

CONTENTS

EXECUTIVE SUMMARY	1
1. STRATEGIC CONSIDERATIONS	7
1.1. Introduction	7
1.2. Present status	8
1.3. Medium and long term trends	10
1.4. Nuclear fuel cycle back end choices	11
2. PLUTONIUM FEED PRODUCTION, HANDLING AND STORAGE	13
2.1. Introduction	13
2.2. Plutonium feed production	14
2.2.1. Precipitation of plutonium oxalate	14
2.2.2. Thermal de-nitration methods	16
2.2.3. Co-precipitation methods	16
2.2.4. Gel precipitation methods	17
2.2.5. Methods of conversion of plutonium metal to oxide	18
2.2.6. Feed production finishing lines	19
2.3. Handling and storage of plutonium dioxide powder	19
2.3.1. Evolution of storage methodology	20
2.3.2. Potential hazards associated with storage and handling	20
2.3.3. Description of storage containers	21
2.4. Longer term developments	24
2.5. Conclusions	24
3. MOX FUEL FABRICATION	25
3.1 Present status	25
3.1.1 Fabrication capacities	25
3.1.2. Fabrication processes	29
3.1.2.1. Powder processing routes	29
3.1.2.2. Fabrication technology	33
3.1.3. Fabrication records	35

3.1.4. Fuel quality	37
3.1.4.1. Homogeneity of plutonium distribution	37
3.1.4.2. Uniformity of plutonium isotopic composition ...	41
3.1.5. Scraps and wastes	43
3.2. Issues and challenges	44
3.3. Future developments	45
3.4. Conclusions	46
4. LWR FUEL ASSEMBLY DESIGN, IN-CORE FUEL MANAGEMENT AND LICENSING	46
4.1. Status of experience	46
4.2. Qualification of neutronic fuel assembly and core design methods	46
4.3. Neutronic fuel assembly design	48
4.3.1. General aspects and design targets	48
4.3.2. MOX carrier material and plutonium composition	51
4.3.2.1. Carrier material for plutonium	51
4.3.2.2. Plutonium composition	52
4.4. Neutronic core design	53
4.4.1. Current status	53
4.4.2. Current trends	55
4.4.3. Reload strategies	56
4.4.4. MOX impact on normal reactor operation	56
4.4.4.1. PWRs	56
4.4.4.2. BWRs	57
4.4.5. MOX impact on transients	57
4.4.5.1. Reactor kinetics	57
4.4.5.2. Decay heat power	57
4.4.5.3. Xenon/samarium	58
4.4.5.4. PWRs	58
4.4.5.5. BWRs	58
4.5. Future developments	59
4.6. Conclusions	60
5. LWR MOX FUEL DESIGN AND PERFORMANCE	60
5.1. Fuel design and safety related characteristics of MOX fuel	60
5.2. MOX fuel performance: experiment and modelling	61

5.2.1. Analytical and irradiation test programmes	62
5.2.1.1. Belgium	62
5.2.1.2. Canada	63
5.2.1.3. Commission of the European Communities	64
5.2.1.4. France	64
5.2.1.5. Germany	66
5.2.1.6. Japan	68
5.2.1.7. The OECD Halden reactor project	68
5.2.1.8. United Kingdom	69
5.2.1.9. USA	70
5.2.2. Commercial irradiation and surveillance programmes	70
5.2.3. MOX fuel performance and modelling	75
5.2.3.1. Radial power and burnup profiles	75
5.2.3.2. Thermal properties	76
5.2.3.3. Fission gas release and fuel microstructure	77
5.2.3.4. Operational transient behaviour and fuel creep	78
5.2.3.5. Helium generation and release	78
5.2.3.6. Defective fuel rod behaviour	79
5.3. Medium and long term developments	79
5.4. Conclusions	80
 6. TRANSPORTATION	81
6.1. Introduction	81
6.2. Regulatory requirements	81
6.3. Current status of MOX fuel transport	82
6.3.1. PuO ₂ powder	83
6.3.2. Fresh MOX rods	84
6.3.3. MOX fresh fuel assemblies	85
6.3.3.1. European power plants	85
6.3.3.2. Japanese power plants	86
6.3.4. Spent MOX fuel	88
6.4. Ongoing developments	88
6.4.1. ANF-18	88
6.4.2. FS-65 I	89
6.4.3. M4/12	89
6.4.4. Advanced MOX casks	89
6.5. Outlook	91
6.6. Conclusions	91

