

## **TABLE OF CONTENTS**

<b>PREFACE</b>	<b>v</b>
<b>NOTES ON THE SECOND EDITION</b>	<b>vi</b>
<b>ABOUT THE AUTHORS</b>	<b>viii</b>
<b>ACKNOWLEDGEMENTS</b>	<b>viii</b>
<b>CONTENTS IN BRIEF</b>	<b>ix</b>
<b>TABLE OF CONTENTS</b>	<b>xiii</b>
<b>SYMBOLS, PARAMETERS AND ABBREVIATIONS</b>	<b>xxiii</b>
<b>1 INTRODUCTION</b>	<b>1</b>
1.1 ADVANCES IN SECONDARY WASTEWATER TREATMENT	1
1.2 TERTIARY WASTEWATER TREATMENT	3
1.3 TEMPERATURE INFLUENCE ON ACTIVATED SLUDGE DESIGN	4
1.4 OBJECTIVE OF THE TEXT	6
<b>2 ORGANIC MATERIAL AND BACTERIAL METABOLISM</b>	<b>7</b>
2.1 MEASUREMENT OF ORGANIC MATERIAL	7
2.1.1 The COD test	7
2.1.2 The BOD test	10
2.1.3 The TOC test	14
2.2 COMPARISON OF MEASUREMENT PARAMETERS	14
2.3 METABOLISM	17
2.3.1 Oxidative metabolism	17
2.3.2 Anoxic respiration	19
2.3.3 Anaerobic digestion	20

<b>3 ORGANIC MATERIAL REMOVAL</b>	<b>23</b>
3.1 ORGANIC MATERIAL AND ACTIVATED SLUDGE COMPOSITION	23
3.1.1 Organic material fractions in wastewater	23
3.1.2 Activated sludge composition	26
3.1.2.1 Active sludge	27
3.1.2.2 Inactive sludge	27
3.1.2.3 Inorganic sludge	27
3.1.2.4 Definition of sludge fractions	28
3.1.3 Mass balance of the organic material	28
3.2 MODEL NOTATION	34
3.3 STEADY-STATE MODEL OF THE ACTIVATED SLUDGE SYSTEM	36
3.3.1 Model development	36
3.3.1.1 Definition of sludge age	37
3.3.1.2 COD fraction discharged with the effluent	38
3.3.1.3 COD fraction in the excess sludge	38
3.3.1.4 COD fraction oxidised for respiration	42
3.3.1.5 Model summary and evaluation	43
3.3.2 Model calibration	47
3.3.3 Model applications	51
3.3.3.1 Sludge mass and composition	51
3.3.3.2 Biological reactor volume	54
3.3.3.3 Excess sludge production and nutrient demand	55
3.3.3.4 Temperature effect	59
3.3.3.5 True yield versus apparent yield	60
3.3.3.6 F/M ratio	62
3.3.4 Selection and control of the sludge age	64
3.4 GENERAL MODEL OF THE ACTIVATED SLUDGE SYSTEM	67
3.4.1 Model development	69
3.4.2 Model calibration	72
3.4.3 Application of the general model	73
3.5 CONFIGURATIONS OF THE ACTIVATED SLUDGE SYSTEM	74
3.5.1 Conventional activated sludge systems	75
3.5.2 Sequential batch systems	76
3.5.3 Carrousel	77
3.5.4 Aerated lagoons	79

