

# CONTENTS

1. SUMMARY .....	1
1.1. Introduction .....	1
1.2. Radioactive contamination of the environment .....	2
1.2.1. Conclusions .....	2
1.2.1.1. Radionuclide release and deposition .....	2
1.2.1.2. Urban environment .....	2
1.2.1.3. Agricultural environment .....	3
1.2.1.4. Forest environment .....	4
1.2.1.5. Aquatic environment .....	4
1.2.2. Recommendations for future research and monitoring .....	4
1.2.2.1. General .....	4
1.2.2.2. Practical .....	5
1.2.2.3. Scientific .....	5
1.2.2.4. Specific recommendations .....	5
1.3. Environmental countermeasures and remediation .....	6
1.3.1. Conclusions .....	6
1.3.1.1. Radiological criteria .....	6
1.3.1.2. Urban countermeasures .....	7
1.3.1.3. Agricultural countermeasures .....	7
1.3.1.4. Forest countermeasures .....	8
1.3.1.5. Aquatic countermeasures .....	8
1.3.2. Recommendations .....	8
1.3.2.1. Countries affected by the Chernobyl accident .....	8
1.3.2.2. Worldwide .....	9
1.3.2.3. Research .....	9
1.4. Human exposure .....	9
1.4.1. Conclusions .....	10
1.4.2. Recommendations .....	11
1.5. Radiation induced effects on plants and animals .....	12
1.5.1. Conclusions .....	12
1.5.2. Recommendations for future research .....	13
1.5.3. Recommendations for countermeasures and remediation .....	13
1.6. Environmental and radioactive waste management aspects of the dismantling of the Chernobyl shelter .....	13
1.6.1. Conclusions .....	13
1.6.2. Recommendations for future actions .....	14
Reference to Section 1 .....	15
2. INTRODUCTION .....	16
2.1. Background .....	16
2.2. Objectives of the Chernobyl Forum .....	16
2.3. Method of operation and output of the Chernobyl Forum .....	17
2.4. Structure of the report .....	17
References to Section 2 .....	17
3. RADIOACTIVE CONTAMINATION OF THE ENVIRONMENT .....	18
3.1. Radionuclide release and deposition .....	18
3.1.1. Radionuclide source term .....	18
3.1.2. Physical and chemical forms of released material .....	20

3.1.3.	Meteorological conditions during the course of the accident.	21
3.1.4.	Concentration of radionuclides in air	22
3.1.5.	Deposition of radionuclides on soil surfaces	23
3.1.6.	Isotopic composition of the deposition	25
3.2.	Urban environment	27
3.2.1.	Deposition patterns	27
3.2.2.	Migration of radionuclides in the urban environment	28
3.2.3.	Dynamics of the exposure rate in urban environments.	29
3.3.	Agricultural environment	29
3.3.1.	Radionuclide transfer in the terrestrial environment	29
3.3.2.	Food production systems affected by the accident	30
3.3.3.	Effects on agriculture in the early phase.	30
3.3.4.	Effects on agriculture in the long term phase.	32
3.3.4.1.	Physicochemistry of radionuclides in the soil-plant system	32
3.3.4.2.	Migration of radionuclides in soil.	33
3.3.4.3.	Radionuclide transfer from soil to crops.	34
3.3.4.4.	Dynamics of radionuclide transfer to crops	36
3.3.4.5.	Radionuclide transfer to animals	38
3.3.5.	Current contamination of foodstuffs and expected future trends	40
3.4.	Forest environment	41
3.4.1.	Radionuclides in European forests	41
3.4.2.	Dynamics of contamination during the early phase	42
3.4.3.	Long term dynamics of radiocaesium in forests.	43
3.4.4.	Uptake into edible products	44
3.4.5.	Contamination of wood.	45
3.4.6.	Expected future trends	46
3.4.7.	Radiation exposure pathways associated with forests and forest products	46
3.5.	Radionuclides in aquatic systems	47
3.5.1.	Introduction	47
3.5.2.	Radionuclides in surface waters.	48
3.5.2.1.	Distribution of radionuclides between dissolved and particulate phases.	48
3.5.2.2.	Radioactivity in rivers	48
3.5.2.3.	Radioactivity in lakes and reservoirs.	50
3.5.2.4.	Radionuclides in freshwater sediments.	52
3.5.3.	Uptake of radionuclides to freshwater fish.	53
3.5.3.1.	Iodine-131 in freshwater fish	53
3.5.3.2.	Caesium-137 in freshwater fish and other aquatic biota	53
3.5.3.3.	Strontium-90 in freshwater fish	54
3.5.4.	Radioactivity in marine ecosystems.	55
3.5.4.1.	Distribution of radionuclides in the sea	55
3.5.4.2.	Transfers of radionuclides to marine biota.	56
3.5.5.	Radionuclides in groundwater	56
3.5.5.1.	Radionuclides in groundwater: Chernobyl exclusion zone.	56
3.5.5.2.	Radionuclides in groundwater: outside the Chernobyl exclusion zone.	58
3.5.5.3.	Irrigation water.	58
3.5.6.	Future trends	58
3.5.6.1.	Freshwater ecosystems	58
3.5.6.2.	Marine ecosystems.	60
3.6.	Conclusions	60
3.7.	Further monitoring and research needed	61
	References to Section 3	62

