## **Contents**

L	ist of Abbreviations	XIX
1	Introduction	1
	1.1 The Development of Nuclear Energy in the World	1
	1.2 Technical Applications of Nuclear Fission Energy 1.2.1 Nuclear Power for Electricity and Process Heat Generation 1.2.2 Nuclear Ship Propulsion 1.2.3 Nuclear High Temperature Process Heat 1.2.4 Nuclear Power for Hydrogen Generation	5 5 7 7 8
	1.3 Economic Aspects of Nuclear Energy  1.3.1 Electricity Generating Costs  1.3.2 Load Factors of Nuclear Power Plants	9 9 11
	Selected Literature	12
2	Some Basic Physics of Converter and Breeder Reactors	14
	2.1 Basic Nuclear Physics 2.1.1 Elastic Scattering 2.1.2 Inelastic Scattering 2.1.3 Neutron Capture 2.1.4 Nuclear Fission 2.1.5 Energy Release in Nuclear Fission 2.1.6 Decay Constant and Halflife 2.1.7 Prompt and Delayed Neutrons 2.1.8 Afterheat of the Reactor Core	14 14 15 15 15 16 17 18
	2.2 Neutron Flux and Reaction Rates	20
	2.3 Spatial Distribution of the Neutron Flux in the Reactor Core	21
	2.4 Fuel Burnup, Fission Product and Actinide Buildup	27
	2.5 Conversion Ratio and Breeding Ratio	29
	2.6 Conversion Ratio and Fuel Utilization	31
	2.7 Radioactive Inventories in Fission Reactors	33
	2.8 Inherent Safety Characteristics of Converter and Breeder Reactor Cores     2.8.1 Reactivity and Non-steady State Conditions     2.8.2 Temperature Reactivity Coefficients     2.8.2.1 Fuel Doppler Temperature Coefficient	35 35 37 37



		2.8.3	2.8.2.2 Coefficients of Moderator or Coolant Temperatures	37 38 39 39
	Sele	ected I		42
3	Nu	clear F	Tuel Supply	43
_			duction (The Nuclear Fuel Cycle)	43
			ium Resources and Requirements	44
	<b>ي</b>	3.2.1	Uranium Consumption in Various Reactor Systems	44
		3.2.2	Available Uranium and Thorium Reserves	47
			3.2.2.1 Worldwide Available Uranium Reserves	47 50
			3.2.2.3 Thorium Reserves	52
			Uranium Requirement vs. Uranium Reserves	53
			entration, Purification and Conversion of Uranium	53
	3.4		ium Enrichment	55
			Introduction	55 55
		3.4.3	Uranium Enrichment by Gaseous Diffusion	57
		3.4.4	Gas Ultracentrifuge Process	60 62
		3.4.6	Advanced Separation Processes	63
		3.4.7	Effects of Tails Assay and Economic Optimum	63
	3.5	Fuel	Fabrication	64
	Sele	ected I	_iterature	65
			•	
4	Cor	nverter	Reactors with a Thermal Neutron Spectrum	67
•			Water Reactors	67
	•••	4.1.1	Pressurized Water Reactors	67
			4.1.1.1 Core	70
			4.1.1.2 Coolant System 4.1.1.3 Containment	72 74
			4.1.1.4 Control Systems	76
			4.1:1.5 Protection System	76 76
			4.1.1.5.2 Emergency Power Supply	76
			4.1.1.5.3 Emergency Feedwater System	77
			4.1.1.5.4 Emergency Cooling and Afterheat Removal Systems 4.1.1.5.5 Closure of the Reactor Containment	77 78
		4.1.2	Boiling Water Reactors	78
			4.1.2.1 Core, Pressure Vessel and Cooling System	79
			4.1.2.2 Safety Systems	82 83
			<i>y</i>	

	4.2	4.2.1 Advanced Gas Cooled Reactors  4.2.2 High Temperature Gas Cooled Reactors  4.2.2.1 HTGR with Prismatic Fuel Elements  4.2.2.2 HTR with Spherical Fuel Elements  4.2.2.3 General Safety Considerations of HTGR's and HTR's	84 85 85 89 91
