

# Contents

- 1 Introduction** ..... 1
  - 1.1 Ultraviolet Germicidal Irradiation (UVGI) ..... 1
  - 1.2 Brief History of Ultraviolet Disinfection ..... 2
  - 1.3 Units and Terminology ..... 6
  - 1.4 Air vs. Water Disinfection ..... 8
  - 1.5 Surface Disinfection ..... 9
  - 1.6 Air Disinfection ..... 10
  - 1.7 Air Disinfection Field Studies ..... 10
  - 1.8 Pathogens and Allergens ..... 11
  - 1.9 Current Research ..... 12
  - 1.10 UVGI and the Future of Disease Control ..... 13
  - References ..... 13
  
- 2 UVGI Disinfection Theory** ..... 17
  - 2.1 Introduction ..... 17
  - 2.2 UV Inactivation ..... 17
  - 2.3 UV Absorption Spectra ..... 25
  - 2.4 UV Photoprotection ..... 28
  - 2.5 Covalent Bonding and Photon Interaction ..... 31
  - 2.6 UV Photoproducts ..... 32
  - 2.7 DNA Conformation ..... 33
  - 2.8 Photon Density and Single-Hit Concepts ..... 35
  - 2.9 Photochemistry of RNA Viruses ..... 38
  - 2.10 Photochemistry of DNA Viruses ..... 39
  - 2.11 Photochemistry of Bacteria ..... 39
  - 2.12 Photoreactivation ..... 40
  - 2.13 UV Scattering ..... 42
  - References ..... 47
  
- 3 Mathematical Modeling of UV Disinfection** ..... 51
  - 3.1 Introduction ..... 51
  - 3.2 UV Disinfection Modeling ..... 51
  - 3.3 UV Exposure Dose (Fluence) ..... 52

3.4	Single Stage Decay . . . . .	53
3.5	Two Stage Decay . . . . .	54
3.6	Shoulder Curves . . . . .	57
3.7	Two Stage Shoulder Curves . . . . .	58
3.8	Relative Humidity Effects . . . . .	59
3.8.1	RH Effects on Viruses . . . . .	60
3.8.2	RH Effects on Bacteria . . . . .	62
3.8.3	RH Effects on Bacterial and Fungal Spores . . . . .	67
3.9	Modeling Photoreactivation . . . . .	68
3.10	Air Temperature Effects . . . . .	70
	References . . . . .	70
<b>4</b>	<b>UV Rate Constants . . . . .</b>	<b>73</b>
4.1	Introduction . . . . .	73
4.2	Rate Constants and Survival Curves . . . . .	74
4.3	UV Rate Constant Database . . . . .	74
4.3.1	Bacteria Rate Constants . . . . .	75
4.3.2	Virus Rate Constants . . . . .	76
4.3.3	Fungi Rate Constants . . . . .	81
4.4	Surface UV Rate Constants . . . . .	82
4.5	Water Rate Constants . . . . .	84
4.6	Airborne Rate Constants . . . . .	86
4.7	Narrow Band UVC vs. Broadband UVB/UVC . . . . .	87
4.8	Relative Humidity Effects . . . . .	88
4.9	Rate Constant Determinants . . . . .	90
4.10	UV Scattering in Water . . . . .	94
4.11	Prediction of UV Susceptibility . . . . .	96
	References . . . . .	105
<b>5</b>	<b>UVGI Lamps and Fixtures . . . . .</b>	<b>119</b>
5.1	Introduction . . . . .	119
5.2	Types and Characteristics of UV Lamps . . . . .	120
5.3	Lamp Power, Size, and Nomenclature . . . . .	123
5.4	Lamp Ballasts . . . . .	125
5.4.1	Magnetic Ballasts . . . . .	125
5.4.2	Electronic Ballasts . . . . .	126
5.5	Microwave UV Lamps . . . . .	126
5.6	UV LEDs . . . . .	127
5.7	Pulsed UV Lamps . . . . .	129
5.8	Lamp Ratings . . . . .	129
5.9	Lamp Shapes . . . . .	129
5.10	Lamp Fixtures . . . . .	130
5.11	Upper Room Lamp Fixtures . . . . .	131
5.12	Lamp Cooling Effects . . . . .	132