<b>4 AERATION</b>	<b>83</b>
4.1 Aeration theory	84
4.1.1 Factors affecting $k_{la}$ and $DO_s$	85
4.1.2 Effect of local pressure on $DO_s$	86
4.1.3 Effect of temperature on $k_{la}$ and $DO_s$	87
4.1.4 Oxygen transfer efficiency for surface aerators	89
4.1.5 Power requirement for diffused aeration	91
4.2 Methods to determine the oxygen transfer efficiency	94
4.2.1 Determination of the standard oxygen transfer efficiency	94
4.2.2 Determination of the actual oxygen transfer efficiency	95
<b>5 NITROGEN REMOVAL</b>	<b>103</b>
5.1 FUNDAMENTALS OF NITROGEN REMOVAL	104
5.1.1 Forms and reactions of nitrogenous matter	104
5.1.2 Mass balance of nitrogenous matter	106
5.1.3 Stoichiometrics of reactions with nitrogenous matter	111
5.1.3.1 Oxygen consumption	111
5.1.3.2 Effects on alkalinity	112
5.1.3.3 Effects on pH	116
5.2 NITRIFICATION	118
5.2.1 Nitrification kinetics	118
5.2.2 Nitrification in systems with non aerated zones	127
5.2.3 Nitrification potential and nitrification capacity	130
5.2.4 Design procedure for nitrification	131
5.3 DENITRIFICATION	135
5.3.1 System configurations for denitrification	136
5.3.1.1 Denitrification with an external carbon source	136
5.3.1.2 Denitrification with an internal carbon source	137
5.3.2 Denitrification kinetics	140
5.3.2.1 Sludge production in anoxic/aerobic systems	140
5.3.2.2 Denitrification rates	141
5.3.2.3 Minimum anoxic mass fraction in the pre-D reactor	144
5.3.3 Denitrification capacity	146
5.3.3.1 Denitrification capacity in a pre-D reactor	146
5.3.3.2 Denitrification capacity in a post-D reactor	147
5.3.4 Available nitrate	150
5.4 DESIGNING AND OPTIMISING NITROGEN REMOVAL	152
5.4.1 Calculation of nitrogen removal capacity	152
5.4.2 Optimised design of nitrogen removal	158
5.4.2.1 Complete nitrogen removal	159
5.4.2.2 Incomplete nitrogen removal	161
5.4.2.3 Effect of recirculation of oxygen on denitrification capacity	164
5.4.2.4 Design procedure for optimized nitrogen removal	169

<b>6 INNOVATIVE SYSTEMS FOR NITROGEN REMOVAL</b>	<b>173</b>
6.1 Nitrogen removal over nitrite	175
6.1.1 Basic principles of nitrification	176
6.1.2 Kinetics of high rate ammonium oxidation	178
6.1.3 Reactor configuration and operation	179
6.1.4 Required model enhancements	180
6.2 Anaerobic ammonium oxidation	181
6.2.1 Anammox process characteristics	182
6.2.2 Reactor design and -configuration	183
6.3 Combination of nitrification with Anammox	185
6.3.1 Two stage configuration (nitrification reactor - Anammox)	185
6.3.2 Case study: full scale SHARON - Anammox treatment	188
6.3.3 Single reactor configurations	189
6.4 Bioaugmentation	193
6.5 Side stream nitrogen removal: evaluation and potential	194
<b>7 PHOSPHORUS REMOVAL</b>	<b>197</b>
7.1 BIOLOGICAL PHOSPHORUS REMOVAL	197
7.1.1 Mechanisms involved in biological phosphorus removal	197
7.1.2 Bio-P removal system configurations	202
7.1.3 Model of biological phosphorus removal	205
7.1.3.1 Enhanced cultures	205
7.1.3.2 Mixed cultures	210
7.1.3.3 Denitrification of bio-P organisms	215
7.1.3.4 Discharge of organic phosphorus with the effluent	218
7.2 OPTIMISATION OF BIOLOGICAL NUTRIENT REMOVAL	219
7.2.1 Influence of wastewater characteristics	219
7.2.2 Improving substrate availability for nutrient removal	220
7.2.3 Optimisation of operational conditions	223
7.2.4 Resolving operational problems	227
7.3 CHEMICAL PHOSPHORUS REMOVAL	229
7.3.1 Stoichiometrics of chemical phosphorus removal	229
7.3.1.1 Addition of metal salts	229
7.3.1.2 Addition of lime	231
7.3.1.3 Effects on pH	232
7.3.2 Chemical phosphorus removal configurations	233
7.3.2.1 Pre-precipitation	235
7.3.2.2 Simultaneous precipitation	238
7.3.2.3 Post-precipitation	241
7.3.2.4 Sidestream precipitation	242
7.3.3 Design procedure for chemical phosphorus removal	245