		4.2.2.3.1 Control and Shutdown Systems 4.2.2.3.2 Afterheat Removal and Emergency Cooling 4.2.2.3.3 Design Base Accidents	9: 9:
	4.3	Heavy Water Reactors	92 94
		4.3.1.1 Fuel Elements	9:
		4.3.1.2 Reactivity Control	9
		4.3.1.3 Shutdown Cooling Systems	98 98
		4.3.1.4 Safety Systems	-
	4.4	Near Breeder and Thermal Breeder Reactors	99
		4.4.2 Light Water Breeder Reactors (LWBR's)	9
	Sele	ected Literature	100
5	Bre	eder Reactors with a Fast Neutron Spectrum	102
	5.1	The Potential Role of Breeder Reactors with a Fast Neutron Spectrum	102
		Brief History of the Development of Fast Breeder Reactors	
		The Physics of LMFBR Cores  5.3.1 LMFBR Core Design  5.3.2 Energy Spectrum and Neutron Flux Distribution  5.3.3 Breeding Ratio  5.3.4 Reactivity Coefficients and Control Stability  5.3.5 The Doppler Coefficient  5.3.6 The Coolant Temperature Coefficient  5.3.7 Fuel and Structural Temperature Coefficients  5.3.8 Delayed Neutron Characteristics and Prompt Neutron Lifetime	10: 10: 11: 11: 11: 11:
		Technical Aspects of Sodium Cooled FBR's	
	5.5	SUPERPHENIX – A Commercial Size Demonstration LMFBR 5.5.1 Reactor Core and Blankets	113 120
	5.6	Safety Design Aspects of LMFBR Plants  5.6.1 The Multiple Barrier Principle  5.6.2 Control and Shutdown Systems  5.6.3 Afterheat Removal and Emergency Cooling of LMFBR Cores  5.6.4 Core Instrumentation and Protection against Fault Propagation  5.6.5 Design Bases of the Primary System and Containment  5.6.6 Sodium Fires  5.6.7 Sodium-Water Interactions in Steam Generators	12: 12: 12: 12: 12: 12:

	5.7	Heterogeneous Core Designs of LMFBR's	130
	5.8	LMFBR Cores with Advanced Oxide and Carbide Fuels	131
	5.9	Gas Cooled Fast Breeder Reactors	131
	Sele	ected Literature	132
6	Nuc	clear Fuel Cycle Options	135
	6.1	Fuel Cycle Options for Converter Reactors	135
		6.1.1 The Once-Through Fuel Cycle	135
		6.1.2 Closed Nuclear Fuel Cycles	
		6.1.2.1 Plutonium Recycling	
		6.1.2.2 The Thorium/Uranium-233 Fuel Cycle	
	6.2	Fuel Cycle Options for Breeder Reactors	
	0.2	6.2.1 The Uranium/Plutonium Fuel Cycle	
		6.2.2 The Thorium/Uranium-233 Fuel Cycle	
	6.3	Natural Uranium Consumption in Various Reactor Scenarios	148
	Sele	ected Literature	150
7		chnical Aspects of Nuclear Fuel Cycles	
	7.1	Discharge and Storage of Spent Fuel Elements	152
		7.1.1 Shipping Spent Fuel Elements 7.1.2 Interim Storage of Spent Fuel Elements	
	1.2	The Uranium-238/Plutonium Fuel Cycle 7.2.1 Reprocessing Spent UO <sub>2</sub> Fuel Elements	
		7.2.1.1 LWR Fuel Element Disassembly and Spent Fuel Dissolution	
		7.2.1.2 Gas Cleaning and Retention of Gaseous Fission Products	
		7.2.1.3 Chemical Separation of Uranium and Plutonium	157
		7.2.1.4 Mass Flows of Radioactive Material in a Model LWR Fuel	1.00
		Reprocessing Plant	
		7.2.2 Recycling Plutonium and Uranium	
