

# Contents

Preface.	IX
<b>Introduction .....</b>	
1.1 References	4
<b>Fundamentals of Foam Formation .....</b>	<b>5</b>
2.1 Introduction .....	5
2.2 Fundamental Principles of Foam Formation .....	6
2.2.1 Bubble Formation .....	6
2.2.2 Bubble Growth.....	8
2.2.3 Bubble Stability .....	9
2.3 Supporting Evidence from Specific Foam Systems	
2.3.1 Thermoplastic Foams.....	
2.3.2 Polyurethane Foams.....	12
2.3.3 Cellular Rubber.....	13
2.4 Summary .....	13
2.5 References .....	14
<b>3 Cellular Structure and Properties of Foamed Polymers.....</b>	<b>17</b>
3.1 Introduction .....	17
3.2 Porous and Cellular Systems.....	17
3.2.1 Statistical Meaning of the Concept of a Cell.....	17
3.2.2 Terminology.....	18
3.2.3 Basic Relationships.....	19
3.2.4 Packing Types.....	20
3.3 Open- and Closed-Cell Foamed Plastics .....	22
3.3.1 General Problems.....	22
3.3.2 Open Cells and Density .....	23
3.3.3 Reticulated Foams.....	24
3.4 Density of Foamed Polymers .....	24
3.4.1 Classification .....	24
3.4.2 Density and Cell Size.....	25
3.4.3 Density and Wall Thickness .....	26
3.5 Cell Shape of Foamed Polymers .....	28
3.5.1 Cell Shape Models .....	28
3.5.2 12- and 14-Hedrons.....	28
3.5.3 Anisotropy of Cell Shapes .....	30
3.6 Cell Size of Foamed Polymers .....	33
3.6.1 Methods of Estimation.....	33
3.6.2 Cell Size and Number of Cells.....	34
3.6.3 Cell Size and Wall Thickness .....	34
3.6.4 Microcells .....	35
3.6.5 Cell Size and Physical Properties.....	37
3.7 Models of Cellular Structure and Calculation of Mechanical Properties of Foamed Polymers.....	38

## XII Contents

3.7.1	Flexible Foamed Polymers .....	38
3.7.2	Rigid Foamed Polymers .....	39
3.8	Cellular Structure and Thermal Conductivity of Foamed Polymers.....	40
3.8.1	Thermal Conductivity of the Polymer Phase.....	41
3.8.2	Thermal Conductivity of the Gas Phase.....	41
3.8.3	Radiative Thermal Conductivity .....	44
3.8.4	Convective Thermal Conductivity .....	45
3.8.5	Effects of Variables on the Thermal Conductivity.....	46
3.9	General Concepts.....	47
3.9.1	Three Generations of Polymer Foams .....	47
3.9.2	Six Structural Levels .....	48
3.9.3	Quantitative Parameters of Cellular Structure.....	49
3.9.4	Technological Concepts .....	50
3.9.5	Advantages of Foamed Polymers.....	51
3.10	References .....	52
<b>4</b>	<b>Flexible Polyurethane Foams.....</b>	<b>55</b>
4.1	Introduction .....	55
4.1.1	Applications .....	55
4.1.2	Markets.....	56
4.2	Basic Chemistry.....	57
4.2.1	The Polymerization Reaction .....	59
4.2.2	The Gas-Producing Reaction.....	60
4.2.3	Foam Recipe Components.....	61
4.3	Foam Morphology .....	77
4.3.1	Review of Current Concepts .....	77
4.3.2	Model for Flexible Foam Formation .....	84
4.4	Preparation of Flexible Foam .....	84
4.4.1	General Requirements .....	85
4.4.2	Laboratory-Scale Cup-Foaming .....	86
4.4.3	Laboratory Box-Foams .....	86
4.4.4	Machine-Made Foam .....	87
4.4.5	Mixing Heads .....	88
4.4.6	Commercial-Scale Processes.....	89
4.5	Foam Physical Properties .....	94
4.5.1	Foam Density .....	95
4.5.2	Load Bearing.....	95
4.5.3	Airflow .....	97
4.5.4	Cell Size .....	97
4.5.5	Compression Set.....	98
4.5.6	Tension Properties.....	99
4.5.7	Tear .....	99
4.5.8	Resilience .....	100
4.6	Slabstock Foams .....	100
4.6.1	Slabstock Chemistry.....	100
4.6.2	Alternative Blowing Agent Developments.....	100
4.6.3	High Load Bearing Foams .....	101
4.6.4	High Resilience Foams.....	102

