC 60695-11-10 665
- 50 W vertical flame test method, IEC 60695-11-10 666
- 500 W flame test method, IEC 60695-11-20 668
- ABS 57, 63, 68, 79, 81, 97, 104, 105, 114, 118
- absorption 27, 45
- acrylic 132, 142, 147
- acute effects of fire effluents 186
- acute toxicity 204, 674
- AEGL 229, 238
- aerosols 153, 154, 166, 171, 174, 220
- AFNOR (Association Française de Normalisation) 261
- afterglow 139, 143
- afterglow suppressant 79
- agglomeration 154
- air-conditioning ducts 584
- aircraft 627
- alkoxyamines 100
- aluminum diethyl phosphinate 76, 108, 110, 113, 116
- aluminum hypophosphite 77, 99, 105, 110
- aluminum trihydroxide (See also ATH) 53, 59
- Americas 293
- ammonium borate 176
- ammonium octamolybdate 175
- ammonium phosphate 143, 149
- ammonium polyphosphate (APP) 66, 72, 77, 99, 113, 117, 143, 178
- analytical methods 211, 215
- analytical methods for gas components 588
- analyzer 204, 208
- animal bioassays 223
- animal exposure 193
- ANSI (American National Standards Institute) 261
- anti-dripping agent 61, 106, 110–112, 114
- antimony trioxide (See also ATO) 62, 80, 102, 115, 118, 143, 147
- appliances 686
- Approved Document B, UK 466
- APTA (American Public Transportation Association) 571, 578
- ARHE (Average Rate of Heat Emission) 565
- aromatic nuclei 155
- Asia/Pacific 479
- asphyxiants 187, 222, 226, 229, 234, 235, 240

- ASTM (American Society for Testing and Materials) 298
- ATH 53, 55, 58, 59, 77, 100, 101, 113, 117–119
- ATO 62, 99, 102, 105–107, 109, 113, 115, 118, 119
- Australia 518, 607
- Austria 378
- automobiles 538
- average rate of heat emission *See* ARHE
- avis de chantier 400
- avis technique 399
- azoalkanes 72, 73
- AZONOR 73
- back-coatings 143, 144, 146, 147
- ball pressure test, IEC 60695-10-2 656
- barrier effect 56
- barrier materials 742
- BDP 67
- bedding 270
- bedding components 623
- Belgium 388
- binder, polymeric 48
- bio-based chemicals 81
- biphosphate resorcinol bis(dixylenyl phosphate) 67
- bis(pentabromophenyl) ethane 63, 144
- bisphenol A bis(diphenyl phosphate) 41, 67
- bis(tribromophenoxy)ethane 63
- blowing agent 48, 56, 72
- boehmite 58, 99, 100, 108, 110, 116
- bomb calorimeter 33, 47
- boron-based flame retardants 78
- Bouwbesluit 428
- brominated butadiene–styrene block copolymers 57
- brominated polystyrene 64, 107, 109, 112
- bromine-containing flame retardants 61, 62
- brucite 98
- BSI (British Standards Institution) 261
- Building Code of Australia 518
- Bunsen burner test, 45° 634
- Bunsen burner test, 60° 634
- buses 537–539
- bushfire 519, 526
- cable materials 101
- cables 369
- acidity 721
 - flaming droplets 720
 - large-scale testing 709
 - small-scale testing 705
 - smoke 719
- calcium borate 100, 176
- calorimeter
- micro combustion 47
- Canada 335
- carbonaceous layer 56
- carbon dioxide *See* CO₂
- carbonized acrylic fibers 148
- carbonized acrylics 143
- carbon monoxide (*See also* CO) 187, 198, 220, 674
- carbon nanotubes 59, 61, 101, 110, 114, 119
- carboxyhemoglobin 187, 224
- catastrophic fires 7
- CB scheme 675, 697
- CBUF program 754
- CCC mark 697
- cellulosics 143
- CE marking 694
- GENELEC (European Committee for Electrotechnical Standardization) 259, 375, 650, 691
- GENELEC TC 20 725
- CEN (European Committee for Standardization) 259, 282, 349, 556
- CEN/TC 127 (fire safety in buildings) 284
- CEN/TC 256 557, 569, 693
- CFD (Computational Fluid Dynamics) 755
- CFE (critical heat flux at extinguishment) 547, 561, 562, 564, 601, 603–606, 620
- CFR (Code of Federal Regulations, USA) 259, 299, 628
- chain reaction 43
- chain scission 35

- chain stripping 36
- chain transfer 34