		7.2.2.1 Converting Plutonium Nitrate into Plutonium Oxide	
		7.2.2.2 Converting Uranyl Nitrate into Uranium Oxide	
		7.2.2.3 Mixed Oxide Fuel Fabrication	
		<ul><li>7.2.3 Status of Uranium Fuel Reprocessing Technology</li></ul>	
		7.2.5 Safety Aspects	
		7.2.5.1 Safety Design Measures in Reprocessing Plants	166
		7.2.5.2 Safety Considerations for Mixed Oxide Fuel Fabrication Plants	168
	7.3	The Thorium/Uranium-233 Fuel Cycle	168
		7.3.1 Fuel Element Disassembly	168
		7.3.2 THOREX Process 7.3.3 Uranium-233/Thorium Fuel Fabrication	169 170
	71		
	1.4	The Uranium/Plutonium Fuel Cycle of Fast Breeder Reactors	
		7.4.2 Mass Flow in a Model LMFBR Fuel Cycle	
		7.4.3 Radioactive Inventories of Spent LMFBR Fuel	

		7.4.4	LMFBR Fuel Reprocessing	174
			LMFBR Fuel Fabrication	
			Status of LMFBR Fuel Reprocessing and Refabrication	
	7.5			176
		7.5.1		176
				176
				178
			•	178
				178
			7.5.1.5 Waste Volumes to Be Stored from Reprocessing of Spent LWR Fuel	179
		7.5.2	Radioactive Waste from Uranium-233/Thorium Fuel Reprocessing	181
		7.5.3	Radioactive Waste from Reprocessing Plutonium/Uranium Fuel of	
				181
		7.5.4	Waste Arising in Other Parts of the Fuel Cycle	
			7.5.4.1 Uranium Ore Processing	
			7.5.4.2 Uranium Refining, Conversion and Enrichment	182
			7.5.4.3 Fuel Element Fabrication and Nuclear Power Plants	182
	7.6	Nucle	ear Waste Repositories	182
			Waste Disposal in Deep Geological Formations	
			Direct Disposal of Spent Fuel Elements	
			Health and Safety Impacts of Radioactive Waste Disposal	
	Sala		iterature	
	DCIC	cicu 1	interacure	100
_	10		ALE A PROPERTY OF THE PROPERTY	404
8			ental Impacts and Risks of Nuclear Fission Energy	191
	8.1		oactivity Releases from Nuclear Power Plants and Fuel Cycle Facilities	
			ng Normal Operation	
		8.1.1	Radioactivity Releases and Exposure Pathways	
			8.1.1.1 Exposure Pathways of Significant Radionuclides	
			8.1.1.1.1 Tritium, Carbon-14 and Krypton	
			8.1.1.1.2 Radioisotopes of Iodine	
			8.1.1.1.3 Strontium and Cesium	
			8.1.1.1.4 Plutonium Isotopes	
			8.1.1.1.5 Other Radiobiologically Significant Isotopes	194
			8.1.1.2 Radiation Dose	194
		0.4.2	8.1.1.2 Radiation Dose	194
		8.1.2	8.1.1.2 Radiation Dose	194 195
		8.1.2	8.1.1.2 Radiation Dose  8.1.1.3 Permissible Radiation Exposures  Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle	194 195 196
		8.1.2	8.1.1.2 Radiation Dose  8.1.1.3 Permissible Radiation Exposures  Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle  8.1.2.1 Uranium Mining and Milling	194 195 196 196
		8.1.2	8.1.1.2 Radiation Dose  8.1.1.3 Permissible Radiation Exposures  Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle  8.1.2.1 Uranium Mining and Milling  8.1.2.1.1 Radioactive Effluents from Mining and Milling	194 195 196 196
		8.1.2	8.1.1.2 Radiation Dose 8.1.1.3 Permissible Radiation Exposures Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle 8.1.2.1 Uranium Mining and Milling 8.1.2.1.1 Radioactive Effluents from Mining and Milling 8.1.2.1.2 Radioactive Exposure Pathways for Uranium Mines	194 195 196 196