<b>8 SLUDGE SETTLING</b>	<b>249</b>
8.1 METHODS TO DETERMINE SLUDGE SETTLEABILITY	249
8.1.1 Zone settling rate test	249
8.1.2 Alternative parameters for sludge settleability	253
8.1.3 Relationships between different settleability parameters	253
8.2 MODEL FOR SETTLING IN A CONTINUOUS SETTLER	256
8.2.1 Determination of the limiting concentration $X_l$	259
8.2.2 Determination of the critical concentration $X_c$	260
8.2.3 Determination of the minimum concentration $X_m$	261
8.3 DESIGN OF FINAL SETTLERS	263
8.3.1 Optimised design procedure for final settlers	263
8.3.2 Determination of the critical recirculation rate	266
8.3.3 Graphical optimization of final settler operation	269
8.3.4 Optimisation of the system of biological reactor and final settler	271
8.3.5 Validation of the optimised settler design procedure	274
8.3.5.1 US EPA design guidelines	274
8.3.5.2 WRC and modified WRC design guidelines	275
8.3.5.3 STORA/STOWA design guidelines	275
8.3.5.4 ATV design guidelines	276
8.3.5.5 Solids flux compared with other design methods	276
8.4 PHYSICAL DESIGN ASPECTS FOR FINAL SETTLERS	280
8.5 FINAL SETTLERS UNDER VARIABLE LOADING CONDITIONS	281
<b>9 SLUDGE BULKING AND SCUM FORMATION</b>	<b>285</b>
9.1 Microbial aspects of sludge bulking	285
9.2 Causes and control of sludge bulking	289
9.2.1 Sludge bulking due to a low reactor substrate concentration	289
9.2.2 Guidelines for selector design	291
9.2.3 Control of bulking sludge in anoxic-aerobic systems	293
9.2.4 Other causes of sludge bulking	297
9.3 Non-specific measures to control sludge bulking	298
9.4 Causes and control of scum formation	303

<b>10 MEMBRANE BIOREACTORS</b>	<b>307</b>
10.1 MEMBRANE BIOREACTORS (MBR)	308
10.2 MBR configurations	310
10.2.1 Submerged MBR	311
10.2.2 Cross-flow MBR	313
10.2.3 Comparison of submerged and cross-flow MBR	318
10.3 MBR design considerations	323
10.3.1 Theoretical concepts in membrane filtration	323
10.3.2 Impact on activated sludge system design	326
10.3.3 Pre-treatment	331
10.3.4 Module configuration - submerged MBR	332
10.3.5 Module aeration - submerged MBR	333
10.3.6 Key design data of different membrane types	334
10.4 MBR operation	335
10.4.1 Operation of submerged membranes	335
10.4.2 Operation of cross-flow membranes	335
10.4.3 Membrane fouling	336
10.4.4 Membrane cleaning	337
10.5 MBR technology: evaluation and potential	340
<b>11 MOVING BED BIOFILM REACTORS</b>	<b>343</b>
11.1 MBBR technology and reactor configuration	344
11.1.1 Carriers used in MBBR processes	347
11.1.2 Aeration system	349
11.1.3 Sieves and mixers	349
11.2 Features of MBBR process	350
11.3 MBBR process configurations	353
11.3.1 Pure MBBR	353
11.3.2 MBBR as pre-treatment	354
11.3.3 MBBR as post-treatment	355
11.3.4 Integrated fixed film reactors	355
11.4 Pure MBBR design and performance	357
11.4.1 Secondary treatment of municipal sewage	357
11.4.2 Secondary treatment of industrial wastewater	360
11.4.3 Nitrification	361
11.4.4 Nitrogen removal	363
11.4.5 Phosphorus removal	367
11.5 Upgrading of existing activated sludge plants	367
11.5.1 High rate pre-treatment MBBR for BOD/COD removal	367
11.5.2 Upgrading of secondary CAS to nitrification	369
11.5.3 Nitrification in IFAS processes	369
11.5.4 IFAS for nitrogen removal	372

