



Nuclear Industry Value Chain



– NOTICE –

UxC, LLC (“UxC”) shall have title to, ownership of, and all proprietary rights in this Report. Under United States federal copyright law (17 USC 101 et seq.) it is illegal to reproduce this Report by any means without written permission from UxC.

The information contained in this Report is obtained from sources that UxC believes to be reliable. UxC makes no warranty or representation, express or implied, with respect to the accuracy, completeness or usefulness of the information contained in this Report and UxC, to the maximum extent permitted by law, assumes no liability for the use or effects of any of the information or data contained in this Report.

It is UxC’s strict policy not to endorse, promote, or recommend any particular securities, currencies, or other financial products or instruments. Nothing contained in this Report is intended to constitute investment, legal, tax, accounting or other professional advice and the reader should not rely on the information provided in this Report for making financial decisions.

The Ux U₃O₈ Price[®] and other Ux Price indicators are developed by UxC and are proprietary and exclusive intellectual property of UxC. These price indicators are provided to UxC’s customers through the Ux Weekly[®] publication and are made available on UxC’s public website solely at UxC’s discretion. They may not be reproduced or otherwise used without UxC’s express permission.

UxC[®], Ux Weekly[®], Ux U₃O₈ Price[®], Ux[®], U-PRICE[®], and SWU-PRICE[®] are trademarks of UxC, LLC.

Table of Contents

Introduction & Overview	14
Purpose of Report	14
Key Questions in the Nuclear Markets Today	15
What's New in the 2018 Report?	16
Structure of Report	17
Part I – Nuclear Power in the World Today	19
Brief History of Nuclear Power	19
Nuclear Power's Share of Global Energy	23
• Energy Demand and Supply	23
• Electricity Sector Outlook	24
• Analysis	28
Current State of Nuclear Power	29
Why Nuclear Energy?	30
• Challenges to Nuclear Energy	30
Major Trends in Nuclear Power	31
• Influence of Governments	31
• Need for More Electricity	32
• High Capital Costs	32
• Reactor Shutdowns: Electricity Prices and Oversupply	33
• Life Extensions Instead of New Construction	33
Profiles of Leading Nuclear Power Countries	33
• United States	34
• France	36
• Japan	38
• Russia	40
• China	42
• South Korea	43
• India	44
Nuclear Reactor Technologies	47
• Basic Reactor Designs	47
• Evolution of Reactor Technologies	51
• Generation III and III+ Reactors	52
• Current Reactor Offerings	53
• UxC Expertise in Reactor Technology Analysis	55
UxC Forecasts for Nuclear Power	56
• UxC Base Case Nuclear Power Forecast	57
• Alternative UxC Reactor Forecasts	59
Third Party Forecasts for Nuclear Power	60
• International Atomic Energy Agency (IAEA)	60
• U.S. Energy Information Administration	61
• BP Energy Outlook	62
Part II – Front-End Market Overview	63
Front-End Market Size Overview	64
Current and Future Market Trends	65
• Future Demand Uncertainty	65
• Accelerating Supply Responses	65
• Shifting Nature of China's Approach to Fuel Supply	66
• Continued Prominence of Inventories and Secondary Supplies	66
• Maturing Nature of the Mid-Term Market	66
• Utility Focus on Fuel Cycle Cost Optimization	66
1 – Uranium Mining and Milling	67
Introduction to Sector	67
• Uranium Mining Methods	67
Market Overview	70
• History of Uranium Prices	71

Price Movements and Market Activity	74
• Spot Price Movements	74
• Spot Market Activity	75
• Long-Term Price Movement.....	75
• Long-Term Market Activity	75
Recent Developments	75
• Uranium Production Rationalization.....	76
• Producer Purchasing to Cover Sales Commitments.....	76
• Re-emergence of Investor Interest.....	76
• Shift in U.S. Government Inventory Management Policy	77
• Return of Uranium Trade Wars	77
• Continued Prominence of Spot and Mid-Term Market.....	77
• Utility Long-Term Contracting Remains Limited	78
Key Players	78
• Kazatomprom.....	78
• Orano	79
• Cameco Corporation	79
• Uranium One.....	80
• ARMZ.....	80
• Rio Tinto Uranium	80
• CNNC / CGN.....	81
• BHP Billiton	81
• Navoi Mining and Metallurgical Combine.....	81
• Paladin Energy Ltd.....	81
• Other Producers.....	82
• Secondary Supplies	83
Market Shares	83
Supply and Demand.....	85
Pricing and Profit Margins	86
• Price Forecast.....	86
• Profit Margins.....	87
Total Market Size	88
• Regional Market Sizes	89
Future Market Trends.....	89
• Limited Utility Requirements in Near- to Medium-Term	89
• China: Uranium Demand Wildcard.....	89
• Uncertainty About Future Production.....	90
• Policy and Trade Actions Could Reshape the Market	90
• The Changing Role of Secondary Supplies	90
• Continued Influence of Enrichers on the Uranium Market	91
• Sustained Inventory Drawdown	91
• Gradual Shift from Inventory-Driven to Production Cost-Driven Market	91
• Return of Long-Term Contracting?	91
2 – Uranium Conversion	92
Introduction to Sector	92
Market Overview	94
Price Movements and Market Activity	96
• Spot Price Movements	96
• Spot Market Activity	97
• Long-Term Price Movement.....	97
• Long-Term Market Activity	98
Recent Developments	98
• Metropolis Shutdown and Other Supply Responses	98
• China's Continued Domestic Capacity Expansion	98
• Clearing of Inventory Overhang	99
• Shift of U.S. Government Uranium Inventory Policy	99
• Limited Long-Term Contracting Activity	99
• Narrowing the Spot / Long-Term Price Differential	99

