

Contents

Preface	xi
Fanny BALBAUD-CÉLÉRIER and Céline CABET	
Chapter 1. Materials and Processes for Light Water Reactors	1
Jean-Paul MASSOUD and Eric MOLINIÉ	
1.1. Acronyms	1
1.2. Introduction with general description of the systems	3
1.2.1. Pressurized water reactor	3
1.2.2. BWR	6
1.3. Requirements for materials	9
1.3.1. Brittle fracture	9
1.3.2. Corrosion	10
1.4. Material choices and basic properties	12
1.4.1. Carbon and LASs	14
1.4.2. Austenitic stainless steels	15
1.4.3. Nickel base alloys	16
1.4.4. Other materials	16
1.5. Fabrication and joining	19
1.5.1. Forging of Ferritic components: from ingot to component.	20
1.5.2. Casting ... to forging	22
1.5.3. Forging of PWR SG tube bundle	22
1.5.4. Welding and cladding	23

1.5.5. Heat treatment	23
1.5.6. Manufacturing defects (links with fabrication).	24
1.5.7. Non-destructive testing (links with expected defects).	25
1.6. Main material limitations.	27
1.6.1. BWRs.	27
1.6.2. PWRs	28
1.6.3. Irradiation embrittlement	28
1.6.4. Thermal aging	34
1.6.5. Stress corrosion cracking	37
1.6.6. Flow-assisted corrosion	42
1.6.7. Other main possible mechanisms.	43
1.7. Main material challenges and solutions under evaluation.	48
1.7.1. Precautions to take during manufacturing to ensure the homogeneity of the through wall property of huge components	48
1.7.2. Precautions to take during manufacturing to prevent or mitigate in-service thermal aging, irradiation embrittlement, fatigue and stress corrosion cracking	50
1.7.3. New possible fabrications under evaluation: hot isostatic pressing and additive manufacturing	54
1.8. References	55
Chapter 2. Materials and Processes for Nuclear Fuel Reprocessing	57
Nathalie GRUET, Benoit GWINNER, Pierre LAGHOUTARIS, Beatriz PUGA, Pierre FAUVET, Hervé ANTONY, Valentin ROHR, Eric CAVALETTI, Pierre CHAMBRETTE and Laurent JUNOD	
2.1. Introduction and general description of systems	57
2.1.1. Description of the process and the main functions	57
2.1.2. Description of aging conditions (temperature, nitric acid concentration, etc.)	59
2.2. Requirements for materials	60
2.2.1. Functional requirements associated with the process: mechanical resistance, corrosion resistance and erosion resistance	60
2.2.2. Regulatory context and industrial strategy	61
2.3. Current material choices, fabrication and joining	63
2.3.1. Current material choices	63
2.3.2. Fabrication and joining.	65

2.4. Basic properties	66
2.4.1. Corrosion of austenitic stainless steels	66
2.4.2. Corrosion of zirconium	74
2.5. Parameters influencing corrosion	76
2.5.1. Corrosion products	77
2.5.2. Oxidizing ions	79
2.5.3. Halides (chlorides and fluorides)	83
2.5.4. Temperature and heat flux	85
2.5.5. Irradiation	86
2.5.6. Influence of the metallurgical state (welding)	87
2.6. Operating experience: some examples	88
2.6.1. Dissolver wheel	88
2.6.2. Fission product evaporator–concentrator machines	90
2.6.3. Zirconium thermosiphons	92
2.7. New developments	96
2.8. References	97

Chapter 3. Materials and Processes for Geological Disposal of High-level Waste and Spent Fuel

Fraser KING

3.1. Introduction.	107
3.2. Canister requirements	109
3.3. Choice of material, canister design and canister fabrication	114
3.4. Environmental conditions	117
3.5. Canister performance	122
3.5.1. Corrosion performance.	122
3.5.2. Mechanical performance.	129
3.5.3. Joint mechanical–corrosion performance	131
3.6. Lifetime prediction	132
3.7. Outlook	135
3.8. References	135

