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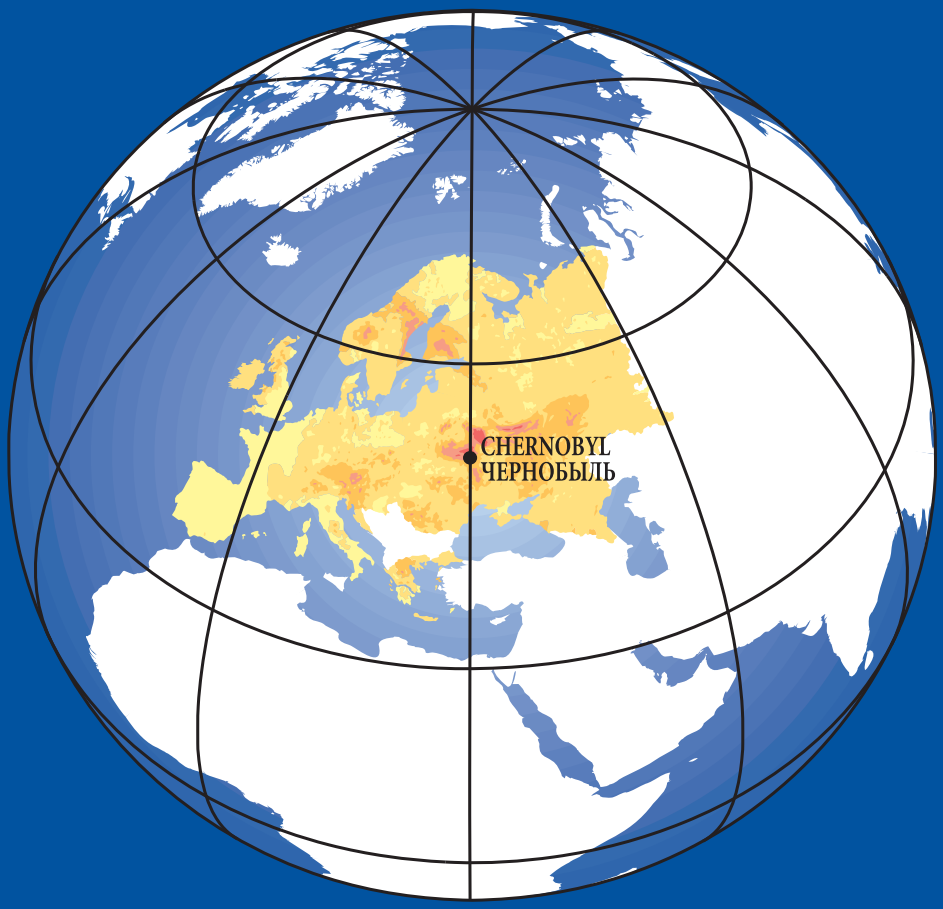
ATLAS

OF CAESIUM DEPOSITION ON EUROPE AFTER THE CHERNOBYL ACCIDENT



1998

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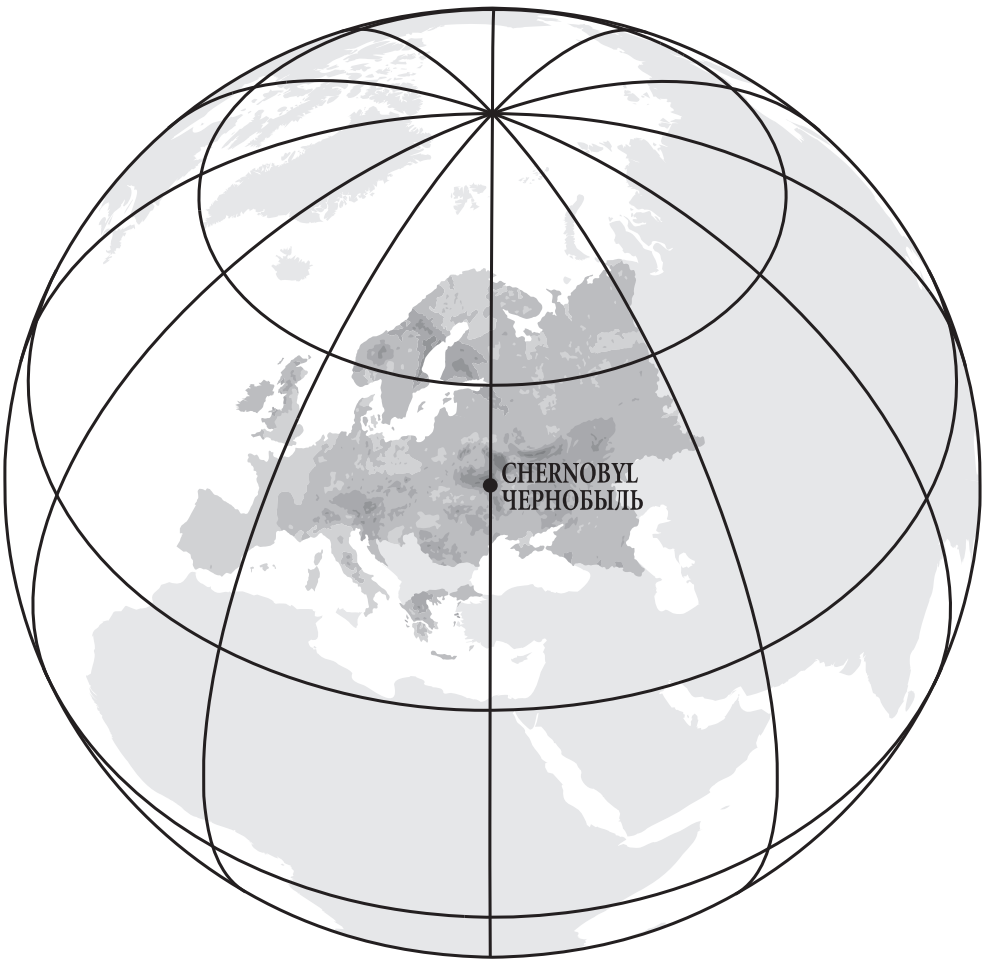

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ATLAS OF CAESIUM DEPOSITION ON EUROPE AFTER THE CHERNOBYL ACCIDENT

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Sadly, one of the main authors of this report, Professor Fridman, died suddenly as the Atlas was at an advanced stage of preparation. His contribution to the Atlas was considerable and his commitment, attention to detail and professionalism will long be remembered by all who had the pleasure of working with him on this and other projects. It is unfortunate that he was unable to see the finished Atlas of which he would have been proud; it will remain, however, a testimony to his work.

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Preface

The European Commission and the Ministries responsible for Chernobyl Affairs in Belarus, Russia and Ukraine have carried out a collaborative programme of research on the consequences of the Chernobyl Nuclear Power Plant accident. This programme was implemented during the period 1992-95 under the auspices of a formal Agreement between the Commission and the relevant Ministries in the three countries. Financial support for the programme was provided through a separate budget approved by the European Parliament. Within this programme some 16 separate projects were implemented dealing with the health and environmental consequences of the accident, their long term management and with emergency management in general. The results of this programme have been published in 16 volumes and were presented at a major international conference held in March 1996 in Minsk.

One of the projects was concerned with the preparation of a comprehensive Atlas of the deposition, over the whole territory of Europe, of radioactive material released during the Chernobyl Nuclear Power Plant accident. Various compilations, of differing resolution and quality, of the deposition in particular countries or regions are available but, prior to this project, no attempt had been made to bring the many data together and develop a coherent and comprehensive picture of the deposition across the whole of Europe. The task in assembling and processing these data has been considerable and those involved with the project are to be commended for what has been achieved. Equally, the Atlas could not have been produced without the input of data from each of the European countries which experienced fallout from the accident; their essential contributions are acknowledged.

The Atlas will be the authoritative reference on this subject for many years to come and it will have wide public and scientific interest. The interest of many will probably not extend much beyond checking for themselves the levels of deposition where they live or might have been around the time of the accident. Others may be interested by the large scale over which material was dispersed and by the very irregular patterns of deposition which are testimony to pollution being no respecter of geographic or national boundaries. The many and diverse data on which the Atlas is based have been compiled in an electronic form and will be an important resource for further scientific work; in particular they will contribute to a better understanding of the complex processes of dispersion and deposition and to the optimisation of environmental monitoring in the event of any future accident.

The Atlas also provides much needed perspective for judging the current radiological significance of the deposition across Europe. This is important generally but particularly so for those continuing to live in areas of the former Soviet Union where the deposition was greatest. Much concern and anxiety continues to be experienced with regard to the potential harm from the residual contamination of the environment. While these concerns are often not commensurate with the actual risks involved, they remain problematic for those affected. Hopefully, the perspective provided by this Atlas will go some way towards allaying such concerns. If so, the Atlas will have a broader social value that is additional to its scientific importance.

The Coordination Board established under an Agreement between the European Commission and Ministries responsible for Chernobyl Affairs in Belarus, Russia and Ukraine on the Consequences of the Chernobyl Accident

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March 1998

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I. General introduction

This Atlas was prepared under the auspices of the EC/CIS collaborative programme of research on the consequences of the Chernobyl Nuclear Power Plant (CNPP) accident. Various institutes in Belarus, the Russia, Ukraine and the European Union (EU) participated in the development of the Atlas through one of the projects (Joint Study Project No. 6) carried out within the collaborative programme. Extensive data on the deposition of radioactive material on Europe resulting from the CNPP accident have been collected and validated: these data have been transformed into maps of deposited material using advanced interpolation techniques and a geographical information system. The resulting Atlas is unique in providing a coherent and comprehensive picture of deposition across the whole of Europe and will, for many years to come, be the authoritative reference on this subject.

A wide spectrum of radionuclides was released to the environment during the CNPP accident and deposited over Europe. Few of these radionuclides, however, contributed significantly to the overall radiological impact from deposited material; iodine radionuclides were most important in the short term (ie, a few weeks) and caesium radionuclides in the medium and long term (ie, from a few months onwards). The radiological importance of a given nuclide depends on the amount released in the accident, its radiation characteristics and how effectively it is transferred through the environment to man. Iodine and caesium are volatile elements (at typical reactor operating temperatures) and substantial fractions of each were released during the CNPP accident; moreover, both are readily transferred through the environment and metabolised by man. This Atlas is concerned solely with those deposited nuclides which have largely determined, and continue to determine, the medium and longer term impacts (ie, from a few months onwards) of the accident. The focus of the Atlas is, therefore, the deposition of caesium radionuclides, in particular caesium-137 and, to a lesser extent, caesium-134. Consideration is also given to the deposition of radionuclides of strontium and plutonium. While the radiological significance of these nuclides is small in comparison with that of caesium radionuclides, they are often the focus of public interest and are included here for perspective and completeness. The maps of deposited strontium and plutonium are, however, not presented for Europe as a whole but limited to smaller areas where most of these elements were deposited.

The main text (Sections I to VI) describes the structure and content of the Atlas and provides perspective to enable readers to assess for themselves the radiological significance of residual levels of deposition. Following the general introduction, the remaining sections contain:

- A description of, and responses to, the Chernobyl Nuclear Power Plant accident;
- A description of the measured data on caesium-137 deposition and how these data were used to compile maps of deposition and to estimate the total amount of ceasium-137 deposited over Europe together with its distribution between countries;
- Information on the deposition of other nuclides (namely, caesium-134, strontium-90 and plutonium -239 and -240);
- Information to enable the reader to judge the radiological significance of the current levels of deposited caesium-137 (ie, indicative levels of annual radiation doses from current deposits and how these compare with other sources (natural and artificial) of exposure of the population).

The maps of caesium-137 deposition comprise the bulk of the Atlas. They are presented at three different levels or scales:

- European - deposition over Europe as a whole;
- National or Regional - deposition over individual countries or regions;
- Smaller Areas - deposition over more limited areas that experienced higher levels of deposition.

In addition maps are provided of:

- The meteorological situation during the accident;
- Relevant geographic and demographic features of Europe.

The legend describing all cartographic symbols and radiological information used throughout the Atlas is located at the beginning of the Maps section.

The Atlas contains eight Appendices which are likely to be of interest to the more specialist reader. They address each of the topics listed below and are intended to provide a fuller understanding of how the measurements were made, how they were used to compile the maps and of various phenomena which may have influenced the pattern of deposition:

- The meteorological situation during the accident (Appendix A);
- A summary of the various deposition measurement techniques and of caesium-137 deposition data used (Appendix B);
- A summary of the data handling techniques used (Appendices C and D);
- Reference maps on population density, land use, soil type and elevation (Appendix E);
- Additional information on data providers and data sources (Appendices F and G);
- List of tables and figures (Appendix H).

II. The accident at the Chernobyl nuclear power plant

A. Description of the accident

At the beginning of 1986 some 14 RBMK pressure tube reactors were being operated in the former Soviet Union; each had a capacity to generate 1,000 MW of electricity. Four of these reactors were in operation at the CNPP which is located in northern Ukraine, some 130 km north-east of Kiev and 18 km north of the town of Chernobyl. The borders of Belarus and Russia are about 12 and 140 km from the power plant, respectively.

The reactor unit No 4 at the CNPP began operation in December 1983 and was destroyed in a major accident on 26 April, 1986. The accident resulted in the release to the atmosphere of a substantial fraction of the more volatile contents of the reactor core. The magnitude of the release far exceeded that of previous accidents at nuclear reactors (ie, Windscale, UK in 1957 and Three Mile Island, USA in 1979) and also that in the accident at the industrial complex "Mayak", USSR in 1957 [1].

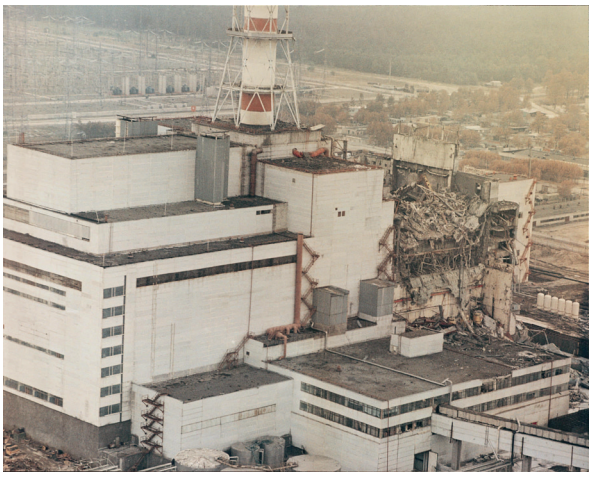

Fig. II.1: The damaged reactor

Based on the results of numerous investigations (eg. [2-5]) there is now general agreement that the main cause of the accident was deficiencies in the design of the reactor; these were compounded by errors made by the operators including serious breaches of the safety rules. As a consequence of these design deficiencies and operator errors, a large and almost instantaneous increase occurred in the reactor power at 01:23 h (Moscow time) on the 26 April, 1986. Two subsequent steam explosions destroyed the reactor, the reactor building and the machine room. The upper reactor cover, weighing 2000 tonnes, was displaced to the upper part of the reactor well at an angle of 15° with the vertical and the reactor core, *per se*, (fuel, graphite, moderator, etc) was ejected from the well mainly to the reactor room [6]. Concrete, graphite and debris heated to very high temperatures escaped through a hole in the roof of the building leaving the reactor core exposed to the environment. Flames and ejected material spread fire to 30 locations around the adjacent reactor (Unit No 3) and turbine buildings [6].