• Reduction in Regional Pricing Differentials.....	100
Key Players.....	100
• Cameco Corporation.....	100
• Honeywell / ConverDyn.....	101
• Orano.....	102
• TVEL / TENEX.....	102
• China National Nuclear Corporation (CNNC).....	103
• Indústrias Nucleares do Brasil (INB).....	103
Market Shares.....	104
Supply and Demand.....	105
• Regional Disparities.....	106
Pricing and Profit Margins.....	107
• Price Forecast.....	107
• Profit Margins.....	107
Total Market Size.....	108
• Regional Market Sizes.....	108
Future Market Trends.....	109
• Uncertainty About Future Conversion Capacity.....	109
• Persistent Tightness of Supply / Demand Fundamentals.....	109
• Changing Role of Secondary Supplies.....	110
• Continued Influence of Enrichers in the Conversion Market.....	110
• Long-Term Price to Remain Tied to Production Costs.....	110
• Policy and Trade Issues to Continue Impact the Market.....	111
• Conversion to Remain the Weakest Link.....	111
3 – Uranium Enrichment.....	112
Introduction to Sector.....	112
Market Overview.....	114
Price Movements and Market Activity.....	116
• Spot Activity and Price Movements.....	116
• Long-Term Activity and Price Movements.....	117
Recent Developments.....	117
• Limited Market Activity.....	117
• Enrichment Prices Decline to Historic Lows.....	117
• Persistent Overcapacity and Gradual Supply Response.....	118
• Cancellation of New Enrichment Projects.....	118
• Changes in Utility Procurement Preferences.....	118
• Enrichers as Uranium “Producers”.....	119
• Trade and Policy Issues: Key Market Uncertainties.....	119
Key Players.....	120
• Orano.....	120
• TVEL / TENEX.....	120
• URENCO.....	121
• China National Nuclear Corporation (CNNC).....	122
• Centrus Energy.....	122
• Global Laser Enrichment (GLE).....	123
• Others.....	123
Market Shares.....	124
Supply and Demand.....	125
Pricing and Profit Margins.....	126
• Price Forecast.....	126
• Profit Margins.....	126
Total Market Size.....	127
• Regional Market Sizes.....	128
Future Market Trends.....	129
• Continued Optimization of Capacity to Address Supply Excess.....	129
• China to Ramp Up in Line with Domestic Requirements.....	129
• Anticipation of SWU Prices Bottoming Out and Gradual Recovery.....	129
• Return of Utilities to the Market.....	130

• Need for Future Investment to Maintain Enrichment Capacity	130
• Continued, but Diminishing Role of Secondary Supplies.....	130
4 – Nuclear Fuel Fabrication	131
Introduction to Sector	131
• Fuel Manufacturing Process	131
• Fuel Assembly Designs.....	132
Market Overview	133
Recent Developments	135
• AREVA NP Becomes Framatome.....	135
• Westinghouse’s Change in Ownership and Operational Issues	135
• TVEL’s Entry into the PWR Reload Market.....	136
• KAP-CGN Fuel Fabrication Partnership.....	136
• U.S. Takes the Lead in Accident Tolerant Fuel Development	136
• Fuel Fabrication Prices Reverse Growth Trend	137
• Policy Issues Become a Factor for Fuel Fabricators.....	137
Key Players	138
• Framatome.....	138
• Global Nuclear Fuel (GNF)	138
• Westinghouse Electric Company	139
• TVEL Fuel Company.....	139
• KEPCO Nuclear Fuel (KNF).....	139
• Regional Suppliers.....	139
Market Shares	140
• Geographic Market Segments	140
• Technical Market Segments.....	140
• Global Market Shares	140
• Regional Market Shares.....	141
Supply and Demand.....	142
Pricing and Profit Margins	144
• Price Forecast.....	146
• Profit Margins.....	147
Total Market Size	147
• Regional Market Sizes	148
Future Market Trends.....	149
• Continued Market Oversupply in Open Markets	149
• Expected Rightsizing of Mega-Vendors	149
• Demand Growth in Self-Sufficient / Closed Fabrication Markets	149
• Japanese Fabrication Industry Consolidation	150
• Emerging International Suppliers: KNF, TVEL, and CNNC	151
• Accident Tolerant and Advanced Fuel Designs	151
MOX Fuel Fabrication	152
• Key Players	152
• MOX Fabrication Market Size and Trends.....	154
• MOX Pricing and Profit Margins.....	154
PHWR Fuel Fabrication.....	155
• PHWR Fuel Fabrication Key Players	155
• PHWR Fuel Fabrication Market Size and Trends	156
Other Non-LWR Fuel Fabrication.....	157
• Gas-Cooled Reactor Fuel Fabrication.....	157
• RBMK Fuel Fabrication	157
Part III – Nuclear Reactor Market Overview	158
5 – New Reactor Construction	159
Introduction to Sector	159
Market Overview	161
• Established Nuclear Power Countries	162
• China: The Nuclear Growth Giant.....	162
• New Nuclear Power Countries.....	162

