BY0000124

The Atlas of Caesium-137 Contamination of Europe after the Chernobyl Accident

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Abstract. The Atlas, which was compiled under the Joint Study Project (JSP6) of the CEC/CIS Collaborative Programme on the Consequences of the Chernobyl Accident, implemented into the European Commission's Radiation Protection Research Action, summarizes the results of numerous investigations undertaken throughout Europe to assess the ground contamination by caesium-137 following the Chernobyl accident. The Atlas incorporates about 100 color maps at a range of scales (1:200k - 1:10M) which characterize the contamination in Europe as a whole, within state boundaries and for zones where the contamination levels are above 40 kBq/m^2 (≈ 2.0% of the European territory) and above 1480 kBq/m^2 (≈ 0.03% of the European territory). Investigations have shown that around 6% of the European territory has been contaminated for more than 20 kBq/m^2 after the Chernobyl accident. The total amount of deposited caesium-137 in Europe is 8× 10^{16} Bq and distributed in the following manner: Belarus 33.5%, Russia 24%, Ukraine 20%, Sweden 4.4%, Finland 4.3%, Bulgaria 2.8%, Austria 2.7%, Norway 2.3%, Romania 2.0%, Germany 1.1%.

1. Introduction

The Chernobyl nuclear power plant (CNPP) accident of 26 April 1986 was followed by a partial destruction of reactor IV which resulted in a significant release of radioactive material into the natural environment. The release from the Chernobyl incident was much greater than either the Windscale (United Kingdom) or the Three Mile Island (USA) reactor accidents.

As a result of the complicated meteorological situation which persisted after the accident and the relatively long exposure of the reactor to the atmosphere, radioactive materials were deposited over a wide area. In the vicinity of the CNPP, graphite and particles from the destroyed reactor were deposited while finer particles were found at substantial distances from the site. Depending on the prevailing wind direction and precipitation events during the weeks immediately following the accident, volatile products such as iodine-131 (with a half-life of 8 days), tellurium-132 (3.2 days) and long-lived caesium-137 (about 30 years) were spread over thousands of kilometers. In the days immediately following the accident, contaminated air masses moved west, then north-west then north-east. As a result territories, in the Ukraine, Belarus, the European part of the Russian Federation and, to a lesser extent, Scandinavia were heavily contaminated. Subsequently, the wind direction switched to the south then swung to the south-west, bringing the radioactive cloud over the Balkans and the Alps. Several days after the accident, the air masses carrying the radioactive particles had traversed almost all European countries.

Based on a series of radioactivity measurements carried out after the accident, it was determined that volatile fission products (Te-132 and I-131) deposited in close proximity to the accident (i.e. up to a distance of 40 km) amounted to about 5% of those in the reactor. Similar studies of refractory products amounted to about 1% while Cs-137 was approximately 2%.

The total radioactive release which was deposited over the European territory amounted to 4% of the total radioactivity accumulated in the reactor, of which Cs-137 was about 15% or $\approx 7.8 \times 10^{16}$ Bq ($\approx 4 \times 10^{16}$ Bq of this amount was deposited over the former USSR territory).

During the initial period of the accident the largest doses resulted from I-131. After the initial period, especially for the area outside of the evacuation zone, caesium-134 and caesium-137 were the major contributors to the exposure of the population. The external dose from caesium-137 between one and fifty years on differently directed patterns was 75-90% of the dose of the total sum of radionuclides deposited over the terrain.

After the Chernobyl accident various compilations have been made of the contamination of particular countries or regions in Europe. These compilations have been made for different purposes and consequently there are significant differences in their resolution and quality. To date no attempt had been made to compile a comprehensive presentation of the contamination over the whole territory of Europe, the continent on which by far the majority of released material was deposited. In many cases improved data have since been, and continue to be, obtained through more refined and extensive monitoring, in particular in those areas where greater contamination occurred.

Therefore it is opportune to prepare a comprehensive atlas of the radioactive deposition of the whole of the European territory consequent upon the Chernobyl accident. The publication of such an atlas by the tenth anniversary of the accident would have wide public and scientific interest. In addition to the more obvious interest in and use of the factual content of the atlas, it would provide most useful and needed perspective, especially in the former Soviet Union, for judging the significance of the contamination.

