2.15	Uranium Oxide and MOX Production T. Abe and K. Asakura	393
2.16	Burnable Poison-Doped Fuel K. Hesketh	423
2.17	Thermal Properties of Irradiated UO ₂ and MOX D. Staicu	439
2.18	Radiation Effects in UO ₂ T. Wiss	465
2.19	Fuel Performance of Light Water Reactors (Uranium Oxide and MOX) D. D. Baron and L. Hallstadius	481
2.20	Fission Product Chemistry in Oxide Fuels B. J. Lewis, W. T. Thompson, and F. C. Iglesias	515
2.21	Fuel Performance of Fast Spectrum Oxide Fuel Y. Guerin	547
2.22	Transient Response of LWR Fuels (RIA) T. Fuketa	579
2.23	Behavior of LWR Fuel During Loss-of-Coolant Accidents F. Nagase	595
2.24	Behavior of Fast Reactor Fuels During Transient and Accident Conditi J. Papin	
2.25	Core Concrete Interaction C. Journeau and P. Piluso	035

VOLUME 3 ADVANCED FUELS/FUEL CLADDING/NUCLEAR FUEL PERFORMANCE MODELING AND SIMULATION

3.01	Metal Fuel <i>T. Ogata</i>	1
3.02	Nitride Fuel Y. Arai	41
3.03	Carbide Fuel A. K. Sengupta, R. Agarwal, and H. S. Kamath	55
3.04	Thorium Oxide Fuel P. R. Hania and F. C. Klaassen	87
3.05	Actinide-Bearing Fuels and Transmutation Targets S. Pillon	109
3.06	TRISO Fuel Production K. Sawa	143
3.07	TRISO-Coated Particle Fuel Performance D. A. Petti, P. A. Demkowicz, J. T. Maki, and R. R. Hobbins	151
3.08	Advanced Concepts in TRISO Fuel K. Minato and T. Ogawa	215
3.09	Inert Matrix Fuel P. Pöml, R. J. M. Konings, J. Somers, T. Wiss, G. J. L. M. de Haas, and F. C. Klaassen	237

3.10	Composite Fuel (cermet, cercer) M. K. Meyer	257
3.11	Sphere-Pac and VIPAC Fuel M. A. Pouchon, G. Ledergerber, F. Ingold, and K. Bakker	275
3.12	Uranium–Zirconium Hydride Fuel D. Olander, K. Konashi, and M. Yamawaki	313
3.13	Molten Salt Reactor Fuel and Coolant O. Beneš and R. J. M. Konings	359
3.14	Uranium Intermetallic Fuels (U-Al, U-Si, U-Mo) Yeon Soo Kim	391
3.15	Metal Fuel–Cladding Interaction D. D. Keiser, Jr.	423
3.16	Ceramic Fuel–Cladding Interaction K. Maeda	443
3.17	Thermal Spectrum Control Rod Materials R. M. Horn, B. D. Frew, and P. Van Diemen	485
3.18	Fast Spectrum Control Rod Materials T. Donomae and K. Maeda	509
3.19	Oxide Fuel Performance Modeling and Simulations P. Van Uffelen and M. Suzuki	535
3.20	Modeling of Fission-Gas-Induced Swelling of Nuclear Fuels <i>J. Rest</i>	579
3.21	Matter Transport in Fast Reactor Fuels M. J. Welland	629
3.22	Modeling of Pellet Cladding Interaction B. Michel, J. Sercombe, C. Nonon, and O. Fandeur	677
3.23	Metal Fuel Performance Modeling and Simulation T. Ogata, Yeon Soo Kim, and A. M. Yacout	713
3.24	TRISO Fuel Performance Modeling and Simulation K. Verfondern	755
3.25	Modeling of Sphere-Pac Fuel M. A. Pouchon, LÅ. Nordström, and Ch. Hellwig	789

3.01 Metal Fuel

T. Ogata

Central Research Institute of Electric Power Industry, Tokyo, Komae, Japan

3.01.1	Introduction	2
3.01.2	Properties of Metal Fuel Alloys	4
3.01.2.1	Physical Properties	4
3.01.2.1.1	Density	4
3.01.2.1.2	Solidus and liquidus temperatures	5
3.01.2.1.3	Phase transition temperatures	6
3.01.2.1.4	Heat capacity	7
3.01.2.1.5	Thermal conductivity	7
3.01.2.1.6	Thermal expansion	8
3.01.2.2	Mechanical Properties	9
3.01.2.3	Diffusion Properties	12
3.01.2.4	Effects of MA Addition	13
3.01.3	Metal Fuel Fabrication	14
3.01.3.1	Fuel Slug Fabrication	15
3.01.3.1.1	Injection casting	15
3.01.3.1.2	Other methods	18
3.01.3.2	Fuel Pin Assembly	19
3.01.4	Steady-State Irradiation Behavior	19
3.01.4.1	Steady-State Irradiation Tests	19
3.01.4.2	Fuel Constituent Migration	20
3.01.4.3	Fission Gas Release and Gas Swelling	21
3.01.4.4	Restructuring and Deformation of the Fuel Slug	25
3.01.4.5	Fuel-Cladding Mechanical Interaction	27
3.01.4.6	Change in Fuel Slug Temperature	28
3.01.4.7	Fuel-Cladding Chemical Interaction	28
3.01.4.8	Behavior of Fission Products	29
3.01.4.9	Behavior of Breached Fuel Pins	30
3.01.4.10	Behavior of MA-Bearing Metal Fuel	31
3.01.4.11	Factors Controlling Fuel Lifetime	31
3.01.5	Transient Behavior	32
3.01.5.1	Transient Tests	32
3.01.5.2	Linear-Power-to-Melting	32
3.01.5.3	Liquefaction at the Fuel-Cladding Interface	33
3.01.5.4	Molten Fuel Motion	35
3.01.5.5	Fuel Pin Failure Mechanism	36
3.01.5.6	Failed Fuel Behavior	37
3.01.6	Summary and Future Development	37
References		37

3.02 Nitride Fuel

Y. Arai

Nuclear Science and Engineering Directorate, Japan Atomic Energy Agency, Ibaraki, Japan

3.02.1	Introduction	41
3.02.2	Fabrication of Nitride Fuel	43
3.02.2.1	Actinide Nitride Compounds	43
3.02.2.2	Preparation from Metal or Hydride	44
3.02.2.3	Carbothermic Reduction	44
3.02.2.4	Other Nitride Formation Processes	45
3.02.2.5	Nitride Pellet Fabrication	46
3.02.2.6	Nitride Particle Fabrication	47
3.02.3	Irradiation Behavior of Nitride Fuel	47
3.02.3.1	Irradiation Experience	47
3.02.3.2	Fuel Design	47
3.02.3.3	Chemical Forms of FP	48
3.02.3.4	Restructuring	49
3.02.3.5	FP Gas Release	50
3.02.3.6	Swelling and FCMI	50
3.02.3.7	Fuel-Clad Chemical Interaction	51
3.02.4	Reprocessing of Nitride Fuel	51
3.02.5	Outlook of Nitride Fuel	52
References		53

3.03 Carbide Fuel

A. K. Sengupta, R. Agarwal, and H. S. Kamath

Bhabha Atomic Research Centre, Mumbai, India

© 2012 Elsevier Ltd. All rights reserved.

3.03.1	Introduction	56
3.03.1.1	History of Carbide Fuel	56
3.03.1.2	Glimpses of Carbide Fuel	57
3.03.2	Physical Properties	59
3.03.2.1	Thermophysical Properties of Carbide Fuel	59
3.03.2.2	Thermochemistry of Carbide Fuels	60
3.03.3	Fabrication of Carbide Fuel	64
3.03.3.1	Melting Casting	64
3.03.3.2	Hydride/Hydrocarbon Route	64
3.03.3.3	Carbothermic Reduction Route	64
3.03.3.3.1	Direct pressing method	65
3.03.3.3.2	Sol–gel (wet) route	66
3.03.3.4	Quality Control	67
3.03.3.4.1	Chemical quality control method	68
3.03.3.4.2	Physical quality control	69
3.03.4	In-Pile Performance	70
3.03.4.1	Introduction	70
3.03.4.1.1	Burnup	70
3.03.4.1.2	Swelling	71
3.03.4.1.3	Performance of Na-bonded and He-bonded fuel pins	72
3.03.4.1.4	Irradiation creep	73
3.03.4.1.5	Experience on irradiation performance	75
3.03.4.1.6	Fuel-clad chemical interaction	78
3.03.4.2	Effects of Burnup on C/M Ratio and Chemical State of Fission Product	79
3.03.4.3	MA-Containing Fuel	80
3.03.5	Fuel Reprocessing and Waste Management	82
3.03.6	Summary	83
References		84

and a second second

in manager washing of a state of the state o

3.04 Thorium Oxide Fuel

P. R. Hania and F. C. Klaassen

ALC: NO

Nuclear Research and Consultancy Group, Petten, The Netherlands

3.04.1	Introduction	88
3.04.2	Incentives for Using Thorium	89
3.04.2.1	Thorium as an Abundantly Available Resource for Nuclear Fuel	89
3.04.2.2	Radiotoxicity Reduction with Thorium	90
3.04.2.3	Reduction of Excess Military Plutonium	90
3.04.3	Physical Properties of Thorium Oxide Fuel	90
3.04.3.1	Crystal Structure	91
3.04.3.2	Thermal Expansion	91
3.04.3.3	Thermal Conductivity	92
3.04.3.4	Thermophysical Properties	93
3.04.3.5	Oxygen Potential	93
3.04.4	Thorium Oxide Fuel Fabrication	94
3.04.4.1	Powder Compaction	94
3.04.4.1.1	ThO ₂	94
3.04.4.1.2	Mixed oxides	95
3.04.4.2	Powder-Plasticizer Methods	96
3.04.4.3	Sol–Gel Methods	96
3.04.5	Behavior of Thorium Oxide Fuel Under Irradiation	97
3.04.5.1	Neutronic Properties of Thorium-Based Fuel	97
3.04.5.2	In-Core Behavior of Thorium Oxide Fuel	99
3.04.5.2.1	Restructuring	100
3.04.5.2.2	Thermal conductivity	100
3.04.5.2.3	CANDU fuel	101
3.04.5.2.4	United States	101
3.04.5.2.5	India	102
3.04.5.2.6	Fission product behavior	102
3.04.5.2.7	(Th,Pu)O ₂	103
3.04.6	Reprocessing and Refabrication	104
3.04.6.1	The THOREX Process	104
3.04.6.2	Beyond Thorex	105
3.04.6.3	Radiation Issues in Reprocessing and Refabrication	106
3.04.7	Conclusions	106
References		106

3.05 Actinide-Bearing Fuels and Transmutation Targets

S. Pillon

Commissariat à l'Energie Atomique, St Paul Lez Durance, France

3.05.1	Introduction: Why Transmutation?	110
3.05.2	The Various Transmutation Strategies of MAs	111
3.05.2.1	Which Reactors for Transmutation?	111
3.05.2.2	Transmutation in SFR	113
3.05.2.2.1	Homogeneous recycling	113
3.05.2.2.2	Heterogeneous recycling in targets	113
3.05.2.2.3	Heterogeneous recycling in breeder blanket	114
3.05.2.3	Transmutation in ADS	114
3.05.3	Composition of Transmutation Fuel	114
3.05.3.1	Actinide Compounds	114
3.05.3.1.1	Oxides	114
3.05.3.1.2	Alternate compounds	115
3.05.3.2	Inert Matrices	116
3.05.3.3	Composition of Fuel and Targets	118
3.05.4	Behavior of Refractory Ceramic Fuel Under Irradiation	118
3.05.4.1	Homogeneous Transmutation Fuel	118
3.05.4.1.1	Beginning-of-life behavior (burnup < 0.5 %FIMA)	118
3.05.4.1.2	Behavior at moderate combustion rate (burnup $< 6-7$ %FIMA)	119
3.05.4.1.3	End-of-life behavior (15–20 %FIMA)	121
3.05.4.2	Inert Matrix Target and Fuel	121
3.05.4.2.1	The main challenges	121
3.05.4.2.2	Neutron damaging	122
3.05.4.2.3	Damage by FPs	125
3.05.4.2.4	Damage by α -particles	126
3.05.4.2.5	The nonoxide composites of ADS	128
3.05.4.3	MA-Bearing Blankets	129
3.05.4.3.1	Specificities of MA-bearing blankets	129
3.05.4.3.2	Status of ongoing irradiation projects	132
3.05.5	Manufacturing of Transmutation Target and Fuel	133
3.05.5.1	Thermal and Radiological Constraints	133
3.05.5.2	Manufacturing Processes	135
3.05.5.2.1	Metallurgical processes	135
3.05.5.2.2	Coprecipitation processes	135
3.05.5.2.3	Sol–gel processes	136
3.05.5.2.4	Vipac/Spherepac process	137
3.05.5.2.5	INRAM process	138
3.05.6	Conclusion	139
References		140

3.06 TRISO Fuel Production

K. Sawa

Japan Atomic Energy Agency, O-arai, Ibaraki, Japan

3.06.1	Introduction	143
3.06.2	Fabrication Processes	144
3.06.2.1	Kernel Fabrication Processes ²	144
3.06.2.2	PyC- and SiC-Coating Processes ^{5,6}	145
3.06.2.3	Manufacturing Process of Fuel Element	146
3.06.2.3.1	The case of the block type (example of the HTTR fuel)	146
3.06.2.3.2	The pebble bed type ⁹	147
3.06.3	Inspection	147
3.06.3.1	The Inspected Parameters	147
3.06.3.2	Characterization Methods	147
3.06.4	Outlook	148
References		149

3.07 TRISO-Coated Particle Fuel Performance

D. A. Petti, P. A. Demkowicz, and J. T. Maki

Idaho National Laboratory, Idaho Falls, ID, USA

R. R. Hobbins

RRH Consulting, Wilson, WY, USA

Published by Elsevier Ltd.