4.6.5	Foam Flammability	102
4.6.6	Non-BHT Foams....	103
4.6.7	Emanations.....	104
4.6.8	Recycling .....	104
	Molded Foam .....	105
4.7.1	Seating Foams.....	105
4.7.2	Comfort.....	106
4.7.3	Durability.....	107
4.7.4	Fogging and Odor ..	108
4.8	References .....	100
	<b>Rigid Polyurethane Foams .....</b>	<b>121</b>
5.1	Introduction .....	121
5.2	Structure .....	122
5.3	Chemistry .....	122
5.4	Reactants .....	123
5.4.1	Isocyanates.....	123
5.4.2	Polyols .....	124
5.4.3	Catalysts.....	125
5.4.4	Stabilizers.....	126
5.4.5	Blowing Agents .....	126
5.4.6	Combustion Modifiers .....	127
5.5	Formulations.....	127
5.6	Foam Preparation .....	128
5.6.1	Block and Sheet .....	129
5.6.2	Pour-in-Place .....	129
5.6.3	Spray .....	130
5.7	Foam Physics.....	130
5.8	Properties.....	131
5.8.1	Density .....	131
5.8.2	Mechanical Properties.....	131
5.8.3	Water, Solvent, and Chemical Resistance.....	132
5.8.4	Thermal Conductivity .....	132
5.8.5	Combustibility .....	134
5.9	Applications .....	136
5.10	Health and Safety .....	136
5.10.1	Isocyanates.....	137
5.10.2	Polyols .....	137
5.10.3	Catalysts.....	137
5.10.4	Blowing Agents .....	137
5.11	Future Trends .....	138
5.12	References .....	138
	Acknowledgement.....	140
<b>6</b>	<b>Polyisocyanurate Foams .....</b>	<b>141</b>
6.1	Introduction .....	141
6.2	Isocyanurate Chemistry.....	143
6.2.1	Catalysts for Cyclotrimerization .....	143

## XIV Contents

6.2.2	Kinetics and Mechanisms of Cyclotrimerization ..	148
6.2.3	Relative Catalytic Activity .....	156
6.3	Preparation of Modified Polyisocyanurate Foams .....	160
6.3.1	Urethane-Modified Polyisocyanurate Foams .....	160
6.3.2	Oxazolidone-Modified Polyisocyanurate Foams ..	175
6.3.3	Amide-Modified Polyisocyanurate Foams .....	178
6.3.4	Carbodiimide-Modified Polyisocyanurate Foams ..	178
6.3.5	Imide-Modified Polyisocyanurate Foams .....	179
6.4	Applications .....	180
6.4.1	Composite Foam Boards .....	180
6.4.2	Flame-Retardant Seamless Insulation [61] .....	181
6.4.3	Building Insulation .....	182
6.4.4	Chemical and Petrochemical Plant Insulation .....	183
6.4.5	High-Rise Building Walls .....	183
6.4.6	Chemical-Resistant Floats .....	183
6.4.7	Cryogenic, Petrochemical, and Solar Energy Applications .....	183
6.4.8	Highly Resilient Flexible Polyurethane Foams ....	184
6.5	References .....	184
<b>7</b>	<b>Polystyrene and Structural Foam .....</b>	<b>189</b>
7.1	Introduction and General Description .....	189
7.1.1	Nomenclature .....	190
7.2	Chemistry and Preparation .....	190
7.2.1	Theory of the Expansion Process .....	191
7.2.2	Blowing Agent Selection .....	193
7.3	Properties and Their Relation to Structure .....	195
7.3.1	Test Methods .....	195
7.3.2	Properties of Commercial Products .....	195
7.3.3	Mechanical Properties .....	199
7.3.4	Thermal Properties .....	204
7.3.5	Moisture Resistance .....	206
7.3.6	Electrical Properties .....	207
7.3.7	Environmental Aging .....	207
7.3.8	Other Properties .....	207
7.4	Commercial Production and Processing .....	208
7.4.1	Manufacturing Process .....	208
7.4.2	Commercial Products and Processes .....	212
7.5	Applications .....	214
7.5.1	Cushioning .....	215
7.5.2	Thermal Insulation .....	216
7.5.3	Packaging .....	217
7.5.4	Structural Components .....	219
7.5.5	Marine Applications .....	219
7.5.6	Electrical Insulation .....	219
7.5.7	Space Filling and Seals .....	219
7.5.8	Other Uses .....	220
7.5.9	Energy Considerations in Foam Insulation .....	220