2. The Objectives

Since caesium-137 presents a long-term threat for the population of Europe and given its wide dispersion across the continent, the European Commission accepted a proposal on a joint study to compile "The Atlas of caesium contamination of Europe after the Chernobyl accident". The goals of the Atlas are:

- to provide generalized and detailed information on the distribution of caesium-137 in soil over the whole European territory, and separately by countries.
- to provide an estimate of the total amount of caesium-137 deposited across Europe and separately by country as a result of the Chernobyl NPP accident.
- to assess the external gamma dose from the Chernobyl caesium-137 and compare it with that from natural radionuclides in soils and rocks, as well as that from cosmic radiation.
- to familiarize the general public, governmental and municipal bodies with a comprehensive view of the pattern of caesium-137 across the whole of the European continent.

In the future, based on the data analysis made for the Atlas, the problem of the harmonization of the different sampling and measurement methods between different countries can be analyzed in order to improve the quality of the information that could be exchanged. Also, because the measurements on which the Atlas is based have been made sometimes at identical locations but at different times, it should be possible to investigate the behavior of the caesium-137 in a wide variety of European soils and under different climates. Finally, the spatial analysis of these data should bring us new information about the way to improve the sampling structures and the analysis of these data.

3. The Content and the Structure of the Atlas

The Atlas contains about 100 color maps, mostly of A2 format, with accompanying texts. Although other artificial radionuclides were released, it was decided to present only caesium-137 levels, because of the availability of the many measurements performed throughout the European countries and because it is by far the major contributor to dose other than in the very short term following the accident. Since this radionuclide was already deposited due to the atomic bomb tests, the situation before and after the Chernobyl accident can be compared.
The following chapters describe the five sections of the Atlas.

3.1. The Introductory Section

This section deals with:

- an overview of the phenomena of radioactivity for the layman (natural and artificial radioactivity, scientific units) as an explanation of external dose. Additionally this is illustrated with small scale maps of Europe containing information about natural and artificial radioactivity:
  - natural radionuclides including external gamma doses;
  - dose rate from cosmic radiation;
- a brief description of the history of the Chernobyl accident, the temporal dynamics of radionuclide fallout together with their volumes, as well as an assessment of the scale of the catastrophe;

3.2. The Data Section

This is by far out the largest part of the Atlas. Because the radioactive material was deposited in a highly inhomogeneous way, and because the various European countries adopted different sampling strategies resulting in maps with varying sampling densities, the Atlas presents the caesium-137 deposition at various scales. All deposition levels are normalised to 10 May 1986, the day at which the radioactive release from the reactor stopped. The scale with isoline values (see Table 1) is based on scientific and administrative considerations: since deposition is purely a physical phenomena, it is normal practice to present it by a consistent logarithmic scale. On the other hand, political and administrative deposition levels which were adopted in the former USSR, i.e. 185, 555 and 1480 kBq/m^2 (resp. 5, 15 and 40 Ci/km^2) have to be considered.
The values chosen for the caesium deposition isolines depend on the scale of map. A summary is presented in Table 1. In order not to overload the European overview map with information, alternative values on this scale are presented. The levels of the highest contamination are only shown on the local maps with deposition values > 1480 kBq/m^2: these areas are relatively small and require a separate scale to show appropriate details.

Table 1: Isoline values of the caesium-137 contamination density by map type.

Contamination levels *		Map type			
		European	Country	Local	
kBq/m^2	Ci/km^2			> 40 kBq/m^2	> 1480 kBq/m^2
0.4	0.01	+	+		
1	0.027		+		
2	0.054	+	+		
4	0.1		+		
10	0.27	+	+		
20	0.54		+	+	
40	1.08	+	+	+	
100	2.7		+	+	
185	5	+	+	+	
555	15		+	+	
1480	40	+	+	+	+
4000	100				+
10000	270				+

(*) The values shown are preliminary and may be subject to changes with respect to those presented in the atlas

3.2.1. The Overview Section

This subsection contains radiological information at a European scale presented in the following maps:

- pre Chernobyl caesium-137 deposition (normalised to 10 May 1986) at scale 1:20M (1:20,000,000);
- post Chernobyl caesium-137 deposition (normalised to 10 May 1986) at scale 1:10M;
- caesium-137 external gamma dose.