The two thermal explosions were the cause of the initial release of radioactive material to the atmosphere, in the form of a cloud several kilometres high that was subsequently dispersed in the form of a plume. This release was both large and energetic and resulted in some of the material penetrating, and being dispersed above, the atmospheric boundary layer (approximately 1200 m) [7]. The exposed reactor core and, in particular, the subsequent burning of the graphite moderator were a source of continuing release of large amounts of radioactive material (in the form of gases, aerosols and particulates) to the atmosphere. The fire in the graphite moderator, which was maintained by the substantial amount of energy released from the decay of fission products in the residual core material, was eventually stopped after ten days and resulted in a large decrease in the amount of radioactive material being released to the atmosphere.

Over this ten day period, due to the changing wind direction, the released material was widely dispersed and deposited across much of Europe. The largest amounts of material were deposited in Belarus, Ukraine and Russia but deposition occurred in most countries within Europe, albeit generally at appreciably lower levels. Some of the material was dispersed throughout the Northern hemisphere and was detected as far away as Japan and the United States, but at very low levels.

Fig. II.2: Construction of the sarcophagus

The radiological situation in the former Soviet Union was investigated by ten aircraft and helicopters equipped with dose rate meters and gamma spectrometers. Air and soil samples were analysed in chemical laboratories. The amount of radioactive material deposited over the European territory of the former Soviet Union by 5 May amounted to about 3.5% of the total radioactive content of reactor core. The release of different elements varied according to their volatility; a few tens of percent of the more volatile elements (eg, iodine) were released whereas the release of the more refractory elements (eg, plutonium) was, at most, a few percent [6-8]. The radioactive material deposited on soil comprised a very large number of different radionuclides created in the fission process or by activation of reactor materials. Some of the more radiologically significant radionuclides that were measured in the immediate aftermath of the accident include: zirconium-95, niobium-95, molybdenum-99, ruthenium-103, ruthenium-106, tellurium-132, iodine-131, iodine-132, barium-140, lanthanum-140, cerium-141, cerium-144, caesium-134, caesium-137, neptunium-239, etc. [8]. Transuranic radionuclides, plutonium-238, -239 and -240 were also measured in soil samples and subsequently americium-241 and curium-242 and -244 [7]. The composition of the deposited radionuclides varies with direction from the reactor reflecting, *inter alia*, the changing composition of released material as the accident progressed.

Estimates [11-13] of the total release of the more radiologically significant radionuclides are summarised in Table II.1 and the temporal pattern of the overall release of radioactive material is illustrated in Figure II.3. In the very early stages of the accident the short lived radionuclides were, radiologically, the most important. In the following days and weeks radionuclides of iodine (and especially iodine-131) were the main source of both internal and external exposure. The radiological significance of caesium radionuclides was initially small (ie, contributing only about 10% of the total external dose within the first year) but their importance increased with time, becoming by far the most important (for both internal and external exposure) one year after the accident, especially at larger distances.

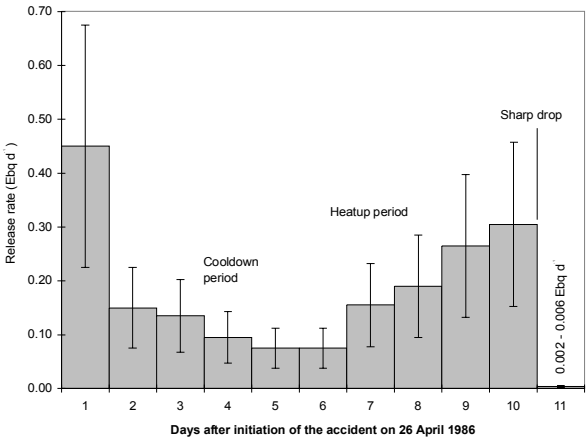

Fig. II.3: Daily release rate (and ± 50% error bars) of radioactive material into the atmosphere [14,15]

Radioactive material released in the form of debris was deposited in close proximity to the damaged reactor. That released in the form of particulates of relatively large size (eg, fuel particles and the more refractory elements) was largely deposited within a few tens of kilometres of the reactor. The

more volatile elements and those released largely in the form of fine particulates or aerosols (eg, iodine, tellurium and caesium) were dispersed and deposited over many hundreds and thousands of kilometres from the source of the release.

Table II.1: Core inventory and some estimates of the total release of the more significant radionuclides during the CNPP accident (taken largely from [16])

Element group	Radio-nuclide	Half-life	Core inventory in PBq (MCi) [10,14]		Estimate of the total release of the specific radionuclide during the accident in PBq (MCi) [1] [11]		[12,13]	
Inert gases	^{133}Xe	5.3 d	6500	*(180)*	6500	*(180)*	6500	*(180)*
Volatile elements	^{131}I	8.04d	3200	*(87)*	≈ 1800	*(48)*	1200 - 1700	*(32 - 46)*
	^{132}Te	3.26 d	2700	*(73)*	≈ 1200	*(31)*	1000	*(27)*
	^{134}Cs	2.06 a	180	*(4.9)*	≈ 54	*(1.5)*	44 - 48	*(1.2 - 1.3)*
	^{137}Cs	30.1 a	280	*(7.6)*	≈ 85	*(2.3)*	74 - 85	*(2 - 2.3)*
Elements with intermediate volatility	^{89}Sr	50.6 d	2300	*(62)*	≈ 120	*(3.1)*	81	*(2.2)*
	^{90}Sr	28.5 a	200	*(5.4)*	≈ 10	*(0.27)*	8	*(0.22)*
	^{103}Ru	39.4 d	4800	*(130)*	> 170	*(4.5)*	170	*(4.6)*
	^{106}Ru	367 d	2100	*(57)*	> 73	*(2.0)*	30	*(0.81)*
	^{140}Ba	12.8 d	4800	*(130)*	≈ 240	*(6.4)*	170	*(4.6)*
Refractory elements	^{95}Zr	64.0 d	5600	*(150)*	200	*(5.3)*	170	*(4.6)*
	^{99}Mo	2.75 d	4800	*(130)*	> 170	*(4.5)*	210	*(5.7)*
	^{141}Ce	32.5 d	5600	*(150)*	196	*(5.3)*	200	*(5.4)*
	^{144}Ce	284 d	3300	*(89)*	≈ 120	*(31)*	140	*(3.8)*
	^{238}Pu	86.4 a	1	*(0.027)*	0.035	*(0.001)*	0.03	*(0.001)*
	^{239}Pu	24100 a	0.85	*(0.032)*	0.03	*(0.001)*	0.03	*(0.001)*
	^{240}Pu	6553 a	1.2	*(0.023)*	0.042	*(0.001)*	0.044	*(0.001)*
	^{241}Pu	14.7 a	170	*(4.6)*	≈ 6	*(0.16)*	5.9	*(0.16)*
	^{242}Cm	162.8 d	26	*(0.70)*	≈ 0.9	*(0.024)*	0.93	*(0.025)*

[1] *See also section III.G*

The meteorological situation during the release of radioactive material was complex, and is described further in Appendix A. Because of the long duration of the release and the changing meteorological conditions during this period, the released material was dispersed in many different directions; consequently, material was effectively dispersed over, and deposited on, most of the territory of Europe. Changing meteorological conditions during the dispersion of released material (eg, slowing down or speeding up of the wind, rainfall, etc) also greatly affected the nature and extent of radioactive material in the environment and provided essential information patterns of deposition which were very uneven. Measurements and assessments of the levels of radionuclides in the environment and dose rates were made from the very beginning of the accident and continue, albeit at lower frequencies, to this day. These measurements delineated the nature and extent of radioactive material in the environment and provided essential information for managing the off-site consequences of the accident. Released material was dispersed beyond the borders of the former Soviet Union within about a day of the accident occurring and was detected subsequently in most European countries.

B. Response to the accident

The off-site response to the accident locally was rapid. The town of Prypiat, some 4 km away, was closed within a few hours and people instructed to shelter indoors. Iodine tablets were subsequently distributed by volunteers from home to home. The town of Prypiat (44,500 inhabitants) was evacuated by 14:00h on 27 April (by means of some 1,200 buses, 1,700 private cars, and 3 special rail-

way trains). The rest of the population within a radius of 10 km of the CNPP was also evacuated progressively within a few days [4]. On 2 May, the Governmental Commission passed a Resolution based on a map of the radiation situation within 100 km of the CNPP. The evacuation zone was defined as an area within a radius of 30 km around the plant plus other areas where the dose rate exceeded 50 μSv h^{-1} (5 mrem h^{-1}) (normalised to 10 May, 1986). The evacuation of the population from this zone began on 3 May. By the end of 1986 inhabitants from 188 settlements (including the town of Prypiat) had been evacuated, in total some 116,000 people. Simultaneously about 60,000 cattle and other farm animals were evacuated from the zone. Thousands of apartments were made available in Kiev, Zhitomir, Chernigov and in other towns to house the evacuees; in addition, 21,000 new buildings were constructed in 1986 in rural areas for the same purpose [4].

During the evacuation of the 30 km zone, various preventative and decontamination measures were taken (particular attention was given to the decontamination of cars, roads and road sides). To prevent high levels of radionuclides being transferred to rivers feeding the Kiev reservoir, some 140 dams and dikes were constructed and the banks of all rivers close to the CNPP were diked. The underground space below the NPP site was contained by a "wall in the ground" with a depth of 29-32 m (the impermeable clay layer) and a length of 2.3 km to prevent the flow of contaminated water into the Prypiat river and subsequently into the Dnieper river. To protect underground water against contamination and to prevent the flow of contaminated water from the cooling pond to the Prypiat river, various underground drainage systems, several tens of kilometres in length (including wells), were constructed.

Table II.2: Definition of the various zones used to control exposures

Zone	Caesium-137 deposition	
	(kBq m^{-2})	(Ci km^{-2})
Occasional control	37 - 555	1 - 15
Permanent control	555 - 1480	15 - 40
Strict control	> 1480	> 40

Various criteria were established by the Soviet authorities, based on input from a wide range of leading specialists in the fields of radiation medicine, nuclear geophysics and agricultural radiology, to manage the consequences of the accident in its initial and later phases. These criteria and their evolution are described in [17,18]. Among the more significant criteria adopted in the early phase were the following dose rates (normalised to 10 May) for the total exclusion or prohibited zone (>200 μSv h^{-1} (>20 mrem h^{-1})), for evacuation of the whole population (>50 μSv h^{-1} (>5 mrem h^{-1})) and for partial evacuation (30 - 50 μSv h^{-1} (3-5 mrem h^{-1})). On 10 May, 1986, the extent of the exclusion and evacuation zones were 1,100 km^2 and 2,940 km^2, respectively. The area of the former Soviet Union contaminated at levels above 2 μSv h^{-1} (0.2 mrem h^{-1}) was about 50,000 km^2 [8]. In May 1986, criteria were established, *inter alia*, in terms of ground contamination by long-lived radionuclides, in particular for caesium-137 (555 kBq m^{-2} (15 Ci km^{-2}) - initially a value of 7 Ci km^{-2} was adopted), for strontium-90 (111 kBq m^{-2} (3 Ci km^{-2})) and for plutonium-239 and 240 (3.7 kBq m^{-2} (0.1 Ci km^{-2})) [17]. The criteria (eg, limits on annual and lifetime doses, ground contamination, concentrations of nuclides in foodstuffs, etc) evolved over time, generally becoming more restrictive [4,18]. The criteria summarised in Table II.2 were established by the former Soviet Union to manage the affected territories; they were subsequently adopted in Belarus, Russia and Ukraine, albeit with some refinement over time in how they are implemented. These criteria are also used as the basis for payment of compensation to those continuing to live in these areas.

In the very early stages of the accident the main sources of radiation exposure were inhalation of, and external radiation from, the passing cloud of radioactive material. Inhalation of iodine radionuclides, (eg, iodine-131 and iodine-133), which result in the exposure of the thyroid, was one of the more important exposure pathways initially; exposure via this pathway was, for some people, mitigated by the timely issue of stable iodine tablets. Ingestion of iodine in contaminated foodstuffs (especially milk) proved to be a major source of exposure in those areas where restrictions on foodstuffs were delayed. High doses were received by many children among whom a large excess of

thyroid cancers is currently being observed (more than one thousand cases to date). Several months after the accident, deposited caesium-134 and -137 became the major sources of exposure of the population; with time the importance of caesium-137 relative to caesium-134 increased, due to its greater half-life, and it now largely determines the overall levels of exposure, both internal and external. The contribution of other nuclides (eg, strontium-90 and plutonium-239 and -240) to the exposure of the population in the medium and longer term is, especially beyond the evacuation zone, small by comparison (ie, at most a few percent of that from caesium-137 and often less). The overriding importance of caesium-137 in determining the medium and long term exposure of the population is the reason why it is the focus of this Atlas.

In addition to the major deposition of radioactive material that occurred on the territories of the former Soviet Union [19,20], many countries in the rest of Europe experienced significant fallout from the accident (in excess of 100 kBq m^{-2} (2.7 Ci km^{-2}) in some cases, albeit over limited areas). This resulted in intensive monitoring programmes, especially in those countries where higher values of deposition were observed eg, Scandinavia, the Alpine region and Greece. Deposition was measured by various techniques including soil sampling

and gamma spectrometry, both fixed and mobile (see Appendix B). Contamination of foodstuffs represented the major, but not sole problem in these other countries (eg, stable iodine was administered to potentially affected populations in Poland to mitigate the effects of the inhalation of radioactive iodine from the dispersing radioactive cloud). Restrictions were imposed on foodstuffs in several countries (eg, for milk consumption in the first weeks after the accident). In some cases these restrictions (eg, on sheep in parts of the United Kingdom, on deer in some parts of the Nordic countries) remain in place more than a decade after the accident, albeit over decreasing areas with time. Disparate criteria were used to control foodstuffs in different countries and this was a source of much confusion and concern for the general population. Broadly agreed criteria for the international trade of foodstuffs have, however, since been developed (eg, Codex Alimentarius, EC) [21-23].

III. The deposition of caesium-137 on the territory of Europe

A. Introduction

The main content of the Atlas, the maps of caesium-137 deposition on the territory of Europe, are described in this section. Consideration is given to the situation just prior to and immediately after the CNPP accident. Just prior to the accident the deposition was mainly a result of fallout from the testing of atomic weapons in the atmosphere; these deposits occurred predominantly, but not exclusively, in the mid 1950s and early 1960s. In a few localised areas, enhanced levels (ie, enhanced relative to levels typical of global fallout from atomic weapons) of deposition existed due to accidents other than at the CNPP, eg, the accident that occurred in 1957 at the industrial complex "Mayak" in Russia [24], and as a result of discharges to the environment from nuclear installations, eg, liquid effluents from the fuel reprocessing plant at Sellafield in the United Kingdom.

The basic data and the methods used to process them into the maps presented in this Atlas are summarised. More detailed descriptions of both the data and methods can be found in Appendices B - D; these are likely to be of interest to the more specialist reader. The maps of caesium deposition are presented on three geographic scales: European, national/regional and local. A number of the more prominent features of the maps are highlighted in order to illustrate points of potential interest to the reader.

The maps of deposition have been used to estimate the total amount of caesium-137 deposited on the territory of Europe as a result of the CNPP accident and its distribution among the affected countries. Comparisons are made with estimates of the total amount of caesium-137 released in the accident.

B. The basic data

The data which underlie the maps are summarised in Appendix B and their origins are indicated in Appendix G. Each data point comprises one or more measurements attributed to a single location. For settlements which have been the subject of extensive surveys (eg, in the more affected areas of Belarus, Ukraine and Russia) hundreds, in some cases thousands, of measurements may have been attributed to a single location.