3.07.1	Introduction	153
3.07.2	Irradiation Performance	154
3.07.2.1	Overview of Irradiation Facilities and Testing	154
3.07.2.1.1	BR-2	154
3.07.2.1.2	IVV-2M	154
3.07.2.1.3	HFR Petten	155
3.07.2.1.4	HFIR	155
3.07.2.1.5	ATR	155
3.07.2.1.6	SAFARI	155
3.07.2.1.7	TRISO-coated particle fuel irradiation testing	156
3.07.2.1.8	Thermal and physics analysis considerations	156
3.07.2.1.9	Gas control system considerations	158
3.07.2.1.10	FPMS considerations	159
3.07.2.2	German Experience	160
3.07.2.2.1	R2-K12 and R2-K13	160
3.07.2.2.2	BR2-P25	161
3.07.2.2.3	HFR-P4	162
3.07.2.2.4	SL-P1	162
3.07.2.2.5	HFR-K3	163
3.07.2.2.6	FRJ2-K13	163
3.07.2.2.7	FRJ2-K15	164
3.07.2.2.8	FRJ2-P27	164
3.07.2.2.9	HFR-K6 and HFR-K5	165
3.07.2.3	US Experience	165
3.07.2.3.1	F-30	166
3.07.2.3.2	HRB-4 and HRB-5	167
3.07.2.3.3	HRB-6	169
3.07.2.3.4	OF-2	170
3.07.2.3.5	HRB-14	171
3.07.2.3.6	HRB-15B	173
3.07.2.3.7	R2-K13	174
3.07.2.3.8	HRB-15A	174
3.07.2.3.9	HRB-16	175
3.07.2.3.10	HRB-21	176
3.07.2.3.11	NPR-1 and NPR-2	177
3.07.2.3 <i>.</i> 12	NPR-1A	178
3.07.2.3.13	AGR-1	178
3.07.2.4	European Experience	180
3.07.2.5	Chinese Experience	181
3.07.2.6	Japanese Experience	184
3.07.2.7	Irradiation Performance Summary	185
3.07.2.7.1	Heavy metal contamination	185
3.07.2.7.2	In-service failures	186
3.07.2.7.3	Failure mechanisms	186
3.07.2.7.4	Acceleration effects	187

3.07.3	Safety Testing	189
3.07.3.1	Facility Overview	189
3.07.3.1.1	KüFA at ITU	189
3.07.3.1.2	INL'S FACS	190
3.07.3.1.3	ORNL's Core Conduction Cooldown Test Facility	192
3.07.3.1.4	KORA	193
3.07.3.2	German Experience	193
3.07.3.3	European Experience	199
3.07.3.3.1	AVR 73/21	199
3.07.3.3.2	AVR 74/18	199
3.07.3.3.3	HFR K6/3	200
3.07.3.3.4	HFR K6/2	200
3.07.3.4	US Experience and Future Plans	202
3.07.3.4.1	Past experience	202
3.07.3.4.2	Future plans	205
3.07.3.5	Japanese Experience	206
3.07.4	Conclusions	209
References		212

3.08 Advanced Concepts in TRISO Fuel

K. Minato and T. Ogawa

Japan Atomic Energy Agency, Tokai-mura, Ibaraki, Japan

3.08.1	Introduction	216
3.08.2	ZrC-Coated Particle Fuel	216
3.08.2.1	Designs of ZrC-Coated Particle Fuel	216
3.08.2.2	Fabrication of ZrC-Coated Particle Fuel	217
3.08.2.3	Characterization Techniques for ZrC-Coated Particle Fuel	219
3.08.2.4	Performance of ZrC-Coated Particle Fuel	220
3.08.2.4.1	Irradiation performance	220
3.08.2.4.2	Resistance to chemical attack by fission products	221
3.08.2.4.3	High-temperature stability	222
3.08.2.4.4	Retention of fission products	225
3.08.2.4.5	Behavior under oxidizing conditions	227
3.08.3	ZrC-Containing TRISO-Coated Particle Fuel	227
3.08.3.1	Designs of ZrC-Containing TRISO-Coated Particle Fuel	227
3.08.3.2	Performance of ZrC-Containing TRISO-Coated Particle Fuel	229
3.08.3.2.1	Irradiation performance	229
3.08.3.2.2	Retention of fission products	230
3.08.4	SiC-Containing TRISO-Coated Particle Fuel	231
3.08.4.1	Designs of SiC-Containing TRISO-Coated Particle Fuel	231
3.08.4.2	Fabrication of SiC-Containing TRISO-Coated Particle Fuel	232
3.08.4.3	Performance of SiC-Containing TRISO-Coated Particle Fuel	233
3.08.4.3.1	Irradiation performance	233
3.08.4.3.2	Behavior under simulated conditions	233
3.08.5	TiN-Coated Particle Fuel	234
3.08.5.1	Designs of TiN-Coated Particle Fuel	234
3.08.5.2	Fabrication of TiN-Coated Particle Fuel	234
3.08.6	Outlook	235
References		235

3.09 Inert Matrix Fuel

P. Pöml, R. J. M. Konings, J. Somers, and T. Wiss

European Commission, Joint Research Centre, Institute for Transuranium Elements, Karlsruhe, Germany

G. J. L. M. de Haas and F. C. Klaassen

Nuclear Research and Consultancy Group, Petten, The Netherlands

		an analyzed a second statement of the second statement of t
3.09.1	Introduction	238
3.09.2	History	238
3.09.3	Neutronic Considerations	239
3.09.3.1	Burnup Indicators of Inert Matrix Fuels	241
3.09.4	Fabrication	241
3.09.4.1	Liquid Processes	242
3.09.4.2	Powder Blending Processes	242
3.09.5	Fuel Properties	243
3.09.5.1	Phase Relations	243
3.09.5.2	Thermal Conductivity	245
3.09.5.2.1	Zirconium-based SS fuels	245
3.09.5.2.2	Composite fuels	245
3.09.5.3	Radiation Stability	246
3.09.5.4	Chemical Properties	246
3.09.6	Irradiation Behavior	247
3.09.6.1	The 1960s US Programs	247
3.09.6.1.1	NUMEC: $PuO_2 - UO_2 - ZrO_2$	247
3.09.6.1.2	Hanford: ZrO_2 -PuO ₂	247
3.09.6.1.3	Hanford: MgO-PuO ₂	249
3.09.6.2	JAEA: ROX	250
3.09.6.3	PSI: YSZ IMF	252
3.09.6.4	Other Programs	254
3.09.6.4.1	ENEA, Italy	254
3.09.6.4.2	Institute of Physics and Power Engineering, IPPE, Obninsk, Russia	254
3.09.6.4.3	Current US program	254
3.09.7	Summary and Outlook	254
References		255

3.10 Composite Fuel (cermet, cercer)*

M. K. Meyer

Idaho National Laboratory, Idaho Falls, ID, USA

 $\ensuremath{\textcircled{}^\circ}$ 2012 Published by Elsevier Ltd.

3 10 1	Introduction	258
3.10.2	Description of Composite Fuels	258
3.10.3	Theory of Composite Fuel Behavior	260
3.10.3.1	Cermet Fuels	260
3.10.3.2	Cercer Fuels	263
3.10.4	Fuel Fabrication	263
3.10.4.1	Fabrication of Fuel Particles	263
3.10.4.1.1	Internal gelation	263
3.10.4.1.2	External gelation (sol-gel)	263
3.10.4.1.3	Infiltration of porous microspheres	264
3.10.4.2	Cermet Fuel Fabrication	264
3.10.4.2.1	Coextrusion and roll-bonding	264
3.10.4.2.2	Sintering and hot pressing	264
3.10.4.2.3	Melt infiltration	264
3.10.4.3	Cercer Fuel Fabrication	264
3.10.5	Fuel Properties	265
3.10.5.1	Thermal Conductivity of Composite Fuels	265
3.10.6	Irradiation Behavior	266
3.10.6.1	Cermet Fuels	266
3.10.6.1.1	Stainless steel matrix fuels	266
3.10.6.1.2	Zirconium and silicon-aluminum alloy cermet fuel	267
3.10.6.1.3	High-temperature cermet fuels	268
3.10.6.2	Irradiation Behavior of Ceramic Matrix Composite Fuels	268
3.10.6.2.1	MgAl ₂ O ₄ (spinel) matrix fuels	268
3.10.6.2.2	Magnesia-based composite fuels	269
3.10.6.2.3	Transient testing of oxide cercer fuels	270
3.10.6.2.4	Carbide matrix composite fuels	270
3.10.6.2.5	Other carbides and nitrides as fuel matrix materials	270
3.10.6.2.6	Graphite matrix fuels	271
References		271

3.11 Sphere-Pac and VIPAC Fuel

M. A. Pouchon

Paul Scherrer Institut, Villigen PSI, Switzerland

G. Ledergerber

Kernkraftwerk Leibstadt AG, Leibstadt, Switzerland

F. Ingold

Swiss Federal Office of Energy, Bern, Switzerland

K. Bakker

Nuclear Research and Consultancy Group, Petten, The Netherlands

3.11.1	Introduction to Particle Fuel Systems	277
3.11.1.1	Vipac Fuel	277
3.11.1.2	Sphere-pac Fuel	278
3.11.2	Features of Particle Fuel	279
3.11.3	Safety Aspects of Particle Fuel	279
3.11.4	Concepts of Particle Fuel	281
3.11.4.1	Vipac Fuel	281
3.11.4.2	Sphere-pac Concept	281
3.11.4.2.1	Two size fractions, by infiltration filling	281
3.11.4.2.2	Two size fractions, by parallel filling	283
3.11.4.2.3	Three size fraction, by parallel filling	283
3.11.4.2.4	Combination of parallel and infiltration filling	283
3.11.5	Production of Particle Fuel	283
3.11.5.1	Vipac Fuel	283
3.11.5.1.1	Particle production	283
3.11.5.1.2	Pin filling	283
3.11.5.2	Sphere-pac Fuel	284
3.11.5.2.1	Particle production	284
3.11.5.2.2	Pin filling	289
3.11.6	Conducted Irradiation Programs	292
3.11.6.1	Vipac Fuel	292
3.11.6.1.1	Studies at Risø in Denmark	292
3.11.6.1.2	BOR-60 Dimitrovgrad: transmutation of neptunium	293
3.11.6.1.3	BN-600 Belojarsk: burning weapon grade plutonium	293
3.11.6.1.4	HFR Petten: FUJI program – Vipac fuel	294
3.11.6.2	Sphere-pac Fuel	294
3.11.6.2.1	US irradiation programs conducted at/for the Oak Ridge National Laboratory	294
3.11.6.2.2	German Sphere-pac program	295
3.11.6.2.3	Italian Sphere-pac program	296
3.11.6.2.4	Netherlands joint Sphere-pac research program	297
3.11.6.2.5	BR2 reactor: experiment MFBS 7 – uranium plutonium carbide	300
3.11.6.2.6	Dounreay Fast Reactor: experiment DFR 527/1 – uranium plutonium carbide	301
3.11.6.2.7	FFTF: AC-3 experiment – uranium plutonium carbide	303
3.11.6.2.8	Siemens-PSI Gösgen PWR: uranium oxide	304
3.11.6.2.9	HBWR Halden: ramp testing of uranium oxide Sphere-pac fuel	304
3.11.6.2.10	NOK Beznau/HFR Petten-M308 program: uranium plutonium oxide	305
3.11.6.2.11	HFR Petten: FUJI program	305
3.11.7	Conclusions	307
References		309