Recent Developments	163
NSSS Key Players	164
• EDF/Framatome	164
• Rosatom.....	165
• China General Nuclear Power Group (CGN).....	173
• China National Nuclear Corporation (CNNC)	175
• State Power Investment Corporation (SPIC)	176
• Toshiba Corporation	178
• Westinghouse Electric Company	179
• GE-Hitachi (GEH) / Hitachi-GE (HGE).....	180
• Korea Electric Power Corporation (KEPCO).....	182
• Mitsubishi Heavy Industries (MHI)	184
• SNC-Lavalin (formerly AECL).....	185
• Nuclear Power Corporation of India Ltd. (NPCIL).....	186
NSSS Market Shares	187
Reactor Supply Chain Key Players	190
• Heavy Forging Suppliers.....	191
• Engineering, Procurement, and Construction (EPC) Companies	192
Reactor Supply Chain Market Shares	193
Supply and Demand.....	195
• UxC New Reactor Construction Forecasts	195
• Current New Reactor Projects	196
Prices and Profit Margins	197
• New Reactor Project Costs	198
• Profit Margins.....	202
Total Market Size	204
Future Market Trends.....	206
• Emerging vs. Established Markets.....	206
• China: A Growing Superpower	206
• Vendors Relying on Home Government Support.....	207
6 – Reactor Operations and Services	208
Introduction to Sector	208
Market Overview	209
• The World’s Nuclear Utilities.....	210
• Recent Reactor Operating Trends	212
Recent Developments.....	213
• Planned and Unplanned Maintenance Outages	213
• Recent O&M Contracts	214
Key Players	215
• Technical Support Organizations.....	219
Market Shares.....	222
Supply and Demand.....	222
• Critical Spare Parts Inventories	223
Prices and Profit Margins	226
• Operating Costs	226
• Lifecycle Costs.....	228
• Profit Margins.....	229
Total Market Size	229
• Global Reactor Services Market Size Forecasts	229
• Regional Reactor Services Market Size Forecasts.....	231
• Breakdown of Reactor Services Market by Cost Component.....	231
Future Market Trends.....	232
• Shrinking Markets	232
• Negative Economic Pressures and Uncertain Reactor Lifetimes	233
• Supplier Consolidation and Strategic Partnerships.....	233
• Utility Consolidation and Teaming Arrangements.....	233
7 – Reactor Capital Upgrades	234
Introduction to Sector	234

Market Overview	235
• Lifetime Extensions	236
• Power Upgrades	239
• Other Types of Major Upgrades	240
• Life After Sixty: Long-Term Operation	243
Recent Developments	248
• Latest New Capital Upgrade Projects	248
Key Players	250
• Framatome	250
• SNC-Lavalin	250
• GE-Hitachi	251
• Toshiba	251
• KEPCO	251
• MHI	251
• Rosatom	252
• Westinghouse	252
• BWXT	253
• Doosan	253
• ENSA	253
• Ansaldo Nucleare	253
• AECON	253
• AECOM	253
• Bechtel	254
Market Shares	254
Supply and Demand	255
• Demand for Major Component Replacements	256
Prices and Profit Margins	259
• Profit Margins	259
Total Market Size	259
Future Market Trends	261
• Uncertain Policies on Lifetime Extensions	261
• Difficult Power Markets	261
• Aging Plants Need More Capital Upgrades	262
• Still Easier to Upgrade than Build a New Plant	262
• New Technologies and Methods Can Reduce Downtime and Costs	262
• New Technologies Can Reduce the Need for Capital Upgrades	262
• Increased Competition Among Suppliers	263
8 – Advanced and Small Modular Reactors	264
Introduction to Sector	264
• Definition of an SMR	265
• Characteristics of an SMR	265
• Reasons for Heightened Interest in SMRs and ARs	267
Market Overview	268
• United States	268
• Russia	269
• South Korea	270
• China	271
• Japan	273
• Canada	274
• United Kingdom	275
Recent Developments	278
Key Players	279
• China General Nuclear (China)	279
• CNNC (China)	280
• SNPTC (China)	280
• INET/Huaneng Group (China)	281
• NuScale Power (United States)	281
• Holtec (United States)	282

• GE-Hitachi (U.S./Japan)	284
• Advanced Reactors Concepts (United States)	285
• General Atomics (United States)	285
• Terrapower (United States).....	286
• X-energy (United States)	287
• HolosGen (United States).....	288
• OKBM Afrikantov (Russia).....	288
• NIKIET (Russia).....	289
• CNEA (Argentina)	290
• KAERI (South Korea).....	291
• Terrestrial Energy (Canada)	292
• U-Battery Developments Ltd (UK/Netherlands).....	293
• Moltex Energy (United Kingdom)	294
Market Shares.....	295
Supply and Demand.....	295
Prices and Profit Margins.....	296
Total Market Size	298
Future Market Trends.....	300
• Overcoming the “Chicken and Egg” Challenges.....	300
• Government Financial Support Remains Key.....	300
• Demonstration Projects and Commercialization Efforts.....	300
• Uncertainty about Construction Timelines	301
• Industry Synergies and Alliances.....	301
• SMR/ARs in a World with Increasing Renewables	301
Part IV – Back-End Market Overview	302
9 – Spent Fuel Treatment, Storage and Disposal	306
Introduction to Sector	306
Market Overview	309
Spent Fuel Storage Overview	312
Spent Fuel Recent Developments	316
Spent Fuel Storage Key Players.....	331
• Doosan Heavy Industries.....	331
• EnergySolutions.....	332
• Equipos Nucleares S.A. (ENSA).....	333
• Gesellschaft fur Nuklear Service (GNS)	334
• Holtec International.....	335
• Interim Storage Partners (ISP).....	336
• NAC International.....	337
• Orano	338
Spent Fuel Storage Market Analysis Results.....	340
Spent Fuel Storage Future Market Trends.....	342
Reprocessing Overview	343
Reprocessing Recent Developments.....	344
Reprocessing Key Players	349
• China National Nuclear Corporation (CNNC)	349
• Indian Reprocessors	350
• Japan Atomic Energy Agency (JAEC)	350
• Japan Nuclear Fuels Ltd (JNFL)	351
• Orano	352
• Rosatom.....	352
• Sellafield Ltd.	353
Reprocessing Market Analysis Results.....	354
Reprocessing Future Market Trends.....	355
Geological Disposal Overview	357
Geological Disposal Recent Developments.....	358
Geological Disposal Key Players	365
• ANDRA	365
• Arius.....	366