Most of the data have been provided by or through national contact points in each country who were responsible for the quality and validity of the data. Consequently, validation of the data by the project staff was fairly rudimentary and essentially limited to the identification and correction of internal inconsistencies in the data and/or of discontinuities at national boundaries. Subjecting the basic data to more rigorous validation in future would no doubt be worthwhile in a scientific context but would be unlikely to alter materially the main features of the maps presented in this Atlas.

The data are diverse both in terms of their spatial resolution and the type of measurement on which they were based. The reported levels of deposition are based, *inter alia*, on airborne gamma surveys, *in situ* measurements of gamma dose rates and spectrometry, measurements of soil profiles (often to different depths), etc. Each type of measurement has its strengths and weaknesses which, in a more rigorous analysis, could be taken into account quantitatively in estimating patterns of deposition. Such analyses, while worthwhile in the future, were beyond the resources of this project. For the purposes of this study the assumption was made that all reported data represented the total amount of caesium-137 deposited at the time when and where the measurement was made (apart from a few exceptions, see Appendix B, Table B.1).

C. Methods used to process the basic data

Maps have been compiled separately on a European, national and local scale from the basic data on deposition levels. The basic data have been interpolated onto a grid of dimensions 2 by 2 km using an Inverse Distance Weighting (IDW) method. This method and its mode of application are described further in Appendix D. Isolines of deposition have been constructed from the interpolated values of deposition in each of the gridded cells. In some cases the output from the strict application of this method was further refined to take account of additional information that was strictly not part of the basic data used within the project in the interpolation process. This additional information comprised the following; firstly, the original measurements of deposition, as opposed to aggregated data that were available to and used within the project (in some cases several hundreds or exceptionally several thousands of measurements may have been aggregated into single points in the data base); secondly, the quality or reliability of each measurements or type of measurement; and thirdly, characteristics of the surface on which the deposition was measured or was being interpolated. This additional information had been used previously in compiling national maps of deposition for Belarus, Russia and Ukraine and advantage of these earlier analyses was taken here.

D. Caesium deposition on a European scale (see Plate 1)

D.1 Deposition prior to the Chernobyl Nuclear Power Plant accident

Prior to the CNPP accident the deposition of caesium-137 on the territory of Europe was principally due to global fallout from the atmospheric testing of nuclear weapons. The spatial distribution of deposited caesium-137 from this source is illustrated in Figure III.1 where the deposition levels are those pertaining just prior to the accident. The quality or reliability of the deposition patterns, however, varies considerably over Europe. For the European part of the former Soviet Union, the deposition patterns are based on airborne gamma surveys (with flight paths of 50 km separation) carried out in the period 1969 to 1973 [25] (ie, after atmospheric testing of nuclear weapons had largely ceased). Given the nature and resolution of these surveys, the resulting deposition patterns can be viewed with confidence. For the remainder of Europe the patterns were derived from maps of strontium-90 deposition across the Northern Hemisphere prepared by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [26]; the caesium-137 deposition levels were obtained by scaling the measured strontium-90 levels by the ratio of the total amounts of the respective nuclides released in the atmospheric testing of nuclear weapons. The deposition patterns for this area of Europe are based on relatively few measurements and, consequently, are associated with much greater uncertainty than those for the European part of the former Soviet Union. For comparison, more recent UNSCEAR reports [eg, 27] contain estimates of the average levels of deposition of fallout nuclides as a function of latitude. For caesium-137, average levels just prior to the CNPP accident were about 1.8, 2.4 and 2.2 kBq m^{-2} (0.049, 0.065 and 0.059 Ci km^{-2}) for latitudes 30-40°N, 40-50°N and 50-60°N, respectively; these are, in general, consistent with the levels depicted in Figure III.1. The total amount of caesium-137 from weapons' fallout that remained deposited on the European landmass just prior to the Chernobyl accident is estimated to be 20 PBq (0.54 MCi).

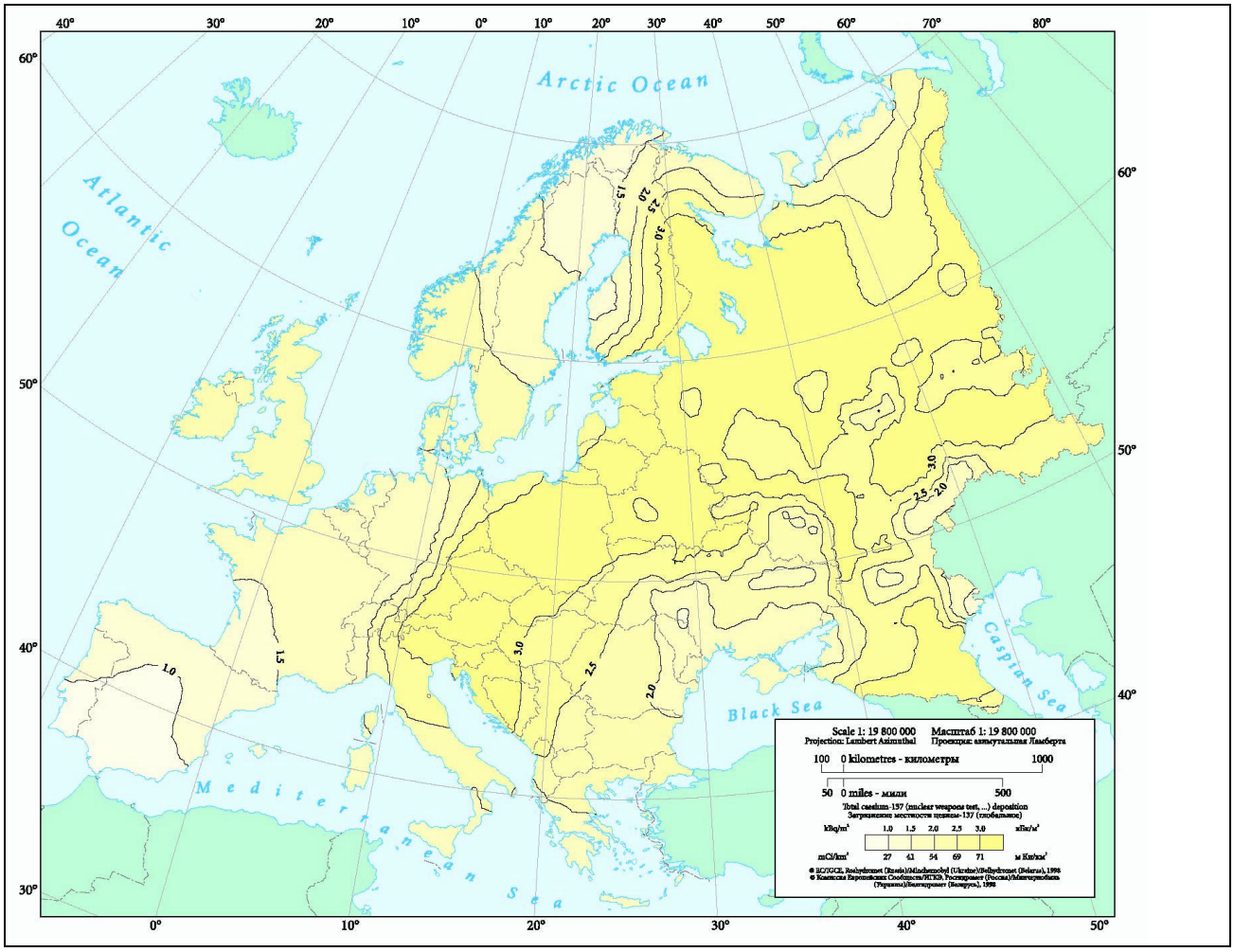

Fig. III.1: Residual levels (in May 1986) of caesium-137 deposition from the atmospheric testing of nuclear weapons

D.2 Deposition after the Chernobyl Nuclear Power Plant accident

The deposition patterns of caesium-137 across the whole of Europe immediately after the CNPP accident are illustrated on Plate 1 (scale 1:11 250 000). In this map, as for all caesium-137 maps in this Atlas, the reported levels are for the total amount of caesium-137 deposited, irrespective of its source (ie, from the CNPP accident, weapons' tests, etc), but taking account of loss through radioactive decay up to May 1986. The deposition patterns show many striking features but only a few can be highlighted here. For perspective, the reader may wish to note that the lowest band of deposition illustrated (< 2 kBq m^{-2} (< 0.054 Ci km^{-2}) and coloured yellow) is typical of that from weapons' testing; consequently, the 2 kBq m^{-2} deposition isoline can be used as a convenient, albeit oversimplified, dividing line between areas affected and unaffected by deposition from the CNPP accident. Reference, however, should be made to the national maps, which have higher resolution.

The deposition patterns reflect the characteristics of the release, especially its long duration, and the changing meteorological conditions during this period (see Appendix A). It is apparent that caesium-137 was dispersed over almost the whole of Europe, with relatively few areas not affected. Several distinctive patterns of deposition are evident.

The patchiness or irregularities in the deposition patterns are particularly striking, as are the enhanced levels of deposition at locations far removed from Chernobyl. These features reflect the inherent complexity of the processes that govern the dispersion of material in, and its deposition from,

the atmosphere. If meteorological and other conditions remain constant, the level of deposition decreases in general with increasing distance from a source. However, changing conditions radically alter this simple picture and are responsible for the complex patterns illustrated on Plate 1. Significant relative increases in deposition can occur for many reasons, eg, the wind speed drops, the dispersing material encounters rainfall, the height of the mixing boundary layer in the atmosphere decreases, the roughness of the underlying surface increases (eg, forests compared with grassland), etc; conversely, decreases in deposition can occur for the opposite reasons. Rain, falling through the radioactive cloud, can result in large increases in deposition and was responsible for many of the enhanced levels that occurred at distances far removed from Chernobyl. The release, during the initial stages of the accident, of material above the atmospheric boundary layer was a further contributor to the enhanced levels found at very large distances.

The enhancement of deposition at distances far removed from Chernobyl is best exemplified by reference to the situation in southern Germany, Austria, Finland, Norway, Sweden and the middle Volga region in Russia. In these areas (which are more than 1,000 km from Chernobyl) there are significant areas where the deposition is greater than 40 kBq m^{-2} (1.08 Ci km^{-2}).

E. Caesium deposition on a national scale (see Plates 3 to 25)

Maps for each country in Europe (with a few exceptions where insufficient data were available) have been compiled to represent the levels of total deposition of caesium-137 immediately after the release had terminated and the plumes had dispersed beyond the territory of Europe. Some 20 maps have been prepared with scales ranging from 1:1,000,000 to 1:2,500,000. In a few cases, for ease of presentation, some of the countries have been grouped into regional maps (ie, the Benelux countries and France, the Baltic States, etc). In other cases, countries or geographic regions were subdivided (ie, Russia, Scandinavia) so that a similar scale could be used for all of the maps. An index of the national/regional maps and their scales is given on Plate 2.

Each map includes the following main elements:

- Patterns of the total (Chernobyl, nuclear weapons' fallout, etc) amount of caesium-137 deposited (corrected for radioactive decay to 10 May 1986) immediately after the accident;
- A number of geographic features, eg, international boundaries, major roads, railways, rivers, lakes, and towns with more than 10,000 inhabitants, etc;
- A general legend showing the map scale and the colours used to represent different levels of deposition, unavailability of data, etc;
- An insert which indicates the location and deposition level for each of the data used in compiling the map;
- An insert, at the top-right hand corner, which indicates the location of each map relative to the rest of Europe;
- Plate numbers of adjacent maps.

The insert, showing the location and deposition level for each of the data used in compiling the maps, is in general presented in the form of a Voronoi polygon (see also Appendix D); the colour of the polygon is determined by the measured level of deposition. Each polygon represents one or more measurements attributed to a single location; in some cases, the number of measurements attributed may be large although this cannot be ascertained directly from the information presented (see Appendix B). In other cases, the density of data is too great for them to be represented in the form of a Voronoi polygon (eg, for Russia); the basic data are then depicted as points coloured in accordance with the associated level of deposition.

It is beyond the scope of this Atlas to provide a detailed commentary on each of the national/regional maps. A number of general and more specific features, however, warrant comment. The reliability of the patterns of deposition differs greatly between countries. In general, the reliability of the deposition patterns will increase with the spatial density of data used in their compilation. The Voronoi polygons, included as inserts in each map, provide the reader with a rapid, albeit approximate, means of assessing this, at least in relative terms. In general, the spatial density of the measurements is, as would be expected, greatest in those countries or regions which experienced the greatest fallout from the CNPP accident. In those countries which experienced little, if any, fallout the measurements tend to be sparse and the interpolated deposition patterns are associated with much greater uncertainty. Such cases can be readily identified from cursory inspection of the maps and, in particular, the Voronoi polygons.

The national/regional maps provide much greater resolution and fine structure than the European map. The patchiness or irregularity in the deposition patterns is even more pronounced but its origins are as described previously. By far the highest levels of deposition occurred on the territories of Belarus, Russia and Ukraine. Levels in excess of 40 kBq m^{-2} (1.08 Ci km^{-2}) occur in many countries outside the former Soviet Union and, in several of these, the levels exceed 100 kBq m^{-2} (2.7 Ci km^{-2}).

Two of the maps require clarification as some of the enhanced levels illustrated are a result neither of fallout from weapons testing nor from the CNPP accident.

The first concerns the map of the United Kingdom (Plate 6) where the enhanced levels along the north-west coastline of England and the south-west coastline of Scotland are a result of the discharge to the Irish Sea of caesium-137 in liquid effluents from the reprocessing of Magnox fuel at Sellafield; these discharges were particularly elevated in the 1970s but have since been substantially reduced through, *inter alia*, the commissioning of improved waste treatment facilities. The enhanced levels along some parts of the coast line, particularly in estuarine areas, have resulted from the deposition of sea-borne silts on land which is occasionally flooded at high tides.

The second concerns the map of Russia (eastern part of European territory and southern Urals), Plate 24, where the deposition of caesium-137 resulting from the accident at the industrial complex "Mayak" in 1957 is illustrated. Strictly, this should not be included in the Atlas because "Mayak" is located east of the Urals and beyond the territory of Europe. However, because of its proximity to the European border, the additional perspective it brings and the likely interest of many readers in deposition from the Mayak accident, it has been included in the Atlas. Deposition from this source has not, however, been taken into account when estimating the amount of caesium-137 deposited over the territory of Europe.

F. Caesium deposition on a local scale (see Plates 27 to 60)

More detailed maps are presented of the patterns of total caesium-137 deposition for those areas where the levels are particularly enhanced. Two sets of maps have been compiled and are distinguished by the levels of deposition which they depict. The first concerns areas where the deposition level exceeds 40 kBq m^{-2} (1.08 Ci km^{-2}) at a scale of 1:500,000 and the second areas where the level exceeds 1480 kBq m^{-2} (40 Ci km^{-2}) at a scale of 1:250,000. Apart from the Voronoi polygons, the local scale maps include the same elements as for the national/regional maps (see section III.E). The content of these maps is, however, limited to those areas where the deposition exceeds one or other of the specified levels. The reader should refer to the national/regional maps for further information on levels and patterns of deposition in adjacent areas which are not depicted in the local scale maps.

Areas where deposition exceeds 1480 kBq m^{-2} (40 Ci km^{-2}) are confined to Belarus, Ukraine and Russia, whereas the level of 40 kBq m^{-2} (1.08 Ci km^{-2}) is exceeded in several countries outside the former Soviet Union. The areas exceeding the specified levels are identified on Plate 26 where an index is given for each of the maps and the scale on which it is presented. Some 34 local scale maps are presented.