3.12 Uranium-Zirconium Hydride Fuel

D. Olander

University of California, Berkeley, CA, USA **K. Konashi** Tohoku University, O-arai, Ibaraki, Japan **M. Yamawaki** University of Tokyo, Tokyo, Japan

		014
3.12.1	Introduction	314
3.12.1.1	Measures of Composition	315
3.12.1.2	The SNAP Reactors	315
3.12.1.3	TRIGA Reactors	316
3.12.1.4	Advanced Reactors	317
3.12.2	(U, Zr) Hydride Properties	317
3.12.2.1	Hydrogen (Ordinary) Diffusion	317
3.12.2.2	Hydrogen Thermal Diffusivity	319
3.12.2.3	Thermodynamic Properties	319
3.12.2.4	Thermal and Mechanical Properties	320
3.12.2.5	Chemical Properties	321
3.12.2.5.1	Stainless-steel liner	322
3.12.2.5.2	SiC internal coating or sleeve	322
3.12.2.5.3	Glass-enamel coating	322
3.12.2.5.4	Zirconia coatings	322
3.12.2.6	(U, Th, Zr) Hydride Properties	322
3.12.2.7	Thermodynamic and Thermophysical Properties of the Actinide Hydrides	323
3.12.2.7.1	Th–H system	324
3.12.2.7.2	Pa–H system	326
3.12.2.7.3	U–H system	326
3.12.2.7.4	Np–H system	328
3.12.2.7.5	Pu–H system	329
3.12.2.7.6	Am–H system	331
3.12.2.7.7	Cm–H system	331
3.12.2.7.8	Th–Zr–H system	332
3.12.2.7.9	Np–Zr–H, Am–Zr–H, and Pu–Zr–H systems	333
3.12.3	Irradiation Effects	333
3.12.3.1	Burnup Units	333
3.12.3.2	Fuel Swelling due to Void Formation	335
3.12.3.2.1	Temperature dependence	336
3.12.3.2.2	Burnup rate	336
3.12.3.2.3	Saturation of swelling	337
3.12.3.3	Fuel Swelling due to FPs	338
3.12.3.4	Fission-Gas Release	338
3.12.3.5	Chemical and Physical States of the FPs	340
3.12.3.6	Irradiation Behavior of (U, Th, Zr) Hydride	340
3.12.4	In-Reactor Chemical Behavior	342
3.12.4.1	Impurity Oxygen	342
3.12.4.2	Oxygen Potential in Hydride Fuel	342
3.12.4.3	Reduction of the H/Zr Ratio During Irradiation	343
3.12.4.4	Hydrogen Loss to the Gas Phase	344
3.12.4.5	Stability of Hydride Fuel in Water	345

3.12.5	Comparison of LM-Bonded Hydride Fuel and Oxide Fuel in LWRs	345
3.12.6	Hydride Fuel Fabrication	347
3.12.7	Gap Closure During Operation	349
3.12.7.1	Fuel Swelling	349
3.12.7.1.1	Thermal expansion	350
3.12.7.1.2	Hydrogen expansion	351
3.12.7.1.3	Solid fission-product swelling	351
3.12.7.1.4	Total fuel-surface strain	351
3.12.7.2	Cladding Creepdown	351
3.12.7.2.1	Secondary thermal creep	351
3.12.7.2.2	Primary thermal creep	351
3.12.7.2.3	Irradiation creep	351
3.12.7.2.4	Total cladding creep strain	352
3.12.7.3	Gap Closure	352
3.12.7.3.1	Dimension changes	352
3.12.7.3.2	Parameters of typical hydride fuel element	352
3.12.7.3.3	Combined effect	352
3.12.8	Conclusions	353
Appendix A	Permeation of Hydrogen Through Stainless Steel	354
Appendix B	Effect of Fission Products on H/Zr Ratio of Fuel	354
••	Reaction of Impurity Oxygen	354
	Subsequent Change in H/Zr with Burnup	355
References		355

3.13 Molten Salt Reactor Fuel and Coolant

O. Beneš and R. J. M. Konings

European Commission, Joint Research Centre, Institute for Transuranium Elements, Karlsruhe, Germany