• CNNC.....	366
• Japan Atomic Energy Agency (JAEA).....	366
• Korea Radioactive Waste Agency (KORAD)	366
• National Cooperative for the Disposal of Radioactive Waste (NAGRA)	367
• Nuclear Waste Management Organization (NWMO)	368
• Nuclear Waste Management Organization (NUMO).....	369
• Posiva Oy.....	370
• Radioactive Waste Management (RWM).....	373
• Swedish Nuclear Fuel and Waste Management Company (SKB).....	373
• U.S. Department of Energy (DOE).....	376
• Summary.....	378
Geological Disposal Market Analysis Results	380
Geological Disposal Future Market Trends.....	382
Spent Fuel Market Prices and Profit Margins.....	382
10 – Radioactive Waste Management and Disposal	383
Introduction to Sector	383
Analysis Uncertainties.....	384
Market Overview	384
Recent Developments.....	385
Key Players	389
• ANDRA.....	389
• Atomic Energy of Canada Limited (AECL).....	390
• Canadian Nuclear Laboratories (CNL).....	390
• Babcock International Group PLC.....	391
• Belgian Agency for Radioactive Waste and Enriched Fissile Materials	391
• Cavendish Nuclear.....	391
• Central Organization for Radioactive Waste (COVRA).....	392
• Cyclife	392
• EnergySolutions.....	393
• ENRESA	393
• IHI Corporation.....	394
• Jacobs/CH2M.....	394
• Japan Nuclear Fuel Limited (JNFL)	395
• Korea Radioactive Waste Agency (KORAD)	395
• LLW Repository Ltd (LLWR)	396
• NAGRA	396
• NuVision Engineering Inc.....	397
• RosRAO	397
• SE RAW (Bulgaria)	397
• Swedish Nuclear Fuel and Waste Management Company (SKB).....	398
• Studsvik.....	399
• Veolia	399
• Waste Control Specialists, LLC (WCS).....	400
Market Analysis Results	403
Analysis Methodology	404
Pricing and Profit Margins	404
Future Market Trends.....	405
11 – Decontamination and Decommissioning	406
Introduction to Sector	406
Market Overview	407
• Decommissioning Milestones	410
Recent Developments.....	411
• U.S. Decommissioning Business Models.....	413
Key Players	416
• AECOM.....	416
• Accelerated Decommissioning Partners (ADP)	417
• BWX Technologies (BWXT).....	417
• Bechtel	419

• Cabrera Services	419
• Cavendish Nuclear.....	420
• Costain.....	420
• Cyclife	421
• Doosan Power Systems.....	422
• Enercon.....	423
• <i>EnergySolutions</i>	423
• Fluor.....	425
• Holtec International.....	425
• Jacobs Engineering Group/CH2M	427
• Javys.....	428
• Manafort Brothers Incorporated.....	428
• NorthStar.....	428
• Nuclear Decommissioning Authority (NDA)	429
• NUKEM Technologies Engineering Services.....	430
• Sellafield Ltd.	431
• SNC-Lavalin.....	431
• Sogin S.p.A.....	432
• Stoller Newport News Nuclear (SN3).....	433
• Studsvik	433
• Veolia.....	434
• Westinghouse Electric Company	435
• Wood Group.....	436
Market Analysis Results.....	437
Analysis Methodology	441
Prices and Profit Margins.....	444
Future Market Trends.....	445
Part V – Summary and Conclusions	446
Nuclear Industry Interrelationships.....	447
Nuclear Market Size Analysis and Forecasts.....	448
• Future Market Size Outlook to 2035	449
• Market Size Forecast Details.....	450
• Shifts in Market Size Forecasts Since 2011	451
Final Thoughts	452
Glossary	453
Appendix A – UxC Nuclear Power Regions	454
Appendix B – Reactor Capacities Anticipated by 2035 by Country	455
Appendix C – Worldwide Reactors Under or Near Construction	457
Appendix D – Nuclear Reactor Supply Chain Companies	459
Appendix E – Nuclear Industry Alliances and Partnerships	472