Chapter 4. Structural Materials for Sodium Cooled Fast Reactors

Hayato YAMASHITA and Tai ASAYAMA

4.1. Introduction.	145
4.2. Requirements for structural materials	148

4.3. Development of structural materials and evaluation methods	151
4.3.1. Creep-fatigue evaluation methods	151
4.3.2. Improvement of creep-fatigue properties and materials	154
4.3.3. Creep-fatigue damage evaluation for 316FR steel and modified 9Cr-1Mo steel	157
4.3.4. Effect of operating environment on creep-fatigue properties	159
4.4. Ongoing activities	165
4.5. Conclusion	166
4.6. References	166
Chapter 5. Materials and Processes for Heavy Liquid Metal Cooled Reactors	169
Serguei GAVRILOV	
5.1. Introduction.	169
5.2. Requirements for materials	176
5.3. Material choices and basic properties	178
5.4. Fabrication and joining	181
5.5. Main material limitations.	182
5.5.1. Liquid metal corrosion	182
5.5.2. Liquid metal embrittlement	186
5.5.3. Corrosion fatigue and corrosion creep.	187
5.5.4. Limitations for material qualification	188
5.6. Main material challenges and solutions under evaluation.	189
5.7. References	193
Chapter 6. Materials and Processes for Molten Salts Reactors	197
Céline CABET, Yann DE CARLAN and Laure MARTINELLI	
6.1. Introduction with general description of the systems	197
6.1.1. Background	198
6.1.2. MSR research emphasis	200
6.2. Requirements for materials	203
6.2.1. Graphite performance (thermal spectrum)	203
6.2.2. Neutron reflector (fast spectrum).	204
6.2.3. Structural materials	204
6.3. Legacy materials and basic properties	205
6.4. Main material limitations.	207
6.4.1. Corrosion in molten fluorides.	208

6.4.2. Corrosion in molten chlorides.	212
6.4.3. Tellurium embrittlement.	214
6.4.4. Irradiation embrittlement	215
6.5. Mitigation of corrosion by salt purification and chemical control.	216
6.5.1. Molten fluorides.	217
6.5.2. Molten chlorides	218
6.6. Main material challenges and solutions under evaluation.	218
6.7. References	219
Chapter 7. Materials and Processes for Fusion Reactors	225
Giacomo AIELLO	
7.1. Introduction and general description of the systems	225
7.2. Requirements for materials	228
7.2.1. Requirements for the structural material of the BB system	228
7.2.2. Requirements for the materials of the Divertor system	230
7.3. Material choices and basic properties	232
7.3.1. EUROFER97 as structural material for the BB	232
7.3.2. Tungsten and copper-chromium-zirconium as armor and heat sink materials for the Divertor targets	238
7.4. Fabrication and joining	246
7.4.1. Manufacturing techniques for the BB	246
7.4.2. Manufacturing techniques for the Divertor targets	249
7.5. Main material limitations and solutions under evaluation	250
7.5.1. Limits for structural material EUROFER97 and development of advanced/risk mitigation steels	251
7.5.2. Advanced armor and heat sink materials for the Divertor targets	254
7.6. References	256
Chapter 8. Advanced Materials: Ceramics and Composite Materials	261
James BRAUN	
8.1. Introduction.	261
8.2. Current interest in nuclear systems	263
8.3. Manufacturing and joining.	266
8.4. Material properties	269
8.5. Main challenges and solutions under evaluation	271
8.6. References	272

Chapter 9. Advanced Materials: Oxide-Dispersion Strengthened Steels	279
Satoshi OHTSUKA, Takashi TANNO, Yasuhide YANO and Takeji KAITO	
9.1. General introduction to the ODS	279
9.2. Actual interest in nuclear systems.	280
9.3. Fabrication and joining	283
9.4. Material properties	286
9.5. Main material challenges and solutions under evaluation.	292
9.6. References	293
Chapter 10. Materials Discovery	299
Andrea JOKISAARI, Cheng SUN and Jian GAN	
10.1. Materials discovery – numerical design	299
10.1.1. What is materials discovery and is it needed in the nuclear industry?	299
10.1.2. Historical perspective.	300
10.1.3. Modern approach	302
10.1.4. Future needs	307
10.2. Materials discovery – advanced manufacturing processes	309
10.2.1. AM technologies	309
10.2.2. AM materials under nuclear environments	312
10.2.3. Challenges of AM processes for nuclear materials	316
10.2.4. Summary	318
10.3. Materials discovery – high-throughput characterization.	318
10.3.1. Material fabrication and sample preparation	319
10.3.2. Microstructural characterization	320
10.3.3. High-throughput mechanical and corrosion property evaluation.	322
10.3.4. High-throughput irradiation and characterization	325
10.4. Summary	327
10.5. References.	328
List of Authors	337
Index	341