		8.1.2	8.1.1.2 Radiation Dose 8.1.1.3 Permissible Radiation Exposures Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle 8.1.2.1 Uranium Mining and Milling 8.1.2.1.1 Radioactive Effluents from Mining and Milling 8.1.2.1.2 Radioactive Exposure Pathways for Uranium Mines and Mills	194 195 196 196 197
		8.1.2	8.1.1.2 Radiation Dose 8.1.1.3 Permissible Radiation Exposures Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle 8.1.2.1 Uranium Mining and Milling 8.1.2.1.1 Radioactive Effluents from Mining and Milling 8.1.2.1.2 Radioactive Exposure Pathways for Uranium Mines and Mills 8.1.2.2 UF <sub>6</sub> Conversion, Enrichment, and Fuel Fabrication	194 195 196 196 197 198
		8.1.2	8.1.1.2 Radiation Dose 8.1.1.3 Permissible Radiation Exposures Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle 8.1.2.1 Uranium Mining and Milling 8.1.2.1.1 Radioactive Effluents from Mining and Milling 8.1.2.1.2 Radioactive Exposure Pathways for Uranium Mines and Mills 8.1.2.2 UF <sub>6</sub> Conversion, Enrichment, and Fuel Fabrication 8.1.2.3 Nuclear Power Plants	194 195 196 196 197 198
		8.1.2	8.1.1.2 Radiation Dose 8.1.1.3 Permissible Radiation Exposures Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle 8.1.2.1 Uranium Mining and Milling 8.1.2.1.1 Radioactive Effluents from Mining and Milling 8.1.2.1.2 Radioactive Exposure Pathways for Uranium Mines and Mills 8.1.2.2 UF <sub>6</sub> Conversion, Enrichment, and Fuel Fabrication 8.1.2.3 Nuclear Power Plants 8.1.2.3.1 Radioactive Effluents of Nuclear Power Plants	194 195 196 196 197 198 198
		8.1.2	8.1.1.2 Radiation Dose 8.1.1.3 Permissible Radiation Exposures Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle 8.1.2.1 Uranium Mining and Milling 8.1.2.1.1 Radioactive Effluents from Mining and Milling 8.1.2.1.2 Radioactive Exposure Pathways for Uranium Mines and Mills 8.1.2.2 UF <sub>6</sub> Conversion, Enrichment, and Fuel Fabrication 8.1.2.3 Nuclear Power Plants 8.1.2.3.1 Radioactive Effluents of Nuclear Power Plants 8.1.2.3.2 Radioactive Effluents from PWR's	194 195 196 196 197 198
		8.1.2	8.1.1.2 Radiation Dose 8.1.1.3 Permissible Radiation Exposures Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle 8.1.2.1 Uranium Mining and Milling 8.1.2.1.1 Radioactive Effluents from Mining and Milling 8.1.2.1.2 Radioactive Exposure Pathways for Uranium Mines and Mills 8.1.2.2 UF <sub>6</sub> Conversion, Enrichment, and Fuel Fabrication 8.1.2.3 Nuclear Power Plants 8.1.2.3.1 Radioactive Effluents of Nuclear Power Plants 8.1.2.3.2 Radioactive Effluents from PWR's 8.1.2.3.3 Comparison of Radioactive Effluents from PWR's and	194 195 196 196 197 198 198 199