3.13.2 Historical Background 361 3.13.3 Fuel Concepts of MSR 362 3.13.4 Properties of the MSR Fuels and Coolants 363 3.13.4.1 Structural Aspects of Molten Salts 363 3.13.4.2 Phase Diagrams 366 3.13.4.2.1 LiF-PoFg 366 3.13.4.2.2 LiF-PoFg 366 3.13.4.2.4 BeFg-TNFa 366 3.13.4.2.5 BeFg-TNFa 367 3.13.4.2.6 LiF-AnFa 367 3.13.4.2.7 LiF-BeFg-AnFa 369 3.13.4.2.8 LiF-NaF-BeFg-AnFa 371 3.13.4.2.9 NAF-NaBFA 371 3.13.4.2.10 LiF-NaF-BeFg-AnFa 371 3.13.4.2.3 ThFa in molten LiF-BeFg 371 3.13.4.3.1 ThFa in molten LiF-BeFg 371 3.13.4.3.2 ThFa in molten LiF-MaF-BeFg 373 3.13.4.3.3 UFa in molten LiF-MaF-BeFg 373 3.13.4.3.4 PuFg in molten LiF-MaF-BeFg 373 3.13.4.3.5 PuFa in molten LiF-MaF-BeFg 373 3.13.4.3.4 PuFa in molten LiF-MaF-	3.13.1	Introduction	360
3.13.3 Fuel Concepts of MSR 962 3.13.4.1 Properties of the MSR Fuels and Coolants 363 3.13.4.1 Structural Aspects of Molten Salts 363 3.13.4.2 Phase Diagrams 365 3.13.4.2 LiF-BeF2 365 3.13.4.2.1 LiF-BeF2 365 3.13.4.2.3 NaF-PuF3 366 3.13.4.2.4 BeF2-PUF3 366 3.13.4.2.5 BeF2-PuF3 366 3.13.4.2.6 LiF-AnF4 367 3.13.4.2.7 LiF-BeF2-AnF4 367 3.13.4.2.8 LiF-NaF-BeF2-AnF3 370 3.13.4.2.9 NaF-NaBF4 371 3.13.4.2.9 NaF-NaBF4 371 3.13.4.2.9 NaF-NaBF4 371 3.13.4.2.10 LiF-NaF-KF 373 3.13.4.2.3 UF4 in molten LiF-BeF2 373 3.13.4.3 Solubility of Actinides in the Fluoride Melt 371 3.13.4.3.1 ThF4, in molten LiF-BeF2 373 3.13.4.3.4 PUF3 in molten LiF-BeF2 373 3.13.4.3.5 PUF3 in molten LiF-BeF2 373 <	3.13.2	Historical Background	361
3.13.4 Properties of the MSR Fuels and Coolants 863 3.13.4.1 Structural Aspects of Molten Salts 863 3.13.4.2 LiF-BeF ₂ 865 3.13.4.2.1 LiF-PuF ₃ 865 3.13.4.2.2 LiF-PuF ₃ 866 3.13.4.2.3 NaF-PuF ₃ 866 3.13.4.2.4 BeF ₂ -PuF ₃ 866 3.13.4.2.5 DeF ₂ -AnF ₄ 867 3.13.4.2.6 LiF-NaF-BeF ₂ -AnF ₄ 869 3.13.4.2.7 LiF-BeF ₂ -AnF ₄ 869 3.13.4.2.8 LiF-NaF-BeF ₂ -AnF ₃ 870 3.13.4.2.9 NaF-NaBF ₄ 871 3.13.4.2.10 LiF-NaF-BeF ₂ -AnF ₃ 871 3.13.4.2.3 Subility of Actinides in the Fluoride Melt 871 3.13.4.3.4 Diff-In molten LiF 873 3.13.4.3.3 Diff-In molten LiF-BeF ₂ 873 3.13.4.3.4 Diff-In molten LiF-BeF ₂ 873 3.13.4.3.4 Diff-In molten LiF-BeF ₂ 874 3.13.4.3.4 Diff-In molten LiF-BeF ₂ 874 3.13.4.3.4 Diff-In molten LiF-BeF ₂ 874 3.13.	3.13.3	Fuel Concepts of MSR	362
3.13.4.1 Structural Aspects of Molten Salts 863 3.13.4.2 Phase Diagrams 365 3.13.4.2.1 LiF-BoF2 365 3.13.4.2.2 LiF-PuF5 365 3.13.4.2.3 NaF-PuF6 366 3.13.4.2.4 BeF2-PuF6 366 3.13.4.2.5 BeF2-PuF6 366 3.13.4.2.6 LiF-AnF4 367 3.13.4.2.7 LiF-BoF2-AnF4 369 3.13.4.2.8 LiF-NaF-BeF2-AnF6 370 3.13.4.2.9 NaF-NaFF4 371 3.13.4.2.9 NaF-NaFF4 371 3.13.4.2.10 LiF-NaF-KF 371 3.13.4.3.1 ThF4 in molten LiF-BeF2 373 3.13.4.3.2 ThF4 in molten LiF-BeF2 373 3.13.4.3.3 UF4 in molten LiF-MaFBeF2 373 3.13.4.3.4 PuF3 in molten LiF-MaFBeF2 374 3.13.4.3.5 PuF4 in molten LiF-MaFBeF2 374 3.13.4.4.1 LiF-BeF2 374 3.13.4.3.5 PuF3 in molten LiF-MaFBeF2 374 3.13.4.4.5 PuF3 in molten LiF-MaFBeF2 374 <t< td=""><td>3.13.4</td><td>Properties of the MSR Fuels and Coolants</td><td>363</td></t<>	3.13.4	Properties of the MSR Fuels and Coolants	363
3.13.4.2 Phase Diagrams 365 3.13.4.2.1 LF-BeF2 365 3.13.4.2.2 LF-PUF3 365 3.13.4.2.3 NaF-PUF3 366 3.13.4.2.4 Bef2-PUF3 367 3.13.4.2.5 Bef2-PUF3 367 3.13.4.2.6 LIF-AnF4 367 3.13.4.2.7 LIF-Bef2-AnF4 369 3.13.4.2.8 LIF-NaF-Bef2-AnF3 370 3.13.4.2.9 NaF-NaBF4 371 3.13.4.2.10 LIF-NaF-Bef2-AnF3 371 3.13.4.3 Solubility of Actinides in the Fluoride Melt 371 3.13.4.3.1 ThF4 in molten LIF-BeF2 373 3.13.4.3.2 ThF4 in molten LIF-DeF2 373 3.13.4.3.3 UF3 in molten LIF-DeF2 373 3.13.4.3.4 PUF3 in molten LIF-DeF2 373 3.13.4.3.5 PUF3 in molten LIF-DeF2 373 3.13.4.3.4 DuF3 in molten LIF-DeF2 373 3.13.4.3.4 DuF3 in molten LIF-DeF2 374 3.13.4.3.5 PUF3 in molten LIF-DeF2 374 3.13.4.4 Density and Viscosity 374	3.13.4.1	Structural Aspects of Molten Salts	363
3.134.2.1 LIF-BUF2 965 3.134.2.2 LIF-PUF3 966 3.134.2.3 NaF-PUF3 966 3.134.2.4 BeF2-PUF3 966 3.134.2.5 BeF2-ThF4 967 3.134.2.6 LIF-AnF4 967 3.134.2.7 LIF-BeF2-AnF4 969 3.134.2.8 LIF-NaF-BeF2-AnF3 370 3.134.2.9 NaF-NaBF4 371 3.134.2.9 LIF-NaF-BeF2-AnF3 371 3.134.2.9 NaF-NaBF4 371 3.134.2.9 NaF-NaBF4 371 3.134.2.10 LIF-NaF-MEF2 371 3.134.3.3 Dubliky of Actinides in the Fluoride Melt 371 3.134.3.4 Duff in molten LIF-DeF2 373 3.134.3.5 PUF3 in molten LIF-DeF2 373 3.134.3.6 PUF3 in molten LIF-DeF2 373 3.134.3.6 PUF3 in molten LIF-DeF2 373 3.134.3.6 PUF3 in molten LIF-DeF2 373 3.134.4.4 Density and Viscosity 374 3.134.4.5 PuF3 in molten LIF-DeF2 374 3.134.4.6	3.13.4.2	Phase Diagrams	365
3134.2.2 LIF-PUF3 365 313.4.2.3 NaF-PUF3 366 313.4.2.4 BeF2-PUF3 366 313.4.2.5 BeF2-TNF4 367 313.4.2.6 LIF-AnF4 367 313.4.2.7 LIF-BeF2-AnF4 369 313.4.2.8 LIF-NAF-BeF2-AnF4 369 313.4.2.9 NaF-NaBF4 371 313.4.3.1 ThF4 in molten LIF-BeF2 371 313.4.3.1 ThF4 in molten LIF-BeF2 373 313.4.3.5 PuF3 in molten LIF-BeF2 373 313.4.3.6 PuF3 in molten LIF-BeF2 373 313.4.4 Density and Viscosity 374 313.4.4.1 LIF-AnF4 374 313.4.4.2 LIF-AnF4 376 313.4.4.3 LIF-BeF2-ThF4 376 313.4.4.4 LIF-NaF-KF 376 3	3.13.4.2.1	LiFBeF ₂	365
3134.2.3 NaF-PuF3 366 313.4.2.4 BeF2-PuF3 366 313.4.2.5 BeF2-ThFa 367 313.4.2.6 LiF-AnF4 367 313.4.2.7 LiF-BeF2-AnF4 367 313.4.2.8 LiF-NaF-BeF2-AnF4 369 313.4.2.9 NaF-NaBF4 371 313.4.2.10 LiF-NaF-KF 371 313.4.2.10 LiF-NaF-KF 371 313.4.3.1 ThF4 in molten LiF 371 313.4.3.3 UF4 in molten LiF-BeF2 373 313.4.3.3 UF4 in molten LiF-BeF2 373 313.4.3.4 PuF3 in molten LiF-BeF2 373 313.4.3.5 PuF3 in molten LiF-BeF2 373 313.4.3.6 PuF4 in molten LiF-BeF2 373 313.4.3.5 PuF3 in molten LiF-BeF2 373 313.4.4.3 UF-AnF4 374 313.4.3.4 PuF5 in molten LiF-BeF2 373 313.4.4.3 LiF-BeF2 373 313.4.4.4 LiF-NaF-K 374 313.4.5.1 LiF-BeF2-AnF4 374 313.4.5.2 LiF-NaF-A <	3.13.4.2.2	LiF–PuF ₃	365
313.4.2.4 BeF_PUF3 366 313.4.2.5 BeF_PTnF4 367 313.4.2.6 LIF-AnF4 369 313.4.2.7 LIF-BeF2-AnF4 369 313.4.2.8 LIF-NAF-BeF2-AnF3 370 313.4.2.9 NAF-NABF4 371 313.4.2.9 NAF-NABF4 371 313.4.2.10 LIF-NAF-KF 371 313.4.3.1 ThF4 in molten LIF-BeF2 371 313.4.3.2 ThF4 in molten LIF-BeF2 373 313.4.3.3 UF4 in molten LIF-BeF2 373 313.4.3.4 PuF3 in molten LIF-BeF2 373 313.4.3.5 PuF3 in molten LIF-BeF2 373 313.4.3.6 PuF3 in molten LIF-BeF2 373 313.4.3.4 Density and Viscosity 374 313.4.4.1 LIF-BeF2 374 313.4.4.2 LIF-AnF4 374 313.4.4.3 LIF-BeF2 377 313.4.4.4 LIF-AnF4 374 313.4.5.4 LIF-AnF4 376 313.4.5.4 LIF-AnF4 376 313.4.5.4 LIF-AnF4 377 <td>3.13.4.2.3</td> <td>NaF-PuF₃</td> <td>366</td>	3.13.4.2.3	NaF-PuF ₃	366
313.4.2.5 BeF ₂ -ThF ₄ 867 313.4.2.6 LiF-AnF ₄ 867 313.4.2.6 LiF-NeF-BeF ₂ -AnF ₄ 869 313.4.2.8 LiF-NeF-BeF ₂ -AnF ₃ 370 313.4.2.9 NaF-NaBF ₄ 371 313.4.2.0 LiF-NeF-BeF ₂ -AnF ₃ 371 313.4.2.10 LiF-NeF-KF 371 313.4.3.1 ThF ₄ in molten LiF 371 313.4.3.2 ThF ₄ in molten LiF-BeF ₂ 373 313.4.3.3 UF in molten LiF-BeF ₂ 373 313.4.3.4 PuF ₃ in molten LiF-NeF-BeF ₂ 373 313.4.3.5 PuF ₃ in molten LiF-NeF-BeF ₂ 373 313.4.3.6 PuF ₃ in molten LiF-NeF-BeF ₂ 374 313.4.4 LiF-AnF ₄ 374 313.4.4.1 LiF-BeF ₂ -ThF ₄ 374 313.4.4.2 LiF-AnF ₄ 374 313.4.4.3 LiF-NeF-BeF ₂ -ThF ₄ 374 313.4.4.4 LiF-NeF-BeF ₂ -ThF ₄ 374 313.4.5 NaF-NaBF ₄ 376 313.4.5 LiF-NeF-BeF ₂ -ThF ₄ 376 313.4.5.1 LiF-NeF-BeF ₂ -ThF ₄	3.13.4.2.4	BeF ₂ -PuF ₃	366
3.13.4.2.6 LIF-AnF ₄ 367 3.13.4.2.7 LIF-BeF ₂ -AnF ₄ 369 3.13.4.2.8 LIF-NeF-KF 371 3.13.4.2.9 NaF-NaBF ₄ 371 3.13.4.2.10 LIF-NeF-KF 371 3.13.4.2.3 Solubility of Actinides in the Fluoride Melt 371 3.13.4.3.1 ThF ₄ in molten LIF 371 3.13.4.3.2 ThF ₄ in molten LIF-BeF ₂ 373 3.13.4.3.3 UF _a in molten LIF-BeF ₂ 373 3.13.4.3.5 PuF ₃ in molten LIF-BeF ₂ 373 3.13.4.3.6 PuF ₃ in molten LIF-BeF ₂ -ThF ₄ 373 3.13.4.3.6 PuF ₃ in molten LIF-BeF ₂ -ThF ₄ 374 3.13.4.3.4 LIF-BeF ₂ 374 3.13.4.3.5 PuF ₃ in molten LIF-BeF ₂ -ThF ₄ 374 3.13.4.4 LIF-AnF ₄ 374 3.13.4.3 LIF-BeF ₂ -ThF ₄ 374 3.13.4.4.1 LIF-AnF ₄ 376 3.13.4.5 NaF-NaBF ₄ 376 3.13.4.5.4 LIF-NaF-BeF ₂ -AnF ₄ 376 3.13.4.5.5 NaF-NaBF ₄ 376 3.13.4.6.6 <td< td=""><td>3.13.4.2.5</td><td>BeF₂-ThF₄</td><td>367</td></td<>	3.13.4.2.5	BeF ₂ -ThF ₄	367
$3.13.4.2.7$ $LIF-BeF_2-AnF_4$ 369 $3.13.4.2.8$ $LIF-NaF-BeF_2-AnF_3$ 370 $3.13.4.2.9$ $NaF-NaBF_4$ 371 $3.13.4.2.9$ $NaF-NaBF_4$ 371 $3.13.4.2.9$ $NaF-NaBF_4$ 371 $3.13.4.2.9$ $NaF-NaBF_4$ 371 $3.13.4.3.1$ ThF_4 in moten LIF 371 $3.13.4.3.1$ ThF_4 in moten $LIF-BeF_2$ 373 $3.13.4.3.2$ ThF_4 in moten $LIF-BeF_2$ 373 $3.13.4.3.4$ PuF_3 in moten $LIF-BeF_2$ 373 $3.13.4.3.5$ PuF_4 in moten $LIF-MaF-BeF_2$ 373 $3.13.4.3.6$ PuF_3 in moten $LIF-MaF-BeF_2$ 373 $3.13.4.3.6$ PuF_3 in moten $LIF-MaF-BeF_2$ 373 $3.13.4.4$ $Density$ and $Viscosity$ 374 $3.13.4.4$ $LIF-AnF_4$ 374 $3.13.4.4.5$ $NaF-NaBF_4$ 376 $3.13.4.5$ $NaF-NaBF_4$ 376 $3.13.4.5.4$ $LIF-NaF-KF$ 376 $3.13.4.5.5$ $NaF-NaBF_4$ 376 $3.13.4.5.6$ $LIF-NaF-MaF_4$ 377	3.13.4.2.6	LiF–AnF ₄	367
3.13.4.2.8 LiF-NaF-BeF ₂ -AnF ₃ 370 3.13.4.2.9 NaF-NaBF ₄ 371 3.13.4.2.10 LiF-NaF-KF 371 3.13.4.3.1 ThF ₄ in molten LiF 371 3.13.4.3.1 ThF ₄ in molten LiF-BeF ₂ 371 3.13.4.3.2 ThF ₄ in molten LiF-BeF ₂ 373 3.13.4.3.3 UF ₄ in molten LiF-BeF ₂ 373 3.13.4.3.4 PUF ₃ in molten LiF-BeF ₂ 373 3.13.4.3.5 PUF ₃ in molten LiF-BeF ₂ 373 3.13.4.3.6 PUF ₃ in molten LiF-BeF ₂ 373 3.13.4.3.6 PUF ₃ in molten LiF-BeF ₂ -ThF ₄ 374 3.13.4.3.6 PUF ₃ in molten LiF-BeF ₂ -ThF ₄ 374 3.13.4.3.4 LiF-BeF ₂ -ThF ₄ 374 3.13.4.3.5 Huer See See See See See See See See See S	3.13.4.2.7	LiF-BeF ₂ -AnF ₄	369
3.13.4.2.9 NaF-NaBF ₄ 371 $3.13.4.2.10$ LIF-NaF-KF 371 $3.13.4.3.1$ ThF ₄ in molten LIF 371 $3.13.4.3.2$ ThF ₄ in molten LIF-BeF ₂ 371 $3.13.4.3.2$ ThF ₄ in molten LIF-ThF ₄ 373 $3.13.4.3.3.1$ UF ₄ in molten LIF-BeF ₂ 373 $3.13.4.3.4$ PuF ₃ in molten LIF-BeF ₂ 373 $3.13.4.3.5$ PuF ₃ in molten LIF-BeF ₂ 373 $3.13.4.3.6$ PuF ₃ in molten LIF-BeF ₂ 373 $3.13.4.3.6$ PuF ₃ in molten LIF-BeF ₂ 373 $3.13.4.3.6$ PuF ₃ in molten LIF-BeF ₂ 374 $3.13.4.3.6$ PuF ₃ in molten LIF-BeF ₂ 374 $3.13.4.4.1$ LIF-BeF ₂ 374 $3.13.4.4.2$ LIF-AnF ₄ 374 $3.13.4.5.1$ LIF-BeF ₂ -ThF ₄ 374 $3.13.4.5.5$ NaF-NaBF ₄ 376 $3.13.4.5.6$ LIF-NaF-KF 376 $3.13.4.5.6$ LIF-NaF-KF 377 $3.13.4.5.5$ NaF-NaBF ₄ 379 $3.13.4.5.6$ LIF-NaF-KF 379 <td< td=""><td>3.13.4.2.8</td><td>LIF-NaF-BeF₂-AnF₃</td><td>370</td></td<>	3.13.4.2.8	LIF-NaF-BeF ₂ -AnF ₃	370
3.13.4.2.10 LIF-NaF-KF 371 3.13.4.3.1 ThF4 in molten LiF 371 3.13.4.3.1 ThF4 in molten LiF-BeF2 371 3.13.4.3.2 ThF4 in molten LIF-BeF2 371 3.13.4.3.3 UF4 in molten LIF-BeF2 373 3.13.4.3.4 PuF3 in molten LIF-BeF2 373 3.13.4.3.5 PuF3 in molten LIF-BeF2 373 3.13.4.3.6 PuF3 in molten LIF-BeF2 373 3.13.4.3.6 PuF3 in molten LIF-BeF2 373 3.13.4.3.6 PuF3 in molten LIF-BeF2 373 3.13.4.4 Density and Viscosity 374 3.13.4.4.1 LIF-BeF2 374 3.13.4.4.2 LIF-AnF4 374 3.13.4.4.3 LIF-BeF2 374 3.13.4.4.4 LIF-NaF-KF 376 3.13.4.5 NaF-NaBF4 376 3.13.4.5.1 LIF-NaF-KF 376 3.13.4.5.1 LIF-NaF-KF 377 3.13.4.5.1 LIF-AnF4 377 3.13.4.5.1 LIF-AnF4 379 3.13.4.5.5 NaF-NaBF4 379 3.13.4.5.6	3.13.4.2.9	NaFNaBF4	371