4.	ENVIRONMENTAL COUNTERMEASURES AND REMEDIATION.....	69
4.1.	Radiological criteria.....	69
4.1.1.	International radiological criteria and standards.....	69
4.1.2.	National radiological criteria and standards.....	71
4.2.	Urban decontamination.....	72
4.2.1.	Decontamination research.....	73
4.2.2.	Chernobyl experience.....	73
4.2.3.	Recommended decontamination technologies.....	74
4.3.	Agricultural countermeasures.....	75
4.3.1.	Early phase.....	75
4.3.2.	Late phase.....	77
4.3.3.	Countermeasures in intensive agricultural production.....	78
4.3.3.1.	Soil treatment.....	79
4.3.3.2.	Change in fodder crops grown on contaminated land.....	80
4.3.3.3.	Clean feeding.....	80
4.3.3.4.	Administration of caesium binders.....	81
4.3.4.	Summary of countermeasure effectiveness in intensive production.....	81
4.3.5.	Countermeasures in extensive production.....	81
4.3.6.	Current status of agricultural countermeasures.....	83
4.3.7.	A wider perspective on remediation, including socioeconomic issues.....	83
4.3.8.	Current status and future of abandoned land.....	84
4.3.8.1.	Exclusion and resettlement zones in Belarus.....	84
4.3.8.2.	Rehabilitation of contaminated lands in Ukraine.....	85
4.3.8.3.	Abandoned zones in the Russian Federation.....	86
4.4.	Forest countermeasures.....	86
4.4.1.	Studies on forest countermeasures.....	87
4.4.2.	Countermeasures for forests contaminated with radiocaesium.....	87
4.4.2.1.	Management based countermeasures.....	87
4.4.2.2.	Technology based countermeasures.....	87
4.4.3.	Examples of forest countermeasures.....	89
4.5.	Aquatic countermeasures.....	90
4.5.1.	Measures to reduce doses at the water supply and treatment stage.....	90
4.5.2.	Measures to reduce direct and secondary contamination of surface waters.....	91
4.5.3.	Measures to reduce uptake by fish and aquatic foodstuffs.....	92
4.5.4.	Countermeasures for groundwater.....	93
4.5.5.	Countermeasures for irrigation water.....	93
4.6.	Conclusions and recommendations.....	93
4.6.1.	Conclusions.....	93
4.6.2.	Recommendations.....	94
4.6.2.1.	Countries affected by the Chernobyl accident.....	94
4.6.2.2.	Worldwide.....	95
4.6.2.3.	Research.....	95
	References to Section 4.....	96
5.	HUMAN EXPOSURE LEVELS.....	100
5.1.	Introduction.....	100
5.1.1.	Populations and areas of concern.....	100
5.1.2.	Exposure pathways.....	100
5.1.3.	Concepts of dose.....	101
5.1.4.	Background radiation levels.....	101
5.1.5.	Decrease of dose rate with time.....	102
5.1.6.	Critical groups.....	102