List of Figures

Figure 1. Worldwide Commercial Reactors by Startup Year.....	20
Figure 2. Atomic Energy Commission Projection of U.S. Nuclear Growth, 1974.....	21
Figure 3. World Primary Energy Demand by Fuel and Scenario (Mtoe).....	24
Figure 4. Electricity Demand Growth by End Use and Generation by Source in the NPS	25
Figure 5. Installed Power Capacity by Source in the NPS	25
Figure 6. Global Power Generation Capacity Additions and Retirements in the NPS	26
Figure 7. World Electricity Generation by Source and Scenario (TWh).....	27
Figure 8. Nuclear Capacity to 2040 without Life Extensions or New Builds	28
Figure 9. Boiling Water Reactor Graphical Depiction.....	47
Figure 10. Pressurized Water Reactor Graphical Depiction	48
Figure 11. Evolution of Nuclear Reactor Generations.....	52
Figure 12. Nuclear Generating Capacity Percentages by Region, 2015, 2020, 2030 & 2035.....	57
Figure 13. UxC World Detailed Reactor & Nuclear Capacity Base Case Forecast, 2008-2035.....	58
Figure 14. UxC Base, High, and Low Case Nuclear Capacity Forecasts, 2008-2035.....	59
Figure 15. Share of Net Electricity Generation, 2010-2040 (TWh)	61
Figure 16. Shares of Total Power Generation, 1970-2040	62
Figure 17. The Nuclear Fuel Cycle.....	63
Figure 18. UxC Global Nuclear Fuel Market Forecast, 2018-2035	64
Figure 19. Open Pit Uranium Mine.....	68
Figure 20. Underground Uranium Mine.....	68
Figure 21. In-Situ Recovery Uranium Mine	68
Figure 22. Global Distribution of Identified Uranium Resources (<US\$130/kgU)	70
Figure 23. Uranium Production by Country in 2017	71
Figure 24. Uranium Spot Price, 1987-2018.....	72
Figure 25. Uranium Production by Company in 2017	83
Figure 26. Primary and Secondary Supplies of Uranium in 2017	84
Figure 27. World Uranium Market Demand vs. Mid-Case Supply, 2008-2035	85
Figure 28. Existing and New World Uranium Production, 1998-2035.....	86
Figure 29. UxC Uranium Spot Price Forecast, 1987-2035.....	87
Figure 30. UxC Uranium Market Size Forecast, 2008-2035	88
Figure 31. UxC Uranium Regional Market Size Forecast, 2008-2035.....	89
Figure 32. UF ₆ Crystals	92
Figure 33. UF ₆ Conversion Processes: Dry versus Wet	93
Figure 34. Historical Spot Conversion Prices and Significant Events, 1990-2018.....	94
Figure 35. Uranium Conversion Market Shares (Primary Only).....	104
Figure 36. Uranium Conversion Market Shares (Including Secondary).....	104
Figure 37. Base World Conversion Supply vs. Demand, 2008-2035.....	105
Figure 38. Regional Conversion Capacities vs. Demand in 2017	106
Figure 39. UxC Conversion Spot Price Forecast, 1987-2035	107
Figure 40. UxC Conversion Market Size Forecast, 2008-2035.....	108
Figure 41. UxC Conversion Regional Market Size Forecast, 2008-2035	109
Figure 42. Gas Centrifuges used for Uranium Enrichment	113
Figure 43. Uranium Enrichment Market Shares (Primary Only).....	124
Figure 44. Uranium Enrichment Market Shares (Including Secondary).....	124
Figure 45. Base Case Enrichment Supply vs. Demand, 2008-2035.....	125
Figure 46. UxC SWU Price Forecast, 1987-2035	126
Figure 47. UxC Enrichment Market Size Forecast, 2008-2035.....	128
Figure 48. UxC Enrichment Regional Market Size Forecast, 2008-2035	128
Figure 49. The Fuel Fabrication Process	132

Figure 50. Typical BWR (left) and PWR (right) Fuel Assemblies	133
Figure 51. Global Breakdown of Fuel Fabrication Production Capacities	141
Figure 52. Regional Breakdowns of Fuel Fabrication Production Capacities	141
Figure 53. UxC LWR Fuel Fabrication Supply vs. Demand Forecast, 2008-2035.....	143
Figure 54. Total LWR Nuclear Fuel Price Breakdown.....	144
Figure 55. UxC BWR and PWR Fabrication Price Forecast for U.S., 2008-2035.....	146
Figure 56. UxC LWR Fuel Fabrication Market Size Forecast, 2008-2035	148
Figure 57. UxC LWR Fabrication Regional Market Size Forecast, 2008-2035.....	148
Figure 58. Nuclear Reactor Market Summary, 2008-2035.....	158
Figure 59. New Reactor Main Players.....	160
Figure 60. JSC ASE EC's Portfolio as of End of 2017	167
Figure 61. JSC ASE EC's International Footprint.....	169
Figure 62. Percentages of Current Operating Reactor Types	188
Figure 63. Percentages of New Reactor Types, 2018-2030	188
Figure 64. Percentages of New Reactor Vendors, 2018-2030.....	189
Figure 65. New Reactor Startups and Total MWe Added, 2018-2030.....	196
Figure 66. Overnight Costs of Recent Generation III Reactors.....	200
Figure 67. Akkuyu NPP Cost Breakdown	201
Figure 68. Cost Index Variation by EPC Contract Type	204
Figure 69. Global New Reactor Market Estimates, 2008-2035	205
Figure 70. Nuclear Power Capacity Growth by Market Sectors, 2008-2035.....	206
Figure 71. U.S. Nuclear Reactor Operating Costs, 2006-2017	209
Figure 72. U.S. Nuclear Reactor Capacity Factor Averages, 1971-2017	212
Figure 73. U.S. Nuclear Reactor Refueling Outage Duration Averages (Days), 1990-2016	213
Figure 74. Technical Support Organizations and their Interfaces	219
Figure 75. Total Value of Onsite Materials (in US\$)	225
Figure 76. U.S. Average Nuclear Generating Costs in 2017 (US\$/MWh).....	226
Figure 77. U.S. Nuclear Plant Costs by Type, 2002-2017 (US\$/MWh).....	227
Figure 78. U.S. Average Nuclear Generating Costs by Size & Site in 2017 (US\$/MWh)	227
Figure 79. Estimated Levelized Costs of New Electricity Generation Technologies	228
Figure 80. Base and High Case Global Reactor Operating Costs, 2008-2035.....	230
Figure 81. Reactor Operating Costs by Region, 2008-2035	231
Figure 82. Global Reactor Operating Costs by Type, 2008-2035	232
Figure 83. LTO Projects at Olkiluoto Units 1 & 2.....	245
Figure 84. Total LTO Investments at Doel Units 1 & 2.....	246
Figure 85. Breakdown of LTO Costs at Doel Units 1 & 2	246
Figure 86. Loss of Current Nuclear Capacity Under Various Average Lifetimes	247
Figure 87. U.S. Reactors with Replacement Steam Generators, 1973-2005	258
Figure 88. Global Operating Reactor Capital Expenditures, 2008-2035.....	260
Figure 89. Projected Evolution of EU's Existing Reactor Fleet (GWe).....	261
Figure 90. SMR/AR Market Size Forecast, 2008-2035	299
Figure 91. Back-End Nuclear Fuel Cycle Market Summary, 2015-2035	304
Figure 92. Spent Fuel in Storage and Reprocessed through 2018 and 2035 (in MTU).....	314
Figure 93. Spent Fuel in Wet Storage	314
Figure 94. Connecticut Yankee Dry Storage Facility.....	315
Figure 95. Zwiilag – Centralized Interim Storage Facility.....	326
Figure 96. Chinshan ISFSI	327
Figure 97. Artist Rendering of WCS CISF	330
Figure 98. Pictorial View of Proposed HI-STORE CIS Facility Under NRC Review	331
Figure 99. Holtec Dry Storage System at Callaway NPP	336
Figure 100. NUHOMS HSM Matrix.....	339
Figure 101. Overall Dry Cask Storage Market Size, 2015-2035	341

