## **Contents**

Foreword V Preface to the Second Edition XVII List of Contributors XIX List of Symbols and Abbreviations XXIII

## Part One Measuring Organic Indoor Pollutants

1	Application of Solid Sorbents for the Sampling of Volatile Organ Compounds in Indoor Air 3		
	Erik Uhde		
1.1	Introduction 3		
1.2	Solid Sorbents – A Brief Overview 4		
1.3	Active or Passive Sampling 7		
1.4	Thermal Desorption or Solvent Extraction 8		
1.5	Sampler Design 8		
1.6	Breakthrough Volumes 11		
1.7	Safe Sampling Volume 11		
1.8	Artifacts and Interferences 12		
1.8.1	Water Affinity – A Chromatographic Problem 12		
1.8.2	Sorbent Degradation Products and Sorbent Background 13		
1.8.3	Target Compound Degradation and Artifact Formation 15		
1.9	Conclusions 16		
2	Sampling and Analysis of SVOCs and POMs in Indoor Air 19		
	Per Axel Clausen, Vivi Kofoed-Sørensen		
2.1	Introduction 19		
2.2	Definitions and Properties of SVOCs and POMs 19		
2.2.1	Gas/Particle Partitioning in Indoor Air 20		
2.2.2	Surface Adsorption 21		
2.2.3	Health Related Properties 22		
2.3	Compounds and Matrices in the Indoor Environment 22		
2.4	Sampling, Transport and Storage of SVOC/POM Samples 23		
2.4.1	Preparation of Sampling and Analysis Equipment 23		

Organic Indoor Air Pollutants. 2nd Edition. Edited by Tunga Salthammer and Erik Uhde Copyright © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim ISBN: 978-3-527-31267-2

VIII	Contents

2.4.1.1	Background Contamination and Loss of Target Compounds 23
2.4.1.2	Cleaning of Filters 24
2.4.1.3	Cleaning of Sorbents 24
2.4.1.4	Cleaning of Glassware and Other Equipment 24
2.4.2	Sampling SVOCs/POMs in Air 25
2.4.2.1	Filter/Sorbent Sampling 25
2.4.2.2	Determination of the Gas/Particle Partitioning: Denuder Sampling 26
2.4.2.3	Artifact Formation Caused by Reactive Gases in Indoor Air 26
2.4.2.4	Air Sampling Pumps 27
2.4.3	SVOCs/POMs in Surface Dust 27
2.4.3.1	Filter Sampling with Vacuum Cleaner 27
2.4.3.2	Specially Designed Dust Sampler 28
2.4.4	SVOCs/POMs in Building Materials and Consumer Products 28
2.4.4.1	Indoor Material Samples Containing SVOCs/POMs 28
2.4.4.2	Testing Emission of SVOCs from Indoor Materials in Chambers 28
2.5	Preparation of SVOC/POM Samples for Analysis 30
2.5.1	Extraction of SVOCs/POMs from Samples 30
2.5.1.1	Cleaning of Extraction Equipment 31
2.5.2	Concentrating Extracts of SVOC/POM Samples 32
2.6	Analysis of SVOCs/POMs 32
2.6.1	Gas Chromatography (GC) 32
2.6.1.1	On-Column Injection (OC) 34
2.6.1.2	Large Volume Injection (LVI) 34
2.6.1.3	Thermal Desorption (TD) 34
2.6.1.4	'Cold Spots' and Other Adsorption Problems 35
2.6.1.5	Flame Ionization Detection (FID) 35
2.6.1.6	Mass Spectrometric Detection (MS) 35
2.6.2	High Performance Liquid Chromatography (HPLC) 36
2.6.2.1	HPLC with Fluorescence Detection (HPLC-FD) 36
2.6.2.2	HPLC with Mass Spectrometric Detection (LC-MS) 36
2.6.3	Analysis Sequences 36
2.7	Quality Assurance and Control 37
2.7.1	Method Validation 37
2.7.1.1	Calibration Curves 39
2.7.1.2	Limit of Detection (L <sub>D</sub> ) and Limit of Quantification (L <sub>Q</sub> ) 39
2.7.2	Controls and Control Charts 41
2.7.3	Documentation 41
	References 42
3	Application of Diffusive Samplers 47
	Derrick Crump
3.1	Introduction 47
3.2	Principles of Diffusive Sampling 48
3.3	Selection of Appropriate Methods 50
3.4	Performance of Diffusive Samplers for the Measurement of VOCs in
	Indoor Air 50