5.13	Ozone Generation . . . . .	135
5.14	Lamp Maintenance . . . . .	135
	References . . . . .	136
<b>6</b>	<b>Systems and Equipment . . . . .</b>	<b>139</b>
6.1	Introduction . . . . .	139
6.2	Air Disinfection Systems . . . . .	139
6.2.1	In-Duct Air Disinfection . . . . .	140
6.2.2	Recirculation Units . . . . .	142
6.2.3	Upper Room Systems . . . . .	143
6.2.4	UV Barrier Systems . . . . .	144
6.2.5	Overhead Tank Disinfection . . . . .	145
6.3	Surface Disinfection Systems . . . . .	145
6.3.1	Equipment and Packaging Disinfection . . . . .	146
6.3.2	Cooling Coil Disinfection . . . . .	147
6.3.3	Lower Room Disinfection . . . . .	148
6.3.4	Overhead Surgical Site Disinfection . . . . .	149
6.3.5	Area/Room Disinfection . . . . .	150
6.3.6	Food Surface Disinfection . . . . .	151
6.3.7	Mold Remediation Systems . . . . .	152
6.3.8	UV Hand Wands . . . . .	152
6.4	UV Reflective Materials . . . . .	153
6.5	UV Light Baffles . . . . .	153
6.6	UV-Transmittant Materials . . . . .	155
6.7	UV Absorbers . . . . .	155
6.8	Flow Straighteners . . . . .	156
6.9	PCO Systems . . . . .	156
6.10	Controls and Integral Sensors . . . . .	157
	References . . . . .	157
<b>7</b>	<b>UVGI System Modeling . . . . .</b>	<b>159</b>
7.1	Introduction . . . . .	159
7.2	UV Lamp Modeling . . . . .	160
7.3	UV Reflectivity Modeling . . . . .	163
7.3.1	Modeling Specular Enclosures . . . . .	163
7.3.2	Modeling Diffuse Enclosures . . . . .	166
7.3.3	Combined Specular and Diffusive Reflectivity . . . . .	170
7.4	Air Mixing Effects . . . . .	171
7.5	UV System Optimization . . . . .	173
	References . . . . .	175
<b>8</b>	<b>Airstream Disinfection . . . . .</b>	<b>177</b>
8.1	Introduction . . . . .	177
8.2	UV Air Disinfection Performance . . . . .	177
8.3	Filtration Performance . . . . .	185

8.4	Combined Performance of Filtration and UVGI . . . . .	186
8.5	In-duct Air Disinfection Systems . . . . .	190
8.6	EPA Test Results . . . . .	191
8.7	Unitary UV Systems . . . . .	195
8.8	Barrier Systems . . . . .	197
8.9	Zonal Modeling . . . . .	198
8.9.1	Steady State Single Zone Model . . . . .	198
8.9.2	Transient Modeling . . . . .	200
8.9.3	Multizone Modeling . . . . .	203
8.10	Zonal Protection Factors . . . . .	203
8.11	UV Air Disinfection Field Trials . . . . .	206
	References . . . . .	207
<b>9</b>	<b>Upper Room UV Systems . . . . .</b>	<b>211</b>
9.1	Introduction . . . . .	211
9.2	Types and Design of Fixtures . . . . .	212
9.3	Upper Room System Sizing . . . . .	216
9.4	Air Mixing Effects . . . . .	220
9.5	Room Design . . . . .	223
9.6	Performance . . . . .	224
9.7	Testing . . . . .	227
9.8	Upper Room UV Safety . . . . .	229
	References . . . . .	230
<b>10</b>	<b>UV Surface Disinfection . . . . .</b>	<b>233</b>
10.1	Introduction . . . . .	233
10.2	Microbial Growth Control . . . . .	233
10.3	Modeling Surface Disinfection . . . . .	234
10.4	UV Cabinets . . . . .	236
10.5	Area Disinfection Systems . . . . .	238
10.6	Cooling Coil Irradiation . . . . .	239
10.7	Overhead Surgical Site Systems . . . . .	246
10.8	Lower Room Systems . . . . .	249
10.9	Food and Packaging Irradiation . . . . .	250
10.10	Summary . . . . .	252
	References . . . . .	252
<b>11</b>	<b>UVGI Guidelines and Standards . . . . .</b>	<b>255</b>
11.1	Introduction . . . . .	255
11.2	UVGI Electrical Guidelines . . . . .	256
11.3	Testing Guidelines and Standards . . . . .	258
11.4	UVGI Application Guidelines . . . . .	262
11.5	UVGI Safety Guidelines . . . . .	277
	References . . . . .	283