7.5.10	Health and Safety Factors .....	224
7.6	References .....	225
<b>Polyolefin Foam .....</b>		
8.1	Introduction .....	233
8.2	Chemistry and Preparation .....	234
8.2.1	Foam Expansion with a Physical Blowing Agent .....	237
8.2.2	Foam Expansion with a Chemical Blowing Agent .....	248
8.3	Properties and Their Relation to Structure .....	262
8.3.1	Properties of Commercial Products .....	266
8.3.2	Relationships Between Structure and Properties .....	267
8.4	Commercial Production and Processing .....	275
8.4.1	Extrusion Processes .....	275
8.4.2	Processes for Manufacturing Moldable Polyolefin Beads .....	278
8.4.3	Cross-Linked Polyolefin Foam Sheet Processes .....	281
8.4.4	Cross-Linked Polyolefin Foam Bun Stock Processes .....	286
8.5	Applications .....	288
8.5.1	Fabrication .....	288
8.5.2	Major Applications .....	289
8.6	References .....	293
<b>9</b>	<b>PVC Foams .....</b>	<b>301</b>
9.1	Introduction .....	301
9.2	Characteristics of PVC .....	303
9.2.1	PVC Structures .....	304
9.2.2	Structure Changes During Processing .....	305
9.2.3	Influence of PVC Fusion on Physical Properties .....	305
9.3	Formulation Technology .....	305
9.3.1	Overview of Formulas for PVC Foam .....	305
9.3.2	Effects of Formulation Ingredients on the Foaming Process and Properties of Foamed Products .....	308
9.3.3	Use of Recycled PVC in Foam Formulations .....	317
9.3.4	Design of Experiment (DOE) for Foam Formulation Development .....	318
9.4	Processing Technology .....	320
9.4.1	Extrusion of PVC Foams .....	321
9.4.2	Injection Molding of PVC Foams .....	328
9.4.3	Foaming of PVC at Atmospheric Pressure .....	329
9.4.4	Microcellular PVC Foams .....	331
9.4.5	PVC/Wood Flour Composite Foams .....	334
9.5	Mechanical Property Analyses and Test Standards .....	335
9.5.1	Mechanical Properties .....	336
9.5.2	ASTM and ISO Standards .....	340
9.6	References .....	341
<b>10</b>	<b>Epoxy Foams .....</b>	<b>347</b>
10.1	Introduction .....	347
10.2	Epoxy Chemistry and Formulations .....	347
10.3	Blowing or Foaming Agents and Processes .....	349

10.3.1 Inert Gas Blowing Agents .....	350
10.3.2 Inert Liquid Blowing Agents.....	350
10.3.3 Reactive Blowing Agents.....	350
10.3.4 Expanding Syntactic Fillers.....	351
10.3.5 Frothed Epoxies .....	352
10.3.6 Epoxy Emulsions.....	352
10.3.7 Non-Aqueous Liquid Extractable Pore Formers and CIPS	352
10.3.8 Solid Extractable Pore Formers.....	353
10.3.9 Stereolithography .....	353
10.4 Combinations of Epoxy and Isocyanate Based Thermosets .....	354
10.5 Three-Phase Syntactics.....	355
10.6 Fiber-Reinforced Foams .....	356
10.7 Removable Foams .....	356
10.8 Applications.....	357
10.8.1 Automotive (also See Adhesive Applications Below) .....	357
10.8.2 Electronics Encapsulation .....	359
10.8.3 Adhesives .....	361
10.8.4 Building Retrofitting .....	361
10.8.5 Dams, Tanks and Bridges.....	362
10.8.6 Expanding Cores .....	362
10.8.7 Sports Equipment .....	362
10.8.8 Personal Care Products.....	363
10.8.9 Thermoplastic Processing and Recycling.....	363
10.8.10 Lung Substitutes.....	363
10.9 References .....	363
<b>11 Latex Foam and Sponge .....</b>	<b>367</b>
11.1 Introduction .....	367
11.2 Dunlop Process .....	369
11.2.1 Compounding Ingredients ...	369
11.2.2 Processing Notes .....	370
11.2.3 Foaming.....	371
11.3 Freeze Process .....	373
11.3.1 Original Freeze Process.....	374
11.3.2 Newer Freeze Process .....	374
11.4 Sponge 374	
11.4.1 Open-Cell Sponge Rubber...	374
11.4.2 Closed-Cell Sponge Rubber	375
11.5 References .....	378
<b>12 Silicone Foams.....</b>	<b>379</b>
12.1 Background and Development.....	379
12.1.1 Background .....	379
12.1.2 Development of Silicone Foams .....	379
12.1.3 Development of Flame-Retardant Foam Technology	381
12.2 Chemistry and Preparation .....	381
12.2.1 Foam Formation .....	381
12.2.2 Optional Ingredients.....	381