Figure 102. Worldwide Reprocessing Throughput, 2015-2035.....	354
Figure 103. Worldwide Reprocessing Market Size, 2015-2035.....	355
Figure 104. Graphical Depiction of Deep Geological Repository.....	357
Figure 105. Cigéo Project 3D Block Diagram.....	360
Figure 106. Timeline of Japan’s Geological Disposal Program.....	370
Figure 107. Posiva’s Repository Schedule.....	372
Figure 108. KBS-3 Disposal Method in Sweden.....	376
Figure 109. Estimated Distribution of Spent Fuel Discharged Through 2035.....	381
Figure 110. Estimated Distribution of Disposal Costs for Spent Fuel & HLW Through 2035.....	381
Figure 111. Basic Stages of Radioactive Waste Management.....	384
Figure 112. WCS Compact Waste Facility.....	401
Figure 113. Estimated Market Size of Radioactive Waste Management, 2015-2035.....	403
Figure 114. Total Costs of Radioactive Waste Management and Disposal, 2015-2035.....	403
Figure 115. Decontamination and Decommissioning Project Flow.....	407
Figure 116. Connecticut Yankee Site Before and After Decommissioning.....	409
Figure 117. Map of 17 NDA Sites.....	430
Figure 118. Total D&D Market Sizes by Country, 2015-2035.....	437
Figure 119. Reactor D&D Market Sizes by Country, 2015-2035.....	438
Figure 120. Fuel Cycle Facility D&D Market Sizes by Country, 2015-2035.....	438
Figure 121. Decommissioning Annual Costs by Project Type, 2015-2035.....	440
Figure 122. Decommissioning Annual Costs by Country, 2015-2035.....	440
Figure 123. Nuclear Industry Sector Interrelationships.....	447
Figure 124. Global Nuclear Market Size Overview in 2018.....	448
Figure 125. Global Nuclear Market Size Percentages, 2018-2035.....	449
Figure 126. Global Nuclear Market Size Details, 2018-2035.....	450
Figure 127. Nuclear Power in CRIS vs. Rest of World, 2008-2035.....	452
Figure 128. Map of UxC Nuclear Regions.....	454

List of Tables

Table 1. Generation and Capacity under the NPS by 2040.....	28
Table 2. World Nuclear Power Status in December 2018.....	29
Table 3. World Nuclear Power Status by Region in December 2018.....	29
Table 4. Top Five “Reasons for Nuclear Power”.....	30
Table 5. Top Five Challenges to Nuclear Power.....	31
Table 6. Current Global Reactor Technology Breakdown.....	47
Table 7. Current Leading Large Reactor Designs.....	53
Table 8. Sampling of Current Small Modular Reactor Designs.....	54
Table 9. Global Nuclear Power 2015 vs. 2025, 2030, and 2035.....	56
Table 10. World Reactor & Nuclear Capacity Forecast, 2017-2030.....	58
Table 11. UxC Base, High, and Low Case Nuclear Reactor and Capacity Forecasts, 2018-2035.....	59
Table 12. UxC Global Nuclear Fuel Market Forecast, 2018-2035.....	64
Table 13. World Uranium Supply by Producer in 2017.....	84
Table 14. Conversion Supply by Source, 2014-2017.....	105
Table 15. Enrichment Supply by Source, 2014-2017.....	125
Table 16. Worldwide LWR Fuel Fabrication Capacity in 2018.....	142
Table 17. Current Worldwide PHWR Fuel Fabrication Capacity.....	156
Table 18. Reactors Under Construction by Country.....	161
Table 19. Reactor Vendors for Operating Reactors.....	187
Table 20. New Reactor Vendors, 2018-2030.....	189