		8.1.2	8.1.1.2 Radiation Dose 8.1.1.3 Permissible Radiation Exposures Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle 8.1.2.1 Uranium Mining and Milling 8.1.2.1.1 Radioactive Effluents from Mining and Milling 8.1.2.1.2 Radioactive Exposure Pathways for Uranium Mines and Mills 8.1.2.2 UF <sub>6</sub> Conversion, Enrichment, and Fuel Fabrication 8.1.2.3 Nuclear Power Plants 8.1.2.3.1 Radioactive Effluents of Nuclear Power Plants 8.1.2.3.2 Radioactive Effluents from PWR's	194 195 196 196 197 198 198 199
		8.1.2	8.1.1.2 Radiation Dose 8.1.1.3 Permissible Radiation Exposures Radionuclide Effluents and Radiation Exposures from Various Parts of the Fuel Cycle 8.1.2.1 Uranium Mining and Milling 8.1.2.1.1 Radioactive Effluents from Mining and Milling 8.1.2.1.2 Radioactive Exposure Pathways for Uranium Mines and Mills 8.1.2.2 UF <sub>6</sub> Conversion, Enrichment, and Fuel Fabrication 8.1.2.3 Nuclear Power Plants 8.1.2.3.1 Radioactive Effluents of Nuclear Power Plants 8.1.2.3.2 Radioactive Effluents from PWR's 8.1.2.3.3 Comparison of Radioactive Effluents from PWR's and BWR's	194 195 196 196 198 198 198 199 201

		8.1.2.3.5 Radiation Exposures Caused by Emissions from Nuclear Power Plants	202
		<ul> <li>8.1.2.4 Spent Fuel Reprocessing and Waste Treatment Centers</li> <li>8.1.2.4.1 Radioactive Effluents from an LWR Low Enriched UO<sub>2</sub> Spent Fuel Reprocessing and Waste Treatment</li> </ul>	203
		8.1.2.4.2 Estimated Radioactive Effluents from a Reprocessing and Waste Treatment Center for Spent PuO <sub>2</sub> /UO <sub>2</sub>	205
		8.1.2.4.3 Radiation Exposure Caused by Reprocessing and	206
	8.1.3	Waste Treatment Centers	<ul><li>208</li><li>211</li></ul>
8 2		Assessment of Nuclear Fission Reactors	
0.2		Methods and Procedures	
	0.2.1	8.2.1.1 General Procedure	
		8.2.1.2 Event Tree Method	
		8.2.1.3 Fault Tree Analysis	216
	8.2.2	Releases of Fission Products from a Reactor Building Following a Core	
		Meltdown Accident	216
		8.2.2.1 Initiating Events	
		8.2.2.2 Failure of the Containment	
		8.2.2.3 Releases of Radioactivity	
		8.2.2.4 External Events	
		Accident Consequence Model and Human Exposure	
	8.2.4	Results of Reactor Safety Studies	
		8.2.4.1 Results of Event Tree and Fault Tree Analysis	
		8.2.4.2.1 The German Risk Study	
		8.2.4.2.3 More Recent Improvements in Risk Studies	
	825	Risk Studies of Other Types of Reactors	
		Risk Studies of Fuel Cycle Plants	
		Comparison with Risks of Other Technical Systems	
0 2			230
0.5		History	230
		The IAEA Safeguards System	
	0.5.2	8.3.2.1 Material Balance Measurements	
	8.3.3	Safeguards Techniques	
		Safeguards Implementation	
		Advanced Approaches	243
		8.3.5.1 Near-Real Time Accountancy and Extended Containment/Sur-	
		veillance Systems	243
		8.3.5.2 International Plutonium Storage	
	8.3.6		245
		8.3.6.1 Quantities of Fissile Nuclear Material	245
	0 2 7	8.3.6.2 Technical Measures to Improve Diversion Resistance	245
		International Agreements and Institutional Arrangements	247
		Remaining Proliferation Risk	248
		ted Literature	249
Sub	ject Ir	dex	252