In zones where the deposition level is less than 40 kBq m^{-2} (1.08 Ci km^{-2}), the annual average dose (in 1998) will, with a very high degree of confidence, not exceed 1 mSv (100 mrem); this level of dose is adopted by the authorities of Belarus, Russia and Ukraine as a threshold for taking countermeasures and introducing privileges for the affected population.

Deposition levels in excess of 40 kBq m^{-2} (1.08 Ci km^{-2}) are observed out to much larger distances (Plates 27 to 57). In Eastern Europe these levels are found mainly in flat areas while, in Western Europe, they are found largely in mountainous areas. Some spots were formed in precipitation zones, some in regions with increased break of the relief or on mountain slopes blocking or cutting the dispersing radioactive plumes.

The second set of local maps (scale 1:250,000, Plates 58 to 60) depicts areas with caesium-137 deposition levels in excess of 1480 kBq m^{-2} (40 Ci km^{-2}). The map of the close-in CNPP zone is based largely on extensive data from soil sampling from a special network established in 1986. This comprises 540 measurement sites within a radius of 60 km, where soil samples were taken twice a year in the period 1986-1990. Other complementary data (eg, measurements obtained from soil sampling in settlements, *in situ* measurements along special pedestrian routes, detailed airborne gamma-spectrometry, terrain characteristics, etc) were also used.

The most intensive caesium spot (see Plate 60) is located in the immediate vicinity of the CNPP, and extends to a distance of about 60 km around the reactor over the territory of Ukraine and Belarus. The pattern of deposition is very non-uniform (for much the same reasons as in the national and European scale maps), with the highest levels to the north. The main release trajectories can be identified from the deposition patterns.

The Bryansk-Gomel-Mogilev spot (see Plates 58 and 59), which is located in Belarus and Russia, about 150 - 250 km from the CNPP, is more pronounced on the local scale maps. Despite its large distance from the CNPP, the level of deposition in some areas of this spot exceed those in parts of the spot around the reactor itself. Caesium-137 deposition levels of up to about 8,000 kBq m^{-2} (216 Ci km^{-2}) are found in the Bryansk-Gomel-Mogilev spot and up to about 40,000 kBq m^{-2} (1080 Ci km^{-2}) in the central spot.

G. The amount of caesium-137 deposited on Europe and its spatial distribution

Estimates have been made of the total amount of caesium-137 deposited on each country and on the territory of Europe as a whole as a result of the CNPP accident. The following approach was used. The total deposition (ie, from weapons' fallout, the CNPP accident, etc) of caesium-137 on a grid of 1 by 1 km was estimated for the whole of Europe from interpolation of the data used to compile the national scale maps. The total deposition on Europe and in individual countries was obtained by summation over the relevant cells in the grid. Corrections had to be made for those areas or countries where no deposition data were available. For countries where data were missing for relatively small areas (eg, Sicily in Italy) the average level of deposition in that country was assumed to be applicable to the missing areas. Where data were missing for a whole country (namely Albania, Bosnia-Herzegovina, Bulgaria, Former Yugoslavian Republic of Macedonia (FYROM), Iceland, Portugal, Serbia) the average level of deposition in immediately adjacent countries was assumed.

Table III.1: Total caesium-137 deposition on Europe just after the Chernobyl accident (All values quoted to two significant figures)

Country	Surface area (10^3 km^2)	Area (in 10^3 km^2) with deposition in the specified range (kBq m^{-2} (Ci km^{-2}))										caesium-137 deposit [3]				
		0 - 1 (0-0.027)	1 - 2 (0.027-0.054)	2 - 4 (0.054-0.11)	4 - 10 (0.11-0.27)	10 - 20 (0.27-0.54)	20 - 40 (0.54-1.08)	40 - 100 (1.08-2.7)	100 - 185 (2.7-5)	185 - 555 (5-15)	555-1480 (15-40)	> 1480 (>40)	Total		Chernobyl		
													PBq	(kCi)	PBq	(kCi)	(% of Europe)
Austria	84	0.01	0.13	2.7	17	28	25	11	0.08				1.8	(49)	1.6	(42)	2.4
Belarus	210		30	46	50	22	16	21	8.7	9.4	4.4	2.6	15	(410)	15	(400)	23
Belgium	31	8.1	10	12	0.09								0.053	(1.4)	0.01	(0.26)	0.02
Croatia	56	0.07	10	6.2	29	11	0.03						0.37	(9.9)	0.21	(5.8)	0.33
Czech Republic	79			21	42	13	3.5	0.21	< 0.01				0.6	(16)	0.34	(9.3)	0.54
Denmark	45	5.4	20	19	0.80								0.087	(2.4)	0.016	(0.43)	0.02
Estonia	45	0.05	3.0	31	8.7	1.7	0.28	< 0.01					0.18	(4.7)	0.051	(1.4)	0.08
Finland	340	1.9	130	45	50	32	59	19					3.8	(100)	3.1	(83)	4.8
France	550	290	100	97	54	1.2							0.93	(25)	0.35	(9.4)	0.55
Germany	350	8.4	58	140	110	29	14	0.32					1.9	(51)	1.2	(32)	1.8
Greece	130	6.4	16	39	37	21	8.3	1.2	0.04				0.95	(26)	0.69	(19)	1.1
Hungary	93	2.9	25	31	29	5.2	0.23						0.37	(10)	0.15	(4.1)	0.24
Ireland	70	0.08	1.0	21	47	1.3	0.01						0.35	(94)	0.21	(5.6)	0.33
Italy[1]	280	140	42	37	37	15	7	1.3	0.05				0.93	(25)	0.57	(15)	0.90
Latvia	64	0.01	0.05	43	21								0.25	(6.8)	0.055	(1.5)	0.09
Lithuania	65		3.1	14	48	0.05							0.44	(12)	0.24	(6.5)	0.38
Luxembourg	2.6		0.09	2.4	0.12								0.008	(0.21)	0.003	(0.08)	< 0.01
Moldavia	34			0.04	13	19	1.9						0.4	(11)	0.34	(9.2)	0.53
Netherlands	35	6	19	9.1	0.64								0.062	(1.7)	0.01	(0.26)	0.02
Norway	320	14	76	68	89	44	23	7.1	0.08				2.5	(69)	2.0	(53)	3.1
Poland	310	0.44	110	120	71	10	3.5	0.52					1.2	(32)	0.4	(11)	0.63
Rumania	240	1.6	9.4	34	120	54	13	1.2					2.1	(55)	1.5	(41)	2.4
Russia (European part)	3800	3.3	300	1900	1100	250	180	44	7.2	5.9	2.2	0.46	29	(780)	19	(520)	30
Slovak Republic	49		0.01	9.3	32	6.8	0.61	0.02					0.32	(8.8)	0.18	(4.7)	0.28
Slovenia	20	< 0.01	0.03	0.14	2.5	8.1	8.7	0.61					0.39	(11)	0.33	(8.9)	0.52
Spain	500	390	100	0.51									0.38	(10)	0.031	(0.83)	0.05
Sweden	450	120	100	78	55	31	33	23	0.44	< 0.01			3.5	(94)	2.9	(79)	4.6
Switzerland	41		< 0.01	6.2	26	6.4	2.3	0.73					0.36	(9.8)	0.27	(7.3)	0.43
Turkey (European part)	24			0.35	23	0.04							0.16	(4.2)	0.10	(2.8)	0.16
Ukraine	600	0.26	14	140	240	120	43	29	4.3	3.6	0.73	0.56	13	(350)	12	(310)	18
United Kingdom	240	58	48	51	64	15	1.7	0.09	0.04	0.03			0.88	(24)	0.53	(14)	0.83
Reporting countries	9200	1100	1200	3000	2400	740	440	160	25	20	8.1	2.8	82	(2200)	63	(1700)	99
Europe	9700												84	(2300)	64	(1700)	100
World (Europe + 20%)															77	(2100)	

(1) Excluding Sicily
(2) Sum of the values from reporting countries corrected (see Section III.G) for non reporting countries/regions (ie, Albania, Bosnia-Herzegovina, Bulgaria, FYROM, Iceland, Portugal, Serbia and Sicily)
(3) Derived as the sum of the average caesium-137 deposit in each 1 x 1 km cell apart from Belarus, Russian Federation and Ukraine. For the latter countries the values were derived as the sum of the products of the area and average deposition for each deposition interval

In order to estimate the deposition that had resulted from the CNPP accident, the contribution from weapons' testing had to be subtracted from the total (the contribution from the terrestrial deposition of caesium-137 discharged in liquid effluents from Sellafield is sufficiently small that no explicit correction needed to be made). The average contribution from weapons' fallout in each 1 by 1 km cell was subtracted from the total caesium-137 deposits estimated for the same cell. Where this average level exceeded the total deposition predicted for a 1 by 1 km cell, the contribution from the CNPP accident was assumed to be zero. This approach has clear limitations and may result in large uncertainties in estimates of the amount of Chernobyl caesium-137 deposited in some countries. These uncertainties will, however, be greatest for those countries which experienced the lowest levels of deposition and will be of little significance in determining the overall amount of Chernobyl caesium-137 deposited on Europe. Nonetheless, this aspect warrants further attention in future with a view to making more rigorous estimates of Chernobyl deposition in the less affected countries.

Table III.2: Areas in each country with caesium-137 deposition in excess of specified levels

Country	Local scale maps (In 1,000 km^2)	
	> 40 kBq m^{-2} (*>1.08 Ci km^{-2}*)	> 1480 kBq m^{-2} (*> 40 Ci km^{-2}*)
Austria	11	
Belarus	46	2.6
Czech Republic	0.21	
Estonia	< 0.01	
Finland	19	
Germany	0.32	
Greece	1.2	
Italy (1)	1.3	
Norway	7.1	
Poland	0.52	
Rumania	1.2	
Russia (European part)	60	0.46
Slovak Republic	0.02	
Slovenia	0.61	
Sweden	24	
Switzerland	0.73	
Ukraine	38	0.56
United Kingdom	0.16	

(1) *Excluding Sicily*

The estimates of the total and Chernobyl deposits of caesium-137 are summarised in Table III.1 for each country and for Europe as a whole. The total amount of Chernobyl caesium-137 deposited on the land mass of Europe is estimated to be about 64 PBq (1.7 MCi). A fraction of the caesium-137 released in the accident will also have been deposited over European water bodies and some will have been transported beyond the air masses above Europe and deposited over other continents and oceans. It is unlikely, however, that these amounts will exceed more than twenty per cent of the amount deposited over the European land mass [28]. Assuming that not more than 20% was dispersed and deposited beyond Europe, the total amount of caesium-137 estimated to be released in the CNPP is less than 77 PBq (2.1 MCi). This is in broad agreement with previously published estimates of 74 - 85 PBq (2 - 2.3 MCi) [11-13].

Estimates are also given in Table III.1 of the areas in each country, and for Europe as a whole, with levels of total caesium-137 deposition within specified ranges. The percentage of Chernobyl caesium-137 deposited in each European country is also indicated in Table III.1 together with the areas where deposition exceeds, or falls within, particular intervals. The areas in each country where the deposition level of caesium-137 exceeds one or other of the levels adopted in compiling the local maps of enhanced deposition are given in Table III.2.

IV. Chernobyl deposits other than caesium-137

A. Introduction

This Atlas is concerned with those deposited radionuclides which have largely determined, and continue to determine, the medium and longer term radiological impact of the accident. The focus of the Atlas is, therefore, the deposition of caesium-137 and, to a lesser extent, caesium-134. Consideration is also given to the deposition of radionuclides of strontium and plutonium because they are often the focus of public interest; their radiological significance, in comparison with caesium-137, is however small.

B. Deposition patterns for caesium-134

Caesium-134 was also an important constituent of the radioactive material released in the accident. In terms of activity (ie, in Bq or Ci), its release was about 56% of that of caesium-137 (see Table II.1). The deposition patterns of caesium-134 are essentially replicas (albeit with different levels of deposition) of those for caesium-137; consequently, maps of caesium-134 are not presented in the Atlas. The deposition levels of caesium-134 can, however, be readily estimated from the maps of caesium-137 by appropriate scaling. Where the total deposition levels of caesium-137 are high compared with those from weapons' fallout, the caesium-134 levels can be obtained by scaling the caesium-137 levels by a factor of 0.56; where this is not the case, the weapons' fallout should first be subtracted from the total caesium-137 level before scaling. There are two exceptions to this generalisation; these concern those areas with elevated deposition caused by the Mayak accident and liquid discharges from Sellafield. The deposition maps of caesium-137 and the levels of caesium-134 derived in the above manner represent deposition levels pertaining in May 1986 just after the release had terminated and the released material had been dispersed beyond the boundaries of Europe. Deposition levels of each nuclide at other times can be readily estimated from the maps by scaling the reported levels by the factors below.

Table IV.1: The factor by which the deposition levels of caesium-137 reported in the maps should be scaled to obtain deposition levels of caesium-134 and -137 at different times

Time after deposition ceased (a)	The factor by which the deposition levels of caesium-137 reported in the maps should be scaled to obtain deposition levels of caesium-134 and -137 [1]	
	caesium -134	caesium-137
0	0.56	1
0.5	0.47	0.99
1	0.40	0.98
2	0.29	0.96
5	0.10	0.89
10	0.019	0.79
20	0.0007	0.63
50	≈ 0	0.32
100	≈ 0	0.10

[1] *Values are quoted to two significant figures*

Because of its much shorter half life (2.06 a) the deposition levels of caesium-134 have declined rapidly in comparison with caesium-137. Some 12 years after the accident, the residual deposition levels (in terms of activity) of caesium-134 are only about 1% of those of caesium-137. In terms of exposure of the population, however, the relative importance of caesium-134 (per unit activity deposit) is about three times greater than would be indicated by a direct comparison of their respective deposition levels; this is due to the energy of the radiation emitted when caesium-134 decays being about three times that for caesium-137. As a consequence, the contribution of caesium-134 to the exposure of the population during the first one to two years of the accident exceeded that of caesium-137.

C. Deposition patterns for strontium-90 and plutonium -239, -240

Maps for these nuclides are included solely for completeness and because concern is often expressed about their importance. Their radiological significance on a European scale is small in comparison with that of caesium-137; consequently, relatively little effort has been allocated in most European countries to measuring their patterns of deposition. Moreover, because of their lower volatility and the forms in which they were released in the accident, nuclides of strontium and plutonium were deposited more rapidly from the atmosphere than those of caesium and their significance is limited to relatively small (in a European context) areas. Deposition patterns of strontium-90, plutonium-239, -240 are illustrated in Figures IV.1 and IV.2 for the region around the CNPP where these nuclides were preferentially deposited.

