

*Editor-in-Chief*  
Michel A. Aegerter

*Editors*  
Nicholas Leventis  
Matthias M. Koebel

# Aerogels Handbook

 Springer

# Contents

Preface .....	v
List of Contributors.....	xxvii
<b>Part I History of Aerogels</b>	
<b>1 History of Aerogels .....</b>	<b>3</b>
<i>Alain C. Pierre</i>	
1.1. The Founding Studies by Kistler.....	3
1.2. Further Studies on the Synthesis Chemistry of Aerogels.....	6
1.3. Technical Characterization of Aerogels and Development of Their Applications.....	8
1.4. Recent Aerogel Developments.....	11
Acknowledgments .....	12
References.....	12
<b>Part II Materials and Processing: Inorganic – Silica Based Aerogels</b>	
<b>2 SiO<sub>2</sub> Aerogels.....</b>	<b>21</b>
<i>Alain C. Pierre and Arnaud Rigacci</i>	
2.1. Elaboration .....	21
2.1.1. Sol–Gel Synthesis .....	21
2.1.2. Ageing .....	24
2.1.3. Drying .....	25
2.1.4. Synthesis Flexibility.....	28
2.2. Main Properties and Applications of Silica Aerogels .....	29
2.2.1. Texture .....	29
2.2.2. Chemical Characteristics.....	33
2.2.3. Physical Properties and Some Related Applications .....	34
2.3. Conclusion.....	38
Acknowledgments .....	38
References.....	39

<b>3</b>	<b>Hydrophobic Silica Aerogels: Review of Synthesis, Properties and Applications</b> .....	47
	<i>Ann M. Anderson and Mary K. Carroll</i>	
3.1.	Introduction .....	47
3.2.	Aerogel Fabrication Techniques .....	48
3.2.1.	Forming the Wet Sol Gel .....	48
3.2.2.	Drying the Wet Gel .....	50
3.3.	Hydrophobic Aerogels .....	57
3.3.1.	What Makes an Aerogel Hydrophobic? .....	57
3.3.2.	How Do We Measure Hydrophobicity? .....	60
3.4.	A Review of the Literature .....	63
3.4.1.	Review of Co-precursor Methods .....	68
3.4.2.	Review of Silylation Methods .....	69
3.4.3.	Effect of Drying Method on Hydrophobicity .....	70
3.5.	Applications .....	71
3.5.1.	Environmental Clean-up and Protection .....	71
3.5.2.	Biological Applications .....	72
3.5.3.	Superhydrophobic Surfaces .....	73
3.6.	Conclusion .....	73
	Acknowledgments .....	73
	References .....	74
<b>4</b>	<b>Superhydrophobic and Flexible Aerogels</b> .....	79
	<i>A. Venkateswara Rao, G. M. Pajonk, Digambar Y. Nadargi, and Matthias M. Koebel</i>	
4.1.	Introduction .....	79
4.2.	Synthesis and Characterization .....	80
4.2.1.	Sol–Gel Synthesis and Supercritical Drying .....	81
4.2.2.	Materials Characterization .....	83
4.3.	Water–Surface Interactions .....	85
4.3.1.	Water Droplet Sliding .....	86
4.3.2.	Liquid Marbles: Superhydrophobic Aerogel-Coated Water Droplets .....	88
4.4.	Mechanical and Elastic Properties .....	89
4.4.1.	Effect of Synthesis Parameters on Material Elasticity .....	90
4.4.2.	Potential Applications in Mechanical Damping .....	91
4.5.	Hydrocarbon Sorption Behavior .....	94
4.5.1.	Uptake Capacity .....	95
4.5.2.	Desorption Rate .....	96
4.5.3.	Process Reversibility and Reuse of Aerogels .....	98
4.5.4.	Economic Factors .....	99
4.6.	Summary .....	99
	References .....	100
<b>5</b>	<b>Sodium Silicate Based Aerogels via Ambient Pressure Drying</b> .....	103
	<i>A. Venkateswara Rao, G. M. Pajonk, Uzma K. H. Bangi, A. Parvathy Rao, and Matthias M. Koebel</i>	
5.1.	Introduction .....	103
5.1.1.	Silica Aerogels .....	103
5.1.2.	Why Use Sodium Silicate? .....	104