3.5	Studies of VOCs in Indoor Air Using Diffusive Samplers 53
3.6	Other Applications of Diffusive Samplers 59
3.7	Conclusion 59
	References 60
ŀ	Real-Time Monitoring of Indoor Organic Compounds 65
	Yinping Zhang, Jinhan Mo
l.1	Introduction 65
1.2	Proton Transfer Reaction – Mass Spectrometer (PTR–MS) 66
1.2.1	Detection Principles 66
1.2.2	Measuring Method 68
1.2.3	Accuracy, Linearity, Limits of Detection and Precision 69
1.2.4	Applications of PTR–MS 72
1.3	Photo-acoustic Spectroscopy 73
l.3.1	Detection Principles 73
1.3.2	Measuring System and Method 74
1.3.2.1	Discrete Sampling: Nondispersive PAS 74
1.3.2.2	Discrete Sampling: FTIR/PAS 76
1.3.2.3	Continuous Flow-PAS 76
1.3.3	Selectivity, Sensitivity and Accuracy 77
1.3.4	Applications of PAS 78
1.4	Flame Ionization Detection 78
1.4.1	Detection Principle 79
1.4.2	Measuring System and Method 79
1.4.3	Selectivity and Sensitivity 80
1.4.4	Applications of FID 80
ł.5	Photo-ionization Detection 80
1.5.1	Detection Principles 81
1.5.2	Selectivity and Sensitivity 81
1.5.3	Applications of PID 82
1.6	Metal Oxide Sensors 83
1.6.1	Measuring Principle 83
1.6.2	Selectivity and Sensitivity 86
1.7	Air Sampling and Data Recording 87
1.8	Examples of Investigations Using Real-Time Monitoring 87
1.8.1	Laboratory Investigations of VOC Emissions from Building
	Materials 87
F.8.1 <i>.</i> 1	Experimental Principle 88
1.8.1.2	Experimental System 88
1.8.2	Organic Compounds in Outdoor Air 90
1.8.3	The Effect of Photocatalytic Oxidation on VOC Removal 91
1.8.3.1	Detection of Harmful By-Product During the Removal of Toluene by PCO 92
1.8.3.2	Evaluating the Formaldehyde Removal Performance of PCO
1.0.3.2	Reactors 94
	ICCCCIOIS JT

x	Contents	
	4.8.4	Products of Ozone-Initiated Chemistry in a Simulated Aircraft Environment 94
	4.9	Concluding Remarks 96 Acknowledgments 97 References 97
	5	Environmental Test Chambers and Cells 101 Tunga Salthammer
	5.1	Introduction 101
	5.2	Characteristics of Chambers and Cells 102
	5.3	Sink Effects 105
	5.4	Calculation of Emission Rates 106
	5.5	Kinetics and Mass Transfer 108
	5.6	Application of Test Chambers and Cells 109
	5.7	Final Remarks 112
		References 113
		Part Two Investigation Concepts and Quality Guidelines
	6	Standardized Methods for Testing Emissions of Organic Vapors from Building Products to Indoor Air 119 Elizabeth Woolfenden
	6.1	Introduction: The Need for Standardization 119
	6.2	Materials Emissions Testing: A Challenge for Method
	5.2	Standardization 120
	6.2.1	The Range of Products and Materials Requiring Emissions
		Testing 121
	6.2.2	The Range of Potential Target Compounds 121
	6.2.3	Method Variability or Uncertainty 130
	6.2.4	Nonuniformity of Test Methods 130
	6.3	Regulations, Standard Methods and Test/Certification
		Protocols 131
	6.4	Emissions Test Methods for VOCs: An Overview of Basic
		Principles 133
	6.4.1	Standard test Methods for Formal Evaluation and Certification of
		Emissions 133
	6.4.2	Secondary or 'Screening' Methods for Materials Emissions 134
	6.5	The Total-VOC Debate 137
	6.6	Standard Methods and Protocols for Emissions Testing: Current
		Status 138
	6.6.1	Typical Conditions for Emissions Testing Using Chambers/Cells 138

Standard Methods: What Can Go Wrong?