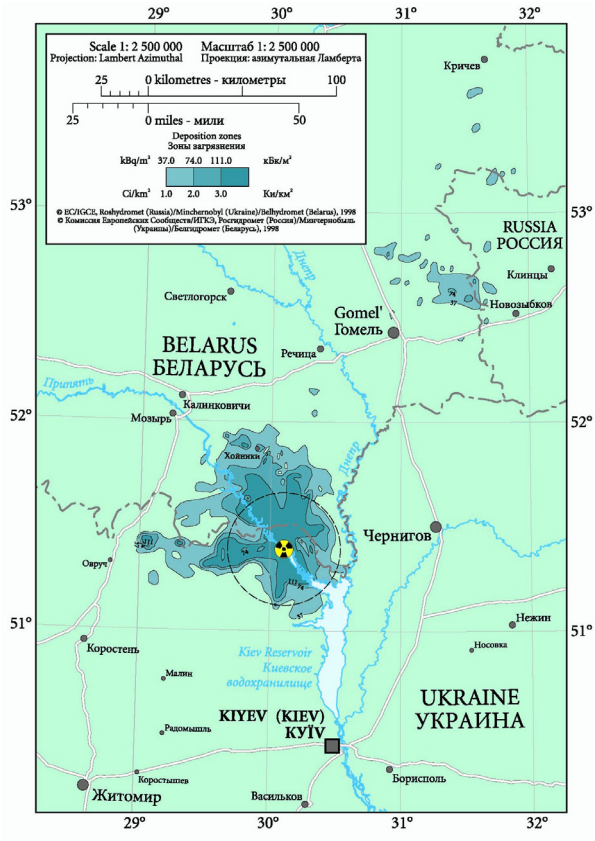

Fig. IV.1: Distribution, in December 1989, of deposited strontium-90 released in the Chernobyl accident

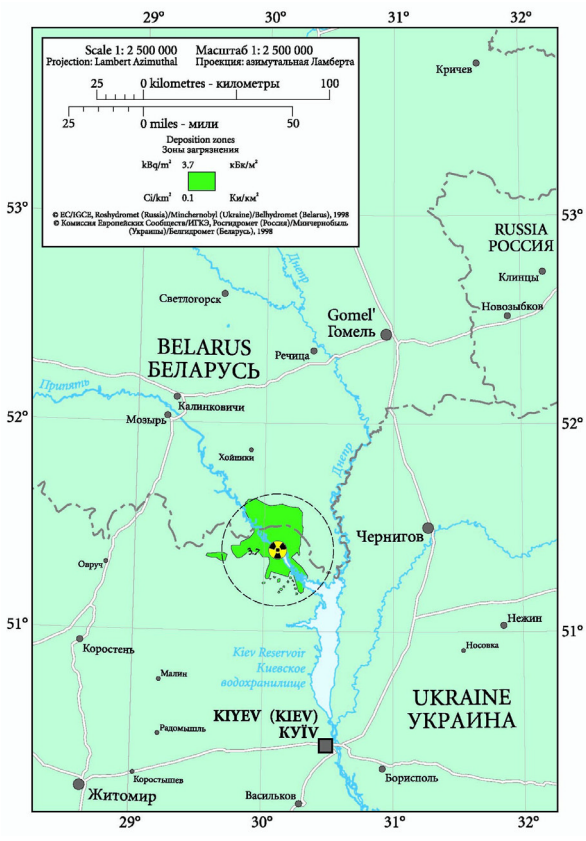

Fig. IV.2: Distribution, in December 1989, of deposited plutonium-239 and plutonium-240 released in the Chernobyl accident

V. The current (ie, in 1998) radiological significance of the Chernobyl deposits

A. Introduction

Man is exposed to ionising radiation from many different sources of both natural and artificial origin. Caesium-137 deposited over Europe as a result of the CNPP accident represents an additional source of exposure, the significance of which varies, *inter alia*, with the level of deposition. For perspective and to enable the reader to better appreciate the radiological significance of the caesium-137 deposits illustrated in this Atlas, current exposures from this source are compared with those from other sources. The broader question of past exposures of the population as a result of the CNPP accident is beyond the scope of this Atlas; those with an interest in this topic should refer to [18, 27-34].

Ionising radiation occurs naturally and can be produced artificially. Natural ionising radiation arises from outer space, where cosmic rays are formed, and in and on the earth, where radionuclides normally present in soil, air, water, food and the body undergo radioactive decay. Ionising radiation from artificial or man-made sources is produced in many ways, for example, in the explosion of nuclear weapons, in the production of electricity by nuclear means, by activation of stable elements, by particle accelerators and by X-ray machines.

Human exposure to radiation occurs by irradiation from sources outside the body (external exposure) or from radioactive material taken into the body through ingestion and inhalation (internal exposure). Radionuclides are characterised by the nature and energy of the radiation they emit when they decay and their half-life (ie, the period over which the initial number of atoms is reduced by a factor of two by decay). The half-life of radionuclides varies from a tiny fraction of a second to billions of years. The half-life of caesium-137, for example, is about 30 years.

The main sources of ionising radiation are described together with the contribution they make, on average, to the exposure of the population of Europe. The dose estimates are taken largely from a recent world-wide review by the United Nations Committee on the Effects of Atomic Radiation (UNSCEAR) [27].

B. Natural sources

Cosmic radiation and cosmogenic radionuclides: Space is permeated by ionising radiation of various types and energies. The primary cosmic radiation, of solar and galactic origin, consists mainly of charged nuclei and extends over a very wide energy range. The secondary cosmic radiation comprises the products of interactions between the primary radiation and the earth's atmosphere. The global *per caput* annual effective dose from external cosmic radiation is about 0.38 mSv (38 mrem) but there is considerable variation with altitude (eg, about 0.27 mSv (27 mrem) at sea level, about 0.8 mSv (80 mrem) at 2.2 km (Mexico City) and about 2 mSv (200 mrem) at 3.9 km (Le Paz, Bolivia)). Cosmic rays also produce a variety of radionuclides through their interaction with elements in the atmosphere. The most significant is carbon-14 which, through its intake into the body, results in a global *per caput* annual effective dose of about 0.012 mSv (1.2 mrem).

Terrestrial radiation: Only radionuclides with half-lives comparable with the age of the earth still exist in terrestrial materials. In terms of human exposure, the principal primordial radionuclides are presented in Table V.1. The average content of uranium, thorium and potassium in the earth's crust is 2.5 10^{-4} %, 1.3 10^{-3} % and 2.5%, respectively, and those in soils (which are determined by the rocks from which they were formed and the processes of soil formation) are on average about a factor of two lower. There is considerable variation with rock and soil type.

Exposure from terrestrial radiation can occur in three main ways: direct external exposure and internal exposure from the ingestion of foodstuffs and from inhalation. The *per caput* annual effective dose from external exposure is about 0.46 mSv (46 mrem) although there is considerable variation about this level depending on local geology; in some regions of the world the dose may be 10 times greater and up to about 100 times greater in specific locations. The internal dose (excluding the inhalation of radon) is about 0.23 mSv (23 mrem); potassium-40 contributes about 75% of this dose with the remainder from radionuclides in the uranium and thorium decay series. The internal dose from potassium-40 is nearly uniform in the population, whereas that from uranium and thorium may vary significantly.

Table V.1: Characteristics of important natural terrestrial radionuclides

Isotope	abundance (%)*	half-life	origin
^{40}K	0.0119	1.28 10^9 a	genesis
^{232}Th	100	1.41 10^{10} a	genesis
^{234}U	0.0055	2.45 10^5 a	^{238}U
^{235}U	0.720	7.04 10^8 a	genesis
^{238}U	99.3	4.47 10^9 a	Genesis

** with respect to the corresponding element*

The inhalation of radon in indoor air is by far the most important contributor to exposure from natural sources. Radon is a noble gas and appears as two radioisotopes: radon-222 which radiologically is the most significant (daughter nucide of radium-226) and radon-220 which is often referred to as thoron (daughter nucide of radium 228). Its level indoors depends on its rate of production (determined by the concentrations of radium-226) in soil and other materials and the efficacy with which it is transported to, and removed from, indoor air. These processes are influenced by many factors (eg, local geology, soil characteristics, building materials, type of construction, ventilation, etc) and hence the levels of indoor radon vary greatly. The global *per caput* annual effective dose from inhalation of radon-222 and its progeny has been estimated as 1.2 mSv (120 mrem) with a further contribution of about 0.07 mSv (7 mrem) from inhalation of thoron. In some geographic regions, however, the *per caput* dose may be 10 times the average. Local geology and the type of construction may combine to give doses several hundred times the global average in houses.

C. Artificial sources

The way in which artificial sources of radiation are produced and how they are used determine who in the population is exposed and to what extent. Those directly involved in the production and use of radiation sources are exposed in the course of their work but this aspect is not given further consideration here. The public is exposed directly (eg, from the use of radiation for diagnosis and therapy in medicine) and indirectly (eg, as a result of the release of radioactive material to the environment in both normal operation of nuclear installations and as a result of accidents).

Medical uses: Ionising radiation is widely used for both the diagnosis and treatment of injuries and disease. The *per caput* annual effective dose in Europe from diagnosis (diagnostic X-rays and nuclear medicine examinations) is about 1.1 mSv (110 mrem). There is significant variation in this average dose between European countries (ranging from about 0.4 to 1.6 mSv (40 - 160 mrem)) with even greater variation on a global scale. The *per caput* annual effective dose from therapy is about 0.7 mSv (70 mrem) (excluding the exposure of the organ or tissue being deliberately exposed in the treatment) with, again, wide variation between countries.

Atmospheric testing of nuclear weapons: Atmospheric testing of nuclear weapons began in 1945 and continued until 1980; more intensive periods of testing occurred in the 1950s and early 1960s. As a result of these tests large amounts of radioactive material were released to the atmosphere. Much of this material was dispersed in the stratosphere and was globally dispersed prior to its deposition on the surface of the earth. The complete spectrum of fission and fusion products generated in

nuclear explosions was released in these tests but current deposits are essentially limited to the longer lived radionuclides, mainly caesium-137 and strontium-90 both with a half-life of approximately 30 years. The distribution, over Europe in 1986, of caesium-137 deposited from weapons' testing is illustrated in Figure III.1 (see Section III.D.1). The largest exposures occurred during the periods of testing but declined significantly once atmospheric testing effectively ceased in the 1960s. The *per caput* annual effective dose in 1998, in the 40°-50° N latitude band (where exposures are largest), is about 0.009 mSv (0.9 mrem), with caesium-137 the major contributor.

Other sources (excluding the CNPP accident): Other sources of exposure include nuclear energy production for civil and defence purposes (including the whole fuel cycle from uranium mining, enrichment of uranium, fuel fabrication, reactor operation, reprocessing, etc), the fabrication of nuclear weapons, radio-isotope production, the re-entry into the atmosphere of satellites which are powered by nuclear means, the use of industrial sources of radiation (eg, industrial radiography, sterilisation, well logging), etc. In general, with the exception of major accidents such as at the CNPP, the contribution these sources make to the *per caput* exposure of the population is small in comparison with other sources of exposure. Typical global *per caput* annual effective doses in the late 1980s/early 1990s from nuclear energy generation and radio-isotope production were about 0.1 μSv and 0.02 μSv (0.01 and 0.002 mrem), respectively. Higher doses are received by those living in close proximity to nuclear installations; for nuclear reactors maximum doses are typically of the order of 1 to 20 μSv (0.1 to 2 mrem) and for large reprocessing plants a few hundred μSv (a few tens mrem).

Chernobyl caesium-137 deposits in 1998: For a given deposit of caesium-137 the dose received by the population will vary with a number of factors, in particular the habits of the population (eg, the time they spend indoors, the type of buildings in which they live and work, dietary habits, etc) and the characteristics of the surfaces, and especially the soils and the vegetation, on which the deposits occur. Soil characteristics can have a major influence on the transfer of deposited caesium from soil to both plants and animals; in extreme cases differences in transfer by a factor of between 10 and 100 can occur. Moreover, the doses may also be influenced by countermeasures taken after the deposition. Consequently, making reliable estimates of doses from deposited caesium is a relatively complex task that must take proper account of many local factors. Such estimates are beyond the scope of this Atlas; for those interested in this topic reference can be made to [18, 27-39].

Indicative estimates can, however, be made for perspective and to enable the reader to judge the radiological significance of the levels of caesium-137 deposition illustrated in this Atlas. Assuming that all food is obtained locally and that no countermeasures are taken, the annual average effective dose (in 1998) per unit deposit of caesium-137 (in 1986) is about 1 to 2 mSv per kBq m^{-2} (3.7 - 7.4 mrem per Ci km^{-2}) [35,40,41]. Values at the lower end of the range are typical for countries in Western Europe and those at the upper end of the range more typical of countries in the former Soviet Union; differences in soil characteristics are the main source of these differences. These indicative doses per unit deposit must not be used out of context. Their use should be limited to providing indicative average doses over relatively large geographic areas; reliable estimates of dose over smaller areas or regions must take account of local factors. This point can be exemplified by reference to some areas of the former Soviet Union where, because of local soil characteristics, the dose per unit deposit is substantially greater, about 20 mSv per kBq m^{-2} (74 mrem per Ci km^{-2}) [41]. These indicative estimates should also not be used where detailed and more rigorous assessments have been, and continue to be, made and published of past and future exposures on a settlement by settlement basis, as is the case in Belarus, Russia and Ukraine.

D. Comparison of indicative doses from Chernobyl caesium-137 with other sources of exposure

A comparison is made in Figure V.1 between current (ie, in 1998) indicative levels of exposure from specified levels of caesium-137 deposition (in 1986) and the *per caput* dose in Europe from other sources of exposure, both natural and artificial. For a deposition level of 100 kBq m^{-2} (2.7 Ci km^{-2}) (in 1986), the indicative dose is small (ie, a few percent) in comparison with the average dose from other sources of radiation, indeed small in comparison with the range of variation in the latter quantity between European countries [27,42]. Current indicative annual average doses from Chernobyl caesium-137 deposits only exceed those from other sources of exposure where the level of deposition exceeds a few thousand kBq m^{-2} (several tens of Ci km^{-2} - 1986 levels).

The comparisons made here between different sources of exposure need qualification. All of the doses compared are average values typical for the population of Europe. For many sources, however, the distribution of doses in a population may be very non-uniform (eg, exposure to radon, exposure to effluents from nuclear installations, therapy, etc). While this qualification should be recognised, it does not detract from the broad conclusions that can be reached from the comparison in Figure V.1 of doses from Chernobyl caesium-137 deposits and those from other sources.

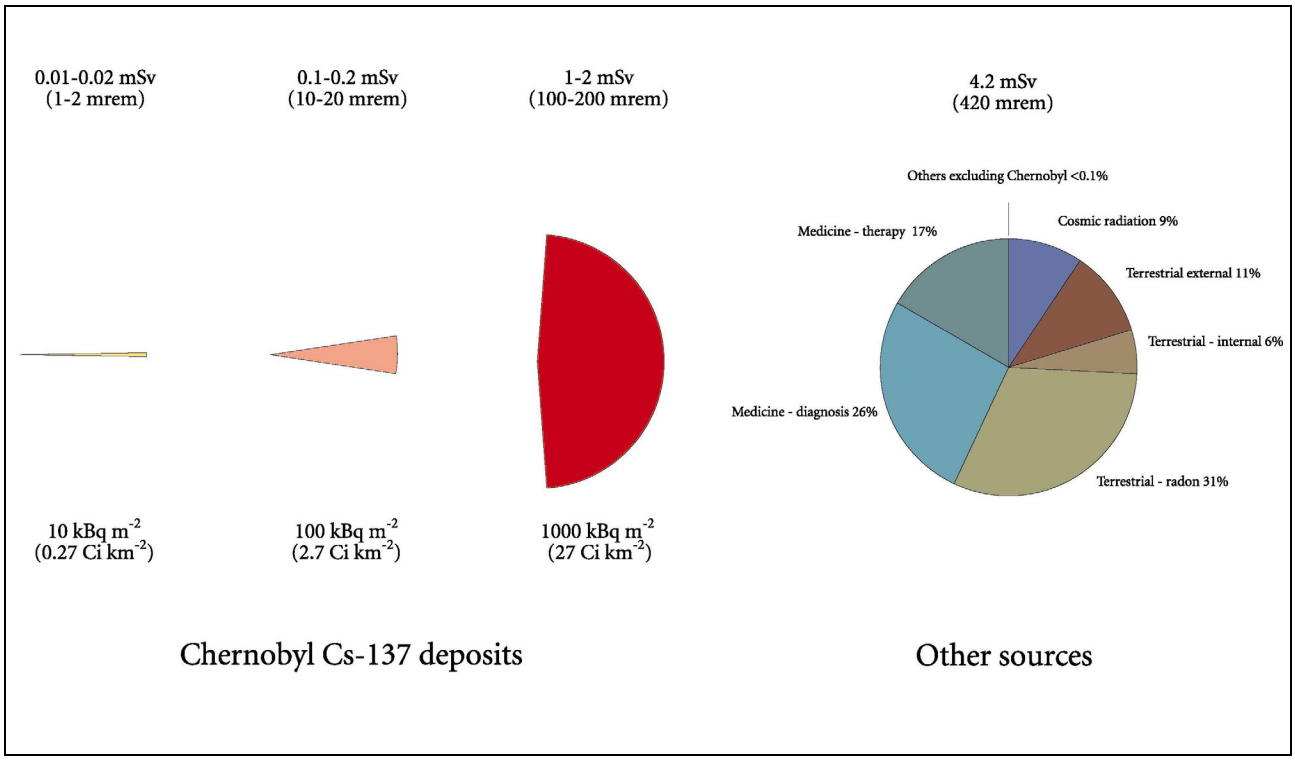

Fig. V.1: Comparison of indicative annual average doses in 1998 from Chernobyl caesium-137 deposits with annual per caput doses in Europe from other sources of radiation exposure (deposition levels are those in 1986; the doses from Chernobyl deposits are based on the assumption of no countermeasures and would be lower were food restrictions imposed).