- 5.1.3. The Need for Ambient Pressure Drying ..... 105
- 5.1.4. Necessity of Surface Chemical Modification ..... 105
- 5.2. Preparation of Sodium Silicate Based Aerogels via Ambient Pressure Drying ..... 106
  - 5.2.1. Gel Preparation by the Sol–Gel Route ..... 107
  - 5.2.2. Washing/Solvent Exchange/Surface Modification ..... 110
  - 5.2.3. Drying of Modified Gels ..... 112
- 5.3. Effects of Various Process Parameters on the Physicochemical Properties of the Aerogels ..... 113
  - 5.3.1. Effect of the Sodium Silicate Concentration in the Sol ..... 113
  - 5.3.2. Effect of Sol pH ..... 114
  - 5.3.3. Effect of Aging ( $t_a$ ) and Washing ( $t_w$ ) Periods ..... 116
  - 5.3.4. Effect of the Type of Exchange Solvent Used ..... 118
  - 5.3.5. Effect of the Amount of Silylating Agent Used and the Duration of the Silylation Treatment ..... 119
  - 5.3.6. Effect of Drying Temperature ..... 121
  - 5.3.7. General Comments About Parameter Optimizations ..... 122
  - 5.3.8. Silica Aerogels as Thermal Insulating Materials ..... 122
- 5.4. Conclusions ..... 122
- References ..... 123

**Part III Materials and Processing: Inorganic – Non-Silicate Aerogels**

- 6 **ZrO<sub>2</sub> Aerogels** ..... 127
 

*Lassaad Ben Hammouda, Imene Mejri, Mohamed Kadri Younes, and Abdelhamid Ghorbel*

  - 6.1. Introduction ..... 127
  - 6.2. Preparation of Zirconia Aerogels ..... 128
  - 6.3. Impact of Preparation Parameters on the Textural and Structural Properties of Zirconia Aerogels ..... 129
    - 6.3.1. Influence of Acid Concentration ..... 130
    - 6.3.2. Influence of Hydrolysis Ratio (H<sub>2</sub>O/Zr) ..... 130
    - 6.3.3. Influence of Zirconium Precursor Concentration ..... 130
    - 6.3.4. Influence of the Supercritical Drying Temperature ..... 130
    - 6.3.5. Zirconia Aerogels Obtained by High- or Low-Temperature SCD ..... 131
    - 6.3.6. Advantages of Zirconia Aerogels Compared to Xerogels ..... 131
    - 6.3.7. Influence of the Gel Aging ..... 132
  - 6.4. Applications of Zirconia Aerogels ..... 132
    - 6.4.1. Zirconia Aerogels and Catalysis ..... 132
    - 6.4.2. Zirconia Aerogels and Ceramics ..... 139
    - 6.4.3. Zirconia Aerogels and Solid Oxide Fuel Cells ..... 140
  - 6.5. Conclusion ..... 140
  - References ..... 141

<b>7 Preparation of TiO<sub>2</sub> Aerogels-Like Materials Under Ambient Pressure</b> .....	145
<i>Hiroshi Hirashima</i>	
7.1. Introduction .....	145
7.2. Principles.....	146
7.3. Templating with Polymer and Surfactant: Methods .....	147
7.3.1. Templating by the Mixing Method .....	147
7.3.2. Templating by the Immersion Method .....	148
7.3.3. Preparation of Aerogels-Like Materials .....	149
7.3.4. Characterization of Dried- and Annealed Gels.....	149
7.4. Templating with Polymer and Surfactant: Results .....	149
7.5. Conclusions .....	152
References.....	152
<b>8 A Robust Approach to Inorganic Aerogels: The Use of Epoxides in Sol-Gel Synthesis</b> .....	155
<i>Theodore F. Baumann, Alexander E. Gash, and Joe H. Satcher Jr.</i>	
8.1. Introduction .....	155
8.2. Mechanisms of Epoxide-Initiated Gelation .....	156
8.2.1. Sol Formation and Gelation .....	157
8.2.2. Hydrolysis and Condensation of Metal Ions .....	158
8.2.3. Epoxide-Initiated Gelation.....	159
8.3. Aerogel Materials by Epoxide-Initiated Gelation .....	164
8.3.1. Metal Oxide Aerogels .....	165
8.3.2. Mixed Metal Oxide and Composite Aerogels.....	166
8.4. Summary.....	168
Acknowledgments .....	168
References.....	168
 <b>Part IV Materials and Processing: Organic – Natural and Synthetic Aerogels</b>	
<b>9 Monoliths and Fibrous Cellulose Aerogels</b> .....	173
<i>Lorenz Ratke</i>	
9.1. Introduction .....	173
9.2. Cellulose Aerogel Monoliths .....	175
9.3. Cellulose Filaments for Textile Applications .....	185
9.4. Conclusions .....	188
References.....	189
<b>10 Cellulosic and Polyurethane Aerogels</b> .....	191
<i>Arnaud Rigacci and Patrick Achard</i>	
10.1. Introduction .....	191
10.2. Polyurethane Aerogels .....	193
10.2.1. Synthesis .....	193
10.2.2. Process and Materials.....	196
10.2.3. Hybrids and Composites .....	201