12.2.3	Preparation .....	384
12.3	Properties and Their Relationship to Structure	384
12.3.1	Structural Features .....	384
12.3.2	Physical Properties.....	384
12.4	Commercial Production and Processing.....	386
12.4.1	Metering.....	386
12.4.2	Mixing.....	386
12.4.3	Dispensing .....	387
12.4.4	Equipment Selection .....	388
12.5	Applications .....	388
12.5.1	Foam Applications.....	388
12.5.2	Forms of Foam.....	388
12.5.3	Features of Silicone Products.....	388
12.5.4	Areas of Application.....	389
12.6	References .....	389
<b>13</b>	<b>Fluoropolymer Foams.....</b>	<b>391</b>
13.1	History and Introduction .....	391
13.2	Chemistry and Physics of Foam Preparation.....	392
13.2.1	Nucleation and Bubble Growth.....	393
13.3	Properties and Their Relation to Cell Structure.....	397
13.3.1	Physical Properties.....	397
13.3.2	Thermal Properties.....	399
13.3.3	Specific Heat.....	400
13.3.4	Electrical Properties .....	400
13.4	Commercial Production and Processing.....	402
13.4.1	Foaming of FEP and PFA Resins .....	402
13.4.2	Foaming of Fluoroelastomer Resins (such as Viton) .....	403
13.4.3	Expansion of PTFE Resin .....	404
13.5	Applications .....	405
13.6	References .....	406
<b>14</b>	<b>Wood Flour Composite Foams.....</b>	<b>409</b>
14.1	Introduction.....	409
14.1.1	Background on Polymeric Composites.....	409
14.1.2	Natural Fibers and Their Properties .....	410
14.1.3	Plastic/Wood Flour Composite Foams.....	413
14.2	Major Issues in Development of PWC Foams .....	415
14.2.1	Thermal Degradation of Natural Fibers .....	416
14.2.2	Moisture Content and Volatile Emissions from Natural Fibers .....	418
14.2.3	Dispersion of Natural Fiber and Fiber-Matrix Bonding.....	420
14.2.4	Processing Difficulties Due to Increased Viscosity .....	420
14.3	Phase Changes in Foaming of PWC.....	421
14.3.1	Changes in Phase Morphology of the Extrudate During Microcellular Foaming and Fine-Celled PWC Foaming .....	421
14.3.2	Polymer/Gas Solution Formation.....	422
14.3.3	Cell Nucleation .....	423
14.3.4	Cell Growth Control .....	424