Table 21. Key Nuclear Reactor Supply Companies	190
Table 22. Main Nuclear-Grade Heavy Forging Suppliers.....	191
Table 23. Key Nuclear EPC and Construction Companies	192
Table 24. Key Component Supply Sources for Selected Chinese Reactors	193
Table 25. Suppliers of Selected Components of AP1000 Projects in China	194
Table 26. New Reactor Startups by Year, 2018-2030.....	195
Table 27. Reactor Projects Under Construction by Reactor Design	196
Table 28. Planned New Reactor Projects.....	197
Table 29. Summary of Reactor Overnight Costs.....	199
Table 30. New Reactor Cost Breakdowns.....	200
Table 31. Akkuyu NPP Cost Breakdown	201
Table 32. Cost Estimate Data for Hinkley Point C in UK.....	202
Table 33. Average Reactor Operating Cost Profile	209
Table 34. Global Nuclear Power Utilities	210
Table 35. Full Outage Statistics During 2016	214
Table 36. Nuclear Plant O&M Services Suppliers	216
Table 37. UxC List of High Probability Strategic Spares	224
Table 38. Recent Reactor Capital Upgrade Projects	248
Table 39. Examples of Framatome's Reactor Capital Upgrade Projects	249
Table 40. Key Players' Capabilities in the Capital Upgrades Sector.....	254
Table 41. Steam Generator Replacements since 2000	256
Table 42. RPVH Replacements since 2000	257
Table 43. Countries Having Expressed Interest in SMRs	296
Table 44. Companies Having Expressed Interest in SMRs	296
Table 45. Rough Construction Cost Estimates for Selected SMR/ARs	297
Table 46. SMR/AR Expenditures by Governments	298
Table 47. SMR/AR Expenditures by Companies.....	299
Table 48. Annual Spent Fuel Discharges, 2015-2035.....	313
Table 49. Current World Reprocessing Capacity	343
Table 50. Spent Fuel Final Repository Status by Country	379
Table 51. Forward Decommissioning Option Selections by Country	442
Table 52. Unit Decommissioning Costs.....	443
Table 53. Decommissioning Profile for DECON.....	444
Table 54. Decommissioning Profile for SAFSTOR.....	444
Table 55. Global Nuclear Market Size Growth vs. 2018	449
Table 56. Global Nuclear Market Sector Sizes, 2018-2035	450
Table 57. Global Nuclear Market Size Growth Forecasts for 2020	451
Table 58. Global Nuclear Market Size Growth Forecasts for 2030.....	451
Table 59. Reactor Units & Nuclear Capacities Anticipated by Country by 2035.....	455
Table 60. Worldwide Near-Term New Reactors, 2018-2025	457
Table 61. UxC Nuclear Power Plant Equipment Suppliers List.....	459
Table 62. Nuclear Industry Alliances & Partnerships	472

Introduction & Overview

UxC, LLC (UxC) is pleased to present this seventh edition of our special report on the *Nuclear Industry Value Chain* (NIVC) to provide an overview of each of the market sectors within the nuclear industry, including the front-end fuel markets, the overall nuclear reactor sector, as well as the back-end of the fuel cycle. This updated December 2018 edition includes detailed data and analysis of every aspect of the global nuclear markets with balanced perspectives on commercial and technical issues affecting all parts of the value chain.

Although the nuclear industry continues to be impacted by the fallout from the Fukushima accident in March 2011 as well as other shifts in the broader energy markets, such as the shale gas boom in the U.S. and increasing levels of renewables, there are still many reasons for a continued expansion of global nuclear power, especially in key countries like China, India, and parts of the Middle East. The key arguments for nuclear expansion include rapid growth in electricity demand, increased concerns over greenhouse gas emissions, and a desire by nations to diversify their energy portfolios in the name of “energy security.” Now is the time to assess the prospects and future course of each of the market sectors in this evolving, global industry. Each market sector has its own unique characteristics, and this report provides the reader with all the necessary tools to start the process of understanding the opportunities and potential pitfalls within each sector.

Purpose of Report

This report’s primary objective is to provide comprehensive analyses of each of the sectors that make up the global nuclear industry. The goal is to examine the current status and future prospects (through 2035) for each sector comprising the entire “nuclear industry value chain,” so as to support future decisions by investors, potential new entrants, as well as current participants in the global nuclear markets.

Combining UxC’s decades of experience and knowledge of the nuclear industry, this report provides detailed data and information along with practical analysis for anyone considering entry or expansion in the dynamic nuclear marketplace. Whatever your position in the nuclear power arena, it is vital to seriously explore the future of the nuclear industry and the broader trends that will impact it going forward.

While the report attempts to follow a standard format in describing each market sector, it is important to understand that each sector is unique and requires special attention to the characteristics that define it. As this is an overview report, it can obviously not do every market sector justice in describing each detail. Nonetheless, our aim is to provide a thorough analysis and context to allow for a broader understanding of the current and future prospects of each market sector.

It should also be noted that although this report is intended as an introduction to the global nuclear markets, it assumes a reasonable level of knowledge of nuclear-related

technologies as well as familiarity with the history of the nuclear industry and developments in the nuclear fuel cycle since the inception of the peaceful use of the atom in the 1950s. If further explanation of anything in this report or related topics is required, UxC's team of nuclear market and technical experts is available for specialized consultations. In addition, UxC publishes many other detailed reports on the various nuclear market sectors that are available for purchase.

Key Questions in the Nuclear Markets Today

The following list presents some of the major issues and concerns that are present in the nuclear energy markets in late 2018. This NIVC report attempts to provide information and analysis to help inform and respond to many of these critical questions.

- Are the nuclear phase-out policies in various countries permanent, or will they realize that turning their back on nuclear may not be in their best interest?
- Can state and federal policies in the U.S. be enacted to keep additional reactors from shutting down?
- Is France's nuclear target to reduce reliance on nuclear power to 50% (down from 75%) achievable? And if so, what time frame will reactor shutdowns occur?
- When and how many of Japan's reactors restart? Can Japan build new reactors in the future to maintain its nuclear capacity level?
- What is causing the slowdown in China's nuclear program and is this a temporary issue or a sign of more trouble in the future?
- Will geopolitics and economic factors impact Russia's domestic reactor program and efforts to export numerous nuclear power plants?
- How can the UK manage the Brexit fallout for its nuclear industry and related international trade?
- Which potential newcomer countries can achieve real progress in developing nuclear power programs?
- Can real progress be made on small modular reactors (SMR) and other advanced reactor designs to make them viable for future deployment?
- What are the competitive positions of the various reactor vendors? Which companies have the upper hand in the current global marketplace?
- Have the uranium, conversion, and enrichment markets hit their bottoms and are the recent price upticks a sign of further upward moves?
- Will the current high level of nuclear fuel inventories lead to rapid dispositions on the part of some utilities?
- Can countries finally make progress with spent nuclear fuel disposal plans?
- Is the decommissioning market primed for fast growth due to all the reactor closures since Fukushima?

What's New in the 2018 Report?