10.3. Cellulose Derivatives Aerogels .....	202
10.3.1. Synthesis .....	202
10.3.2. Process and Materials .....	205
10.3.3. Hybrids and Composites .....	210
10.4. Conclusions .....	210
Acknowledgments .....	211
References .....	212
<b>11 Resorcinol-Formaldehyde Aerogels .....</b>	<b>215</b>
<i>Sudhir Mulik and Chariklia Sotiriou-Leventis</i>	
11.1. Introduction .....	215
11.2. The Resorcinol-Formaldehyde Chemistry .....	216
11.2.1. Base-Catalyzed Gelation .....	217
11.2.2. Acid-Catalyzed Gelation .....	217
11.3. RF Aerogels Prepared by the Base-Catalyzed Route .....	218
11.3.1. Process of Making RF Aerogel via Base-Catalyzed Route ....	220
11.3.2. Factors Affecting the Structure and the Properties of RF Aerogel Prepared Through the Base-Catalyzed Route ....	220
11.4. RF Aerogel Prepared by Acid Catalysis .....	223
11.5. Property Comparison of Base- Versus Acid-Catalyzed RF Aerogels .....	225
11.5.1. Chemical Composition .....	225
11.5.2. Morphology .....	227
11.6. Alternative Approaches for RF Aerogels .....	227
11.7. Commercial Applications of RF Aerogels .....	230
11.8. Summary .....	230
References .....	231
<b>12 Natural Aerogels with Interesting Environmental Features: C-Sequestration and Pesticides Trapping .....</b>	<b>235</b>
<i>Thierry Woinier</i>	
12.1. Introduction .....	235
12.2. Experimental .....	236
12.2.1. Samples Preparation .....	236
12.3. Results .....	237
12.3.1. Analogy Between Allophane Aggregates and Synthetic Gels .....	237
12.3.2. Supercritical Drying .....	239
12.3.3. Pore Properties and Fractal Structure .....	239
12.3.4. Carbon Nitrogen and Pesticides Content in Allophanic Soils .....	241
12.4. Discussions .....	242
12.5. Conclusions .....	244
References .....	245

## Part V Materials and Processing: Composite Aerogels

<b>13</b>	<b>Polymer-Crosslinked Aerogels.....</b>	<b>251</b>
	<i>Nicholas Leventis and Hongbing Lu</i>	
13.1.	Introduction .....	251
13.2.	Addressing the Aerogel Fragility by Compounding with Polymers .....	252
13.3.	Classification of Polymer/Sol–Gel Composites .....	253
13.4.	Ensuring Formation of Class II-Model 2 Aerogels by Polymer Crosslinking of Preformed 3D Networks of Nanoparticles.....	256
13.4.1.	Crosslinking Through Postgelation Introduced Monomers.....	257
13.4.2.	Improving the Processability of Polymer-Crosslinked Aerogels by Crosslinking in One Pot and Crosslinking in the Gas Phase.....	277
13.5.	Conclusions .....	280
	Acknowledgments .....	281
	References.....	282
<b>14</b>	<b>Interpenetrating Organic/Inorganic Networks of Resorcinol-Formaldehyde/Metal Oxide Aerogels .....</b>	<b>287</b>
	<i>Nicholas Leventis</i>	
14.1.	Introduction .....	287
14.2.	Cogelation of <i>RF</i> and Metal Oxide Networks: Native, Crosslinked (X-) <i>RF–MO<sub>x</sub></i> Aerogels, and Xerogels.....	290
14.3.	Materials Properties of Native <i>RF–MO<sub>x</sub></i> Aerogels, Xerogels, and X- <i>RF–MO<sub>x</sub></i> Aerogels .....	296
14.4.	Reactions Between <i>RF</i> and <i>MO<sub>x</sub></i> Nanoparticles.....	301
14.4.1.	Chemical Transformations.....	301
14.4.2.	Morphological Changes During Pyrolysis of the <i>RF–MO<sub>x</sub></i> Systems.....	306
14.5.	Conclusions .....	306
	Acknowledgments .....	310
	References.....	311
<b>15</b>	<b>Improving Elastic Properties of Polymer-Reinforced Aerogels .....</b>	<b>315</b>
	<i>Mary Ann B. Meador</i>	
15.1.	Introduction .....	315
15.2.	Hexyl-Linked Polymer-Reinforced Silica Aerogels.....	318
15.2.1.	Di-isocyanate-Reinforced Aerogels .....	318
15.2.2.	Styrene-Reinforced Aerogels .....	322
15.2.3.	Epoxy-Reinforced Aerogels from Ethanol Solvent .....	324
15.3.	Alkyl Trialkoxysilane-Based Reinforced Aerogels .....	327
15.4.	Future Directions.....	331
15.5.	Conclusions .....	332
	References.....	333