Figure 1 shows an initial attempt to map caesium-137 deposition in Europe. It is possible to show from the map in Fig. 1 that levels > 20, > 40 and > 1480 kBq/m^2 were deposited on respec-

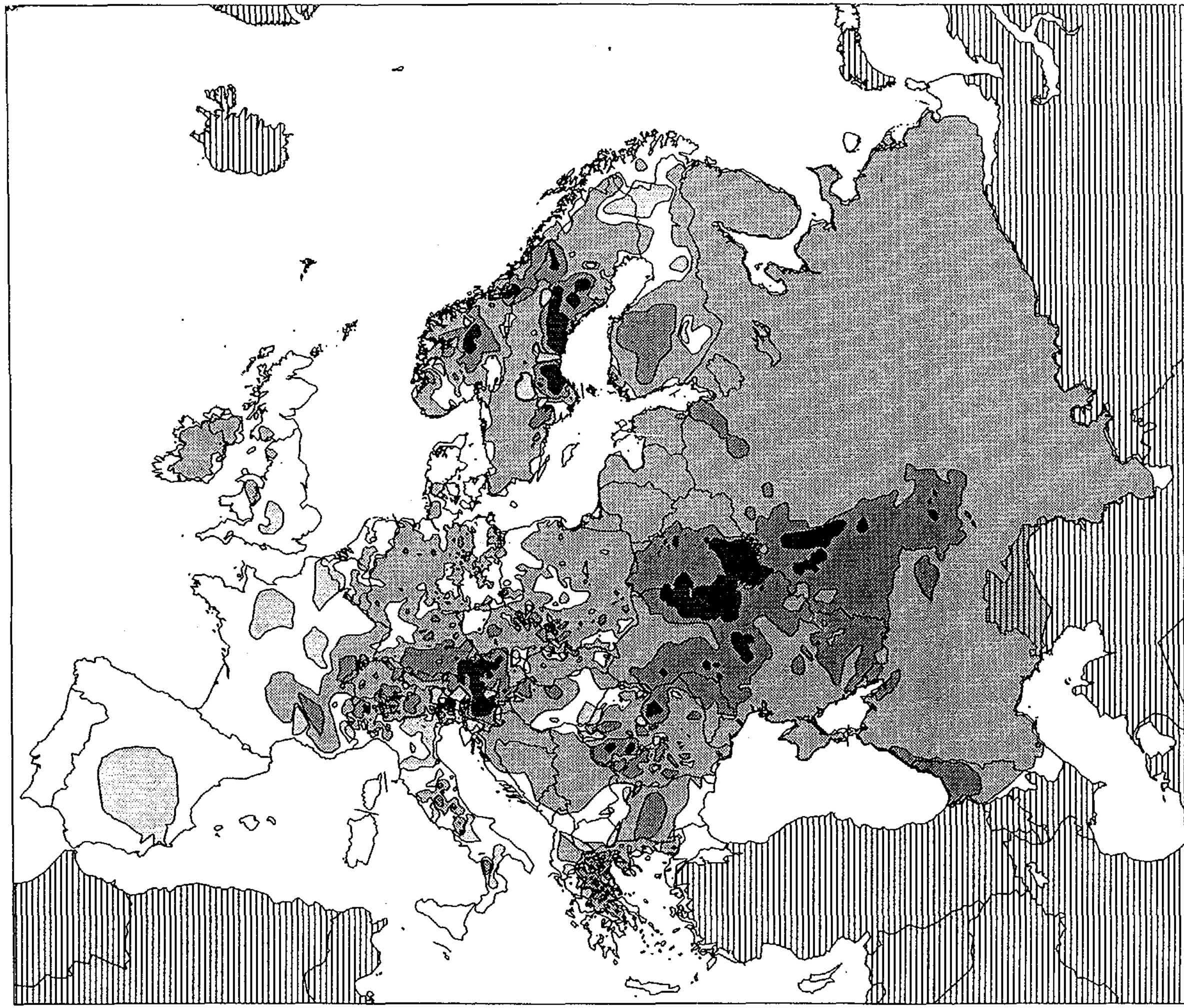

Fig. 1: Initial attempt to map total caesium-137 deposition levels across Europe, normalised to 10 May 1986.

tively ≈6%, ≈2% and ≈0.03% of the European territory. Table 2 shows the areal extent of contamination by caesium-137, for the various deposition intervals, for Europe as a whole. The total amount of caesium-137 deposited in Europe is about 8×10^{16} Bq.