- chair, railways Korea 604
- char 31
 - char layer 32
 - char yield 31
- char-forming 148
- characteristic heat flux for ignition
 - See CHFI
- charring 27, 34, 37
- chemical analysis of fire effluents 204
- CHFI (characteristic heat flux for ignition) 700
- China 479
- chlorinated cycloaliphatics 62
- chlorinated hydrocarbons 62
- chlorinated paraffin 62, 102, 119, 177
- chlorine-containing flame retardants 61, 62
- chronic effects of fire effluents 188
- CIB (International Council for Research and Innovation in Building and Construction) 263
- cigarette test 732, 734, 735, 744
- CIT (Conventional Index of Toxicity) 568
- CO (See also carbon monoxide) 187, 220, 221, 224, 227, 228, 235, 240
- CO₂ 220, 221, 226, 240
- coagulation and agglomeration 159
- coating, intumescent 48
- coatings 149
- code de la construction et de l'habitation 394
- code of design on building fire protection and prevention, China 479
- COHb 224, 225, 227, 228
- combustibility 255, 519, 520, 595
- combustion
 - efficiency 23, 33, 44
 - flaming 24
 - heat 27, 32, 47, 131
- combustion-modified foam 736
- combustion process 54
- combustion products 153
- combustion toxicology 219
- comparative tracking index See CTI
- condensed phase 41, 55, 56, 58, 60, 64, 65, 67, 76, 79, 103, 112
- conduction 24, 27
 - conductive heat transfer 28
- cone calorimeter 38, 47, 132, 163, 176, 273, 291, 312, 496, 500, 501, 517, 596, 750
 - time-to-ignition TTI 132
- confirmational test methods 669
- consumer equipment 698
- convection 27
- conventional index of toxicity See CIT
- corrosion damage 675
- corrosivity 110
- cotton 132, 142
- coupling agents 57, 100
- CPR (Construction Products Regulation) 259, 284, 287, 348, 692
- CPSC (Consumer Product Safety Commission, USA) 738
- CQC mark 697
- critical heat flux 271, 620
- critical heat flux at extinguishment See CFE
- critical radiant flux 310, 493
- cross-linking 37
- CSA (Canadian Standards Association) 690
- CTI (comparative tracking index) 684
- curtains 381
- curtains and drapes 393, 445, 491
- cushions mattresses 572
- decabromodiphenyl ethane 99, 101, 105, 107, 109, 116, 118, 119
- decabromodiphenyl oxide 144
- decking materials 742, 745
- decomposition
 - PET and PA 6 37
 - polymers 34
 - polyolefins 35
 - thermal 30
 - thermo-oxidative 29, 40
- decorating materials 586
- Denmark 432

- DEPAL 68, 76
depolymerization 34
design category 559
design type 600
diethylphosphinic acid salts 68
DIN (Deutsches Institut für Normung) 261
discotheque fires 6
disulfides 74
divisions, ships 623
DKE (German Electrotechnical Commission) 695
dodecachloropentacyclooctadeca-7,15-diene 62
DOPO 62, 65, 69, 106, 108, 110, 113–118, 120
DOPO-HQ 69
dose–response/effect model 219
DOT (U.S. Department of Transportation) 570
dwelling fire 130
dwellings 731
early fire hazard test 523
EASA (European Aviation Safety Agency) 628
EIFS (exterior insulation finish systems) 332
elastomers 97, 119
electrical appliance and material safety act Japan 696
electrical cables 548
electrical engineering 647
electrical equipment 648
electric locomotives 581
electric wires and cables 634
electrotechnical equipment 562
endothermic decomposition 58
end-product testing 648
EN (European standard) 283
environmental effects of fire effluents 189
environmental pressure 147
EPDM rubber 103
epoxy resin 63, 68, 97, 115, 116
EPS 105
equivalence ratio 220
ERPG 229
établissements recevant du public 394
ETICS (External Thermal Insulation Composite System) 385, 387, 409, 414
ethylene bis(tetrabromophthalimide) 101, 112
ethylenediamine 99
euroclasses 350
Europe 348
European General Product Safety Directive 729