NB: the indicative doses attributed to Caesium-137 deposits are provided solely for perspective and are only valid as averages over relatively large geographic areas; where more definitive estimates of dose exist (eg for settlements in the affected areas of Belarus, Russia and Ukraine) comparisons should be made with these doses rather than with the indicative values given here.

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APPENDIX A The meteorological situation during the accident

Radioactive material released in the accident was widely dispersed and deposited over large areas of the earth's surface. The more volatile elements in the reactor core (e.g., iodine, tellurium and caesium) were dispersed over many hundreds and thousands of kilometres, according to the meteorological conditions that prevailed during the accident.

The meteorological situation during the release and in the subsequent dispersion of material was complex. During the first hours of the release on the 26 April, material was transported mainly to the west, then to the north-west (see Figure A.1). In the following days the wind shifted again, resulting in the transport of radioactive material to the north-east. From the 30 April, released material was transported in a southerly direction (see Figure A.2). Consequent upon the long duration of the release (about 10 days) and the changing meteorological situation (especially the wind direction) material was dispersed and deposited over much of Europe. The territories of Belarus, Ukraine and the European part of Russia were most affected. However, areas far removed from Chernobyl also experienced relatively high levels of deposition due, largely but not solely, to the released material encountering precipitation as it passed over these areas.

It is beyond the scope of this Annex to provide a comprehensive description of the actual release and how material was dispersed and deposited over the territory of Europe and beyond. This would require a detailed presentation of the chronology of the release and its main characteristics (e.g., magnitude, composition, height, physico-chemical form, etc.) and of the meteorological conditions it experienced (from a local to European scale), both during the release and during the period before it was essentially dispersed from the air masses above Europe. Nonetheless, it is possible to illustrate some of the key meteorological features that existed during the release and in its subsequent transport, in particular those which had a major influence on the deposition of material.

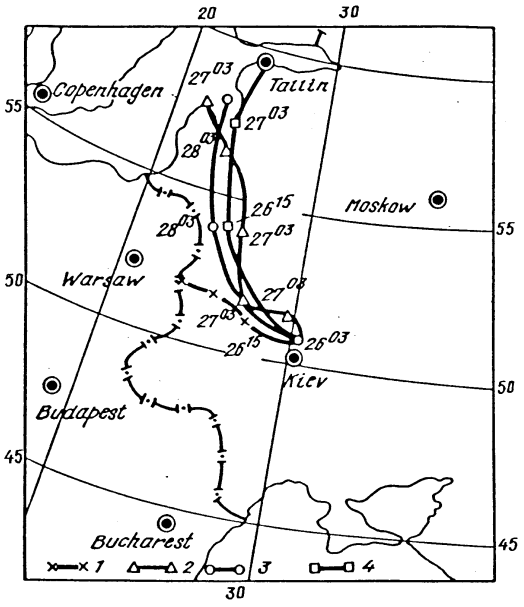

Fig. A.1: Trajectories of particle transport on 26 April, 1986 at 03.00 Moscow time: 1 - ground surface, 2 - height - 0.7 km, 3 - 1,5 km, 4 - 3.0 km.

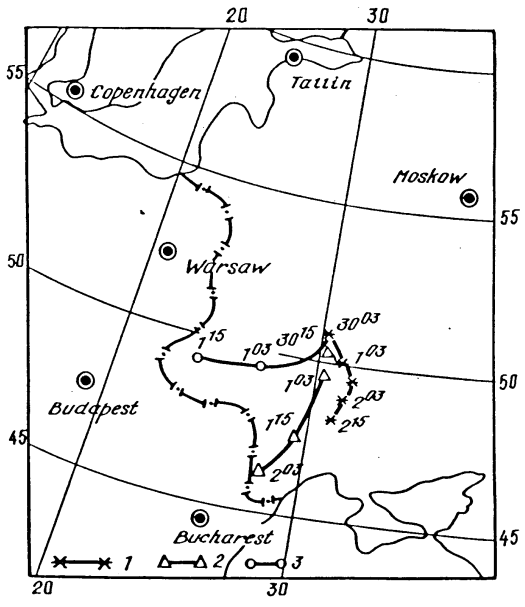

Fig. A.2: Trajectories of particle transport on 30 April, 1986 at 03.00 Moscow time: 1 - ground surface, 2 - height - 0.7 km, 3 - 1,5 km.

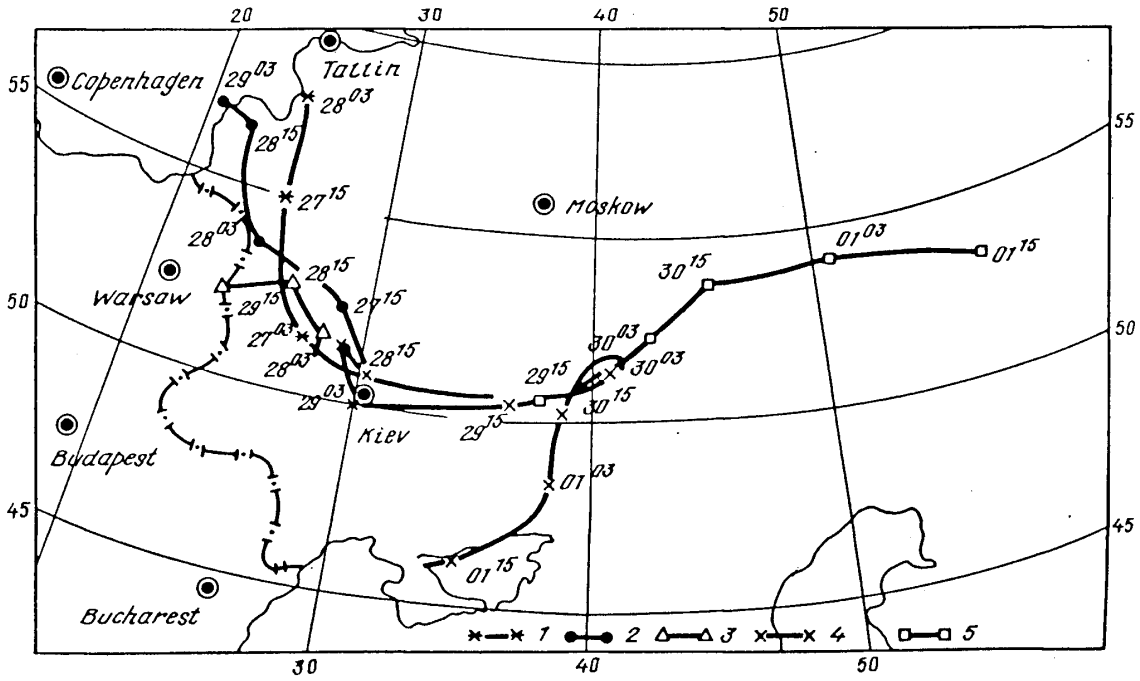

Fig. A.3: Trajectories of particle transport at height of 0,7 km: 1 - from 15.00 on 26 April; 2 - from 03.00 on 27 April; 3 - from 15.00 on 27 April; 4 - from 03.00 on 28 April; 5 - from 03.00 on 29 April

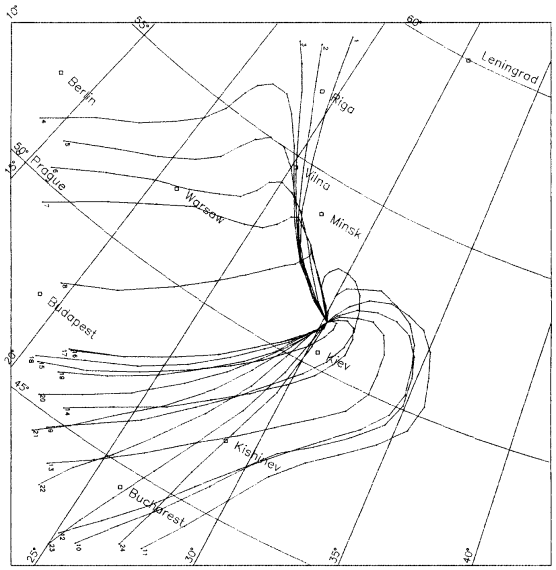

Fig. A.4: Trajectories of particle transport from the power plant region at the level of 925 hPa by 6-hour intervals from 24 April to 1 May 1986. The trajectories 1-4 : transport of momentary portion of particles on 26 April; Trajectories 5-8 on 27 April; Trajectories 21-24 on 1 May 1986.

Trajectories of particle transport at different heights in the atmospheric boundary layer are shown in Figures A.3 and A.4 for different periods of time after the start of the accident.

The variations in the mean wind direction and speed are illustrated in Figure A.5 for two heights in the atmosphere and at various locations (e.g., Kiev, Gomel). On 26 April, 1986, the area around Chernobyl was situated in a low pressure gradient with weak surface winds of variable direction. At a height of between 700 m and 1500 m (the effective height at which material was initially released in the accident) a south-easterly flow with wind velocities of 5-10 m s^{-1} transported the radioactive cloud to the north-west. This was confirmed by environmental measurements and the constructed trajectories of air masses at this height. Material released later on the 26 April was also largely transported to the north-west (in the 700 m to 1500 m layer of the atmosphere) with a subsequent turn to the north. In the layer close to the surface, material was initially transported westward and northwestward and reached the Polish border late on April 26 /early on 27 April. During the following days (27 to 29 April) material in the bound ary layer up to 200 m was transported north and

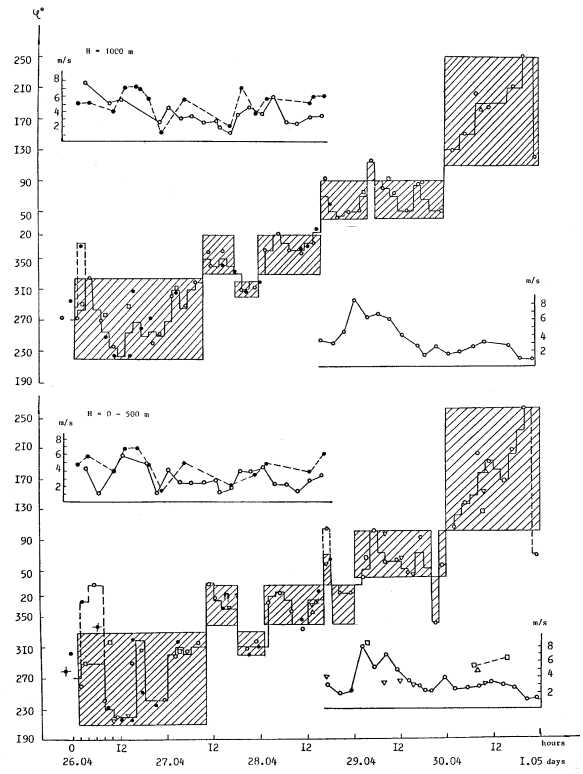

Fig. A.5: Mean values in layer 0-500 m and 0-1000 m of wind direction and speed from 26 April to 1 May 1986 in the region adjacent to the Chernobyl nuclear power plant. + Kiev (radio probe), o Kiev airport, • Borispol, Δ Mozyr, □ Gomel, ∇ Chernigov.

north-eastward from the plant. The release continued until 7 to 8 May under northerly winds resulting in the transport and deposition of material in a generally southerly direction. The effective height at which material was released to the atmosphere in the later stages of the accident was, in general, much lower than that of the initial release. The temporal pattern of released material is illustrated in Figure II.3.

The meteorological situation for the period from 26 April till 11 May is summarised in Plates 61 to 64. Twelve hourly weather maps [A1] are presented together with the total daily precipitation [A2,A3]. The precipitation maps were processed from original measurements. The starting times of measurements of daily precipitation in the respective countries, however, were not identical and differences are tabulated below: these should be taken into account in interpreting the data presented.

Table A.1: Summary of differences in starting times of daily precipitation measurements

Starting hour of measurement (UTC)	Country
5	Bulgaria, Czech Republic, Slovak Republic, Switzerland
6	Austria, Belgium, Denmark, Germany, Finland, France, Greece, Hungary, Luxembourg, Poland, Romania, Sweden
8	Netherlands
9	Iceland, Ireland, Italy, United Kingdom

[A1] European Meteorological Bulletin, Amtsblatt des Deutschen Wetterdienstes, ISSN 0341-2970, Offenbach am Main (in German)

[A2] G Graziani and N Zarimpas, "Meteorological data related to the Chernobyl accident", EUR report 11890, EC, Office of Official Publocations, Luxembourg (November 1988) (in English)

[A3] Yu A Izrael, S M Vakulovski, V A Vetrov, V N Petrov, F Ya Rovinsky and E D Stukin, "Chernobyl: Radioactive contamination of the environment", Leningrad, Gidrometeoizdat, pp. 233-265, (1990) (in Russian)

[A4] Yu A Izrael, S M Vakulovski, V A Vetrov, V N Petrov, F Ya Rovinsky and E D Stukin, "Chernobyl: Radioactive contamination of natural environments", Ed. Yu A Izrael, L. Gidrometeoizdat, 296 pp., (1990) (in Russian)

[A5] Yu A Izrael, V N Petrov and D A Severov, "Modelling of the radioactivity in the close-in zone from the accident on the Chernobyl Nuclear Power Plant: Radioactive environmental contamination in the zone of the Chernobyl Nuclear Power Plant", Moscow Gidrometeoizdat, pp. 5-15, (1988) (in Russian)

APPENDIX B Summary of deposition measuring techniques and data

B.1 Summary of deposition measurements

Deposited radioactive material determines the radiological consequences of an accidental release once the dispersed material has passed overhead. Knowledge of the deposition is the starting point in assessing the transfer of radioactive material through the environment and its impact on man. Equally, it is the starting point in assessing the need for remedial measures to mitigate the consequence of the accident on the affected population.

Various methods to measure radioactive deposition have been developed and continue to be refined. A detailed review of these methods is beyond the scope of this atlas and consideration is limited here to an overview of the most widely used techniques. Further information can be found in the cited references.