6.6.2.1 Effect of the Emission Mechanism 139

139

6.6.2

6.6.2.2	Collection and Transport of Samples Plus Homogeneity Issues 140		
6.6.2.3	Potential Variables Associated with Testing Materials Using Emissions		
	Chambers/Cells: Edge Effects, Sample Orientation and Sample Storage		
	Between Tests 140		
6.6.2.4	Sink Effects 141		
6.6.2.5	Target Analytes and System Calibration 141		
6.6.2.6	· · · · · · · · · · · · · · · · · · ·		
6.7	Confidence Limits for Emissions Test Data for Individual VOCs 143		
6.8	Concluding Remarks 143		
	Acknowledgments 144		
	References 144		
7	Standard Test Methods for the Determination of VOCs and SVOCs in		
	Automobile Interiors 147		
	Michael Wensing		
7.1	Introduction 147		
7.2	Conditioning of the Automobile Interior 149		
7.3	Measurement Procedure 151		
7.3.1	Quantitative Determination 152		
7.3.2	Semi-Quantitative Determination of VOCs (TVOC) 154		
7.3.3	Qualitative Determination of VOCs (Identification) 154		
7.3.4	Identification of SVOCs (Fogging Precipitate) 155		
7.3.5	Measurement of the Sum of Organic Substances (ΣVOC) 155		
7.4	Quantitative and Qualitative Results from Brand New Cars 156		
7.5	Emissions of Organophosphate Esters inside Automobiles 159		
7.6	Conclusion 161		
	References 161		
8	Material and Indoor Odors and Odorants 165		
	Florian Mayer, Klaus Breuer, Klaus Sedlbauer		
8.1	Introduction 165		
8.2	Odor Evaluation 167		
8.2.1	Indoor Environments 167		
8.2.2	Materials 168		
8.2.3	Panels and Scales 168		
8.3	Odor Analysis-Odorant Identification 172		
8.3.1	Methods 172		
8.3.1.1	Sampling of Volatiles and Odorants from Indoor Environments 174		
8.3.1.2	Sampling of Volatiles and Isolation of Odorants from Materials 175		
8.3.1.3	Identification 175		
8.3.2	Examples 176		
8.3.2.1	Cleaning Products, Detergents, Air Fresheners 176		
8.3.2.2	Carpets 176		
8.3.2.3	Adhesives 177		

XII	Contents	
	8.3.2.4	Rubber Materials Used for Sealings, Floorings, Insulations 177
	8.3.2.5	Wood 177
	8.3.2.6	Wood-Based Flooring Materials 178
	8.3.2.7	Linoleum 178
	8.3.2.8	Gypsum-Based Products 179
	8.3.2.9	Plastics 179
	8.3.2.10	Electronic Devices 180
	8.3.3	Odorants and Odor Thresholds 180
	8.3.4	Application of the Combination of Odor Evaluation and Odor Analysis
		for Product Optimization 182
	8.4	Conclusion and Outlook 183
		References 184
	9	Evaluation of Indoor Air Contamination by Means of Reference and
		Guide Values: The German Approach 189
		Birger Heinzow, Helmut Sagunski
	9.1	Introduction 189
	9.2	Definition of Terms 190
	9.2.1	Indoor Environment 190
	9.2.2	Utilization Cycle 190
	9.2.3	Volatile Organic Compounds (VOCs) 191
	9.3	Values for Evaluating the Indoor Air Quality 191
	9.3.1	Toxicologically Based Values 191
	9.3.2	Statistically Defined Values 192
	9.4	Evaluation of Indoor Air Quality with the Aid of Guide Values 192
	9.4.1	Requirements Relating to Guide Values for Indoor Air 192
	9.4.1.1	Health Reference 192
	9.4.1.2	Legal Reference 194
	9.4.2	Basic Scheme for Deriving Guide Values for Indoor Air 194
	9.4.3	Application of the Guide Values in Risk Management 196
	9.4.4	Recommendation 197
	9.4.5	Guide Values by the Ad-hoc WG Not Based on RW I and RW II 197
	9.5	Health Evaluation with the Aid of the TVOC Concept 198
	9.5.1	Recommendation Relating to the Application of TVOC Values 198
	9.5.2	Time Curve of Higher TVOC Concentrations 203
	9.6	Evaluation of Indoor Air Quality with the Aid of Reference
		Values 203
	9.6.1	The Current State of Indoor Air Reference Values 204
	9.6.2	Recommendations 204
	9.7	Application of Measured Values in Order to Evaluate Indoor Air Quality 206