3.13.4.3Solubility of Actinides in the Fluoride Melt3713.13.4.3.1ThF4 in molten LiF3713.13.4.3.2ThF4 in molten LiF-BeF23713.13.4.3.3UF4 in molten LiF-BeF23733.13.4.3.4PuF3 in molten LiF-BeF23733.13.4.3.5PuF3 in molten LiF-BeF23733.13.4.3.6PuF3 in molten LiF-BeF23733.13.4.3.6PuF3 in molten LiF-BeF23733.13.4.3.6PuF3 in molten LiF-BeF23733.13.4.3.6PuF3 in molten LiF-BeF23733.13.4.4Density and Viscosity3743.13.4.4.1LiF-BeF23743.13.4.3LiF-BeF2-ThF43743.13.4.4.2LiF-AnF43743.13.4.3LiF-BeF2-ThF43743.13.4.4.3LiF-NaF-KF3763.13.4.4.4LiF-NaF-KF3763.13.4.5NaF-NaBF43773.13.4.5Heat Capacity and Thermal Conductivity3773.13.4.5.1LiF-BeF23793.13.4.5.2LiF-AnF43793.13.4.5.4LiF-NaF-KF3793.13.4.5.5NaF-NaBF43793.13.4.5.6LiF-NaF-KF3793.13.4.6.1LiF-BeF2-ThF43793.13.4.6.2LiF-NaF-KF3793.13.4.6.3LiF-BeF2-ThF43803.13.4.6.4LiF-NaF-KF3793.13.4.6.5NaF-NaBF43793.13.4.6.4LiF-NaF-KF3803.13.4.6.5NaF-NaBF43803.13.4.6.5NaF-NaBF4	3.13.4.2.10	LIF-NaF-KF	371
3.13.4.3.1 ThF ₄ in molten LiF 371 3.13.4.3.2 ThF ₄ in molten LiF-BeF ₂ 371 3.13.4.3.3 UF ₄ in molten LiF-ThF ₄ 373 3.13.4.3.4 PuF ₃ in molten LiF-BeF ₂ 373 3.13.4.3.5 PuF ₃ in molten LiF-BeF ₂ 373 3.13.4.3.6 PuF ₃ in molten LiF-BeF ₂ 374 3.13.4.4 LiF-AnF ₄ 374 3.13.4.3.1 LiF-AnF ₄ 374 3.13.4.4.2 LiF-AnF ₄ 374 3.13.4.3.4 LiF-NaF-EeF ₂ -ThF ₄ 376 3.13.4.4.5 NaF-NaBF ₄ 376 3.13.4.5.1 LiF-NaF-KF 377 3.13.4.5.2 LiF-AnF ₄ 377 3.13.4.5.4 LiF-NaF-KF 379 3.13.4.5.5 NaF-NaBF ₄ 379 3.13.4.5.4 LiF-NaF-KF 379 3.13.4.5.5 NaF-NaBF ₄ <td>3.13.4.3</td> <td>Solubility of Actinides in the Fluoride Melt</td> <td>371</td>	3.13.4.3	Solubility of Actinides in the Fluoride Melt	371
3.13.4.3.2 ThF ₄ in molten LiF-BeF ₂ 371 3.13.4.3.3 UF ₄ in molten LiF-ThF ₄ 373 3.13.4.3.4 PuF ₃ in molten LiF-BeF ₂ 373 3.13.4.3.5 PuF ₃ in molten LiF-BeF ₂ 373 3.13.4.3.6 PuF ₃ in molten LiF-BeF ₂ 373 3.13.4.3.6 PuF ₃ in molten LiF-BeF ₂ -ThF ₄ 373 3.13.4.4 Density and Viscosity 374 3.13.4.4.1 LiF-BeF ₂ 374 3.13.4.3 LiF-AnF ₄ 374 3.13.4.4.1 LiF-BeF ₂ -ThF ₄ 374 3.13.4.4.2 LiF-AnF ₄ 374 3.13.4.4.3 LiF-BeF ₂ -ThF ₄ 374 3.13.4.4.4 LiF-NaF-KF 376 3.13.4.5 NaF-NaBF ₄ 376 3.13.4.5.5 NaF-NaBF ₄ 376 3.13.4.5.6 LiF-NaF-KF 376 3.13.4.5.7 Heat Capacity and Thermal Conductivity 377 3.13.4.5.8 Heat Capacity and Thermal Conductivity 377 3.13.4.5.1 LiF-NaF-KF 379 3.13.4.5.2 LiF-AnF ₄ 379 3.13.4.5.4 LiF	3.13.4.3.1	ThF ₄ in molten LiF	371
3.13.4.3.3 UF_4 in motten LiF-ThF_43733.13.4.3.4 PuF_3 in motten LiF-BeF_23733.13.4.3.5 PuF_3 in motten LiF-NaF-BeF_23733.13.4.3.6 PuF_3 in motten LiF-NaF-BeF_23733.13.4.4Density and Viscosity3743.13.4.4Density and Viscosity3743.13.4.4LiF-BeF_23743.13.4.4LiF-BeF_2-ThF_43743.13.4.4LiF-NaF_43743.13.4.4LiF-NaF_43743.13.4.4LiF-NaF_43743.13.4.4LiF-NaF_2-AnF_43753.13.4.5NaF-NaBF_23763.13.4.6LiF-NaF-KF3763.13.4.5Heat Capacity and Thermal Conductivity3773.13.4.5LiF-NaF-KF3783.13.4.5.1LiF-NaF-BeF_2-PuF_33793.13.4.5.2LiF-NaF-BeF_2-PuF_33793.13.4.5.4LiF-NaF-KF3793.13.4.5.5NaF-NaBF_43793.13.4.6LiF-NaF-KF3793.13.4.6.1LiF-NaF-KF3793.13.4.6.1LiF-NaF-AF_33803.13.4.6.2LiF-AnF_43793.13.4.6.3LiF-NaF-BF_2-AnF_33803.13.4.6.4LiF-NaF-BF_2-AnF_33803.13.4.6.5NaF-NaBF_43803.13.4.6.5NaF-NaBF_43803.13.4.6.5LiF-NaF-AFF3813.13.6Electroanalytical Chemistry381	3.13.4.3.2	ThF ₄ in molten LiF–BeF ₂	371
3.13.4.3.4PuF_3 in molten LiF-BeF23733.13.4.3.5PuF3 in molten LiF-BeF23733.13.4.3.6PuF3 in molten LiF-BeF23733.13.4.3.6PuF3 in molten LiF-BeF23743.13.4.4Density and Viscosity3743.13.4.4LiF-BeF23743.13.4.4.1LiF-BeF23743.13.4.4.2LiF-AnF43743.13.4.4.3LiF-BeF23743.13.4.4.4LiF-NaF-BeF23743.13.4.5NaF-NaBF43753.13.4.5NaF-NaBF43763.13.4.5NaF-NaBF43763.13.4.5Heat Capacity and Thermal Conductivity3773.13.4.5.1LiF-BeF23773.13.4.5.2LiF-AnF43783.13.4.5.3LiF-BeF2-ThF43783.13.4.5.4LiF-NaF-BeF2-PuF33793.13.4.5.5NaF-NaBF43793.13.4.5.6LiF-NaF-KF3793.13.4.6.1LiF-BeF23793.13.4.6.2LiF-NaF-KF3793.13.4.6.3LiF-BeF2-ThF43793.13.4.6.4LiF-NaF-AF33803.13.4.6.5NaF-NaBF43803.13.4.6.4LiF-NaF-AF33803.13.4.6.5NaF-NaBF43803.13.4.6.4LiF-NaF-KF3813.13.6Electroanalytical Chemistry381	3.13.4.3.3	UF_4 in molten LiF-ThF ₄	373
3.13.4.3.5PuF_3 in molten LiF-NaF-BeF23733.13.4.3.6PuF3 in molten LiF-BeF2-ThF43733.13.4.3.6PuF3 in molten LiF-BeF2-ThF43743.13.4.4Density and Viscosity3743.13.4.4.1LiF-BeF23743.13.4.2LiF-AnF43743.13.4.3LiF-BeF2-ThF43743.13.4.4.3LiF-BeF2-ThF43743.13.4.4.3LiF-BeF2-ThF43743.13.4.4.4LiF-NaF-BeF2-AnF43753.13.4.5NaF-NaBF43763.13.4.5NaF-NaBF43763.13.4.5Heat Capacity and Thermal Conductivity3773.13.4.5.1LiF-BeF23773.13.4.5.2LiF-AnF43783.13.4.5.3LiF-BeF2-ThF43793.13.4.5.4LiF-NaF-BeF2-PuF33793.13.4.5.5NaF-NaBF43793.13.4.6.1LiF-BeF23793.13.4.6.2LiF-NaF-KF3793.13.4.6.3LiF-AnF43793.13.4.6.4LiF-NaF-BeF2-AnF33803.13.4.6.5NaF-NaBF43803.13.4.6.4LiF-NaF-AF533803.13.4.6.5NaF-NaBF43803.13.4.6.6LiF-NaF-KF3803.13.4.6.6LiF-NaF-KF3803.13.4.6.6LiF-NaF43803.13.4.6.6LiF-NaF43803.13.4.6.6LiF-NaF43803.13.4.6.6LiF-NaF43803.13.4.6.6LiF-NaF43803.13.4.6.6LiF-NaF4380 <tr< td=""><td>3.13.4.3.4</td><td>PuF₃ in molten LiF–BeF₂</td><td>373</td></tr<>	3.13.4.3.4	PuF ₃ in molten LiF–BeF ₂	373
$\begin{array}{llllllllllllllllllllllllllllllllllll$	3.13.4.3.5	PuF ₃ in molten LiF–NaF–BeF ₂	373
3.13.4.4Density and Viscosity 374 3.13.4.4.1LiF-BeF2 374 3.13.4.4.2LiF-AnF4 374 3.13.4.4.2LiF-AnF4 374 3.13.4.4.3LiF-BeF2-ThF4 374 3.13.4.4.4LiF-NaF-BeF2-AnF4 375 3.13.4.4.5NaF-NaBF4 376 3.13.4.4.6LiF-NaF-KF 376 3.13.4.5Heat Capacity and Thermal Conductivity 377 3.13.4.5Heat Capacity and Thermal Conductivity 377 3.13.4.5LiF-BeF2 377 3.13.4.5.1LiF-BeF2-ThF4 378 3.13.4.5.2LiF-AnF4 379 3.13.4.5.3LiF-BeF2-ThF4 379 3.13.4.5.4LiF-NaF-AFF 379 3.13.4.5.5NaF-NaBF4 379 3.13.4.6Vapor Pressure 379 3.13.4.6.1LiF-BeF2-ThF4 380 3.13.4.6.2LiF-AnF4 379 3.13.4.6.3LiF-BeF2-ThF4 380 3.13.4.6.4LiF-NaF-KF 380 3.13.4.6.5NaF-NaBF4 380 3.13.4.6.4LiF-NaF-AFF 380 3.13.4.6.5NaF-NaBF4 380 3.13.4.6.6LiF-NaF-KF 381 3.13.4.6.6LiF-NaF-KF 381 3.13.6Felectroanalytical Chemistry 381	3.13.4.3.6	PuF ₃ in molten LiF–BeF ₂ –ThF ₄	373
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	3.13.4.4	Density and Viscosity	374
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	3.13.4.4.1	LiF-BeF ₂	374
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	3.13.4.4.2	LiF–AnF ₄	374
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	3.13.4.4.3	LIF-BeF ₂ -ThF ₄	374
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	3.13.4.4.4	LiF–NaF–BeF ₂ –AnF ₄	375
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	3.13.4.4.5	NaF-NaBF4	376
3.13.4.5Heat Capacity and Thermal Conductivity 377 3.13.4.5.1LiF-BeF2 377 3.13.4.5.2LiF-AnF4 377 3.13.4.5.3LiF-BeF2-ThF4 378 3.13.4.5.4LiF-NaF-BeF2-PuF3 379 3.13.4.5.5NaF-NaBF4 379 3.13.4.5.6LiF-NaF-KF 379 3.13.4.6.1LiF-BeF2 379 3.13.4.6.2LiF-AnF4 379 3.13.4.6.3LiF-BeF2 379 3.13.4.6.4LiF-BeF2 379 3.13.4.6.5NaF-NaBF4 380 3.13.4.6.6LiF-NaF-KF3 380 3.13.4.6.5NaF-NaBF4 380 3.13.4.6.5NaF-NaBF4 380 3.13.4.6.5NaF-NaBF4 380 3.13.4.6.6LiF-NaF-KF 381 3.13.4.6.5NaF-NaBF4 381 3.13.6Electroanalytical Chemistry 381	3.13.4.4.6	LIF-NaF-KF	376
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	3.13.4.5	Heat Capacity and Thermal Conductivity	377
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	3.13.4.5.1	LiF-BeF ₂	377
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	3.13.4.5.2	LIF-AnF ₄	377
3.13.4.5.4LiF-NaF-BeF2-PuF3379 $3.13.4.5.5$ NaF-NaBF4379 $3.13.4.5.6$ LiF-NaF-KF379 $3.13.4.6.6$ Vapor Pressure379 $3.13.4.6.1$ LiF-BeF2379 $3.13.4.6.2$ LiF-AnF4379 $3.13.4.6.3$ LiF-BeF2-ThF4380 $3.13.4.6.3$ LiF-BeF2-AnF3380 $3.13.4.6.5$ NaF-NaBF4380 $3.13.4.6.5$ NaF-NaBF4380 $3.13.4.6.5$ NaF-NaBF4380 $3.13.4.6.6$ LiF-NaF-KF381 $3.13.5$ Role of Oxygen Impurities381 $3.13.6$ Electroanalytical Chemistry381	3.13.4.5.3	LiF-BeF ₂ -ThF ₄	378
3.13.4.5.5NaF-NaBF4 379 $3.13.4.5.6$ LiF-NaF-KF 379 $3.13.4.5.6$ Vapor Pressure 379 $3.13.4.6.1$ LiF-BeF2 379 $3.13.4.6.2$ LiF-AnF4 379 $3.13.4.6.3$ LiF-BeF2-ThF4 380 $3.13.4.6.3$ LiF-BeF2-AnF3 380 $3.13.4.6.5$ NaF-NaBF4 380 $3.13.4.6.5$ NaF-NaBF4 380 $3.13.4.6.6$ LiF-NaF-KF 381 $3.13.5$ Role of Oxygen Impurities 381 $3.13.6$ Electroanalytical Chemistry 381	3.13.4.5.4	LIF-NaF-BeF ₂ -PuF ₃	379
3.13.4.5.6LiF-NaF-KF 379 $3.13.4.6.1$ LiF-BeF2 379 $3.13.4.6.1$ LiF-BeF2 379 $3.13.4.6.2$ LiF-AnF4 379 $3.13.4.6.3$ LiF-BeF2-ThF4 380 $3.13.4.6.3$ LiF-NaF-BeF2-AnF3 380 $3.13.4.6.4$ LiF-NaF-BeF2-AnF3 380 $3.13.4.6.5$ NaF-NaBF4 380 $3.13.4.6.6$ LiF-NaF-KF 381 $3.13.5$ Role of Oxygen Impurities 381 $3.13.6$ Electroanalytical Chemistry 381	3.13.4.5.5	NaFNaBF ₄	379
3.13.4.6Vapor Pressure379 $3.13.4.6.1$ LiF-BeF2379 $3.13.4.6.2$ LiF-AnF4379 $3.13.4.6.3$ LiF-BeF2-ThF4380 $3.13.4.6.4$ LiF-NaF-BeF2-AnF3380 $3.13.4.6.5$ NaF-NaBF4380 $3.13.4.6.5$ NaF-NaBF4380 $3.13.4.6.5$ NaF-NaBF4380 $3.13.4.6.6$ LiF-NaF-KF381 $3.13.5$ Role of Oxygen Impurities381 $3.13.6$ Electroanalytical Chemistry381	3.13.4.5.6	LIF-NaF-KF	379
3.13.4.6.1LiF-BeF2379 $3.13.4.6.2$ LiF-AnF4379 $3.13.4.6.3$ LiF-BeF2-ThF4380 $3.13.4.6.4$ LiF-NaF-BeF2-AnF3380 $3.13.4.6.5$ NaF-NaBF4380 $3.13.4.6.6$ LiF-NaF-KF381 $3.13.5$ Role of Oxygen Impurities381 $3.13.6$ Electroanalytical Chemistry381	3.13.4.6	Vapor Pressure	379
3.13.4.6.2LiF-AnF ₄ 379 $3.13.4.6.3$ LiF-BeF ₂ -ThF ₄ 380 $3.13.4.6.4$ LiF-NaF-BeF ₂ -AnF ₃ 380 $3.13.4.6.5$ NaF-NaBF ₄ 380 $3.13.4.6.6$ LiF-NaF-KF381 $3.13.5$ Role of Oxygen Impurities381 $3.13.6$ Electroanalytical Chemistry381	3.13.4.6.1	LiF-BeF ₂	379
3.13.4.6.3LiF-BeF2-ThF4380 $3.13.4.6.4$ LiF-NaF-BeF2-AnF3380 $3.13.4.6.5$ NaF-NaBF4380 $3.13.4.6.6$ LiF-NaF-KF381 $3.13.5$ Role of Oxygen Impurities381 $3.13.6$ Electroanalytical Chemistry381	3.13.4.6.2	LiF-AnF ₄	379
3.13.4.6.4LiF-NaF-BeF2-AnF3380 $3.13.4.6.5$ NaF-NaBF4380 $3.13.4.6.6$ LiF-NaFKF381 $3.13.5$ Role of Oxygen Impurities381 $3.13.6$ Electroanalytical Chemistry381	3.13.4.6.3	LIF-BeF ₂ -ThF ₄	380
3.13.4.6.5 NaF-NaBF ₄ 380 3.13.4.6.6 LiF-NaFKF 381 3.13.5 Role of Oxygen Impurities 381 3.13.6 Electroanalytical Chemistry 381	3.13.4.6.4	LIF-NaF-BeF ₂ -AnF ₃	380
3.13.4.6.6 LiF–NaF–KF 381 3.13.5 Role of Oxygen Impurities 381 3.13.6 Electroanalytical Chemistry 381	3.13.4.6.5	NaFNaBF4	380
3.13.5Role of Oxygen Impurities3813.13.6Electroanalytical Chemistry381	3.13.4.6.6	LIF-NaFKF	381
3.13.6 Electroanalytical Chemistry381	3.13.5	Role of Oxygen Impurities	381
	3.13.6	Electroanalytical Chemistry	381