<b>16 Aerogels Containing Metal, Alloy, and Oxide Nanoparticles Embedded into Dielectric Matrices</b> .....	335
<i>Anna Corrias and Maria Francesca Casula</i>	
16.1. Introduction .....	335
16.2. Aerogel Containing Oxide Nanoparticles .....	338
16.3. Aerogels Containing Metal and Alloy Nanoparticles .....	348
16.4. Concluding Remarks .....	360
Acknowledgments .....	360
References .....	360
 <b>Part VI Materials and Processing: Exotic Aerogels</b>	
<b>17 Chalcogenide Aerogels</b> .....	367
<i>Stephanie L. Brock and Hongtao Yu</i>	
17.1. Introduction .....	367
17.2. Thiolytic Routes to Chalcogenide Aerogels: GeS <sub>2</sub> .....	368
17.3. Cluster-Linking Routes to Chalcogenide Aerogels .....	369
17.3.1. Aerogels from Main Group Chalcogenide Clusters and Pt <sup>2+</sup> .....	369
17.3.2. Aerogels from MS <sub>4</sub> <sup>2-</sup> (M = Mo, W) Ions and Ni <sup>2+</sup> (Co <sup>2+</sup> ) .....	372
17.4. Nanoparticle Assembly Routes to Chalcogenide Aerogels .....	372
17.4.1. CdS Aerogels .....	373
17.4.2. Application of the Nanoparticle Assembly Route to PbS, ZnS and CdSe: Effect of Oxidant on CdSe Gelation .....	375
17.4.3. Influence of Density and Dimensionality on Quantum Confinement Effects .....	376
17.4.4. Optimizing Photoemission Characteristics .....	376
17.4.5. Controlling Morphology in CdSe Aerogels .....	379
17.4.6. Expanding the Methodology: Ion Exchange .....	381
17.4.7. Expanding the Methodology: Tellurides .....	382
17.5. Conclusions .....	382
References .....	383
<b>18 Biopolymer-Containing Aerogels: Chitosan-Silica Hybrid Aerogels</b> ....	385
<i>Chunhua Jennifer Yao, Xipeng Liu, and William M. Risen</i>	
18.1. Introduction .....	385
18.2. Syntheses .....	387
18.3. Properties .....	389
18.4. Chemical Properties and Novel Aerogel Materials .....	391
18.4.1. Iron-Containing Chitosan-Silica Aerogels .....	392
18.4.2. Transition Metal-Containing Aerogel Chemistry .....	392
18.4.3. Chemistry of Gold-Containing Chitosan-Silica Aerogels .....	394
18.4.4. Diffusion Control of Chemical Reactions in Nanodomains .....	398
18.4.5. Attachment of Chitosan-Silica Aerogels to Polymers and Other Entities .....	398
18.5. Conclusion .....	400
References .....	400



<b>19</b>	<b>Anisotropic Aerogels by Photolithography .....</b>	<b>403</b>
	<i>Massimo Bertino</i>	
19.1.	Introduction .....	403
19.2.	General Principle.....	404
19.3.	Synthesis of Nanoparticles Within the Matrix Pores.....	405
19.3.1.	Infrared Lithography .....	405
19.3.2.	Ultraviolet Lithography .....	407
19.3.3.	X-Ray Lithography .....	408
19.3.4.	Three-Dimensional Patterning .....	410
19.4.	Anisotropy by Polymer Photocross-linking .....	411
19.5.	Physical Properties .....	413
19.5.1.	Absorption and Emission .....	413
19.5.2.	Index of Refraction .....	414
19.5.3.	Mechanical Properties .....	415
19.6.	Conclusions .....	416
	References.....	417
<b>20</b>	<b>Aerogels Synthesis by Sonocatalysis: <i>Sonogels</i> .....</b>	<b>419</b>
	<i>Luis Esquivias, M. Piñero, V. Morales-Flórez, and Nicolas de la Rosa-Fox</i>	
20.1.	The Sonogel Approach.....	419
20.1.1.	An Insight into Cavitation .....	419
20.1.2.	Sonogels.....	420
20.1.3.	Processing Sonogels .....	421
20.1.4.	Physicochemical Aspects of the Hydrolysis.....	422
20.1.5.	Experimental Alternatives .....	424
20.1.6.	Sonogel Gelation .....	424
20.1.7.	Sono-Ormosils .....	427
20.2.	Structure.....	427
20.2.1.	From Sol to Gel .....	427
20.2.2.	Dense Inorganic Sono-Aerogels .....	429
20.2.3.	Light Sono-Aerogels .....	436
20.3.	From Gel to Glass.....	437
20.4.	Mechanical Properties .....	440
20.5.	Applications of Sono-Aerogels .....	440
20.5.1.	Biomaterials.....	440
20.5.2.	Nanocomposites for CO <sub>2</sub> Sequestration .....	440
20.6.	Conclusion .....	441
	References.....	442
<b>Part VII Properties</b>		
<b>21</b>	<b>Structural Characterization of Aerogels .....</b>	<b>449</b>
	<i>Gudrun Reichenauer</i>	
21.1.	Introduction .....	449
21.2.	Structural Parameters and Related Experimental Techniques .....	450