The deposition of gamma emitting nuclides can be measured by taking **soil samples** which are subsequently measured in the laboratory using gamma spectrometry. The depth to which soil is sampled (usually up to 30 cm) as well as the methods of sample treatment (eg, removal of vegetation, drying, etc) can vary between laboratories and the circumstances of the deposition (eg, fresh or aged deposit). This method is generally very precise (depending on the measuring time and sensitivity of the detector) but is time consuming and thus costly; moreover, the measurement is specific to the sampling point and many sample may need to be taken where the deposition pattern is very non-uniform. It is most often used for calibration purposes, for small sampling campaigns (up to several hundreds, exceptionally a few thousands of samples) or when other methods can not be applied (e.g. in mountainous regions). The method has the advantage of enabling the depth profile of deposited material to be determined by dividing the soil sample and measuring separately each part.

Large scale monitoring surveys of radioactive deposition can be directly performed (i.e. without sampling) by means of **ground-based gamma spectrometry**. By this method a gamma spectrometer is placed in a fixed configuration with respect to the soil, can be static (***in situ* gamma spectrometry**) or mobile (mounted on a van). The latter technique was used eg, in Finland, where a combination of gamma spectrometric and GM-tube measurements on board of a vehicle was performed to map the caesium-137 deposition for an area of 19,000 km^2 [B1].

Airborne gamma spectrometers, mounted aboard aircraft or helicopters, capable of flying at low altitude (25-100 m) at a velocity of 100-300 km h^{-1}, are used for rapid surveys of terrestrial and aquatic radioactive material. The method was developed initially for geological surveys but has increasingly been used to measure the deposition of artificial radionuclides of various origins. The survey of an area under study is usually carried out using parallel flight-paths, with line spacings typically varying from 0.1 to 10 km depending on the resolution required and available flight resource. A series of gamma ray spectra are recording along the flight lines together with positional information, from navigational systems such as radio beacons or GPS, and ground clearance data based on radar altimetry. With appropriate processing the method is capable of estimating dose rates and the levels of deposited radionuclides with measure rates some 2-3 orders of magnitude greater than available by ground based methods, and with area coverage (taking account of the fields of view of airborne spectrometers) up to 6 or 7 orders of magnitude greater than core samples. Modern airborne spectrometers comprise either high volume scintillation detectors (typically 1-50 litres of NaI(Tl)) or Ge detectors, the latter providing better spectrometric resolution but lower sensitivity. These systems can operate automatically or semi-automatically, and are capable of reliable measurement even at low deposition levels with sampling time of a few seconds.

The various methods have their strengths and weaknesses and, in a well established monitoring strategy, use is likely to be made of several approaches in combination**.** Laboratory analyses of ground based samples better characterise the deposition at the sampling point, but are subject to small scale local variations. Ground-based *in situ* methods are highly sensitive, but require knowledge of the depth distribution. Airborne gamma spectrometry provides a more rapid and representative survey for larger areas, but is also sensitive to the distribution of activity in the environment. A limited number of soil samples is therefore used to determine the radionuclide vertical distribution, for both *in situ* and airborne spectrometry, to allow for a more precise determination of the terrain radioactive deposition than would otherwise be possible. A combination of airborne gamma spectrometry and ground-based measurements thus provides a most effective measuring method to survey large areas with relatively small variation in elevation.

Because they are efficient and can be used to survey large areas quickly, airborne gamma spectrometry was the principal method used for measuring deposition on the territory of the former Soviet Union following the CNPP accident; an area in excess of 5 million square kilometres was surveyed [B2, B3], Sweden [B4] and the United Kingdom [B5**]**.

B.2 Description of the data-sets used

A summary of the data used to compile the maps in the atlas is given in Table B.1. All of the data have been normalised (ie, corrected for radioactive decay) to 10 May 1986. Most of the data were reported in terms of the total deposition (ie, from weapons' fallout, Chernobyl, etc) of caesium-137. In a few cases, data were reported in terms of only the Chernobyl deposits; these have been modified to total deposits using a procedure agreed with individual data suppliers.

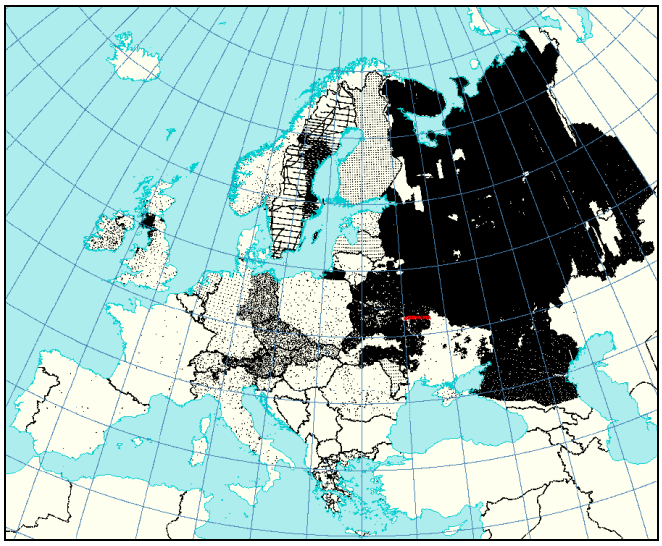

Fig. B.1: Spatial distribution of the caesium-137 deposition data used for the Atlas

The data used in compiling the maps comprised solely those based on soil sampling, *in situ* (static and mobile) and airborne gamma spectrometry**.** Data reported by some countries (e.g. Albania, Bulgaria, Portugal) were in a form that could not be used for the purposes of the atlas, neither directly nor indirectly (eg, measurements of the total deposition of beta emitting radionuclides, concentration of caesium in environmental samples (eg, grass) or foodstuffs, etc). In principle, such data can be used to provide approximate estimates of the terrestrial deposition of caesium-137; however, this was beyond the scope of the project. For these countries and others not reporting any data, maps of caesium deposition could not be prepared; the number of such countries or regions is, however, very small.

The number of discrete data (ie, deposition level at a particular location) used in compiling the maps are indicated in Table B1. They do not, however, necessarily represent the actual number of measurements made nor transmitted. In some countries (especially in Belarus and Ukraine) the reported data are often aggregates of many measurements (eg, to be representative of particular settlements) made in more extensive monitoring campaigns. Where more than one deposition level was reported for the same geographic allocation, the values were averaged by the project staff, after

Table B.1: Summary of data used in compiling the maps of caesium-137 deposition

Country	Surface (1000 km^2)	Number of data used [1]	Type of Sampling	Soil depth (mm)	Modifications made to the reported data [2]
Austria	83.9	1780	SAL	30-400	
Belarus	208	19058	SAL	200	
Belgium	30.5	11	SAL	20	
Croatia	56.5	4	SAL	50-100	
Czech Republic	78.9	776	SAL	30	correction to include global fallout: (Reported level - 0.5)*1.25 + 2.8 kBq m^{-2}
Denmark	43.1	15	SAL	100	
Estonia	45.1	111	AGS	na	
Finland	337	851 8	MGS SAL	na 50	
France	544	35	SAL	ni	
Germany	366	1371	SAL	50-200	
Greece	132	1931	SAL	10,200	
Hungary	93.0	86	FGS	na	
Ireland	68.9	342	SAL	50, ni	
Italy [3]	280	436	SAL	ni, 150	
Latvia	63.7	153	AGS	na	
Lithuania	65.2	90	SAL	na	
Luxembourg	2.59	15	SAL	60-110	
Moldova	33.7	64	AGS	na	
Netherlands	41.2	84	SAL	50	
Norway	324	448	SAL	40	
Poland	313	299	SAL	100	
Romania	238	201	SAL	150	
Russia (European part)	3,800	176971	SAL AGS	150-300 na	
Slovak Republic	49.0	411	SAL	30	correction to include global fallout: (Reported level - 0.5)*1.25 + 2.8 kBq m^{-2}
Slovenia	20.3	57	SAL	120	
Spain	505	31	SAL	ni	
Sweden	450	135848	AGS	na	1.6 kBq m^{-2} added to correct for global fallout
Switzerland	41.3	190	SAL FGS	150-200 na	
Turkey (European part)	24	1	SAL	10	
Ukraine	604	11569	SAL AGS	200 na	
United Kingdom	245	395 45891	SAL AGS	50-150 na	reselection of original data over 1 kBq m^{-2}

SAL: soil sample analysis in laboratory
FGS: field (in-situ) gamma-spectrometry
MGS: mobile gamma-spectrometry
AGS: airborne gamma-spectrometry
ni: no information
na: not applicable

[1] some of these data represent aggregated values obtained from more than one measurement; many of the data for Belarus and Ukraine represent aggregated values obtained from several thousands of original measurements
[2] Corrections in agreement with the data provider
[3] excluding Sicily

correction for radioactive decay. The data for Russia were presented as a grid with different lags (distance between the points). Automatic processing of airborne gamma spectrometric measurements together with soil sampling data was completed by the beginning of this project; a complete map containing the eastern Chernobyl pattern were presented with a lag of 1.3' in latitude and 3' in longitude, the remaining European part of Russia and the Ural region with a lag of 3' latitude and 6' longitude.

The spatial distribution of the data used is illustrated in Figure B.1; wide variation is apparent in the density of measurements in different parts of Europe. Those regions exhibiting the highest density of data (eg, Russian Federation, Sweden, limited areas in the UK) have been surveyed using airborne gamma spectrometry. The data were provided largely by nominated contact points in each country but were supplemented by data from other sources; the sources of data listed in Appendix F

[B1] H Arvela, M Markkanen and H Lemmelä, "Mobile survey of environmental gamma radiation and fall-out levels in Finland after the Chernobyl accident", Radiation Protection Dosimetry, Vol. 32 No. 3, pp. 177-184 (1990)

[B2] R M Kogan, I M Nazarov, Sh D Fridman, "Principles of Environmental Gamma Spectrometry", 3rd ed., rev. and suppl. - Moscow, Energoatomizdat, 233 pp. (1991) (in Russian)

[B3] Yu A Izrael, S M Vakulovski, V A Vetrov, V N Petrov, F Ya Rovinsky and E D Stukin, "Chernobyl: the radioactive contamination of the environmental surroundings", Leningrad, Gydrometeoizdat, 296 pp. (1990) (in Russian)

[B4] H Mellander, "Airborne gamma spectrometric measurements of the fall-out over Sweden after the nuclear reactor accident at Chernobyl, USSR", IAEA internal report IAEA/NENF/NM-89-1

[B5] D C W Sanderson, J D Allyson and A N Tyler, "Environmental Applications of airborne gamma spectrometry", IAEA TECDOC 827, pp. 71-91, IAEA, Vienna (1995)

APPENDIX C Geographic Information Systems and their role within the project

Although the main aim of the atlas is to present information on radioactive deposition, one of the most challenging and innovative aspects of the project were the methods used in the compilation and production of the various maps. The demand for the storage, analysis and display of complex and large sets of environmental data has led to the use of computers, and to the creation of sophisticated information systems. The function of an information system is*, inter alia,* to improve decision making. An information system is that chain of operations that starts with the collection of data which are then analysed to generate new information for the decision making process. A major goal of this project was the use of a computer-based information system to manage, process and display all of the elements that are shown on the maps of this atlas. The tools and methods used to produce these maps are summarised.

By definition, a map is a mathematical representation, to a certain scale and on a flat medium, of a selection of features on, or in relation to, the surface of the Earth [C1,C2]. To be useful, a map must be able to convey information in a clear and unambiguous fashion. In order to achieve this goal, a cartographer must transfer information from the surface of the Earth to a sheet of paper. In an abstract sense, this paper then stores and displays the data that the mapmaker has analysed. In other words a map can be regarded as an information system. A geographic information system is an information system that is designed to work with data which are located by geographic coordinates (also known as spatially referenced). In this sense, a geographic information system (GIS) can be thought of as a high order map product. The term GIS has in recent years become synonymous with a rapidly emerging technology for processing spatial data. A GIS can be defined as a powerful set of computer based tools for collecting, storing, retrieving, transforming and displaying spatial data from the real world for a particular set of purposes [C3]. In simple terms, a GIS can be regarded as a database system for holding information together with an integrated set of operations for working with the data. GIS are rapidly becoming a standard tool for the management of natural resources and the production of high quality output (i.e. maps).

The GIS that was used in this project is ARC/INFO [(1)] version 6.1. In addition to a huge library of tools for processing spatial data and generating high quality maps, ARCINFO includes a relational database interface that allows integration with existing database management systems and an effective programming language (AML) for developing customised applications which was extensively used in this project. ARC/INFO was used because it is probably the most used GIS in the world, which implies that the exchange of information between collaborating groups is relatively straightforward and simple.

The bulk of the cartographic detail for virtually all the maps in the atlas is provided by information contained in the Digital Chart of the World (DCW). The DCW is a global product, produced for the US Defense Mapping Agency [C4] from aeronautical charts. The DCW is a data-set of assorted digital cartographic themes at a scale of 1:1,000,000. Each theme is coded for a number of attributes and the information is presented as latitude/longitude coordinates. The DCW provided a common base from which all maps could be produced. Where necessary, the DCW data have been supplemented by additional information from the European Commission's GISCO database (Eurostat 1994) and from the Lovell Johns 1:5,000,000 European Digital Database. Substantial and extensive editing and re-coding of these data-sets were undertaken in order to satisfy the needs and objectives of the atlas. Some original data capture was performed in order to provide the necessary geographic detail for the larger scale maps.

The information on radioactive sampling from the collaborating laboratories was received in the form of data which could be geographically located by a latitude and longitude coordinate. The spatial information was used to generate a point based theme (or coverage as they are referred to in

ARC/INFO) of the sampling locations. Each point is tagged with a unique identification code and additional information, (eg, the caesium-137 deposition value) and any other attribute information, can then be attached directly.

Because degrees of latitude and longitude are measured in angles from the centre of the Earth, locations listed in degrees cannot be associated with a standard length. Consequently, for any database to be useful for spatial analysis, all data locations must be registered to a common coordinate system. A coordinate system is composed of a spheroid (a mathematical description of the Earth's surface) and a map projection (a mathematical conversion from spherical to planar coordinates). Map projections ensure a known relationship between locations on a map and their true locations on the Earth. For the maps in the atlas, the deposition sampling points were transformed to an equal area map projection (Lambert Azimuth Projection). Once the data have reached this level, the cartographic data (e.g. coastline) can be similarly transformed to the same projection and overlaid to check the locational accuracy of the sampling point coordinates and plotting.

The next phase in the production of the atlas requires the generation of maps that display the point-based sampling data as isolines of caesium deposition. This complex topic is covered more in detail in Appendix D.

Once the deposition maps have been calculated, powerful analysis of the data can be undertaken. The relationship between various themes can be investigated by the simplest of GIS operations such as overlay and buffering. For example, all towns within 100 km of the Chernobyl site can be identified, the relationship between caesium deposition, topography and precipitation levels can be correlated while the effect of urban heat islands on deposition patterns can be assessed.

For any atlas, a crucial element is the presentation of the final results. The deposition data need to be combined with the supporting cartographic data-sets (e.g. roads, rivers, political boundaries) to produce a series of graphic files. As in the case of maps, a GIS provides the user with tools to display data by a range of symbols and colours. Areas can be filled by patterns or solid color, lines can be depicted by varying widths and styles.

It is imperative that the output is of the highest quality. Lovell Johns have developed an innovative routine to transfer ArcInfo coverages into an Apple Macintosh Desk Top Publishing (DTP) environment for the generation of high quality value-added graphics prior to final printing. Once the ARC/INFO files are in this environment, all the elements for plotting appear as individual layers, which further onwards can be arranged appropriately and manipulated as required.