European Union 348
EVA (ethylene-vinyl acetate) 58, 59, 66, 96, 100, 101, 119
EXAP (extended application) 349
expandable graphite 77, 105, 118
exposure 187, 221, 238
exposure concentration 231
exterior cladding 533
exterior fire exposure tests 329
exterior wall assemblies 331, 332
exterior walls 438
external fire exposure 408
external fire spread 445
external sheeting 592
external wall covering systems 463
extinction coefficient 164, 169, 170
FAA (Federal Aviation Administration) 259, 628
fabric 133, 572, 742
– cotton 133
fabrics and films 343, 344, 521
façades 383, 396, 409, 413, 445, 463, 474, 497, 504, 510
– intermediate scale test 279
– large-scale test 279
FAR (Federal Aviation Regulations) 628
FDS (Fire Dynamics Simulator) 755
FEC (fractional effective concentration) 235
FED (fractional effective dose) 234, 240, 584
FIGRA (fire growth rate) 133, 360, 362

- filling/padding component 742
- fillings 735
- filtering system 206
- finishing materials 513
- Finland 432
- fire
 - fully developed 47
 - well-ventilated 47
- fire behavior 27
- fire cause 6
- fire classification 350
- fire effluents 153, 171, 185, 215, 219, 650
- fire enclosure 689, 690
- fire fatalities 11, 14, 16, 17
- firefighters 10, 11
- firefighters' clothing 141
- fire growth rate *See* FIGRA
- fire hazard 23
- fire hazard assessment 652
- fire hazard assessment of cables 705
- fire hazard testing 705
- fire hazard testing, IEC TC 89 650
- fire hazard tests for end-products 655
- fire injuries 17
- fire load 47
- fire losses 19
- fire modeling 154, 281
- fire performance 25
- fire prevention 3
- fire propagation apparatus 275
- fire propagation test 468
- fire protection 3, 4, 9
- fire regulations and standards in Asia 696
- fire resistance 47
- fire resistance tests 325
- fire-resistive construction 500
- fire retardant materials 500, 514
- fire risk 653
- fire risk assessment 222
- fire safety engineering 198, 203, 268
- fire safety regulations and test standards in China 697
- fire scenario 25, 44, 221, 653
- fire spread 45, 255
- FIRESTARR 557
- fire statistics 7, 8, 10-14, 16, 17, 21, 731
 - fatalities 129
 - ships 610
 - UK 129
 - vehicles 538
- fire threat 171
- fire ventilation 220
- first item ignited 6
- flame
 - diffusion 42
 - premixed 42
- flame inhibition 44
- flame inhibitor 41
- flame penetration test, aircraft 641, 643
- flame propagation test, aircraft 642
- flame retardant 65, 118, 143, 147
- flame-retardant cellulosic blends 144
- flame retardant classes 57
- flame-retardant cottons 143
- flame retardant efficiency 54
- flame retardant materials 514
- flame retardant reactive 67, 115, 117
- flame retardants 53, 173, 652
- flame retardants, chemical action 55
- flame retardants in furniture 755
- flame retardants, mode of action 54
- flame retardants, physical action 55
- flame-retardant synthetic fibers 146
- flame-retardant textiles 142
- flame-retardant viscose 144
- flame-retarded plastics 53, 95
- flame-retarded wool and blends 145
- flame spread 42, 269
 - flow 46
 - velocity 46
- flame-spread rating 345
- flame zone 43, 55, 61
- flammability 26
- flammability class 585
- flammability test 140
- flammability testing, aircraft 631
- flammable solids 308
- floor covering 306, 310, 312, 340, 347, 365, 405, 532

- flooring radiant panel test 574
floorings 272, 352, 489, 493, 519, 526, 604
fluoropolymers 80
FMVSS (Federal Motor Vehicle Safety Standards) 541
fogging 62
Fourier transform infrared spectroscopy
 See FTIR
fractional effective concentration *See* FEC
fractional effective dose *See* FED
FRA (Federal Railroad Administration) 570
France 394
FSS Code (Fire Safety Systems Code) 614