5.2.	External exposure. . . . .	103
5.2.1.	Formulation of the model of external exposure. . . . .	103
5.2.2.	Input data for the estimation of effective external dose . . . . .	103
5.2.2.1.	Dynamics of external gamma dose rate over open undisturbed soil . . . . .	103
5.2.2.2.	Dynamics of external gamma dose rate in anthropogenic areas . . . . .	105
5.2.2.3.	Behaviour of people in the radiation field . . . . .	105
5.2.2.4.	Effective dose per unit gamma dose in air . . . . .	106
5.2.3.	Results . . . . .	106
5.2.3.1.	Dynamics of external effective dose . . . . .	106
5.2.3.2.	Measurement of individual external dose with thermoluminescent dosimeters. . . . .	106
5.2.3.3.	Levels of external exposure . . . . .	108
5.3.	Internal dose . . . . .	109
5.3.1.	Model for internal dose. . . . .	109
5.3.2.	Monitoring data as input for the assessment of internal dose . . . . .	109
5.3.3.	Avoidance of dose by human behaviour . . . . .	110
5.3.4.	Results for doses to individuals . . . . .	110
5.3.4.1.	Thyroid doses due to radioiodines. . . . .	110
5.3.4.2.	Long term internal doses from terrestrial pathways . . . . .	112
5.3.4.3.	Long term doses from aquatic pathways. . . . .	115
5.4.	Total (external and internal) exposure . . . . .	116
5.5.	Collective doses . . . . .	118
5.5.1.	Thyroid . . . . .	118
5.5.2.	Total (external and internal) dose from terrestrial pathways. . . . .	118
5.5.3.	Internal dose from aquatic pathways. . . . .	119
5.6.	Conclusions and recommendations . . . . .	119
5.6.1.	Conclusions. . . . .	119
5.6.2.	Recommendations . . . . .	121
	References to Section 5. . . . .	121
6.	<b>RADIATION INDUCED EFFECTS ON PLANTS AND ANIMALS . . . . .</b>	<b>125</b>
6.1.	Prior knowledge of radiation effects on biota. . . . .	125
6.2.	Temporal dynamics of radiation exposure following the Chernobyl accident . . . . .	127
6.3.	Radiation effects on plants . . . . .	128
6.4.	Radiation effects on soil invertebrates. . . . .	130
6.5.	Radiation effects on farm animals . . . . .	131
6.6.	Radiation effects on other terrestrial animals. . . . .	132
6.7.	Radiation effects on aquatic organisms . . . . .	132
6.8.	Genetic effects in animals and plants. . . . .	133
6.9.	Secondary impacts and current conditions . . . . .	135
6.10.	Conclusions and recommendations . . . . .	137
6.10.1.	Conclusions. . . . .	137
6.10.2.	Recommendations for future research . . . . .	137
6.10.3.	Recommendations for countermeasures and remediation . . . . .	138
	References to Section 6. . . . .	138
7.	<b>ENVIRONMENTAL AND RADIOACTIVE WASTE MANAGEMENT ASPECTS OF THE DISMANTLING OF THE CHERNOBYL SHELTER . . . . .</b>	<b>141</b>
7.1.	Current status and the future of unit 4 and the shelter . . . . .	141
7.1.1.	Unit 4 of the Chernobyl nuclear power plant after the accident . . . . .	141
7.1.2.	Current status of the damaged unit 4 and the shelter . . . . .	142
7.1.3.	Long term strategy for the shelter and the new safe confinement. . . . .	144

7.1.4.	Environmental aspects .....	145
7.1.4.1.	Current status of the shelter .....	145
7.1.4.2.	Impact on air .....	145
7.1.4.3.	Impact on surface water .....	145
7.1.4.4.	Impact on groundwater .....	148
7.1.4.5.	Impacts of shelter collapse without the new safe confinement .....	148
7.1.4.6.	Impacts of shelter collapse within the new safe confinement .....	150
7.1.5.	Issues and areas for improvement .....	151
7.1.5.1.	Influence of the source term uncertainty on environmental decisions .....	151
7.1.5.2.	Characterization of fuel-containing material .....	151
7.1.5.3.	Removal of fuel-containing material concurrent with development of a geological disposal facility .....	151
7.2.	Management of radioactive waste from the accident .....	151
7.2.1.	Current status of radioactive waste from the accident .....	153
7.2.1.1.	Radioactive waste associated with the shelter .....	153
7.2.1.2.	Mixing of accident related waste with operational radioactive waste .....	154
7.2.1.3.	Temporary radioactive waste storage facilities .....	154
7.2.1.4.	Radioactive waste disposal facilities .....	155
7.2.2.	Radioactive waste management strategy .....	156
7.2.3.	Environmental aspects .....	157
7.2.4.	Issues and areas of improvement .....	159
7.2.4.1.	Radioactive waste management programme for the exclusion zone and the Chernobyl nuclear power plant .....	159
7.2.4.2.	Decommissioning of unit 4 .....	159
7.2.4.3.	Waste acceptance criteria .....	159
7.2.4.4.	Long term safety assessment of existing radioactive waste storage sites .....	160
7.2.4.5.	Potential recovery of temporary waste storage facilities located in the Chernobyl exclusion zone .....	160
7.3.	Future of the Chernobyl exclusion zone .....	160
7.4.	Conclusions and recommendations .....	161
7.4.1.	Conclusions .....	161
7.4.2.	Recommendations .....	162
	References to Section 7 .....	163
	CONTRIBUTORS TO DRAFTING AND REVIEW .....	165