3.13.7	Radiation Stability of Molten Salts	382
3.13.8	Fission Product Behavior	383
3.13.8.1	Noble Gases	384
3.13.8.2	Salt-Soluble Fission Products	384
3.13.8.3	Insoluble Fission Products	385
3.13.8.4	lodine	385
3.13.9	The Effect of Corrosion Reactions on the Fuel Behavior	385
3.13.10	Summary and Future Work	386
References		387

3.14 Uranium Intermetallic Fuels (U-Al, U-Si, U-Mo)

Yeon Soo Kim

Argonne National Laboratory, Argonne, IL, USA

3.14.1		392
3.14.1.1	Background	392
3.14.1.2	Historical Evolution of U Intermetallic Fuels	392
3.14.1.3	Performance Topics of U Intermetallic Fuels	394
3.14.2	U–AI	395
3.14.2.1	U–Al Fuel Properties	395
3.14.2.2	Thermal Conductivity of U–Al Alloy and UAI _x –Al Dispersions	396
3.14.2.3	U-AI Fabrication	397
3.14.2.3.1	U–Al alloy	397
3.14.2.3.2	UAI _x	397
3.14.2.4	U-Al Irradiation Performance	397
3.14.2.4.1	Fuel swelling by fission products	397
3.14.2.4.2	Interaction between U–AI and AI	400
3.14.2.4.3	U-AI blister threshold temperature	400
3.14.2.5	Summary for U–Al	401
3.14.3	U–Si	401
3.14.3.1	U–Si Fuel Properties	401
3.14.3.2	Thermal Conductivity of (U-Si Intermetallic)-Al Dispersions	401
3.14.3.3	U-Si Fabrication	402
3.14.3.4	U–Si Irradiation Performance	403
3.14.3.4.1	Fuel swelling by fission products	403
3.14.3.4.2	Interaction between U–Si and Al	406
3.14.3.4.3	U–Si blister threshold temperature	410
3.14.3.5	Summary for U–Si	411
3.14.4	U–Mo	411
3.14.4.1	U–Mo Fuel Properties	411
3.14.4.2	Thermal Conductivity of (U–Mo Alloy)–Al Dispersions	413
3.14.4.3	U–Mo Fabrication	413
3.14.4.3.1	U–Mo alloy powder fabrication	413
3.14.4.3.2	U–Mo dispersion plate fabrication	415
3.14.4.4	U-Mo Irradiation Performance	415
3.14.4.4.1	Fuel swelling by fission products	415
3.14.4.4.2	Interaction between fuel particles and AI matrix	416
3.14.4.3	U–Mo alloy blister threshold temperature	419
3.14.4.5	Summary for U-Mo	419
3.14.5	Summary and Outlook	420
References		420

3.15 Metal Fuel-Cladding Interaction

D. D. Keiser, Jr.

Idaho National Laboratory, Scoville, ID, USA

Published by Elsevier Ltd.

	and the second	WARK FRAME, JACK IN NOART BRANK NEAR
3.15.1	Introduction	423
3.15.2	The Fuel-Cladding Interaction Process	424
3.15.2.1	Using Phase Diagrams to Gain Insight into FCCI	424
3.15.2.2	Determination of Kinetics Using Out-of-Pile Experiments	425
3.15.3	Characterization of FCCI in Irradiated Fuel Elements	428
3.15.3.1	FCCI Layer Morphology	428
3.15.3.2	FCCI Layer Composition	430
3.15.3.2.1	Fuel element with U–Pu–Zr fuel and HT-9 cladding	430
3.15.3.2.2	Fuel element with U–Pu–Zr and D9 cladding	432
3.15.3.2.3	Fuel element with U–Zr and HT-9 cladding	433
3.15.3.2.4	Fuel element with U–Zr and D9 cladding	434
3.15.3.2.5	General comments about interdiffusion of fuel, cladding, and fission products at the	
	fuel-cladding interface in an irradiated fuel element	435
3.15.4	High-Temperature Irradiated Fuel Annealing Tests to Investigate Liquefaction	
	in FCCI Zones	437
3.15.5	FCCI in TREAT Reactor Transient Tests	438
3.15.6	Modeling FCCI	439
3.15.7	Development of Diffusion Barriers	439
3.15.8	Outlook	439
References		440
		should be a standard and the standard and t