FTIR (Fourier Transform Infrared Spectroscopy) 567, 618
functional requirements, ships 615
furnishings 325, 729
furniture 497, 729
 – burning rate 750
furniture and bedding 392
furniture calorimeter 746, 751
gas analysis 193
gas bags 211
gas burners 254
gas concentration FTIR 275
gas phase 43, 54–56, 61, 64, 65, 76
gas-solution absorbers 208, 209
General Product Safety Directive 135
generation of fire effluents 193
Germany 403
glowing and smoldering combustion 255
glowing cigarette 733
glow wire flammability index *See* GWFI
glow-wire flammability test 658, 663
glow-wire ignitability test 664, 685
glow wire ignition temperature *See* GWIT
glow wire test 38, 657
glow wire test for end products *See* GWEPT
GPSR (General Product Safety Regulations 2005) 732
graphene 61, 101
GS-mark 694–696
GWEPT (glow wire test for end products) 657, 701
GWFI (glow wire flammability index) 663, 664, 697, 701, 704
GWIT (glow wire ignition temperature) 664, 665, 685, 697, 701, 704
HAI (high-current arc ignition) 684
halogenated dibenzodioxins and furans 189
halogenated flame retardants 53, 55, 57, 61, 174, 177
halogen-free flame retardants 178
HALS 73
hazard level, rail vehicles 559, 601
HBCD (hexabromocyclododecane) 57, 105, 144
HBr *See* hydrogen bromide
HCl *See* hydrogen chloride
HCN *See* hydrogen cyanide
heat capacity 39, 58
heat evolved, total 47
heat flux 28, 55, 98
 – effective heat flux 31
 – external 40, 44
heat flux meters 280
heat release rate *See* HRR
heat release parameter 44
heat-resistant fibers 148
heat shielding effect 45
heat transfer 27
hemoglobin 187, 224
HET acid 62
hexachloro-endo-methylenetetrahydrophthalic acid 62
high-current arc ignition test 687
high-performance polymers 114
high-rise building 4, 11
high-speed craft 624, 625
high-voltage arc resistance to ignition 685
high-voltage, low current, dry arc resistance 684
high-voltage tracking resistance *See* HVTR

- HIPS (high-impact polystyrene) 63, 67, 104, 105, 115
- Home Furnishings and Thermal Insulation Act 739
- horizontal Bunsen burner test 633
- horizontal ladder test methods 718
- hot-wire ignition test 687
- household appliances 698
- HR (heat release) 273, 312, 505, 561, 564, 597, 635, 670, 751
- HRR (heat release rate) 32, 38, 44, 45, 59–61, 131, 273, 277, 584, 751
- Hungary 413
- huntite 100
- HVTR (high-voltage tracking resistance) 684
- HWI (hot-wire ignition) 684
- hydrogen bromide 61, 64, 188
- hydrogen chloride 61, 113, 188, 238
- hydrogen cyanide 187, 220, 221, 224, 235, 240
- hydrogen fluoride 188
- hydrogen halides 56, 61, 63
- hydromagnesite 100
- hypoxia 188, 224
- IAMFTF (International Aircraft Materials Fire Test Forum) 644
- IC₅₀ 219
- ICAO (International Civil Aviation Organization) 135, 260
- ICC (International Code Council) 294
- Iceland 432
- IEC 258, 649
- IEC (International Electrotechnical Commission) 257, 649
- IEC TC 20 705, 709, 717
- IEC TC 46 709
- IEC TC 61 699
- IEC TC 89 699
- IEC TC 89 guidance 654
- IEC TC 89 Liaisons 651
- IFC (International Fire Code) 739
- ignitability 255
- ignition 38, 269, 312
- time to ignition 28, 39
- ignition source 38, 254
- ignition temperature 304
- immeubles de grande hauteur 394
- IMO (International Maritime Organization) 135, 260, 263, 268, 271, 273, 275, 277, 609
- IMO MSC (IMO Maritime Safety Committee) 610
- IMO Resolution A.653 (16) 563
- incapacitation 190, 219, 222, 232, 237, 238, 240
- industrial facilities 443, 446
- inhalation exposure 219
- inhalation toxicity 224, 226
- inhalation toxicology 234
- inherently flame retardant 146
- inherently flame-retardant synthetic fibers 147
- inherently flame retarded 23