<b>12</b>	<b>UVGI Safety</b>	287
12.1	Introduction	287
12.2	The Germicidal UV Spectrum	287
12.3	Biological Effects of UV Exposure	288
12.3.1	UV Effects on Eyes	289
12.3.2	UV Effects on Skin	291
12.4	UV Exposure Limits	293
12.5	UV Measurement	299
12.6	UV Protection and Control Measures	300
12.6.1	In-duct UVGI System Safety	300
12.6.2	Unitary UVGI System Safety	301
12.6.3	Upper Room UVGI Safety	301
12.6.4	Lower Room UVGI Safety	302
12.6.5	Cooling Coil UVGI Safety	303
12.6.6	Equipment Disinfection UVGI Safety	303
12.6.7	Overhead Surgical Site System Safety	304
12.6.8	Area Decontamination UVGI Safety	304
12.7	Personal Protective Equipment (PPE)	305
12.8	Labeling	306
12.9	Ozone Generation Hazards	307
12.10	Lamp Breakage and Mercury Risks	308
	References	309
<b>13</b>	<b>Ultraviolet Radiometry</b>	313
13.1	Introduction	313
13.2	Lamp Electrical Characteristics	313
13.3	UV Irradiance and UV Dose	314
13.4	Measurement Equipment	315
13.5	UV Lamp Ratings	318
13.6	Lamp Irradiance Measurements	319
13.7	Lamp Cooling and Heating Effects	323
13.8	UV Reflectivity	323
13.9	UV Transmittance	325
13.10	UV Absorptance	325
13.11	Reflective Lamp Fixtures and Enclosures	326
13.12	UV Dose Measurement	327
13.13	Spherical Actinometry	328
13.14	Testing Applications	328
13.14.1	Laboratory Testing of Equipment	329
13.14.2	In-duct UVGI System Testing	329
13.14.3	Cooling Coil Systems	330
13.14.4	Overhead Surgical Site Systems	331
13.14.5	Upper Room Systems	332
13.14.6	Lower Room Systems	333

13.14.7	Area Disinfection Systems	333
	References	334
<b>14</b>	<b>Microbiological Testing</b>	337
14.1	Introduction	337
14.2	Microbiological Testing	337
14.3	Biodosimetry	338
14.4	Test Microbes	338
14.5	Test Materials and Equipment	340
14.6	Surface Sampling	341
14.7	Air Sampling	346
14.8	Sampling Applications	348
14.8.1	UV Rate Constants	348
14.8.2	Cooling Coil Disinfection Systems	351
14.8.3	In-duct Air Disinfection Systems	352
14.8.4	Upper Room Systems	353
14.8.5	Lower Room Systems	353
14.8.6	Overhead Surgical Site Systems	354
14.8.7	Area Disinfection Systems	355
14.9	Evaluating Sampling Results	355
14.10	Virus Sampling	357
	References	357
<b>15</b>	<b>UV Effects on Materials</b>	361
15.1	Introduction	361
15.2	UV Effects on Materials	361
15.3	Activation Spectra	365
15.4	Solarization of Glass	366
15.5	Photodiscoloration	367
15.6	Photodegradation	368
15.7	Damage to Houseplants	372
15.8	Ozone Production	372
15.9	Protective Coatings	373
15.10	UV Absorbers	375
15.11	Photodegradation Testing	377
	References	378
<b>16</b>	<b>Pulsed UV Systems</b>	383
16.1	Introduction	383
16.2	Pulsed UV Disinfection	384
16.3	The PUV Spectrum and Germicidal Effectiveness	385
16.4	Modeling PUV Dose	387
16.5	Modeling PUV Decay Curves	389
16.6	A General Model for PUV Disinfection	394
16.7	Pulsed Light Disintegration	395
	References	397

<b>17</b>	<b>Health Care Facilities</b>	399
17.1	Introduction	399
17.2	Nosocomial Infections	400
17.3	Operating Rooms and ICUs	401
17.4	Isolation Rooms	406
17.5	General Areas	408
17.6	Hallways and Storage Areas	410
17.7	Dental Offices	412
17.8	AIDS Clinics	413
17.9	Hospital Laboratories	414
17.10	Animal Laboratories and Veterinary Facilities	414
	References	418
<b>18</b>	<b>Commercial Buildings</b>	423
18.1	Introduction	423
18.2	Office Buildings	423
18.3	Industrial Facilities	425
18.4	Food Industries	427
18.5	Educational Facilities	431
18.6	Museums and Libraries	432
18.7	Agricultural and Animal Facilities	437
18.8	Malls, Airports, and Places of Assembly	441
18.9	Aircraft and Transportation	442
18.10	Sewage and Waste Facilities	443
	References	444
<b>19</b>	<b>Residential Applications</b>	449
19.1	Introduction	449
19.2	Residential Homes	449
19.3	Apartments	452
19.4	Hotels and Dormitories	453
	References	454
<b>20</b>	<b>Bioterrorism Defense</b>	457
20.1	Introduction	457
20.2	Bioweapons	457
20.3	Biodefense of Buildings	461
20.4	UV Systems for Biodefense	464
20.5	UV Bioremediation	467
	References	468
	<b>Appendices</b>	471
	<b>Index</b>	493





Ultraviolet Germicidal Irradiation Handbook

UVGI for Air and Surface Disinfection

Kowalski, W.

2009, XVII, 501 p., Hardcover

ISBN: 978-3-642-01998-2