·

3.16 Ceramic Fuel-Cladding Interaction

K. Maeda

Japan Atomic Energy Agency, O-arai, Ibaraki, Japan

3.16.1	Introduction and Overview of Ceramic Fuel-Cladding Interaction	444
3.16.2	Cladding Compatibility with Oxide Fuels and FPs	445
3.16.2.1	Formation of Protective Oxides on Cladding Materials	445
3.16.2.2	Chemical Interaction Among Oxide Fuels, FPs, and Cladding	446
3.16.3	Morphology of Cladding Attack in Oxide Fuel Pins	447
3.16.3.1	Observations of Cladding Attack	447
3.16.3.1.1	Deep localized cladding attack	447
3.16.3.1.2	FCCI at the top of the fuel column	447
3.16.3.2	Types and Characteristics of Cladding Attack	448
3.16.4	Occurrence of Interaction Between Oxide Fuels and Cladding	449
3.16.4.1	Key Parameters in FCCI Development	449
3.16.4.1.1	Fuel parameters	449
3.16.4.1.2	Effect of temperature	450
3.16.4.1.3	Effect of burnup	451
3.16.4.1.4	Effect of temperature difference between fuel and cladding	452
3.16.4.1.5	Effects of cladding materials	455
3.16.4.2	FCCI Model and Wastage Equation	455
3.16.5	Mechanism of Oxide Fuel and Cladding Interaction	457
3.16.5.1	Oxygen Potential of Irradiated Fuel	457
3.16.5.2	Characteristics of Major Corrosive FPs	458
3.16.5.2.1	lodine	459
3.16.5.2.2	Cesium	459
3.16.5.2.3	Tellurium	460
3.16.5.3	Various Corrosion Reaction Mechanisms	461
3.16.5.3.1	Corrosion early in life	461
3.16.5.3.2	lodine transport of cladding constituents	462
3.16.5.3.3	Cladding corrosion by Cs–Te mixture	463
3.16.6	Inhibition Methods for Oxide Fuel and Cladding Interaction	466
3.16.7	Nonoxide Ceramic Fuels and Cladding Interaction	467
3.16.7.1	FCCI of Carbide Fuel	467
3.16.7.1.1	Chemical reactions with FPs	467
3.16.7.1.2	Formation of intermetallic compounds	467
3.16.7.1.3	Clad carburization	468
3.16.7.1.4	Key parameters of clad carburization	470
3.16.7.2	FCCI of Nitride Fuels	475
3.16.7.2.1	Chemical reactions with FPs	475
3.16.7.2.2	Formation of intermetallic compounds	476
3.16.7.2.3	Clad nitriding	476
3.16.8	Outlook	477
Heferences		478

3.17 Thermal Spectrum Control Rod Materials

R. M. Horn, B. D. Frew, and P. Van Diemen

GE Hitachi Nuclear Energy, LLC, San Jose, CA, USA

© 2012 Elsevier Ltd. All rights reserved.

3.17.1	Overview of Light Water Reactor Control Rod Designs	486
3.17.1.1	BWR CR Design Summary	486
3.17.1.1.1	Summary of BWR general design criteria	487
3.17.1.2	PWR CR Design Summary	487
3.17.1.2.1	Summary of PWR general design criteria	487
3.17.2	Details of BWR CR Designs and Development	488
3.17.2.1	Overview of Poison Approaches	488
3.17.2.2	Duty Requirements for CRBs	489
3.17.2.2.1	Life requirements	489
3.17.2.2.2	Upset load requirements	490
3.17.2.3	GE CR Designs and Development	490
3.17.2.3.1	HPSS development	491
3.17.2.3.2	Development of crevice-free design CRBs	493
3.17.2.3.3	Inclusion of hafnium materials	494
3.17.2.3.4	Cobalt elimination efforts	494
3.17.2.3.5	CRB handle cracking	494
3.17.2.3.6	Summary of the current GEH Marathon CRB design	495
3.17.2.4	Toshiba/Westinghouse (Formerly ABB) BWR CRB Designs and Development	495
3.17.2.4.1	Summary of the current Toshiba/Westinghouse BWR CR99 CRB design	497
3.17.2.5	Other Vendor Designs and Development	497
3.17.2.6	Overview of Limiting Structural Material Properties and IASCC Mechanism	498
3.17.2.7	Summary of BWR CR Structural Problems	500
3.17.2.8	Current Status and Future Development Needs for BWR CRBs	501
3.17.3	PWR CR Development	501
3.17.3.1	Overview of Poison Approaches	501
3.17.3.2	Design Overview for PWR CRs	503
3.17.3.3	Areva/Siemens Designs	503
3.17.3.4	Toshiba/Westinghouse (ABB and CE) Designs	504
3.17.4	Status of Limiting Material Problems in LWR CRs	505
3.17.5	Summary	506
References		507
		and a second

3.18 Fast Spectrum Control Rod Materials

T. Donomae and K. Maeda

Japan Atomic Energy Agency, O-arai, Ibaraki, Japan

© 2012 Elsevier Ltd. All rights reserved.

		the second s
3.18.1	Introduction	509
3.18.2	Absorber Materials	520
3.18.2.1	Performance Requirements of Neutron Absorber Materials	520
3.18.2.2	Variety of Absorber Materials	520
3.18.3	Boron Carbide	521
3.18.3.1	Fabrication	521
3.18.3.2	Structure	522
3.18.3.3	Physical and Chemical Properties	522
3.18.3.3.1	Physical properties	522
3.18.3.3.2	Chemical interactions	522
3.18.3.4	Irradiation Behavior	524
3.18.3.4.1	Swelling	524
3.18.3.4.2	Lattice parameters	525
3.18.3.4.3	Microstructural observation	526
3.18.3.4.4	Thermal conductivity	529
3.18.4	Characteristics of Other Absorber Materials	530
3.18.4.1	Tantalum	530
3.18.4.2	Europium and Its Chemical Compounds	530
3.18.5	Approach to Realize a Long Lifetime for Control Rods in Fast Reactors	531
3.18.5.1	Internal Pressure in Cladding Tube	532
3.18.5.2	B ₄ C Pellet-Cladding Tube Interaction	533
3.18.5.3	Outlook	533
References		534

Abbreviations

AVVICTIC	
ACCI	Absorber-cladding chemical
	interaction
ACMI	Absorber-cladding mechanical
	interaction
BU	Burnup
EFPD	Effective full power days
FBR	Fast breeder reactor
MK-II	Mark-II (core type of JOYO,
	1982–2000)
MK-III	Mark-III (core type of experimental
	fast reactor JOYO, 2003-)
Na bonding	Sodium bonding
NMR	Nuclear magnetic resonance
SEM	Scanning electron microscopy
TD	Theoretical density
TEM	Transmission electron microscopy

3.19 Oxide Fuel Performance Modeling and Simulations

P. Van Uffelen

European Commission, Joint Research Centre, Institute for Transuranium Elements, Eggenstein-Leopoldshafen, Germany **M. Suzuki**

Japan Atomic Energy Agency, Tokai-mura, Ibaraki, Japan

© 2012 Elsevier Ltd. All rights reserved.

3.19.1	Introduction	536
3.19.1.1	Importance of Fuel Performance Modeling	536
3.19.1.2	Geometrical Idealization and Size of the Problem	536
3.19.1.3	Uncertainties and Limitations	537
3.19.2	Basic Equations and State of the Art	538
3.19.2.1	Heat Transfer	538
3.19.2.1.1	Axial heat transfer in the coolant	538
3.19.2.1.2	Heat transport through the cladding	539
3.19.2.1.3	Heat transport from cladding to the fuel pellet	539
3.19.2.1.4	Heat transport in fuel pellets	540
3.19.2.1.5	The structure of the thermal analysis	541
3.19.2.2	Mechanical Analysis	541
3.19.2.2.1	Main assumptions and equations	541
3.19.2.2.2	Calculation of strains	542
3.19.2.2.3	Boundary conditions	546
3.19.2.2.4	Pellet-cladding interaction	547
3.19.2.3	Fission Gas Behavior	551
3.19.2.3.1	Basic mechanisms	551
3.19.2.3.2	Modeling the fission gas behavior	554
3.19.3	Design Basis Accident Modeling	557
3.19.3.1	Loss-of-Coolant Accident	557
3.19.3.1.1	Specific LOCA features	557
3.19.3.1.2	Specific LOCA modeling requirements	558
3.19.3.2	Reactivity-Initiated Accidents	561
3.19.3.2.1	Specific RIA features	561
3.19.3.2.2	Specific RIA modeling requirements	562
3.19.4	Advanced Issues and Future Needs	564
3.19.4.1	Deterministic Versus Probabilistic Analyses	564
3.19.4.2	The High Burnup Structure	566
3.19.4.3	Mixed Oxide Fuels	568
3.19.4.4	Multiscale Modeling	570
3.19.5	Summary and Conclusions	572
References		574

, . .

.

3.20 Modeling of Fission-Gas-Induced Swelling of Nuclear Fuels*

J. Rest

Argonne National Laboratory, Argonne, IL, USA

3.20.1	Introduction	580
3.20.2	Intragranular Bubble Nucleation: Uranium-Alloy Fuel in the High-Temperature	
	Equilibrium γ-Phase	581
3.20.2.1	Introduction	581
3.20.2.2	A Multiatom Nucleation Mechanism	582
3.20.2.3	Calculation of the Fission-Gas Bubble-Size Distribution	584
3.20.2.4	Bubble Coalescence	586
3.20.2.5	Analysis of U-10Mo High-Temperature Irradiation Data	586
3.20.2.6	Conclusions	591
3.20.3	Intergranular Bubble Nucleation: Uranium-Alloy Fuel in the Irradiation-Stabilized	
	γ-Phase	591
3.20.3.1	Introduction	591
3.20.3.2	Calculation of Evolution of Average Intragranular Bubble-Size and Density	591
3.20.3.3	Calculation of Evolution of Average Intergranular Bubble-Size and Density	593
3.20.3.4	Calculation of Intergranular Bubble-Size Distribution	593
3.20.3.5	Comparison Between Model Calculations and Intragranular Data	595
3.20.3.6	Comparison Between Model Calculations and Intergranular Data	596
3.20.3.7	Calculation of Gas-Driven Fuel Swelling Safety Margins	597
3.20.3.8	Conclusions	599
3.20.4	Irradiation-Induced Re-solution	601
3.20.4.1	Introduction	601
3.20.4.2	Flux Algorithm	601
3.20.4.3	Grain-Boundary-Bubble Growth	603
3.20.4.4	Analysis of Bubble Growth on Grain Boundaries	604
3.20.4.5	Discussion and Conclusions	608
3.20.5	Irradiation-Induced Recrystallization	610
3.20.5.1	Introduction	610
3.20.5.2	Model for Initiation of Irradiation-Induced Recrystallization	610
3.20.5.3	Model for Progression of Irradiation-Induced Recrystallization	611
3.20.5.4	Theory for the Size of the Recrystallized Grains	614
3.20.5.5	Calculation of the Cellular Network Dislocation Density and Change in	
	Lattice Parameter	614
3.20.5.6	Calculation of Recrystallized Grain Size	616
3.20.5.7	Evolution of Fission-Gas Bubble-Size Distribution in Recrystallized U–10Mo Fuel	620
3.20.5.8	Effect of Irradiation-Induced Recrystallization on Fuel Swelling	621
3.20.5.9	Discussion and Conclusions	624
3.20.6	Final Thoughts	625
References		625

3.21 Matter Transport in Fast Reactor Fuels

M. J. Welland

European Commission, Joint Research Centre, Institute for Transuranium Elements, Karlsruhe, Germany