Evaluation of Substances Without Reference Values From the IRK/

AOLG Ad-hoc Working Group 207

Acknowledgment 208 References 209

9.8

## Part Three Field Studies

10	Effect of Ventilation on VOCs in Indoor Air 215			
10.1	Kwok Wai Tham, S. Chandra Sekhar, Mohamed Sultan Zuraimi Introduction 215			
10.1.1	Building and Ventilation Characteristics of Office Buildings in a			
10.1.1	Tropical Climate 216			
10.2	VOC Concentration Levels in Eight Singapore Buildings 216			
10.2.1	Concentrations 217			
10.2.2	Health Effects Caused by VOCs in Singapore Buildings 221			
10.2.3	Possible Sources 221			
10.3	Apportionment of VOCs Source Strengths in Five Buildings 221			
10.3.1	Area-Specific Emission Rates of VOCs 221			
10.3.2	Source Apportionment of VOC Sources 225			
10.4	Effects of Typical Ventilation Operations on TVOC Levels 227			
10.5	Effect of Purging on Indoor TVOC Levels 230			
10.5.1	Purging System 230			
10.5.2	Building Characteristics 231			
10.5.3	Purging Measurements 233			
10.6	Summary 236			
	References 237			
11	Occurrence of Semi-Volatile Organic Compounds in the Indoor			
	Environment 239			
	Werner Butte			
11.1	Introduction 239			
11.2	Concentrations of SVOCs in Indoor Air and House Dust 240			
11.2.1	Phenols and Their Derivatives (Other than Biocides) 240			
11.2.2	Biocides 241			
11.2.3	Musk Compounds 242			
11.2.4	Organophosphates 243			
11.2.5	Organotin Compounds 246			
11.2.6	Perfluorinated Compounds 246			
11.2.7	Phthalates 248			
11.2.8	Polybrominated Diphenyl Ethers 253			
11.2.9	Polychlorinated Biphenyls 253			
11.2.10	Polychlorinated Dioxins and Furans 256			
11.2.11	Polycyclic Aromatic Hydrocarbons 257			
11.3	Sources for SVOCs Indoors 260			
11.4	The Indoor Environment: A Source for Exposure? 261			
11.4.1	Indoor Air and House Dust: Associations to Human			
	Biomonitoring 261			
11.4.2	Indoor Biocides: A Reason for Health Impairments? 262			
11.4.3	Reference and Guideline Values 263			