- inorganic fillers 57, 60
- inorganic flame retardants 57, 58, 108, 113
- insulation 519, 593, 605
- aircraft 642
- interior ceiling and wall panels
- aircraft 630
- interior decorative materials 584
- interior finish materials 321, 345
- interior panel 603
- interior products 350
- interior structural materials 584
- interior surfaces 561
- interliners 736
- intermediate-scale calorimeter (ICAL) 275
- international certification 675
- interoperability 557
- intoxication 187
- intumescence 56, 64, 71, 77
- intumescent 99, 102, 119
- intumescent systems 148
- intumescent textiles 149
- Ireland 732
- irradiation 39
- irritants 188, 220, 222, 235, 238

- ISO (International Organization for Standardization) 10, 257, 261, 649
- ISO/TC 61 675
- ISO/TC 92 10, 262, 619, 672
- ISO/TC 92/SC1 264
- ISO/TC 92/SC3 674
- ISPA (International Sleep Product Association) 748
- Italy 417
- Japan 499, 591
- JAR (Joint Aviation Requirements) 259
- JISC (Japanese Industrial Standards Committee) 261
- JRMA (Japan Railway Rolling Stock & Machinery Association) 598
- Korea 512, 599
- laboratory-scale tests 254
- Landesbauordnung 404
- large-scale tests 256, 276, 291
- lateral flame spread 271
- layered double hydroxides 60, 99, 119, 179
- LC₀₁ 220, 222, 224, 229, 235, 238, 240
- LC₅₀ 192, 198, 219, 230, 231, 235
- lethality 190, 191, 237
- lignin 81
- limiting oxygen index *See* LOI
- limit of detection 216
- linear pipe thermal insulation products 351
- lining materials 532
- liquid smoke aerosols 160
- listed products 560
- LOI (limiting oxygen index) 38, 80, 99, 103, 115, 116, 118, 131, 133, 136, 139, 145, 148, 176, 290, 494, 495
- LSC (Life Safety Code) 739
- LVD (Low Voltage Directive) 692
- magnesium dihydroxide *See* MDH
- magnesium hydroxide (*See also* MDH) 59, 79
- manikin 141
- MARHE (maximum average rate of heat emission) 565, 584
- mattresses 732, 734, 740, 746, 748
- mattress smoldering test 740
- maximum average rate of heat emission *See* MARHE
- MDH 58, 77, 98, 100, 103, 105, 108, 113, 117, 119
- MD (Machinery Directive) 692
- Meeker burner (also Meker burner) 314
- Meker burner (also Meeker burner) 515, 516
- melamine 72, 77, 78, 117
- melamine condensates 78
- melamine cyanurate 78, 108, 110, 113, 117
- melamine phosphate 149
- melamine poly(metal phosphates) 116
- melamine polyphosphate 66, 68, 77, 103, 108, 110, 116, 117, 178
- melting behavior 545
- metal hydroxides 57
- methenamine pill test 306
- MHCLG (Ministry of Housing, Communities and Local Government, China) 736
- mineral fillers 57
- MLIT (Ministry of Land, Information, Transport and Tourism, China) 591
- modacrylics 147
- model box test 502, 503
- model predictions 754
- MOLIT (Ministry of Land, Infrastructure and Transport, China) 512
- molybdenum compounds 79
- molybdenum oxide 177
- molybdenum trioxide 175
- montmorillonite 103, 119
- montmorillonite clay 60
- motor vehicles 537
- MPP *See* melamine polyphosphate
- Musterbauordnung, Germany 404
- MVV TB (Muster-Verwaltungsvorschrift Technische Baubestimmungen), Germany 412
- N-alkoxy hindered amines 72
- nanoclays 100

- nanocomposites 45, 59, 99, 104, 106, 110, 121, 128
- NBCC (National Building Code of Canada) 335
- NCC (National Construction Code, Australia) 518
- needle-flame test 660, 686
- Netherlands 428
- NFPA (National Fire Protection Association) 6, 299
- NHTSA (National Highway Traffic Safety Administration) 541
- nightwear 135
- NIST (National Institute of Standards and Technology), USA 8, 9, 740, 748
- nitrogen-containing flame retardants 77
- nitrogen oxides 188
- non-combustibility 269, 339, 357, 617
- non-combustible 289, 513