Table 2: The areal extent of total caesium-137 (bomb fallout + Chernobyl) deposition in Europe

Cs-137 deposition interval (kBq/m^2)	Area ($\times1000$ km^2)	% of the European territory
>1480	3.1	0.03
555-1480	7.2	0.03
185-555	19	0.2
40-185	211	1.7
20-40	432	3.6
10-20	871	11.6

The map in Fig. 1 also indicates the direction of caesium-137 deposition patterns. The eastern pattern, passing from the Chernobyl NPP across the Russian territory to the Urals and further to Siberia, is clearly seen. In the Ukraine, several southern patterns, interrupted by the Black Sea, are observed with their onward contamination being recorded in Bulgaria, Turkey and Greece. The south-western patterns leave noticeable spots in the Ukrainian Carpathians, later on appearing in the Balkan mountains. The western patterns, passing across the territory between the Ukraine and Belarus show a series of northward branches, then turning eastward. This leads to the deposition patterns for Belarus, Poland, Germany, Lithuania, Sweden, Norway, Finland and the Leningrad oblast of Russia. In the Alps, some anomalies with levels above 40 kBq/m^2 are observed.

3.2.2. The Country Map Section

In order to give more geographical and radiological details to reflect the national or regional situation, the country map section includes maps showing the caesium-137 deposition in almost each European country at a medium scale (1:1M - 1:2.5M), together with the sampling/measuring locations.

Table 3 shows the areas of Chernobyl contamination by caesium-137 in European countries as calculated from the map shown in Fig. 1. The results were obtained by multiplying the average deposition value with its corresponding area. These areas were calculated by means of Autocad. Special attention was given to the region around Chernobyl with deposition levels > 1480 kBq/m^2, where the calculation of the corresponding areas was performed on 1:200k maps.

3.2.3. The Section on High Contaminated Zones

This section contains maps that present deposition information for local zones:

- maps with levels above 40 kBq/m^2: zones of enhanced contamination (i.e. parts of Scandinavia, the Alps, Greece, Rumania, Russia, Belarus and Ukraine) are highlighted by means of large scale maps (1:500k);
- maps with levels above 1480 kBq/m^2: the highest contaminated zones, i.e. certain areas of Briansk-Mogilev and Chernobyl-Pripiti, are shown on very large scale maps (1:200k). An example for the 60 km zone around Chernobyl can be found in Fig. 2.