Initial proofing of the maps were carried out on a computer monitor and on paper plots from colour plotters. On completion of the pre-printing stage, a series of postscript files were sent to a high resolution optical film writer which uses a light to transfer the graphics image to colour film. These films were used to produce the master copies for the printing stage.

(1) ARC/INFO is a registered trade mark of ESRI Inc., California, USA

[C1] K G Salishchev, Cartology. MGU, 484 pp (1980) (in Russian)

[C2] C Valenzula, " Basic Principles of Geographic Information Systems" in Remote Sensing and Geographic Information Systems for resource management in Developing countries, edited by A Belward and C Valenzula. Dordrecht: Kluwer Academic, pp. 279 - 295 (1991)

[C3] P Burrough, "Principles of Geographic Information Systems for land resource assessment. Oxford: Clarenden Press (1986)

[C4] Danko, "The digital chart of the world project" in Annual ESRI User Conference 11th, Proceedings: Redlands, Calif., Environmental Systems Research Institute, v. 1, pp. 169-180. (1991)

APPENDIX D Interpolation procedure applied to the basic data

D.1 The point to area conversion

Deposition levels were provided in the form of discrete (point) data located geographically. These data can be of a regular nature (e.g., measurement points along the helicopter flight when using airborne gamma spectrometry survey) or of a rather random nature (e.g., values gridded to settlements, weather stations, research areas, actual point of measurement, etc).

Such data could be presented or displayed in different ways. Presenting the data by points, coloured according to the levels of deposition at the measurement location, is indicative of how thoroughly the territory has been investigated but it disguises the spatial continuity in the deposition patterns. Therefore, as the deposition of caesium-137 is a continuous field, it can be best presented on maps with the help of isolines. Isolines, when connecting equal values of the deposition levels, indicate spatial variation of these levels and single out irregularities in deposition fields.

The data are also presented in the form of Voronoi polygons as this has the added advantage of showing the original structure of the sampling network.

D.1.1 Voronoi polygons

Generally, when the studied variable is continuous, an attempt is made to reconstruct this continuity with the help of models. This can be done with interpolation methods that involve the estimation of the variable at unsampled places. Voronoi polygons, also called Thiessen polygons [D1], have been used to divide each country into areas, with each area representing one data point. These polygons have the property that any point in a given polygon is closer to its associated measurement than that in any other polygon. Each polygon (or data point) is associated with one or more measurement of deposition assigned to a single location. In case more than one data value was found for a single location, the average value was taken. Consequently, areas with small polygons reflect a high density of data points and vice versa. In the following example, data are clustered in the south of the country whereas, elsewhere, they are spatially more homogeneous and less dense.

Fig. D.1: Example: sampling points in Poland

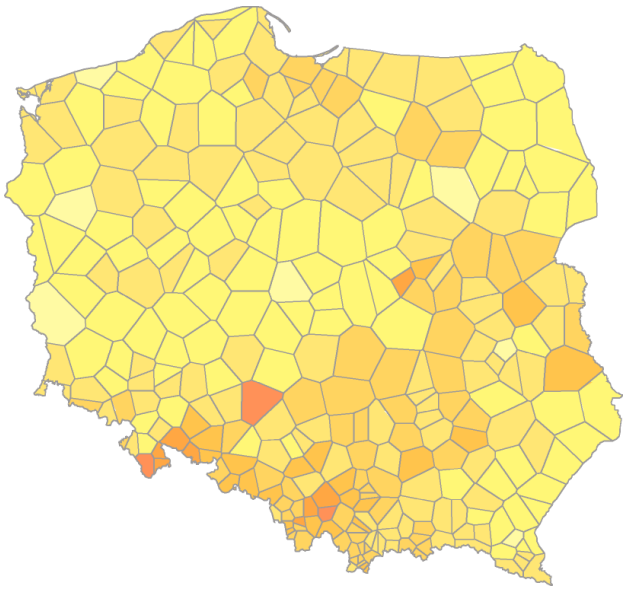

Fig. D.2: Example: Voronoi polygons for the sampling points in Poland

Each data point is taken to represent the deposition value of a certain area; this does not necessarily coincide with the corresponding Voronoi polygon. How representative this area is depends on many factors: the characteristics of the Chernobyl accident, the distance from the CNPP, the relief and the character of the underlying terrain, the nature and intensity of precipitation experienced by the radioactive material as it dispersed over Europe, etc. Therefore, the Voronoi polygons should not be interpreted as a reflection of a real structure of the deposition field, but as a primary model based on the available data. In addition, this method underlines the apparent influence of isolated sampling locations on the general deposition pattern.

D.1.2 Interpolation method used

D.1.2.1 General

The use of Voronoi polygons was not sufficient in our attempt to reconstruct a form of reality. Such technique was indeed mainly based on the need to show to the reader the original data and their relative spatial distribution.

The second approach adopted for the interpolation was to assume the observations to be spatially correlated, i.e., the closer two observations are, the more likely it is that they are similar. Unlike Voronoi polygons, more weight (a scaling factor expressing the importance of a variable) is therefore assigned to nearby points than to distant points. The most common weighting function is the inverse distance weighted (IDW) method [D2] which has, in general, been used here. Although other methods could have been used, this well known method was preferred due to its ease of use and because it provided a good compromise between calculation speed and quality of the interpolation. The use of more sophisticated tools would, in general, have greatly increased the computational resources needed with only marginal improvements in the estimated patterns of deposition. A disadvantage of using the IDW method is that using weighting functions may introduce ambiguity if the characteristics of the deposition patterns, and therefore those of the weighting functions, are not known. Furthermore, this interpolation method is a smoothing procedure, which means that it processes minima and maxima located at sampling points but does not show them on the maps.

D.1.2.2 The inverse distance weighted interpolation method

The inverse distance weighted interpolation method is defined by

$$\hat{v}_i = \frac{\sum_{i=1}^{n} \frac{1}{d_i^p} v_i}{\sum_{i=1}^{n} \frac{1}{d_i^p}} \qquad (1)$$

where $d_1, \ldots, d_n$ are the distances from each of the sample locations to the point $\boldsymbol{v}$ being estimated and $v_1, \ldots, v_n$ are the sample values. The weights are made inversely proportional to the power p of the distance which controls the significance of surrounding points upon the interpolated value. As p decreases, the weights given to the samples become more similar. As p is increased, the individual weights become more dissimilar and almost no weight is given to distant samples so that the local variability becomes more important.

When processing the data, two parameters have to be defined: the search for neighbourhoods and the value of the exponent.

The search for neighbourhoods. Two options were considered in defining a "nearby" sample. Neighbours can be defined by convention as a minimum number of samples or by a maximum radius of search. Using small values for either of these two parameters would increase local variation in the deposition patterns. The preferred approach was to use a search radius when it was possible to define the range of influence of neighboured points.

This can be done with the help of spatial correlation functions, e.g., the semi-variogram which describes the spatial continuity of the data [D3,D4]. The semi-variogram can be defined as

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[z(x_i) - z(x_i + h) \right]^2 \qquad (2)$$

where z(**x**) is the value of the variable (the level of deposition here) at point **x**. The distance and direction between **x** and **x**+**h**, defined by vector **h**, is termed the lag of the semi-variogram. N(**h**) is the number of pairs of observations separated by the lag. The range is defined as the distance at which the observations become independent. The sill is the maximum value reached at the range and is equal to the variance of independent observations.

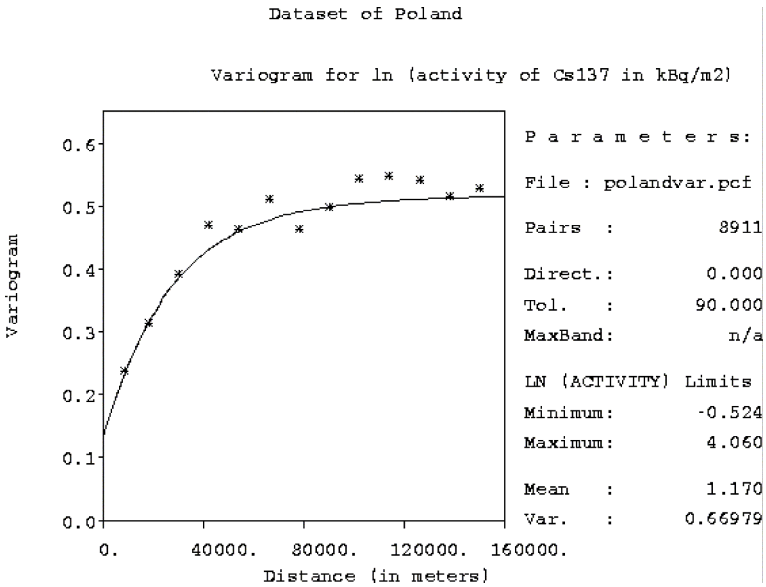

Fig. D.3: Example of a semi-variogram for the Polish dataset

Where possible, the maximum radius of search was defined by the range. Inside this radius, the first 6 neighbours were usually used for interpolation. The choice of 6 neighbours has been often considered here as the best way to show the local variability of the deposition patterns and to reduce the smoothing effect without affecting too much the visualisation of the spatial continuity of the deposition patterns. The structure of the Voronoi diagrams showing the topological weight of the data has been also used in order to define the number of neighbours to use.

As indicated previously, the interpolation approach adopted here is a compromise given the resource and time constraints of the project. The whole topic of interpolation is one which deserves much more detailed analysis than is possible here [D5]. More detailed analysis could lead to the use of more optimal methods and provide greater confidence in the interpolated patterns of deposition. An example of a semi-variogram is shown below (data-set of Poland)

The value of the exponent Because the underlying structure of the deposition pattern is not known, the exponent was estimated empirically with the help of cross validations. Data were randomly extracted from the original data-set and interpolated with increasing exponent values. The estimated values were then compared to the original ones in order to judge the appropriateness of the different values of the exponent. This method has been applied several times for each data-set

with the removal of 5, 15, 25, 35, 45 and 55% of the original data. In general, an exponent of value 2 provided the best fit.

Due to the large number of data used in the interpolation, it is judged that plausible changes in the parameters of the IDW method would not lead to major differences in the deposition patterns in most of the maps presented in the atlas.

D.2 Mapping procedure to present the interpolated values

During the interpolation procedure, the estimated values of the variable at unsampled places were calculated at regular places structured as a square lattice. This procedure is often referred as "gridding". The gridded values can then be converted into a Cartesian matrix consisting of rows and columns. The intersection of the columns and the rows generate cells to which are attributed the value describing the analysed feature. The conversion of an area into such a matrix is known as rasterisation.

In general, rasterised data can be presented in two different ways: by a raster or by isolines. In the case of raster presentation (also called pixel map) every cell is coloured as a function of its value or by isolines. Because of the large variation in the deposition levels, presenting the data in raster format would not have been ideal as it would have required a different colour for every deposition value. It would then have been difficult to see differences between the colours for small variations in the levels of the deposition patterns. Therefore, the use of isolines was chosen to symbolise the continuity of the deposition patterns. Because not all deposition levels can be presented, the reader should recognise that the use of contour intervals always hides the underlying variability of these deposition levels.

On the basis of the general sampling density, the resolution of the raster data was defined by cells of 2 by 2 km for all countries. It should be however clear to the reader that the estimation of unknown values for each cell in cases of low density of sampling locations is not realistic. It was however the only way to keep our techniques as standard as possible, and to facilitate the comparison between the maps. Readers of the atlas should indeed exercise caution when trying to understand or interpret the deposition patterns and should refer to the associated maps presenting the Voronoi diagrams. Subjective judgement played an important role in finalising the maps of deposition. Subjectivity occurred mainly in the interpolation of areas with clustered data and with a high variability. These area had to be filtered as the number of associated isolines were too high and hiding in this way the general pattern. This phenomenon, often encountered when using the IDW interpolation method and generally referred as "bullseyes" effect, can be partly avoided by using resampling techniques which select only the median, the mean, or the most frequent value of surrounding data. The choice of the smoothing technique was based on cross validation techniques and the visual comparison of the original map and its smoothed version.

The users of the Atlas ought not to forget that a map is a model of reality, rather than the reality *per se*. The formal-mathematical procedure of interpolation and computerised mapping is a simplification of the reality as it does not take into account all peculiarities of the environment which have affected the formation of the deposition patterns.

D.3 Application of the procedures

The procedures described above were used to prepare the maps for all countries and at all scales. The maps for Belarus, the Russian Federation and Ukraine were further refined using information not specifically available within the joint project. In this process, account was taken of the totality

of the measured data (as opposed to aggregated data available in the project), their relative quality or reliability, and the characteristics of different surfaces landscapes (eg, forests, industrial areas, agricultural land, etc) onto which deposition was measured or being interpolated.

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[D3] A G Journel and Ch J Huijbregts, “Mining Geostatistics”, Academic Press (1978)

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APPENDIX E Interface between deposition and other geographical features

The significance of the deposits of caesium-137 on the territory of Europe depends on the nature of the underlying surface and uses made of it. For example, had all deposits occurred on sparsely populated areas of the Arctic the radiological impact on man would have been considerably less than had all deposits occurred over areas of high population density or agricultural production. The inter-relation between the distribution of deposition and distributions of such quantities as the population and agricultural production is essential in determining the radiological and environmental impact of a given deposit. While the assessment of environmental impact goes far beyond the scope of this atlas, information on a number of relevant geographic features is presented to enable the reader to gain a better appreciation of how they relate to the distribution of deposited caesium-137. Maps on a European scale are presented for the distribution of population density [E1,E2], soil type [E3], vegetation-land use [E4] and elevation [E5]. (See Plate 65)

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[E2] D Rhind, "Cartographically-related research at Birkbeck College 1987-91" in "The Cartographic Journal", Vol. 28, June 1991, pp. 63-66.

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[E4] "Global Vegetation Index Users' Guide (rev. Oct. 1990)", comp. and ed. by K B Kidwell. Available from the U.S. Department of Commerce, U.S. National Oceanic and Atmospheric Administration

[E5] "European 30 arc-second Digital Elevation Model (DEM)", EROS Data Centre, US

APPENDIX F National contact points - additional data sources

Data sources and national contact points

Data were largely, but not solely, provided through designated national contact points; bold type-face is used to identify the latter.

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E Fleck, Wien
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A Kosovetz, V Vol'shev, State Committee of Hydrometeorology of Ukraine, Kiev
G G Poturidis, Minchernobyl, Kiev

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Scottish Nuclear
Scottish Office Environment Department
Ministry of Agriculture Fisheries and Foods
HTV
District Councils of Cunninghame, Kilmarnock, London, Kyle, Carrick

APPENDIX G Data sources - bibliography

The data were provided largely by nominated contact points in each country but were supplemented by data from other sources; the sources of data listed in Appendix F.

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Belarus

See Russia

I I Matveenko – personal communications

Belgium

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D Cesar, Z Franic, G Marovic, J Sencar; Institute for Medical Research and Occupational Health, Department of Radiation Protection, Zagreb - personal communications

I Valcic, Ministry of the Economy, Departement of Nuclear Safety, Zagreb - personal communications

Czech Republic

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Denmark

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Germany

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Greece

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Hungary

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Ireland

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Italy

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APPENDIX H List of tables and figures

Main text

Appendices

Commission of the European Communities

ATLAS OF CAESIUM DEPOSITION ON EUROPE
AFTER THE CHERNOBYL ACCIDENT

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The atlas contains maps of the deposition on Europe of caesium-137 which was released in the Chernobyl accident in 1986. Maps are provided on three scales: European, national/regional and local. Perspective is also provided on the current radiological significance of these deposits.