- non-combustible materials 501
- non-harmonized construction products 382
- NOR 72, 73
- NOR 116 142
- Nordic countries 432
- NORDTEST 434
- Norway 432
- novoloid 143
- NT FIRE 434
- NTIS (National Technical Information Service) 631
- nucleation 157
- number of fires 12
- nylon fabrics 146
- office equipment 698
- Ohio State University calorimeter 132, 636
- OIB (Österreichisches Institut für Bautechnik, Austrian Institute of Construction Engineering) 378
- OIB (Österreichisches Institut für Bautechnik, Austrian Institute of Construction Engineering)-Guidelines 379
- opacimeters 163
- open corner test 321
- open flame tests 746
- operation category 558, 600
- optical density 164, 575
- organoclays 59
- OSNR (Office of the National Rail Safety Regulator), Australia 607
- OTSZ (Hungarian Fire Safety Code) 413
- oxygen consumption calorimeter 312
- oxygen index (See also LOI, limiting oxygen index) 562, 585
- oxyhemoglobin 187
- oxyimides 72, 100
- pallets 323
- parallel panel test 323
- particle oxidation 160
- particle size 59
- partitions, aircraft 630
- partition walls 561
- passenger compartment 593
- PC/ABS 41, 112
- pentabromobenzyl acrylate 144
- pentaerythritol 71, 149
- perfluorinated sulfonate salts 114
- perimeter fire barriers 329
- peroxide compounds 73
- phenolic formaldehyde resins 118
- phenoxyphosphazenes 68
- phosphate esters 67
- phosphorus-containing flame retardants 57, 62, 64, 112, 113
- photovoltaic 333
- PHRR (peak heat release rate) 60, 75, 81, 99, 101, 132, 748
- physical fire models 193, 195
- plasticizing effect 56, 68, 112
- plenum areas 718
- Poland 435
- polyacrylates 106
- polyacrylonitrile 105
- polyamide 62, 97, 107
- polyamide 6 63, 79, 107, 108
- polyamide 6.6 107
- polyaramide 143, 148
- poly(aramid-aramid) 143, 148

- polybenzimidazole 143, 148
- polybrominated diphenyl ethers 63
- polybutylene terephthalate 62, 63, 109
- polycarbonate 63, 64, 67, 68, 79, 80, 97, 111, 115
- polycarbonate blends 111
- polychloroprene 119
- polycyclic aromatic hydrocarbons (PAHs) 155, 189
- polydibromophenylene oxide 64
- polyester 142, 147
- polyester/cotton 132, 144
- polyesters 97, 109
- polyethersulfones 115
- polyethylene 96, 100
- polyimides 115
- polylactic acid 109, 111
- polymeric brominated polybutadiene–polystyrene (BrPBPS) 63
- polymeric flame retardants 53, 56, 68, 70
- polymeric metal polymelaminephosphate 108
- polymeric methylphosphonates 68
- polymethacrylate 97
- poly(methyl methacrylate) 106, 155
- polyoxymethylene 97, 106, 155
- poly(pentabromobenzyl acrylate) 64, 101
- polyphthalamides 108
- polypropylene 96, 98, 142, 155
- polypropylene fabrics 146
- polystyrene 155
- polystyrene-brominated butadiene–polystyrene block copolymers 101
- polystyrene-brominated polybutadiene–polystyrene block copolymer 105
- polystyrene foam 41
- polystyrene 96, 104
- polysulfone 115
- polytetrafluoroethylene (*See also* PTFE) 41, 61, 114
- polyurethane 62, 97, 117
- polyurethane foams 117
- polyvinylchloride (*See also* PVC) 97, 113, 142
- polyvinylidene chloride 114, 142
- polyvinylidene fluoride 114
- POSS 80
- potassium perfluorobutane sulfonate 111
- potential heat 308
- PRC (People’s Republic of China) 579
- preselection of materials 662
- preselection testing 648
- preselection tests for materials 655
- primary deck coverings 621
- printed circuit boards 63, 68, 115
- probes 205
- property insurers 251
- protective clothing 140
- protective layer 55, 56, 61, 77
- PTFE 97, 104, 105, 109–112, 114
- public areas 736
- PVC 113, 174
- pyrolysis 24, 27, 44, 130
 - anaerobic pyrolysis 29
 - polymer 24, 38, 43
 - zone 25
- pyrolysis products 58
- pyrotechnics 6