21.3.	Microscopy .....	450
21.4.	Scattering Techniques .....	457
	21.4.1. Elastic Scattering .....	457
	21.4.2. Inelastic Scattering.....	468
21.5.	Helium Pycnometry .....	470
21.6.	Gas Sorption Porosimetry .....	471
21.7.	Hg Porosimetry .....	483
21.8.	Thermoporometry.....	486
21.9.	Other Characterization Methods.....	488
21.10.	Conclusions .....	494
	References.....	495
<b>22</b>	<b>Mechanical Characterization of Aerogels .....</b>	<b>499</b>
	<i>Hongbing Lu, Huiyang Luo, and Nicholas Leventis</i>	
22.1.	Introduction .....	499
22.2.	Mechanical Characterization Methods .....	500
	22.2.1. DSC, DMA, and Nanoindentation .....	500
	22.2.2. Tension, Compression, and Loading–Unloading Tests .....	501
	22.2.3. Creep, Relaxation, and Recovery Tests .....	501
	22.2.4. Testing at Moderate to High Strain Rates.....	502
	22.2.5. Ultrasonic Echo Tests .....	502
	22.2.6. Fracture and Fatigue Tests.....	503
22.3.	Mechanical Characterization of Native Aerogels .....	503
22.4.	Mechanical Characterization of X-Aerogels .....	506
	22.4.1. Dynamic Mechanical Analysis .....	508
	22.4.2. Flexural Modulus and Strength.....	509
	22.4.3. Compression at Low Strain Rates .....	510
	22.4.4. Dynamic Compression.....	517
22.5.	Conclusion .....	531
	References.....	532
<b>23</b>	<b>Thermal Properties of Aerogels.....</b>	<b>537</b>
	<i>Hans-Peter Ebert</i>	
23.1.	General Aspects of Heat Transfer in Aerogels.....	537
23.2.	Effective Thermal Conductivity of Optically Thick Aerogels.....	539
	23.2.1. Heat Transfer via the Solid Backbone .....	539
	23.2.2. Heat Transfer via the Gaseous Phase .....	540
	23.2.3. Radiative Heat Transfer .....	544
	23.2.4. Effective Total Thermal Conductivity of Aerogels .....	546
23.3.	Heat Transfer Properties of Optically Thin Aerogels.....	555
23.4.	Thermal Conductivity of Aerogels Powders, Granulates, and Aerogel Composites.....	557
23.5.	Specific Heat of Aerogels .....	560
23.6.	Conclusion .....	562
	References.....	562

**24 Simulation and Modeling of Aerogels Using Atomistic and Mesoscale Methods** ..... 565  
*Lev D. Gelb*

24.1. Introduction ..... 565

24.2. Atomistic Modeling ..... 568

    24.2.1. Underlying Chemistry ..... 568

    24.2.2. Simulations of Oligomerization and Gelation ..... 570

24.3. Coarse-Grained Simulations ..... 574

    24.3.1. Hard-Sphere Aggregation Models ..... 574

    24.3.2. Flexible Coarse-Grained Models ..... 576

24.4. Conclusions and Outlook ..... 578

References ..... 579

**Part VIII Applications: Energy**

**25 Aerogels and Sol–Gel Composites as Nanostructured Energetic Materials** ..... 585  
*Alexander E. Gash, Randall L. Simpson, and Joe H. Satcher Jr.*

25.1. Introduction ..... 585

25.2. Attributes of Aerogels and Sol–Gel Processing for Nanostructured Energetic Materials ..... 587

25.3. General Sol–Gel Nanostructured Energetic Materials ..... 587

    25.3.1. Inorganic Aerogel Materials as Nanostructured Energetic Composites ..... 588

    25.3.2. Aerogel and Sol–Gel Composites Nanostructured Pyrophoric Materials ..... 594

    25.3.3. Organic Aerogel Materials as Nanostructured Energetic Composites ..... 600

25.4. Summary ..... 604

Acknowledgments ..... 604

References ..... 605

**26 Aerogels for Superinsulation: A Synoptic View** ..... 607  
*Matthias M. Koebel, Arnaud Rigacci, and Patrick Achard*