XIV	Contents
XIV	Contents

11.5	Summary 264
	References 265
12	Indoor Pollutants in the Museum Environment 273
	Alexandra Schieweck, Tunga Salthammer, Simon F. Watts
12.1	The Museum Environment: An Introduction 273
12.2	Climatic Conditions 276
12.2.1	Humidity 277
12.2.2	Temperature 278
12.3	Inorganic Atmospheric Compounds 278
12.4	Formaldehyde, Organic Acids (Formic Acid, Acetic Acid) 281
12.5	Volatile Organic Compounds (VOCs) 284
12.6	Semi-volatile Organic Compounds (SVOCs) 287
12.7	Occurrence of Biocides in the Museum Environment 288
12.8	The Role of People 291
12.9	Risk Assessment and Preservation Strategies 292
12.9.1	Recommendations and Guidelines 293
12.10	Conclusion 293
	References 296
	1.1.0.1.01.1
13	Indoor Organic Chemistry 301
12.1	Glenn Morrison
13.1	Introduction 301
13.2	Relevance of Chemistry Using Indoor Air Models 302
13.3	Homogeneous Chemistry 303
13.3.1	Gas-Phase Organic Oxidation Chemistry: Ozone 303
13.3.2	Gas-Phase Organic Oxidation Chemistry: Hydroxyl Radical 308
13.3.3	Gas-Phase Organic Oxidation Chemistry: Nitrate Radical 309
13.3.4	Condensed-Phase Chemistry: Oxidation 310
13.3.5	Condensed-Phase Chemistry: Hydrolysis 311
13.4	Heterogeneous Chemistry 313
13.4.1	Heterogeneous Chemistry: Ozone and Fresh Indoor Surfaces 313
13.4.2	Heterogeneous Chemistry: Ozone and Soiled Surfaces 316
13.4.3	Heterogeneous Chemistry: Acid–Base 318
13.5	Concluding Remarks 319 References 320
	References 320
14	Human Responses to Organic Air Pollutants 327
	Lars Mølhave
14.1	Introduction 327
14.2	VOC Exposures Indoors 329
14.2.1	Health Effects of Indoor Air Pollution 330
14.2.2	Indicators of Indoor Air Quality and Health 332
14.2.3	Classes of Indoor Air Pollutants 334
14.2.4	The TVOC Indicator 336

14.3	Summary of Experimental Evidence of Health Effects of VOC Exposure 337
14.3.1	Symptoms Relevant to VOCs 337
14.3.2	Effect of Exposure Types 342
14.4	Conclusions 342
1.7.7	References 343
	References 575
	Part Four Emission Studies
15	Volatile Organic Ingredients in Household and Consumer
	Products 349
	Godwin A. Ayoko
15.1	Introduction 349
15.2	Literature Survey 350
15.3	Product Classes 351
15.3.1	Newspaper and Journals 351
15.3.2	Insecticides 356
15.3.3	Air Fresheners and Deodorizers 357
15.3.4	Cleaning Agents 358
15.3.5	Polishes 359
15.3.6	Products for Personal Hygiene and Cosmetics 361
15.3.7	Incenses 363
15.3.8	Perfumes and Fragrances 365
15.3.9	Cooking and Cooking Related Products 366
15.3.10	Miscellaneous Products and Studies 366
15.4	Conclusion 368
	References 368
16	Building Products as Sources of Indoor Organic Pollutants 373
	Stephen K. Brown
16.1	Introduction 373
16.2	Organic Pollutants Emitted from Major Building Products 373
16.2.1	Building Products 373
16.2.2	Organic Pollutants 374
16.2.3	VOC Emissions Levels Over Time 375
16.2.4	VOC Emission Limits/Labels 376
16.2.5	TVOC Emissions from Building Materials 377
16.3	Interior Paints 377
16.3.1	Water-Based Paints 379
16.3.2	Solvent-Based Coatings 383
16.3.3	'Natural' Paints 386
16.3.4	Low-VOC/VOC-Free Paints 387
16.4	Floor Covering Systems 388
16.4.1	Adhesives 388

χVI	Contents	
	16.4.2	Carpets and Underlays 389
	16.4.3	Plastic Floorcoverings 392
	16.5	Concrete and Plaster Products 393
	16.6	Wood-Based Panels 394
	16.7	Natural Wood 396
	16.8	Ovens and Heaters 397
	16.9	Concluding Remarks 399
		References 400
	17	Emission of VOCs and SVOCs from Electronic Devices and Office
		Equipment 405
		Tobias Schripp Michael Wensing
	17.1	Introduction 405
	17.2	Test Procedures 408
	17.3	VOC and SVOC Emissions from Various Devices 414
	17.3.1	Printers and Copiers 414
	17.3.2	Personal Computers 419
	17.3.3	Television Sets and Computer Monitors 421
	174	Illtra-Fine Particle Emission from Office Devices 425

Index 431

References 427