

CONTENTS

NOTE TO READERS OF THE CRITERIA MONOGRAPHS	xiii
PREAMBLE	xv
WHO TASK GROUP ON ENVIRONMENTAL HEALTH CRITERIA FOR SELECTED NON-HETEROCYCLIC POLYCYCLIC AROMATIC HYDROCARBONS	xx
ENVIRONMENTAL HEALTH CRITERIA FOR SELECTED NON- HETEROCYCLIC POLYCYCLIC AROMATIC HYDROCARBONS	xxii
1. SUMMARY	1
1.1 Selection of compounds for this monograph	1
1.2 Identity, physical and chemical properties, and analytical methods	1
1.3 Sources of human and environmental exposure	4
1.4 Environmental transport, distribution, and transformation	6
1.5 Environmental levels and human exposure	7
1.5.1 Air	7
1.5.2 Surface water and precipitation	8
1.5.3 Sediment	8
1.5.4 Soil	8
1.5.5 Food	8
1.5.6 Aquatic organisms	8
1.5.7 Terrestrial organisms	9
1.5.8 General population	9
1.5.9 Occupational exposure	9
1.6 Kinetics and metabolism	10
1.7 Effects on laboratory mammals and <i>in vitro</i>	10
1.8 Effects on humans	12
1.9 Effects on other organisms in the laboratory and the field	15
2. IDENTITY, PHYSICAL AND CHEMICAL PROPERTIES, AND ANALYTICAL METHODS	17
2.1 Identity	17
2.1.1 Technical products	17
2.2 Physical and chemical properties	21
2.3 Conversion factors	27
2.4 Analytical methods	27
2.4.1 Sampling	27
2.4.1.1 Ambient air	27
2.4.1.2 Workplace air	36

2.4.1.3	Combustion effluents	37
2.4.1.4	Water	38
2.4.1.5	Solid samples	38
2.4.2	Preparation	38
2.4.3	Analysis	40
2.4.3.1	Gas chromatography	40
2.4.3.2	High-performance liquid chromatography ..	41
2.4.3.3	Thin-layer chromatography	42
2.4.3.4	Other techniques	43
2.4.4	Choice of PAH to be quantified	43
3.	SOURCES OF HUMAN AND ENVIRONMENTAL EXPOSURE	47
3.1	Natural occurrence	47
3.2	Anthropogenic sources	48
3.2.1	PAH in coal and petroleum products	48
3.2.2	Production levels and processes	50
3.2.3	Uses of individual PAH	51
3.2.4	Emissions during production and processing of PAH .	52
3.2.4.1	Emissions to the atmosphere	52
3.2.4.2	Emissions to the hydrosphere	52
3.2.5	Emissions during use of individual PAH	52
3.2.6	Emissions of PAH during processing and use of coal and petroleum products	53
3.2.6.1	Emissions to the atmosphere	53
3.2.6.2	Emissions to the hydrosphere	57
3.2.6.3	Emissions to the geosphere	62
3.2.6.4	Emissions to the biosphere	63
3.2.7	Emissions of PAH caused by incomplete combustion	63
3.2.7.1	Industrial point sources	63
3.2.7.2	Other diffuse sources	75
4.	ENVIRONMENTAL TRANSPORT, DISTRIBUTION, AND TRANSFORMATION	97
4.1	Transport and distribution between media	97
4.1.1	Physicochemical parameters that determine environmental transport and distribution	98
4.1.2	Distribution and transport in the gaseous phase	98
4.1.3	Volatilization	103
4.1.4	Adsorption onto soils and sediments	103
4.1.5	Bioaccumulation	103
4.1.5.1	Aquatic organisms	106
4.1.5.2	Terrestrial organisms	124
4.1.6	Biomagnification	124

4.2	Transformation	126
4.2.1	Biotic transformation	126
4.2.1.1	Biodegradation	126
4.2.1.2	Biotransformation	150
4.2.2	Abiotic degradation	154
4.2.2.1	Photodegradation in the environment	159
4.2.2.2	Hydrolysis	174
4.2.3	Ultimate fate after use	174
5.	ENVIRONMENTAL LEVELS AND HUMAN EXPOSURE	175
5.1	Environmental levels	176
5.1.1	Atmosphere	176
5.1.1.1	Source identification	176
5.1.1.2	Background and rural levels	179
5.1.1.3	Industrial sources	179
5.1.1.4	Diffuse sources	184
5.1.2	Hydrosphere	197
5.1.2.1	Surface and coastal waters	198
5.1.2.2	Groundwater	203
5.1.2.3	Drinking-water and water supplies	205
5.1.2.4	Precipitation	208
5.1.3	Sediment	211
5.1.3.1	River sediment	212
5.1.3.2	Lake sediment	215
5.1.3.3	Marine sediment	216
5.1.3.4	Estuarine sediment	219
5.1.3.5	Harbour sediment	222
5.1.3.6	Time trends of PAH in sediment	222
5.1.4	Soil	225
5.1.4.1	Background values	225
5.1.4.2	Industrial sources	225
5.1.4.3	Diffuse sources	226
5.1.4.4	Time trends of PAH in soil	231
5.1.5	Food	232
5.1.5.1	Meat and meat products	232
5.1.5.2	Fish and marine foods	235
5.1.5.3	Dairy products: cheese, butter, cream milk, and related products	235
5.1.5.4	Vegetables	236
5.1.5.5	Fruits and confectionery	239
5.1.5.6	Cereals and dried food products	239
5.1.5.7	Beverages	240
5.1.5.8	Vegetable and animal fats and oils	240
5.1.6	Biota	249