14.4 Experiments and Discussion.....	426
14.4.1 Effects of Volatile Emissions from Wood Flour During Extrusion Processing.....	427
14.4.2 Foaming Experiments with Varying Content of Extractives.....	431
14.4.3 Critical Processing Temperature in Extrusion Processing of PWC Foams.....	434
14.4.4 Foaming with Various CBAs.....	439
14.5 Conclusions.....	442
14.6 References.....	443
<b>15 Phenolic Foams.....</b>	<b>447</b>
15.1 Chemistry and Foam Formation.....	447
15.1.1 Phenolic Resins.....	447
15.1.2 Crosslinking of Phenolic Resins.....	449
15.1.3 Foam Formation.....	450
15.1.4 Reduction in Corrosivity of Phenolic Foam.....	452
15.2 Properties and Their Relation to Structure.....	452
15.3 Commercial Production and Processing.....	454
15.4 Applications.....	455
15.5 References.....	455
<b>16 Flame Retardancy of Polymeric Foams.....</b>	<b>457</b>
16.1 Introduction.....	457
16.2 The Combustion of Polymeric Foams.....	458
16.2.1 Flame Combustion of Polymeric Foams.....	458
16.2.2 Smoldering Combustion of Polymeric Foams.....	460
16.2.3 Filtration Combustion of Gases in Polymeric Foams.....	462
16.3 Test Methods and Fire Safety Classification Parameters.....	463
of Foamed Materials for the Assessment of Fire Hazards.....	463
16.4 Recent Advances in Flame Retardancy of Polymeric Foams.....	468
16.4.1 The Development of Foams Based on Inherently Thermally Stable and Flame Retardant Polymers.....	468
16.4.2 Chemical and Physical Modification of Polymeric Foams.....	470
16.4.3 Additive Flame Retardants.....	471
16.5 References.....	475
<b>17 Syntactic Polymer Foams.....</b>	<b>479</b>
17.1 Introduction.....	479
17.2 Hollow Sphere Fillers.....	480
17.2.1 General Information.....	480
17.2.2 Glass Microspheres.....	480
17.2.3 Polymeric Microspheres.....	481
17.2.4 Miscellaneous Other Microspheres.....	482
17.2.5 Macrospheres.....	482
17.3 Syntactic Foam Processing.....	482
17.3.1 General Considerations.....	482
17.3.2 Rheology of Syntactic Mixtures.....	483
17.3.3 Casting and Molding Compositions.....	483

17.3.4	Regulating the Apparent Density .....	484
17.3.5	Microsphere Space Factors and Packing.....	485
.7.4	Syntactic Foam Production .....	487
17.4.1	Epoxy Syntactic Foams.....	487
17.4.2	Oligoester Syntactic Foams .....	488
17.4.3	Phenolic Syntactic Foams .....	488
17.4.4	Organosilicone Syntactic Foams.....	489
17.4.5	Polyimide Syntactic Foams.....	489
17.4.6	Carbonized Syntactic Foams.....	489
17.4.7	Syntactic Prepregs.....	490
17.4.8	Miscellaneous Syntactic Foams .....	491
.7.5	Physical Properties of Syntactic Foams.....	491
17.5.1	Strength Properties.....	491
17.5.2	Water Absorption and Resistance to Hydrostatic Pressure .....	494
17.5.3	Thermal Properties.....	496
.7.6	Recent Developments and Main Applications .....	497
17.6.1	Sub-Sea and Shipbuilding Applications.....	497
17.6.2	Structural Applications .....	500
17.6.3	Aerospace Applications .....	502
17.6.4	Other Applications .....	503
.7.7	References .....	503
<b>18</b>	<b>Blowing Agents for Polymeric Foams.....</b>	<b>505</b>
18.1	Introduction .....	505
18.2	Classification.....	505
18.3	Chemical Blowing Agents.....	507
18.3.1	Main Characteristics .....	507
18.3.2	Inorganic Blowing Agents .....	509
18.3.3	Organic Blowing Agents.....	511
18.3.4	Blowing Agents that Liberate Gases as a Result of Chemical Interaction between the Components .....	532
18.3.5	Practical Guide for Selection of CBAs .....	536
18.4	Physical Blowing Agents and Environmental Problems .....	539
18.4.1	Main Characteristics .....	539
18.4.2	Volatile Liquids .....	540
18.4.3	Solid Blowing Agents .....	546
18.5	Gases .....	546
18.6	Nucleazites .....	546
18.7	References .....	547
<b>Appendix 1</b>	.....	<b>549</b>
Letters of the Roman Alphabet.	.....	549
Capital Greek Letters.....	.....	550
Lower Case Greek Letters.....	.....	551
<b>Appendix 2</b>	.....	<b>552</b>
Conversion Factors between English and S.I. Units for Quantities Used in Describing the Physical Properties of Foams .....	.....	552