7.	SPENT MOX FUEL MANAGEMENT	93
7.1.	Specific characteristics of MOX fuels	93
7.2.	Storage and final disposal options	93
7.2.1.	Interim storage	96
7.2.2.	Spent fuel disposal	96
7.2.2.1.	Retrievability and reversibility	96
7.2.2.2.	Plutonium degradation	98
7.2.2.3.	Helium buildup	98
7.3.	Reprocessing of MOX fuel	99
7.3.1.	R&D programmes on MOX fuel reprocessing	99
7.3.1.1.	Laboratory investigations	99
7.3.1.2.	Japanese experiments	100
7.3.1.3.	French experiments	100
7.3.1.4.	Russian experiments	102
7.3.2.	Industrial experience	102
7.3.2.1.	UK experience with fast reactor fuel reprocessing	102
7.3.2.2.	French industrial MOX fuel reprocessing	103
7.3.3.	Lessons learned from reprocessing experience	105
7.4.	Refabrication experience	105
7.5.	Future trends	106
7.6.	Conclusions	107
8.	WASTE TREATMENT AND DECOMMISSIONING	107
8.1.	Introduction	107
8.2.	Background	108
8.2.1.	Issues in decommissioning plutonium facilities	108
8.2.2.	Strategy and regulatory'controls on decommissioning activities	109
8.3.	Waste treatment of MOX arisings 	110
8.3.1.	European experience of MOX waste treatment	111
8.3.2.	Japanese experience of MOX waste treatment	111
8.4.	Decommissioning techniques	111
8.5.	Examples of decommissioning activities	113
8.5.1.	French experience	113
8.5.2.	German experience	113
8.5.3.	Italian experience	116
8.5.4.	Japanese experience	116

8.5.5. British experience	116
8.5.6. US experience	117
8.5.7. The Eurochemic finishing line	119
8.5.8. Weapons plutonium facilities	120
8.6. Future perspectives	120
8.7. Conclusions	121
9. APPLICATION OF SAFEGUARDS AND PHYSICAL PROTECTION TO MOX FUEL	121
9.1. Introduction	121
9.2. The automation of MOX fuel fabrication and the evolution of IAEA safeguards technology	124
9.3. Basis of the safeguards concept: objectives and boundary conditions	125
9.4. Nuclear materials accountancy	127
9.5. Safeguards tools	127
9.5.1. Destructive analysis	127
9.5.2. Non-destructive assay	128
9.5.3. Containment and surveillance	129
9.5.4. In-process monitoring	130
9.6. Security and physical protection	130
9.6.1. Legal requirements	130
9.6.2. IAEA standards and recommendations	131
9.6.3. Guidelines for implementation of standards	132
9.7. Future developments	132
9.8. Conclusions	133
10. SPECIFIC ASPECTS OF FAST REACTOR MOX FUEL	134
10.1. Introduction	134
10.2. Characteristics of FBRs	135
10.3. Historical background	136
10.3.1. Experimental reactors	136
10.3.2. Prototype fast reactors	137
10.3.3. Commercial fast reactors	138
10.4. Pin and assembly design	138
10.5. Fuel performance issues	140
10.5.1. Fuel restructuring during irradiation	140

10.5.2. Pin irradiation experience	140
10.5.3. Fuel failure experience	142
10.5.4. Irradiation capabilities of MOX fuel	143
10.6. Further technical issues associated with fuel in FBRs	143
10.6.1. Types of radiation damage	144
10.6.2. Effects of radiation damage	144
10.6.3. Fuel behaviour in transient and accident conditions	145
10.7. Future trends and possibilities	146
10.8. Conclusions	148
11. ALTERNATIVE APPROACHES	149
11.1. Introduction	149
11.2. Advanced fast breeder and converter reactors	150
11.3. Plutonium and actinide partitioning and transmutation	151
11.4. Advanced fissile material extraction (reprocessing)	152
11.5. Alternative fuels	153
11.5.1. Inert matrix fuels	153
11.5.2. Thorium fuels	154
11.5.3. Carbide and nitride fuels	154
11.5.4. Rock-like fuels	155
11.6. Conclusions	155
REFERENCES	156
ACRONYMS AND ABBREVIATIONS	173
CONTRIBUTORS TO DRAFTING AND REVIEW	179