5.1.7	Animals	250
5.1.7.1	Aquatic organisms	250
5.1.7.2	Terrestrial organisms	263
5.2	Exposure of the general population	267
5.2.1	Indoor air	267
5.2.2	Food	273
5.2.3	Other sources	276
5.2.4	Intake of PAH by inhalation	276
5.2.5	Intake of PAH from food and drinking-water	276
5.3	Occupational exposure	277
5.3.1	Occupational exposure during processing and use of coal and petroleum products	281
5.3.1.1	Coal coking	281
5.3.1.2	Coal gasification and coal liquefaction	282
5.3.1.3	Petroleum refining	282
5.3.1.4	Road paving	285
5.3.1.5	Roofing	286
5.3.1.6	Impregnation of wood with creosotes	289
5.3.1.7	Other exposures	289
5.3.2	Occupational exposure resulting from incomplete combustion of mineral oil, coal, and their products	290
5.3.2.1	Aluminium production	290
5.3.2.2	Foundries	291
5.3.2.3	Other workplaces	291
6.	KINETICS AND METABOLISM IN LABORATORY MAMMALS AND HUMANS	295
6.1	Absorption	295
6.1.1	Absorption by inhalation	296
6.1.2	Absorption in the gastrointestinal tract	297
6.1.3	Absorption through the skin	298
6.2	Distribution	299
6.3	Metabolic transformation	300
6.3.1	Cytochromes P450 and PAH metabolism	302
6.3.1.1	Individual cytochrome P450 enzymes that metabolize PAH	302
6.3.1.2	Regulation of cytochrome P450 enzymes that metabolize PAH	304
6.3.2	Metabolism of benzo[a]pyrene	305
6.4	Elimination and excretion	312
6.5	Retention and turnover	314
6.5.1	Human body burdens of PAH	314
6.6	Reactions with tissue components	315
6.6.1	Reactions with proteins	315
6.6.2	Reactions with nucleic acids	316
6.7	Analytical methods	316

7.	EFFECTS ON LABORATORY MAMMALS AND IN VITRO	325
7.1	Toxicity after a single exposure	325
7.1.1	Benzo[<i>a</i>]pyrene	325
7.1.2	Chrysene	329
7.1.3	Dibenz[<i>a,h</i>]anthracene	329
7.1.4	Fluoranthene	329
7.1.5	Naphthalene	329
7.1.6	Phenanthrene	330
7.1.7	Pyrene	330
7.2	Short-term toxicity	330
7.2.1	Subacute toxicity	330
7.2.1.1	Acenaphthene	330
7.2.1.2	Acenaphthylene	330
7.2.1.3	Anthracene	330
7.2.1.4	Benzo[<i>a</i>]pyrene	330
7.2.1.5	Benz[<i>a</i>]anthracene	333
7.2.1.6	Dibenz[<i>a,h</i>]anthracene	333
7.2.1.7	Fluoranthene	333
7.2.1.8	Naphthalene	333
7.2.1.9	Phenanthrene	334
7.2.1.10	Pyrene	334
7.2.2	Subchronic toxicity	334
7.2.2.1	Acenaphthene	334
7.2.2.2	Anthracene	334
7.2.2.3	Benzo[<i>a</i>]pyrene	336
7.2.2.4	Fluorene	336
7.2.2.5	Fluoranthene	336
7.2.2.6	Naphthalene	337
7.2.2.7	Pyrene	337
7.3	Long-term toxicity	338
7.3.1	Anthracene	338
7.3.2	Benz[<i>a</i>]anthracene	338
7.3.3	Dibenz[<i>a,h</i>]anthracene	339
7.4	Dermal and ocular irritation and dermal sensitization	339
7.4.1	Anthracene	339
7.4.2	Benzo[<i>a</i>]pyrene	339
7.4.3	Naphthalene	340
7.4.4	Phenanthrene	340
7.5	Reproductive effects, embryotoxicity, and teratogenicity	340
7.5.1	Benzo[<i>a</i>]pyrene	340
7.5.1.1	Teratogenicity in mice of different genotypes	340
7.5.1.2	Reproductive toxicity	341
7.5.1.3	Effects on postnatal development	346
7.5.1.4	Immunological effects in pregnant rats and mice	346