26.1. Superinsulation: Global Necessity and Building Specificity ..... 607

    26.1.1. Why Superinsulation? ..... 607

    26.1.2. Zoom on Thermal Insulation for Buildings ..... 609

26.2. High-Performance Insulation or Superinsulation: The Basics ..... 610

    26.2.1. Range of Thermal Conductivity Values and the Physics of Heat Transport ..... 610

    26.2.2. Vacuum Insulation Panels, Vacuum Glazings, and Aerogel Glazings ..... 613

26.3. Overview of the World’s Insulation Markets ..... 614

26.4. Current Status of the Superinsulating Aerogels and Associated Components ..... 616

    26.4.1. Superinsulating Silica Aerogels ..... 616

    26.4.2. Superinsulating Organic Aerogels ..... 621

26.4.3.	Composites and Hybrids .....	623
26.4.4.	Commercial Products .....	624
26.5.	Applications for Aerogel-Based Products .....	625
26.5.1.	Off-Shore Oil and Gas .....	627
26.5.2.	Aeronautics and Aerospace Applications.....	627
26.5.3.	High Temperature.....	627
26.5.4.	Cryogenic Applications.....	627
26.5.5.	Apparel and Appliances (Refrigeration Systems, Outdoor Clothing, and Shoes) .....	628
26.5.6.	A Closer Look at Aerogels for Building Insulation: Startup and Testing Phase .....	628
26.6.	Toxicity, Health, and Environmental Considerations .....	630
26.7.	Conclusions .....	630
	References.....	631

## Part IX Applications: Chemistry and Physics

<b>27</b>	<b>Aerogels as Platforms for Chemical Sensors.....</b>	<b>637</b>
	<i>Mary K. Carroll and Ann M. Anderson</i>	
27.1.	Introduction: Why Use Aerogels for Sensor Applications?.....	637
27.2.	Optical Sensors Based on Silica Aerogel Platforms.....	638
27.2.1.	Photoluminescent Modification of the Aerogel Itself .....	639
27.2.2.	Covalent Attachment of Probe Species.....	640
27.2.3.	Electrostatic Attachment of Probe Species .....	641
27.2.4.	Entrapment of Probe Species .....	642
27.2.5.	Silica Aerogels as Sample Holders for Raman Scattering Measurements .....	645
27.2.6.	Silica Composite Materials .....	645
27.3.	Conductimetric Sensors Based on Aerogel Platforms.....	646
27.3.1.	Silica Aerogel Platforms as Conductimetric Sensors .....	646
27.3.2.	Carbon-Based Aerogel Composites as Conductimetric Sensors .....	647
27.4.	Other Aerogel Platforms that Show Promise for Sensing Applications.....	647
27.4.1.	Titania Aerogels as Sensor Platforms .....	647
27.4.2.	Clay Aerogels for Sensing Applications.....	648
27.5.	Summary and Future Directions .....	648
	Acknowledgments .....	649
	References.....	649
<b>28</b>	<b>Transparent Silica Aerogel Blocks for High-Energy Physics Research.....</b>	<b>651</b>
	<i>Hiroshi Yokogawa</i>	
28.1.	Introduction .....	651
28.2.	Hydrophobic Silica Aerogel Blocks .....	651
28.2.1.	Manufacturing Process.....	652
28.2.2.	Optical Properties .....	653

28.3.	Aerogel Cherenkov Counter .....	653
28.3.1.	Threshold-Type Cherenkov Counter .....	655
28.3.2.	Ring Imaging Cherenkov Counter .....	656
28.4.	KEK B-Factory Experiment .....	657
28.4.1.	Objective .....	657
28.4.2.	Aerogel Cherenkov Counter of BELLE Detector .....	657
28.4.3.	Results of B-Factory .....	659
28.5.	Achievements of Other Experiments .....	660
28.6.	Specifications of “Panasonic” Silica Aerogels .....	660
28.7.	Conclusions .....	661
	Acknowledgments .....	662
	References .....	662
<b>29</b>	<b>Sintering of Silica Aerogels for Glass Synthesis: Application to Nuclear Waste Containment .....</b>	<b>665</b>
	<i>Thierry Woignier, Jerome Reynes, and Jean Phalippou</i>	
29.1.	Introduction .....	665
29.2.	Glasses Obtained by the Sol-Gel Process .....	667
29.3.	Principle of the Containment Process .....	668
29.4.	Synthesis of Silica Aerogel Host Materials .....	669
29.4.1.	Partially Sintered Aerogels .....	670
29.4.2.	Composite Aerogels .....	670
29.4.3.	Permeability .....	670
29.5.	Synthesis of the Nuclear Glass Ceramics .....	671
29.6.	Characterization of the Glass Ceramic .....	672
29.6.1.	Structure .....	672
29.6.2.	Aqueous Erosion Behavior .....	674
29.6.3.	Mechanical Properties of the Nuclear Glass Ceramics .....	676
29.7.	Conclusion .....	677
	References .....	678
 <b>Part X Applications: Biomedical and Pharmaceutical</b>		
<b>30</b>	<b>Biomedical Applications of Aerogels .....</b>	<b>683</b>
	<i>Wei Yin and David A. Rubenstein</i>	
30.1.	Introduction .....	683
30.2.	Aerogels Used for Cardiovascular Implantable Devices .....	684
30.3.	Aerogels as Tissue Engineering Substrates .....	690
30.4.	Aerogels as Drug Delivery Systems .....	692
30.5.	The Future of Aerogels in Biomedical Applications .....	693
30.6.	Conclusion .....	694
	References .....	694