11.6 Solids removal from MBBR effluent	372
11.6.1 Gravity settling	373
11.6.2 Micro-sand ballasted lamella sedimentation	375
11.6.3 Dissolved air flotation	375
11.6.4 Micro screening	375
11.6.5 Media filtration	379
11.6.6 Membrane filtration	380
<b>12 SLUDGE TREATMENT AND DISPOSAL</b>	<b>381</b>
12.1 EXCESS SLUDGE QUALITY AND QUANTITY	381
12.2 SLUDGE THICKENERS	385
12.2.1 Design of sludge thickeners using the solids flux theory	385
12.2.2 Design of sludge thickeners using empirical relationships	389
12.3 AEROBIC DIGESTION	392
12.3.1 Kinetic model for aerobic sludge digestion	392
12.3.1.1 Variation of the volatile sludge concentration	393
12.3.1.2 Variation of the oxygen uptake rate	394
12.3.1.3 Variation of the nitrate concentration	395
12.3.1.4 Variation of the alkalinity	395
12.3.1.5 Variation of the BOD	399
12.3.2 Aerobic digestion in the main activated sludge process	399
12.3.3 Aerobic digester design	402
12.3.4 Optimisation of aerobic sludge digestion	407
12.3.5 Operational parameters of the aerobic digester	412
12.4 ANAEROBIC DIGESTION	418
12.4.1 Stoichiometry of anaerobic digestion	420
12.4.2 Configurations used for anaerobic digestion	423
12.4.3 Influence of operational parameters	425
12.4.4 Performance of the high rate anaerobic digester	429
12.4.4.1 Removal efficiency of volatile suspended solids	429
12.4.4.2 Biogas production	429
12.4.4.3 Energy generation in anaerobic sludge digesters	431
12.4.4.4 Solids destruction and stabilised excess sludge production	432
12.4.4.5 Nutrient balance in the anaerobic digester	432
12.4.5 Design and optimisation of anaerobic digesters	438
12.5 STABILISED SLUDGE DRYING AND DISPOSAL	440
12.5.1 Natural sludge drying	441
12.5.2 Design and optimisation of natural sludge drying beds	445
12.5.2.1 Determination of the percolation time ( $t_2$ )	445
12.5.2.2 Determination of the evaporation time ( $t_4$ )	446
12.5.2.3 Influence of rain on sludge drying bed productivity	453
12.5.3 Accelerated sludge drying with external energy	455
12.5.3.1 Use of solar energy	456
12.5.3.2 Use of combustion heat from biogas	458

<b>13 ANAEROBIC PRETREATMENT</b>	<b>461</b>
13.1 ANAEROBIC TREATMENT OF MUNICIPAL SEWAGE	462
13.1.1 Configurations for anaerobic sewage treatment	464
13.1.1.1 Anaerobic filter	464
13.1.1.2 Fluidised and expanded bed systems	465
13.1.1.3 Upflow Anaerobic Sludge Blanket (UASB) reactor	466
13.1.1.4 The RALF system	467
13.1.2 Evaluation of different anaerobic configurations	468
13.2 FACTORS AFFECTING MUNICIPAL UASB PERFORMANCE	469
13.2.1 Design and engineering issues	471
13.2.2 Operational- and maintenance issues	478
13.2.3 Inappropriate expectations of UASB performance	479
13.2.4 Presence of sulphate in municipal sewage	480
13.2.5 Energy production and greenhouse gas emissions	484
13.2.5.1 Carbon footprint	484
13.2.5.2 Biogas utilization	489
13.3 DESIGN MODEL FOR ANAEROBIC SEWAGE TREATMENT	498
13.3.1 Sludge age as the key design parameter	499
13.3.2 Influence of the temperature	503
13.3.3 Characterisation of anaerobic biomass	505
13.4 UASB REACTOR DESIGN GUIDELINES	510
13.5 POST-TREATMENT OF ANAEROBIC EFFLUENT	520
13.5.1 Secondary treatment of anaerobic effluent	523
13.5.1.1 Applicability of the ideal steady state model for COD removal	525
13.5.1.2 Stabilisation of aerobic excess sludge in the UASB reactor	536
13.5.2 Nitrogen removal from anaerobic effluent	542
13.5.2.1 Bypass of raw sewage to the activated sludge system	543
13.5.2.2 Anaerobic digestion with reduced methanogenic efficiency	546
13.5.2.3 Application of innovative nitrogen removal configurations	547
13.5.3 Future developments	549
13.5.3.1 Two stage anaerobic digestion	549
13.5.3.2 Psychrophilic anaerobic wastewater treatment	550
13.6 ANAEROBIC TREATMENT OF INDUSTRIAL WASTEWATER	551