7.5.2	Naphthalene	346
7.5.2.1	Embryotoxicity	346
7.5.2.2	Toxicity in cultured embryos	351
7.6	Mutagenicity and related end-points.....	351
7.7	Carcinogenicity	352
7.7.1	Single substances	476
7.7.1.1	Benzo[<i>a</i>]pyrene	476
7.7.1.2	Benzo[<i>e</i>]pyrene	477
7.7.2	Comparative studies	477
7.7.2.1	Carcinogenicity	478
7.7.2.2	Further evidence	481
7.7.3	PAH in complex mixtures	482
7.7.4	Transplacental carcinogenicity	483
7.7.4.1	Benzo[<i>a</i>]pyrene	483
7.7.4.2	Pyrene	484
7.8	Special studies	484
7.8.1	Phototoxicity	484
7.8.1.1	Anthracene	484
7.8.1.2	Benzo[<i>a</i>]pyrene	485
7.8.1.3	Pyrene	485
7.8.1.4	Comparisons of individual PAH	485
7.8.2	Immunotoxicity	485
7.8.2.1	Benzo[<i>a</i>]pyrene	485
7.8.2.2	Dibenz[<i>a,h</i>]anthracene	488
7.8.2.3	Fluoranthene	488
7.8.2.4	Naphthalene	488
7.8.2.5	Comparisons of individual PAH	489
7.8.2.6	Exposure <i>in utero</i>	489
7.8.2.7	Mechanisms of the immunotoxicity of PAH	490
7.8.3	Hepatotoxicity	491
7.8.3.1	Benzo[<i>a</i>]pyrene	491
7.8.3.2	Comparisons of individual PAH	491
7.8.4	Renal toxicity	491
7.8.5	Ocular toxicity of naphthalene	492
7.8.6	Percutaneous absorption	492
7.8.7	Other studies	493
7.8.7.1	Benzo[<i>k</i>]fluoranthene	493
7.8.7.2	Benzo[<i>a</i>]pyrene	493
7.8.7.3	Phenanthrene	494
7.8.7.4	Comparisons of individual PAH	494
7.9	Toxicity of metabolites	495
7.9.1	Benzo[<i>a</i>]pyrene	495
7.9.2	5-Methylchrysene	503
7.9.3	1-Methylphenanthrene	503

7.10	Mechanisms of carcinogenicity	503
7.10.1	History	503
7.10.2	Current theories	503
7.10.3	Theories under discussion	506
7.10.3.1	Acenaphthene and acenaphthylene	507
7.10.3.2	Anthracene	507
7.10.3.3	Benzo[a]pyrene	507
7.10.3.4	Benz[a]anthracene	509
7.10.3.5	Benzo[c]phenanthrene	509
7.10.3.6	Chrysene	509
7.10.3.7	Cyclopenta[c,d]pyrene	510
7.10.3.8	Fluorene	510
7.10.3.9	Indeno[1,2,3-cd]pyrene	510
7.10.3.10	5-Methylchrysene	511
7.10.3.11	1-Methylphenanthrene	512
7.10.3.12	Naphthalene	513
7.10.3.13	Phenanthrene	513
7.10.3.14	Investigations of groups of PAH	513
8.	EFFECTS ON HUMANS	515
8.1	Exposure of the general population	515
8.1.1	Naphthalene	515
8.1.1.1	Poisoning incidents	516
8.1.1.2	Controlled studies	517
8.1.2	Mixtures of PAH	517
8.1.2.1	PAH in unvented coal combustion in homes	517
8.1.2.2	PAH in cigarette smoke	518
8.1.2.3	PAH in coal-tar shampoo	518
8.2	Occupational exposure	519
8.3	Biomarkers of exposure to PAH	541
8.3.1	Urinary metabolites in general	541
8.3.2	1-Hydroxypyrene	542
8.3.2.1	Method of determination	542
8.3.2.2	Concentrations	543
8.3.2.3	Time course of elimination	560
8.3.2.4	Suitability as a biomarker	561
8.3.3	Mutagenicity in urine	562
8.3.4	Genotoxicity in lymphocytes	562
8.3.5	DNA adducts	563
8.3.5.1	Method of determination	563
8.3.5.2	Concentrations	564
8.3.5.3	Suitability as a biomarker	570
8.3.6	Antibodies to DNA adducts	571
8.3.7	Protein adducts	571
8.3.8	Activity of cytochrome P450	571