With a some later waters

and a state of the state of the

0.04.4	he has also all a s	000
3.21.1	Introduction	630
3.21.2	Transport Phenomena	632
3.21.2.1	The Theory of Irreversible Processes	632
3.21.2.2	Solid State Mass Transport	634
3.21.2.2.1	Mass transport	634
3.21.2.2.2	Mass and heat transport	637
3.21.2.2.3	Other thermodynamic driving forces	640
3.21.2.3	Vapor Phase Transport	641
3.21.2.3.1	Factors affecting equilibrium vapor pressure	641
3.21.2.3.2	Temperature-driven vapor phase transport	642
3.21.3	Microscopic Structures	644
3.21.3.1	Sintering and Grain Growth	644
3.21.3.1.1	Sintering	644
3.21.3.1.2	Grain growth	644
3.21.3.2	Void Migration	645
3.21.3.2.1	Void migration mechanisms	646
3.21.3.2.4	Void migration forces	648
3.21.3.2.5	Comparison of void migration behavior and experimental applications	649
3.21.3.3	Pores Migration	650
3.21.3.3.1	The origin of pores	651
3.21.3.3.2	The shape of migrating pores	651
3.21.3.3.3	Pore migration speed	653
3.21.3.3.4	Redistribution of constituents	654
3.21.4	Bulk Phenomena	655
3.21.4.1	Cracks	655
3.21.4.2	Porosity Evolution	656
3.21.4.2.1	Columnar grain growth	656
3.21.4.2.2	Central void	656
3.21.4.3	Melting	656
3.21.5	Fuels	657
3.21.5.1	Mixed Oxide Fuels	657
3.21.5.1.1	MOX restructuring	658
3.21.5.1.2	U–Pu redistribution	662
3.21.5.1.3	Oxygen redistribution	665
3.21.5.1.4	Fission products and other elements	667
3.21.5.2	U-Pu-C-N	669
3.21.5.3	U–Pu–Zr	671
3.21.5.4	TRISO Particles	672
3.21.6	Summary	674
References		674

3.22 Modeling of Pellet Cladding Interaction

B. Michel, J. Sercombe, and C. Nonon

Commissariat à l'Energie Atomique, DEN, DEC, St Paul Lez Durance, France **O. Fandeur**

Commissariat à l'Energie Atomique, DEN, DM2S, Gif-sur-Yvette, France

3.22.1	Introduction	678
3.22.2	Phenomenological Aspects of PCI and Modeling Bibliography	678
3.22.3	Experimental Simulation	679
3.22.4	Numerical Simulation	682
3.22.4.1	Multiphysics Problem	682
3.22.4.2	Nuclear Power Deposition Computation	682
3.22.4.3	Thermohydraulic Computation	683
3.22.4.4	Thermal Computation	683
3.22.4.5	Mechanical Computation	683
3.22.4.5.1	Pellet	683
3.22.4.5.2	Cladding	684
3.22.4.5.3	Pellet-cladding interface	685
3.22.4.6	Chemical–Physical Behavior of Fuel Pellet	685
3.22.4.6.1	Solid swelling and densification	685
3.22.4.6.2	Behavior of gaseous fission products	685
3.22.4.7	Coupling of Gaseous Swelling and Mechanical Behavior	687
3.22.4.7.1	Approach	687
3.22.4.7.2	Convergence acceleration algorithm	688
3.22.4.8	Multidimensional PCI Modeling	689
3.22.4.8.1	The PLEIADES fuel simulation platform	689
3.22.4.8.2	The four computation schemes of ALCYONE	689
3.22.4.8.3	Thermomechanical finite element solver of the PLEIADES platform	691
3.22.5	Modeling Contribution to a Better Understanding of PCI	692
3.22.5.1	Pellet–Cladding Gap Closure Mechanisms and Fuel Element Behavior Under Irradiation	692
3.22.5.1.1	Base irradiation (see Figure 12)	692
3.22.5.1.2	Power ramp test (see Figure 13)	693
3.22.5.2	Analysis of Residual Displacement After Irradiation	695
3.22.5.3	Analysis of Cladding Global Loading Under a Transient Power Ramp Test	697
3.22.5.4	Analysis of the Cladding Local Loading	699
3.22.5.4.1	Stress and strain concentration in the cladding	699
3.22.5.4.2	Impact of the shear stress at pellet-cladding interface	701
3.22.5.4.3	PCI failure criterion	703
3.22.5.5	Interpretation of the Power Ramp Experimental Database	705
3.22.5.5.1	Loading parameters and experimental PCI failure curve	705
3.22.5.5.2	Different types of PCI behaviors	707
3.22.6	Conclusions	708
References		711

3.23 Metal Fuel Performance Modeling and Simulation

T. Ogata

Central Research Institute of Electric Power Industry, Komae, Tokyo, Japan **Yeon Soo Kim and A. M. Yacout** Argonne National Laboratory, Argonne, IL, USA

© 2012 Elsevier Ltd. All rights reserved.

. . .

3.23.1	Introduction	714
3.23.2	Models for Constituent Migration	715
3.23.2.1	Introduction	715
3.23.2.2	Phase Diagram	717
3.23.2.3	Temperature Prediction	718
3.23.2.4	Modeling	720
3.23.2.5	Migration of Minor Actinides and Lanthanide FPs	721
3.23.3	LIFE-METAL	723
3.23.3.1	Background	723
3.23.3.2	Code Structure and Models	724
3.23.3.2.1	Code structure and thermomechanical analysis	724
3.23.3.2.2	Constituent redistribution	725
3.23.3.2.3	Fuel-cladding chemical interaction	726
3.23.3.2.4	Fuel swelling and fission gas release	728
3.23.3.3	LIFE-METAL Validation	729
3.23.3.4	LIFE-METAL Code Status and Future Activities	732
3.23.4	ALFUS	732
3.23.4.1	Background	732
3.23.4.2	Models in ALFUS	732
3.23.4.2.1	Calculation flow in ALFUS	732
3.23.4.2.2	Stress-strain analysis model	733
3.23.4.2.3	Gas swelling model	738
3.23.4.2.4	Effect of radial cracks	742
3.23.4.2.5	Solid FP swelling model	744
3.23.4.2.6	Correlation of cladding wastage by rare-earth FPs	744
3.23.4.2.7	Temperature calculation model	744
3.23.4.2.8	Adjustment of the model parameters in ALFUS	746
3.23.4.3	Validation of ALFUS	747
3.23.4.3.1	Fission gas release	747
3.23.4.3.2	Axial elongation of the fuel slug	747
3.23.4.3.3	Cladding diametral strain and FCMI	748
3.23.5	Summary and Outlook	750
References		751

3.24 TRISO Fuel Performance Modeling and Simulation

K. Verfondern

Institute for Energy Research - Safety Research and Reactor Technology (IEF-6), Jülich, Germany

		1900 - Mour Doc Alle 6 19 girl an Arrow States
3.24.1	Introduction	756
3.24.2	The HTGR Fuel Element Design	757
3.24.3	The Modeling of TRISO-Coated Particle Performance During Reactor	
	Operation and Under Accident Conditions	759
3.24.3.1	Physical Phenomena in Coated Particle Behavior	759
3.24.3.1.1	Pressure buildup from carbon monoxide formation	759
3.24.3.1.2	Impact of irradiation on pyrocarbon layers	761
3.24.3.1.3	Kernel migration	761
3.24.3.1.4	Pressure vessel failure	762
3.24.3.1.5	Fission product attack	763
3.24.3.1.6	Thermal decomposition of the SiC layer	764
3.24.3.2	Simulation of Coated Particle Performance	765
3.24.3.2.1	Simple 'Soap bubble' approach in the PANAMA code	765
3.24.3.2.2	Other approaches	767
3.24.3.3	Efforts on Verification and Validation of Coated Particle Performance Models	768
3.24.4	The Behavior of Fission Product Release from TRISO-Coated Particle Fuel	769
3.24.4.1	Safety Relevance	769
3.24.4.2	Fission Product Transport Phenomena	771
3.24.4.2.1	Types of particles	771
3.24.4.2.2	Inventory buildup	771
3.24.4.2.3	Initial distribution in accidents	772
3.24.4.2.4	Recoil	773
3.24.4.2.5	Chemisorption effect of metallic fission products	773
3.24.4.2.6	Influence of chemical reactions on release behavior	774
3.24.4.2.7	Influence of hydrolysis on release behavior	774
3.24.4.3	Simulation of Fission Product Transport and Release	775
3.24.4.3.1	Diffusive transport of metallic fission products	775
3.24.4.3.2	Release of long-lived or stable fission products from the particle kernel	776
3.24.4.3.3	Release of short-lived fission products from the particle kernel	777
3.24.4.3.4	Release of fission gases from hydrolysis	778
3.24.4.4	Simulation of Fission Product Transport and Release Behavior	779
3.24.4.4.1	Diffusion model	779
3.24.4.4.2	Integrated particle failure and release model	780
3.24.4.3	Diffusion coefficients	781
3.24.4.4.4	Sorption isotherms	781
3.24.4.5	Efforts on Verification and Validation of Fission Product Transport and	
	Release Models	782
3.24.5	Further Work	785
3.24.6	Summary and Conclusions	786
References		787

		СР	Coated particles
ADDR		CRP	Coordina
AVR	Arbeitsgemeinschaft Versuchsreaktor	EDN	Equivaler
BISO	Bi-structural		

3.25 Modeling of Sphere-Pac Fuel

M. A. Pouchon and L.-Å. Nordström

Paul Scherrer Institut, Villigen PSI, Switzerland

Ch. Hellwig

Fachgebietsleiter Kernbrennstoff-Technologie, Baden, Switzerland

3.25.1	Introduction to the Sphere-pac and Vipac Fuel Concepts	790
3.25.1.1	Overview	790
3.25.1.2	Important Terms and Definitions for Particle Fuel Modeling	791
3.25.1.3	History and Past Experience of Sphere-pac Fuel	792
3.25.2	Modeling of the Thermal Properties	792
3.25.2.1	Geometrical Model	793
3.25.2.2	Modeling of Heat Transport in the Basic Cells	794
3.25.2.2.1	Heat conduction assuming parallel heat flow (one-dimensional case)	794
3.25.2.2.2	Two-dimensional approximation of heat conduction	795
3.25.2.2.3	Evaluation of the thermal conductivity and the heat transfer value	795
3.25.2.2.4	Application to two-fractional packages	796
3.25.3	Modeling of Fuel Restructuring	797
3.25.3.1	Sintering and Neck Growth	797
3.25.3.1.1	Stages of sintering	797
3.25.3.1.2	Driving forces of sintering	797
3.25.3.1.3	Sintering mechanisms	798
3.25.3.1.4	Sintering in different regions of sphere-pac fuel	800
3.25.3.2	Creep	801
3.25.3.2.1	Steady-state thermal creep	801
3.25.3.2.2	Transition stress	801
3.25.3.2.3	Time-independent thermal creep rate	801
3.25.3.2.4	Time dependence of thermal creep rate	801
3.25.3.3	Pore Migration and Restructuring	802
3.25.3.3.1	The porosity conservation equation	802
3.25.3.3.2	Olander's model for pore velocity	802
3.25.3.3.3	The finite difference solution of porosity equation	803
3.25.3.4	Grain Size and Grain Growth	803
3.25.4	Modeling of Other Properties	804
3.25.4.1	Fission Gas Release	804
3.25.4.1.1	General	804
3.25.4.1.2	Intragranular gas	804
3.25.4.1.3	Gas release	807
3.25.4.1.4	Final comments	808
3.25.4.2	Mechanical Properties	808
3.25.4.2.1	Bed pressure	808
3.25.4.2.2	Cladding deformation	809
3.25.5	Implementation and Validation	810
3.25.5.1	The Predicting Tools SPACON and SPHERE	810
3.25.5.2	Experimental Validations of the SPACON and SPHERE Codes	810
3.25.5.2.1	AC-3	810
3.25.5.2.2	Siemens-PSI Gösgen PWR	811
3.25.5.2.3	PSI-Halden BWR	812
3.25.5.2.4	FUJI	813
3.25.6	Modeling of Vipac Fuel	815

3.25.6.1	Basic Thermal Conductivity	815
3.25.6.1.1	For the nonsintered region	815
3.25.6.1.2	Introduction of metallic particles (getter concept)	816
3.25.7	Conclusions	816
References		816