- quantitative risk assessment of fire effluents 190
- quasi-non-combustible materials 500, 502
- radiant ignition sources 255
- radiant panel 272
- radiant panel flame spread test to ASTM E162 682
- radiation 24
- radical 34, 56, 61, 65, 66, 72
 - forming agents 57, 72, 74
 - free 43
 - generator 35, 41, 100
 - hydroxyl 43
 - mechanism 55
- rail vehicles 135, 554, 693
- railway rolling stock cables 725
- railway sleepers 597
- RD (Royal Decree, Belgium) 388

- REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) 756
- reaction to fire 289, 357, 361, 377, 391, 405, 408, 500
- reactive flame retardants 53
- recycling 54, 80
- red phosphorus 66, 101, 105, 113, 117
- reference gas components concentrations 587
- reference scenario for cables 371
- Regulation (EU) No. 305/2011 293
- relative thermal index *See* RTI
- repeatability 203, 217
- reproducibility 203, 217
- resorcinol bis(diphenyl phosphate) 67, 112, 115
- respiratory tract irritants 229
- respiratory ventilation 228
- retreat effect 56, 75
- Riser test UL 1666 715
- roof coverings 329, 330, 366, 433, 460, 467
- roof deck construction 323
- roofing assemblies 320
- roofs 291, 365, 366, 397, 408, 429
- room calorimeter 752
- room corner test 273, 276, 318, 360, 502
- RTI (relative thermal index) 685
- rubber materials 584
- SAC (Standardization Administration of the People's Republic of China) 261
- sampling conditions 208
- sampling line 205, 207
- sandwich panels 488, 507
- large room test 278
 - small room test 278
- SBI (single burning item) 291, 360, 361, 493
- Schlyter test 382
- seats 560, 583, 584, 594
- seat shells 562
- selectivity 215
- semi-non-combustible 514
- sensitivity 215
- Setchkin furnace 304
- ships 609
- side effects of a fire 669
- side effects of cable fires 719
- silicon-containing compounds 79
- silicone rubbers 120
- silk 132
- silsesquioxanes 80
- SI (Statutory Instrument, UK) 732
- single burning item *See* SBI
- small flame test 269, 732
- small room test 266
- pipe insulation 278
- small scale tests 193
- SMOGRA (smoke growth rate) 362
- smoke 256
- smoke and toxicity 618
- smoke and toxicity from fire effluents 185
- smoke box 375
- smoke density 309, 495, 561, 566
- smoke developed classification 345
- smoke development and measurement 153
- smoke emission
- aircraft 637
- smoke formation 179
- smoke generation 154, 173, 275, 588
- smoke inhalation 185
- smoke measurement 165
- smoke obscuration 234, 274, 564, 672
- smoke opacity 162, 672
- smoke production 161, 273
- smoke production rate *See* SPR
- smoke suppressants 78, 79, 114, 173
- smoke suppressants for PVC 174
- smoke suppression 61, 79, 147
- smoke toxicity 185, 193, 497
- smoldering 38, 40, 364, 740
- smolder resistance 739
- soft upholstery 734
- SOLAS (International Convention for the Safety of Life at Sea) 609, 612
- solid sorption tubes 210

- soot 171
 - particles 155, 156, 160
 - production rate 170
 - yield 154
- Spain 442
- SPCS (Sleep Products Safety Council) 748
- SPR (smoke production rate) 277, 312
- spread of flame 271, 561, 563
- Steiner tunnel 315, 317, 718
- stowage compartments
 - aircraft 630
- styrene butadiene rubber 119
- styrene copolymers 105
- substantial component, building 356
- sulfenamides 72, 100
- sulfur-based compounds 72
- sulfur dioxide 188
- surface burning characteristics 315, 340
- surface flammability 573, 574, 620
- surface spread of flame, IEC 60695-9-1 669
- surface spread of flame test BS 476 part 7 470
- Sweden 432
- Switzerland 451
- synergist 62, 72, 77, 79, 108, 109, 116, 120, 147
- synergistic 101
- synergistic effect 56, 58, 75, 79
- TBBA (tetrabromobisphenol A) 63, 64, 116