<b>14 INTEGRATED COST-BASED DESIGN AND OPERATION</b>	<b>559</b>
14.1 PREPARATIONS FOR SYSTEM DESIGN	560
14.1.1 The basis of design	560
14.1.1.1 Wastewater characteristics	561
14.1.1.2 Kinetic parameters and settleability of the sludge	566
14.1.2 Costing data	566
14.1.2.1 Investment costs	566
14.1.2.2 Operational costs	571
14.1.2.3 Annualised investment costs	572
14.1.3 Performance objectives	574
14.1.4 Applicable system configurations	575
14.1.5 Limitations and constraints	578
14.2 OPTIMISED DESIGN PROCEDURE	579
14.2.1 System A1: Conventional secondary treatment	579
14.2.2 System A2: Secondary treatment with primary settling	590
14.2.3 System B1: Combined anaerobic-aerobic treatment	593
14.2.4 System C1: Nitrogen removal	604
14.2.5 System C2: Nitrogen and phosphorus removal	609
14.2.6 System comparison	615
14.3 FACTORS INFLUENCING DESIGN	617
14.3.1 Influence of the wastewater temperature	617
14.3.2 Influence of the sludge age	618
14.4 OPERATIONAL OPTIMISATION	620
14.4.1 Comparison of different operational regimes	620
14.4.2 Optimised operation of existing treatment plants	623
14.5 INTEGRATED DESIGN EXAMPLES	626
14.5.1 Nutrient removal in different configurations	626
14.5.2 Membrane bioreactor design – case study	639
14.6 FINAL REMARKS	650
<b>APPENDICES</b>	<b>653</b>
<b>A1 DETERMINATION OF THE OXYGEN UPTAKE RATE</b>	<b>655</b>
A1.1 DETERMINATION OF THE APPARENT OUR	656
A1.2 CORRECTION FACTORS OF THE APPARENT OUR	656
A1.2.1 Representativeness of mixed liquor operational conditions	656
A1.2.2 Critical dissolved oxygen concentration	657
A1.2.3 Hydraulic effects	658
A1.2.4 Absorption of atmospheric oxygen	659
A1.2.5 The relaxation effect	661

<b>A2 CALIBRATION OF THE GENERAL MODEL</b>	<b>665</b>
A2.1 CALIBRATION WITH CYCLIC LOADING	666
A2.2 CALIBRATION WITH BATCH LOADING	670
<b>A3 THE NON-IDEAL ACTIVATED SLUDGE SYSTEM</b>	<b>673</b>
<b>A4 DETERMINATION OF NITRIFICATION KINETICS</b>	<b>677</b>
<b>A5 DETERMINATION OF DENITRIFICATION KINETICS</b>	<b>685</b>
<b>A6 EXTENSIONS TO THE IDEAL MODEL</b>	<b>691</b>
A6.1 IMPERFECT SOLID-LIQUID SEPARATION IN FINAL SETTLER	691
A6.1.1 Particulate organic nitrogen and phosphorus in the effluent	691
A6.1.2 Excess sludge production and composition	694
A6.2 NITRIFIER FRACTION IN THE VOLATILE SLUDGE MASS	695
<b>A7 EMPIRIC METHODS FOR FINAL SETTLER SIZING</b>	<b>699</b>
A7.1 STORA DESIGN GUIDELINES (1981)	699
A7.1.1 Theoretical aspects	699
A7.1.2 Application of the STORA 1981 design guidelines	702
A7.1.3 Modifications to the STORA 1981 design guidelines	704
A7.2 FINAL SETTLER DESIGN COMPARISON METHODOLOGY	706
A7.3 ATV DESIGN GUIDELINES (1976)	709
A7.3.1 Theoretical aspects	709
A7.3.2 Modifications to the ATV 1976 design guidelines	711
<b>A8 DENITRIFICATION IN THE FINAL SETTLER</b>	<b>713</b>
<b>A9 AEROBIC GRANULATED SLUDGE</b>	<b>721</b>
A9.1 Benefits of aerobic granular sludge systems	723
A9.2 System design and operation	728
A9.2.1 Process configurations	728
A9.2.2 Reactor configuration	730
A9.2.3 Operation of AGS systems	731
A9.2.4 Start-up of aerobic granular sludge reactors	733
A9.3 Granular biomass: evaluation and potential	734
<b>SUBJECT INDEX</b>	<b>737</b>
<b>REFERENCE LIST</b>	<b>745</b>