8.3.9	Cell surface differentiation antigens in lung cancer	572
8.3.10	Oncogene proteins	572
9.1	EFFECTS ON OTHER ORGANISMS IN THE LABORATORY AND THE FIELD	573
9.1.1	Laboratory experiments	574
9.1.1.1	Microorganisms	574
9.1.1.1.1	Water	574
9.1.1.1.2	Soil	582
9.1.1.2	Aquatic organisms	582
9.1.1.2.1	Plants	582
9.1.1.2.2	Invertebrates	582
9.1.1.2.3	Vertebrates	602
9.1.1.2.4	Sediment-dwelling organisms	618
9.1.1.2.5	Toxicity of combinations of PAH.....	619
9.1.1.3	Terrestrial organisms	620
9.1.1.3.1	Plants	620
9.1.1.3.2	Invertebrates	620
9.1.1.3.3	Vertebrates	621
9.1.2	Field observations	621
9.1.2.1	Microorganisms	621
9.1.2.1.1	Water	621
9.1.2.1.2	Soil	621
9.1.2.2	Aquatic organisms	622
9.1.2.2.1	Plants	622
9.1.2.2.2	Invertebrates	622
9.1.2.2.3	Vertebrates	622
9.1.2.3	Terrestrial organisms	623
9.1.2.3.1	Plants	623
9.1.2.3.2	Invertebrates	623
9.1.2.3.3	Vertebrates	623
10.1	EVALUATION OF RISKS TO HUMAN HEALTH AND EFFECTS ON THE ENVIRONMENT	625
10.1.1	Human health	625
10.1.1.1	Exposure	625
10.1.1.1.1	General population	625
10.1.1.1.2	Occupational exposure	628
10.1.1.2	Toxic effects	628
10.1.1.2.1	Bioavailability	628
10.1.1.2.2	Acute toxicity	628
10.1.1.2.3	Irritation and allergic sensitization	629
10.1.1.2.4	Medium-term toxicity	629
10.1.1.2.5	Carcinogenicity	630
10.1.1.2.6	Reproductive toxicity	632
10.1.1.2.7	Immunotoxicity	632
10.1.1.2.8	Genotoxicity	633

10.2	Environment	633
10.2.1	Environmental levels and fate	633
10.2.2	Ecotoxic effects	634
10.2.2.1	Terrestrial organisms	634
10.2.2.2	Aquatic organisms	634
11	RECOMMENDATIONS FOR PROTECTION OF HUMAN HEALTH AND THE ENVIRONMENT	637
11.1	General recommendations	637
11.2	Protection of human health	637
11.3	Recommendations for further research	638
11.3.1	General	638
11.3.2	Protection of human health	638
11.3.3	Environmental protection	638
11.3.4	Risk assessment	638
12	PREVIOUS EVALUATIONS BY INTERNATIONAL BODIES	641
12.1	International Agency for Research on Cancer	641
12.2	WHO Water Quality Guidelines	641
12.3	FAO/WHO Joint Expert Committee on Food Additives	641
12.4	WHO Regional Office for Europe Air Quality Guidelines	643

I	APPENDIX I . SOME APPROACHES TO RISK ASSESSMENT FOR POLYCYCLIC AROMATIC HYDROCARBONS	645
I.1	Introduction	645
I.2	Approaches to risk assessment	647
I.2.1	Toxicity equivalence factors and related approaches	647
I.2.1.1	Principle	648
I.2.1.2	Development and validation	649
I.2.1.2.1	Derivation of the potency of benzo[a]pyrene	649
I.2.1.2.2	Derivation of the relative potency of PAH other than benzo[a]pyrene	651
I.2.1.3	Application	659
I.2.2	Comparative potency approach	661
I.2.2.1	Principle	661
I.2.2.2	Development and validation	661
I.2.2.3	Key implicit and explicit assumptions	662
I.2.2.4	Application	662
I.2.3	Benzo[a]pyrene as a surrogate for the PAH fraction of complex mixtures	662
I.2.3.1	Principle	662
I.2.3.2	Development and validation	664
I.2.3.3	PAH profiles of complex mixtures	665
I.2.3.4	Potency of complex mixtures	670

I.2.3.5	Key implicit and explicit assumptions	670
I.2.3.6	Application	671
I.3	Comparison of the three procedures	672
I.3.1	Individual PAH approach	672
I.3.2	Comparative potency approach	672
I.3.3	Benzo[<i>a</i>]pyrene surrogate approach	676
APPENDIX II; SOME LIMIT VALUES		677
II.1	Exposure of the consumer	677
II.2	Occupational exposure	677
II.3	Classification	677
II.3.1	European Union	677
II.3.2	USA	685
REFERENCES		687
RESUME		841
RESUMEN		863