<b>31</b>	<b>Pharmaceutical Applications of Aerogels</b> .....	<b>695</b>
	<i>Irina Smirnova</i>	
31.1.	Introduction .....	695
31.2.	Silica Aerogels as Host Matrix for Drugs (Drug Carriers) .....	696
	31.2.1. Loading of Aerogels by Adsorption.....	696
	31.2.2. Release of the Drugs from Silica Aerogels .....	699
31.3.	Modified Silica Aerogels: Influence of Functional Groups on the Drug Adsorption and Release Kinetics .....	701
	31.3.1. Adsorption .....	701
	31.3.2. Release Kinetics .....	702
31.4.	Pharmaceutical Formulations with Silica Aerogels .....	704
	31.4.1. Semisolid Formulations.....	705
	31.4.2. Solid Formulations.....	706
31.5.	Crystallization/Precipitation of Drugs in Aerogels.....	708
31.6.	Silica Aerogels as Carriers for Enzymes and Proteins.....	710
31.7.	Organic Aerogels as Drug Delivery Systems .....	711
	31.7.1. Drug Release.....	713
31.8.	Aerogels Based on Biopolymers as Drug Carriers.....	714
31.9.	Conclusion .....	715
	References.....	716

## Part XI Applications: Space and Airborne

<b>32</b>	<b>Applications of Aerogels in Space Exploration</b> .....	<b>721</b>
	<i>Steven M. Jones and Jeffrey Sakamoto</i>	
32.1.	Introduction .....	721
32.2.	Hypervelocity Particle Capture.....	722
	32.2.1. Initial on Orbit Studies .....	722
	32.2.2. The Stardust Mission .....	722
	32.2.3. The SCIM Mission (proposed) .....	727
	32.2.4. Nonsilica Aerogels.....	729
	32.2.5. Calorimetric Aerogel .....	731
32.3.	Thermal Insulation.....	732
	32.3.1. 2003 Mars Exploration Rovers .....	732
	32.3.2. Mars Science Laboratory .....	734
	32.3.3. Thermoelectrics .....	735
	32.3.4. Advanced Stirling Radioisotope Generators .....	740
32.4.	Cryogenic Fluid Containment .....	742
32.5.	Conclusion .....	744
	Acknowledgments .....	744
	References.....	745
<b>33</b>	<b>Airborne Ultrasonic Transducer</b> .....	<b>747</b>
	<i>Hidetomo Nagahara and Masahiko Hashimoto</i>	
33.1.	Transducers for Ultrasonic Sensing .....	747
33.2.	Acoustic Properties of Aerogels.....	749

33.3.	Design of Ultrasonic Transducer .....	751
33.4.	Fabrication of Aerogel Acoustic Matching Layer .....	753
33.5.	Aerogel Ultrasonic Transducer .....	755
33.6.	Conclusion .....	760
	References .....	760
<b>Part XII Applications: Metal Industry</b>		
<b>34</b>	<b>Aerogels for Foundry Applications .....</b>	<b>763</b>
	<i>Lorenz Ratke and Barbara Milow</i>	
34.1.	General Aspects of Mold Preparation for Castings .....	763
34.2.	Functional Requirements for Molds and Cores .....	764
34.3.	Resorcinol–Formaldehyde Aerogels as Binders .....	765
34.4.	Mechanical Properties of AeroSand .....	766
34.5.	Drying of RF Aerogel–Sand Mixtures .....	769
34.6.	Thermal Decomposition .....	771
34.7.	Gas Permeability .....	772
34.8.	Carbon Aerogels as Binder Materials .....	774
34.9.	Aerogels as Nanoadditives for Foundry Sands .....	777
34.10.	Aerogels in Solidification and Casting Research .....	779
	34.10.1. Form Filling .....	780
	34.10.2. Aerogels for Directional Solidification .....	784
34.11.	Conclusions .....	787
	References .....	787
<b>Part XIII Applications: Art</b>		
<b>35</b>	<b>AER( )SCULPTURE: A Free-Dimensional Space Art .....</b>	<b>791</b>
	<i>Ioannis Michaloudis</i>	
35.1.	An Artist View of Aerogels .....	791
35.2.	About the Artistic Development and Realization .....	792
	Acknowledgments .....	810
	References .....	810
<b>Part XIV Applications: Other</b>		
<b>36</b>	<b>Preparation and Application of Carbon Aerogels .....</b>	<b>813</b>
	<i>Jun Shen and Dayong Y. Guan</i>	
36.1.	Introduction .....	813
36.2.	Synthesis of Carbon Aerogels .....	815
	36.2.1. Synthesis of RF Aerogels .....	815
	36.2.2. Preparation of Carbon Aerogels .....	816
36.3.	Characterization of Carbon Aerogels .....	817
	36.3.1. Scanning Electron Microscopy .....	817
	36.3.2. Nitrogen Sorption Measurements .....	818
	36.3.3. X-Ray Diffraction .....	819

