

Contents

Preface	IX
1 Introduction	1
1.1 References	4
2 Fundamentals of Foam Formation	5
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	11
2.3.1 Thermoplastic Foams.....	11
2.3.2 Polyurethane Foams.....	12
2.3.3 Cellular Rubber.....	13
2.4 Summary	13
2.5 References	14
3 Cellular Structure and Properties of Foamed Polymers	17
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

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
4	Flexible Polyurethane Foams.....	55
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
4.7	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.....	109
5	Rigid Polyurethane Foams.....	121
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
6	Polyisocyanurate Foams.....	141
6.1	Introduction.....	141
6.2	Isocyanurate Chemistry.....	143
6.2.1	Catalysts for Cyclotrimerization.....	143

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
7	Polystyrene and Structural Foam	189
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
8	Polyolefin Foam	233
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
9	PVC Foams	301
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
10	Epoxy Foams	347
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
11 Latex Foam and Sponge.....	367
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
12 Silicone Foams.....	379
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
13	Fluoropolymer Foams.....	391
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
14	Wood Flour Composite Foams.....	409
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
15 Phenolic Foams.....	447
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
16 Flame Retardancy of Polymeric Foams.....	457
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 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
17 Syntactic Polymer Foams.....	479
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
17.4	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
17.5	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
17.6	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
17.7	References	503
18	Blowing Agents for Polymeric Foams.....	505
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
Appendix 1	549
Letters of the Roman Alphabet.....		549
Capital Greek Letters.....		550
Lower Case Greek Letters		551
Appendix 2	552
Conversion Factors between English and S.I. Units for Quantities Used in Describing the Physical Properties of Foams		552