- technical building code Spain 442
- test mark 251
- testo unico di prevenzione incendi, Italy 418
- tetrabromobisphenol-A-bis(2,3-dibromopropylether) 63, 101
- tetrabromophthalate diol 63
- tetrabromophthalate ester 64
- tetrabromophthalic anhydrides 63
- tetrakis(hydroxymethyl)phosphonium (THP) salt 143
- textile fibers and fabrics
 - burning behavior 130
- textiles 129
 - fire regulations 134
 - flammability testing 134
 - test categorization 136
- textiles and films 313, 622
- The Building Regulations UK 465
- thermal conductivity 55, 58
- thermal decomposition 36
- thermal degradation 196
- thermal inertia 28
- thermal insulation 47, 584
- thermally thin 25, 29
- thermal stability 36
- thermal transitions fibers 131
- thermofixation 146
- thermogravimetry 30
- thermoplastic polyurethanes 112
- thermoplastics 98
- thermosets 115
- THR (total heat release) 44, 132, 748
- timber 334, 346, 533
- time-dose-response 235
- total heat release *See* THR
- toxicants 199, 220, 228
- toxic combustion gases 755
- toxic effect 191, 193
- toxic endpoints 229
- toxic gases 751
- toxic hazard assessment 672
- toxic hazards 221
- toxicity 256, 502, 510, 514, 561, 567
 - aircraft 637
 - fire effluent 674
 - testing 199, 200, 202
- toxic load model 236
- toxicological hazard assessment 222
- toxicological risk assessment 234
- toxic potency 194, 198, 214, 674
- TRANSFEU 557
- translational toxicology 223
- transportation 259
- transportation fires 7
- trihydroxymethylphosphine oxide 70
- triphenyl phosphate 67, 118
- tris(1,3-dichloro-2-propyl)phosphate 62

- tris(1-chloro-2-propyl)phosphate 117
- tris(2-chloroethyl)phosphate 62, 117
- tris(chloroisopropyl)phosphate 62
- tris(tribromoneopentyl)phosphate 99, 101, 142
- tris(tribromophenyl)cyanurate 105
- tube furnace 398
- UFAC construction criteria 742
- UFAC test rig 742
- UFAC (Upholstered Furniture Action Council, USA) 739
- UIC (Union Internationale des Chemins de Fer) 260
- UL 94 flammability tests 678
 - 5 V 680
 - HB 666, 678
 - HB 40, HB 75 665, 678
 - HBF, HF-1, or HF-2 680
 - V-0 59, 67, 68, 73, 99, 100, 102, 114, 118
 - V-0, V-1, and V-2 679
 - V-2 59
 - VTM-0, VTM-1, and VTM-2 679
- UL 746 C 653
- UL listing 678
- UL listing mark 677
- UL product directories 677
- UL recognized component directory 678
- UL standards for safety 677
- UL (Underwriters' Laboratories) 297, 676
- under-ventilated fire 171
- UNECE (United Nations Economic Commission for Europe) 260, 539
- United Kingdom 465, 732
- United States of America 293, 738
- unsaturated polyesters 97, 118
- upholstered furniture 129, 270, 302, 385, 397, 425, 426, 445, 491, 492, 497, 622, 732
- Upholstered Furniture (Safety) Regulations 732
- VDE mark 694, 695
- VDE regulations and approval procedures 694
- vehicle fires 537
- ventilated fire 171
- ventilation-controlled fires 220
- vertical burning test single insulated wire or cable 705, 709
- vertical flame propagation test 644
- vertical ladder test methods 709
- vertical tube furnace 307
- visas de façades 401
- viscose 133, 142
- viscosity 25, 41
- visibility 153, 162, 169, 170
- VKF Fire Protection Register 464
- VKF Guidance 452
- VKF (Vereinigung Kantonaler Feuerversicherungen) 451
- volatile fuel production 27
- volatile hydrocarbons 189
- wall and ceiling linings 519, 525
- well-ventilated fires 199, 220
- welt cord 742
- wire and cable 491, 584
- wires 605
- wood crib 255, 737
- wool 132, 133, 142
- XPS 105
- yarn 133
- yellow card 678, 690
- zeolites 72
- zinc borate 78, 99, 119, 176, 179
- zinc hydroxystannate 79, 99, 147, 175, 177, 179
- zinc stannate 79, 108, 147, 175, 177, 178