36.4.	Effect of Process Control on the Carbon Aerogel Structure .....	820
36.4.1.	The Drying Process .....	820
36.4.2.	Pyrolysis (Carbonization) Technology .....	822
36.5.	Applications .....	823
36.5.1.	Electrical Applications.....	823
36.5.2.	Hydrogen Storage and Adsorption.....	824
36.5.3.	Catalyst Supports.....	826
36.5.4.	Materials for Thermal Insulation .....	826
36.5.5.	Other Applications .....	826
36.6.	Conclusion .....	827
	References.....	827

**Part XV Commercial Products**

<b>37</b>	<b>Insights and Analysis of Manufacturing and Marketing Consumer Products with Aerogel Materials .....</b>	<b>835</b>
	<i>Bruce McCormick</i>	
37.1.	Introduction .....	835
37.2.	Insulating Solutions .....	835
37.2.1.	Current Insulating Materials .....	835
37.2.2.	The Synthetic Revolution .....	836
37.3.	Market Opportunities for Aerogel Products .....	837
37.3.1.	Innovation Diffusion of Aerogel Products.....	837
37.3.2.	The Internet and Aerogel .....	839
37.3.3.	Production Costs and Obstacles .....	839
37.4.	“Low Hanging Fruit” and Aerogel Products .....	840
37.4.1.	Wet and Under Pressure Test Results .....	841
37.4.2.	Aerogel Products in Wal-Mart? .....	842
37.4.3.	Consumer Awareness of Aerogel.....	843
37.4.4.	Fashion Versus Performance.....	843
37.4.5.	The Cost Factor .....	844
37.5.	Summary of Commercialization of Aerogel in Consumer Markets .....	845
	Reference.....	845
<b>38</b>	<b>Aerogel by Cabot Corporation: Versatile Properties for Many Applications .....</b>	<b>847</b>
	<i>Hilary Thorne-Banda and Tom Miller</i>	
38.1.	Introduction .....	847
38.2.	Cabot Aerogel.....	847
38.3.	History .....	848
38.3.1.	Timeline: Cabot Pioneers Atmospheric Aerogel Production .....	848
38.4.	Applications .....	849
38.4.1.	Architectural Daylighting .....	849
38.4.2.	Building Insulation.....	849
38.4.3.	Oil and Gas Pipelines .....	850



38.4.4.	Industrial and Cryogenic Applications .....	850
38.4.5.	Outdoor Gear and Apparel.....	851
38.4.6.	Specialty Chemicals and Coatings.....	852
38.4.7.	Personal Care.....	852
38.5.	Products .....	853
38.5.1.	Properties.....	853
38.5.2.	Green Material .....	855
38.6.	Conclusion .....	856
	References.....	856
<b>39</b>	<b>American Aerogel Corporation: Organic Aerogel Commercialization...</b>	<b>857</b>
	<i>Robert Mendenhall</i>	
39.1.	Introduction .....	857
39.2.	History .....	857
39.3.	<i>Aerocore</i> Description: Small Pore Area Material .....	858
39.4.	Observations on Commercialization.....	860
39.5.	Conclusion .....	862
	References.....	863
<b>40</b>	<b>Aerogels Super-thermal Insulation Materials by Nano Hi-tech.....</b>	<b>865</b>
	<i>Chengli Jin</i>	
40.1.	About Nano High-Tech.....	865
40.1.1.	Chronology of Nano High-Tech .....	866
40.2.	Main Products.....	867
40.2.1.	Flexible Thermal Insulation Felt (FM) .....	867
40.2.2.	Thermal Insulation Panel (IP) .....	867
40.2.3.	Cylinders and Special-Shaped Parts for Thermal Insulation (CS) .....	869
40.2.4.	Daylighting Panels (TP) .....	871
40.2.5.	Aerogel Powders, Particles (AP) and Monoliths .....	872
40.3.	Fields of Application and Customers .....	874
40.4.	R&D and Future Applications .....	876
40.5.	Conclusion .....	877
	References.....	877
<b>41</b>	<b>OKAGEL: High Insulating Day Lighting Systems .....</b>	<b>879</b>
	<i>Frank Schneider</i>	
41.1.	Introduction .....	879
41.2.	Insulating Capacity.....	880
41.3.	Translucent Insulation Materials.....	882
41.4.	Silica Aerogels .....	883
41.5.	Multifunctional, High Insulating Façade Elements .....	884
41.6.	Applications .....	885
41.7.	Conclusion .....	887
	References.....	887

**Contents**

xxv

**Part XVI Conclusion**

<b>42 Concluding Remarks and Outlook.....</b>	<b>891</b>
<i>Michel A. Aegerter, Nicholas Leventis, and Matthias M. Koebel</i>	
<b>Glossary, Acronyms and Abbreviations.....</b>	<b>893</b>
<b>Subject Index.....</b>	<b>917</b>