Given that this is the seventh edition of the NIVC report, UxC has once again endeavored to make significant improvements over past editions in terms of the content, presentation of the information, and overall analysis in this global review of the nuclear marketplace. Highlights of the latest improvements in this new report include:

- The report begins with a broad introductory section on “Nuclear Power in the World Today,” which has been updated to the current market situation as of late 2018. This section provides the overarching context for the global nuclear industry to help inform the follow-on analyses of the specific nuclear market sectors.
- Forecasts for nuclear power as well as supply/demand and prices for each market sector have been updated and extended out to 2035 based on UxC’s complete review of the world on a country-by-country basis. The forecasts in this report reflect those published in other UxC reports as of the fourth quarter (Q4) of 2018.
- Current and future market trends are provided for each industry sector with a view to describing how the new realities in today’s market will lead to significant changes in each market sector over the coming two decades.
- Each of the four front-end fuel chapters includes detailed discussions of how recent events (e.g., reduced demand, increased enricher underfeeding, cutbacks in production at mines and fuel cycle facilities, high inventory levels, shifts in contracting activity, etc.) are creating significant changes in each market sector.
- As part of our updated chapter on reactor capital upgrades, we have analyzed the potential impacts of nuclear plants operating up to 80 years. The possibility of “Life After 60” for numerous reactors could have huge implications for the global nuclear industry and the capital spending profile for the existing fleet.
- A brand new chapter on advanced and small modular reactors (SMRs) has been included for the first time in this edition of the NIVC. The SMR/AR market is extremely dynamic with considerable activity by existing reactor designers as well as numerous new entrants developing groundbreaking new technologies to fit an array of specialized energy applications.
- Given the high rate of reactor shutdowns in many parts of the world, the decommissioning chapter in this edition has been greatly expanded. This is one of the fastest growth sectors of the nuclear market, and it deserves increased attention.
- Enhanced data and modeling support all of the price and market size forecasts presented in this report for each sector. This new modeling relies on extensive research of empirical market data as well as expert UxC insights to provide the most accurate outlooks possible for the nuclear marketplace through 2035.

Structure of Report

This report includes separate chapters for the different market sectors in the nuclear industry. Given the structure of the nuclear energy markets, this report is split into four main parts as follows:

Part I – Nuclear Power in the World Today introduces the nuclear energy markets with a broad overview of all the main issues affecting the current state of nuclear power. This section reviews the history and current state of nuclear power, leading countries and technologies in the industry, as well as forecasts for future developments in nuclear power.

Part II – Front-End Market Overview provides a broad overview of the nuclear fuel cycle front-end markets with some initial market size forecasts for the entire front-end of the fuel cycle (i.e., uranium mining through fuel fabrication). **Chapter 1 – Uranium Mining and Milling** offers a detailed review of the uranium mining and milling market as it relates to the supply of uranium ore concentrate (U_3O_8 or “yellowcake”). **Chapter 2 – Uranium Conversion** covers the uranium conversion market (the chemical process of converting U_3O_8 to uranium hexafluoride or UF_6). **Chapter 3 – Uranium Enrichment** reviews and analyzes the current and future prospects of the uranium enrichment market (the service of separative work units or SWU for enriching natural uranium to low enriched levels necessary for light water reactor fuel). In **Chapter 4 – Nuclear Fuel Fabrication**, we provide a discussion of the fuel fabrication market (the manufacture of completed nuclear fuel assemblies), including both fresh uranium fuel as well as mixed oxide (MOX) fuel from reprocessed plutonium for light water reactors (LWRs) as well as non-LWRs.

Part III – Nuclear Reactor Market Overview looks at the largest of the nuclear energy market divisions: nuclear power plant construction and operations. It begins with **Chapter 5 – New Reactor Construction**, which covers the current and expected future status of the nuclear construction market with a focus on reactor vendors and the global reactor supply chain. In **Chapter 6 – Reactor Operations and Services**, we discuss the market for operations, services, and maintenance supplies for the current and expected future operating nuclear reactor fleet around the world. **Chapter 7 – Reactor Capital Upgrades** then provides a detailed analysis of the specific market for large capital upgrades for current and future operating reactors, focusing on major projects that are required to maintain safe and efficient operations of these plants over the long-term. **Chapter 8 – Advanced and Small Modular Reactors** presents an overview and analysis of the dynamic and rapidly evolving market for small modular reactors (SMRs) and advanced reactors (ARs).

Part IV – Back-End Market Overview provides an overview of the various nuclear fuel cycle back-end and radioactive waste management markets. **Chapter 9 – Spent Fuel Treatment, Storage and Disposal** reviews and analyzes the market for used or “spent” fuel reprocessing, storage, and disposal. This chapter has separate sections focused on each of these three spent nuclear fuel areas: treatment/reprocessing, storage, and disposal. **Chapter 10 – Radioactive Waste Management and Disposal**

offers our perspectives on the radioactive waste markets as focused on low-level and intermediate-level radioactive wastes (LLW and ILW). **Chapter 11 – Decontamination and Decommissioning (D&D)** covers the various aspects of the market for D&D of commercial/civilian nuclear facilities, which is often considered the final step in the nuclear value chain.

Ultimately, in **Part V – Summary and Conclusions**, we summarize our analysis of the overall nuclear industry value chain and consider future market prospects.

A number of additional useful items related to the various sectors and broader nuclear industry are found in the attached **Glossary** and **Appendices** at the end of the report. The appendices primarily consist of additional data collections, as follows:

Appendix A – UxC Nuclear Power Regions

Appendix B – Reactor Capacities Anticipated by 2035 by Country

Appendix C – Worldwide Reactors Under or Near Construction

Appendix D – Nuclear Reactor Supply Chain Companies

Appendix E – Nuclear Industry Alliances and Partnerships