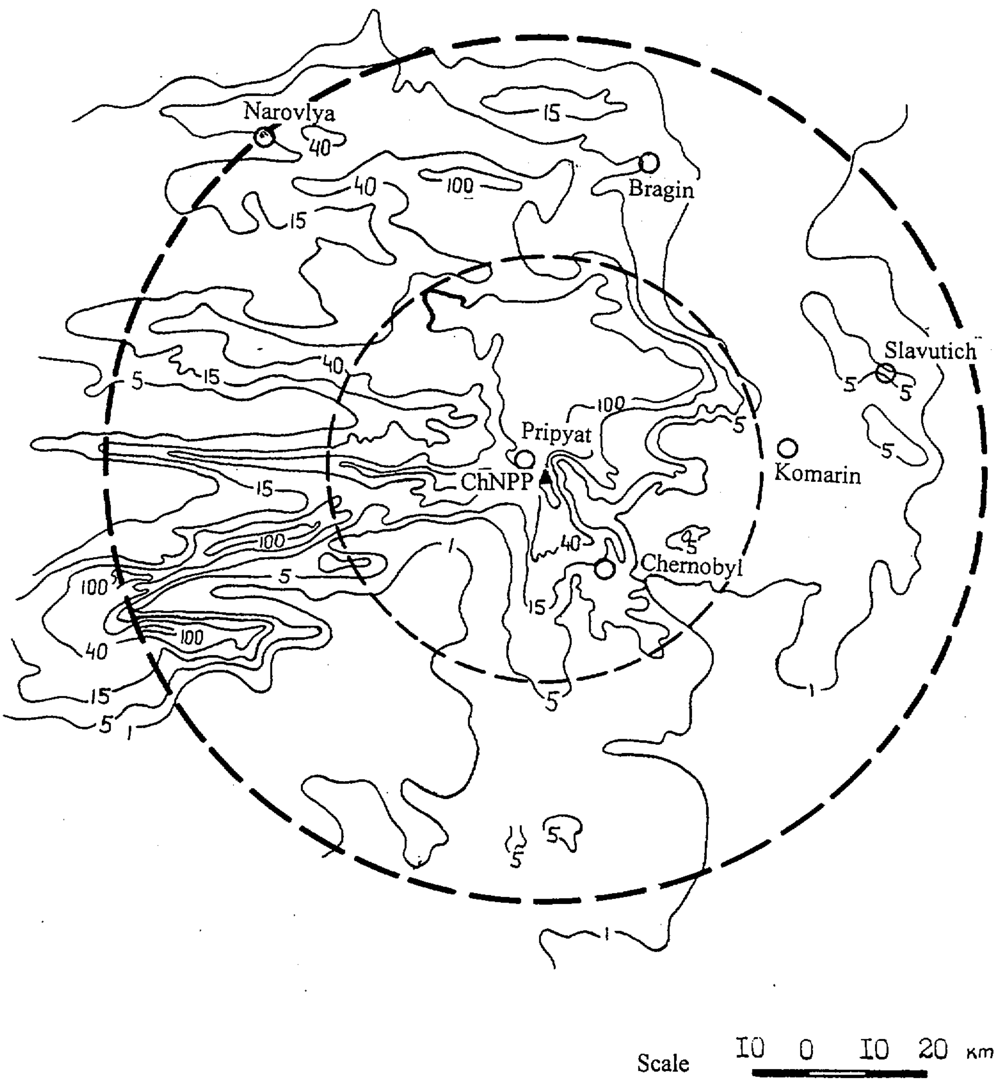

Fig. 2. *sixty km zone map around Chernobyl. Deposition levels of caesium-137 (1989) for 185, 555, 1480 and 3700 kBq/m^2 (on the map indicated as 5, 15, 40 and 100 Ci/km^2)*

The quality of the mapping is determined largely by the density of sampling and measurement points. Hundreds of thousands of measurements were performed in the Ukraine, Belarus, Russia and Sweden by aerogamma surveys conducted at scales of 1:200k and 1:1M at flight altitudes of 50-150 m. About ten thousand soil samples were taken in Central and Western European countries. The territories of Norway, Finland, UK, Greece, Germany, the Netherlands, Austria, and Switzerland are most completely investigated.

Table 3: caesium-137 (total) contaminated areas in European countries in thousand km²

Countries	Area (in 1000 km²) contaminated above specified levels (kBq/m²)						% of contamination deposited in Europe (%)
	10-20	20-37	37-185	185-555	555-1480	>1480	
Belarus	60	30	29.9	10.2	4.2	2.2	33.5
Russia	300	100	48.8	5.7	2.1	0.3	23.9
Ukraine	150	65	37.2	3.2	0.9	0.6	20
Sweden	37.4	42.6	12.0	-	-	-	4.4
Finland	48.8	37.4	11.5	-	-	-	4.3
Bulgaria	27.5	40.4	4.8	-	-	-	2.8
Austria	27.6	24.7	8.6	-	-	-	2.7
Norway	51.8	13.0	5.2	-	-	-	2.3
Romania	14.2	43.0	-	-	-	-	2.0
Germany	28.2	12.0	-	-	-	-	1.1
Greece	16.6	6.4	1.2	-	-	-	0.8
Slovenia	8.6	8.0	0.3	-	-	-	0.5
Italy	10.9	5.6	0.3	-	-	-	0.5
Moldova	20	0.10	0.06	-	-	-	0.45
Switzerland	5.9	1.9	1.3	-	-	-	0.35
Poland	8.6	1.0	-	-	-	-	0.23
Estonia	4.3	-	-	-	-	-	0.08
Czech Rep.	3.4	0.36	-	-	-	-	0.09
Slovak Rep.	2.1	-	-	-	-	-	0.05
Lithuania	1.2	-	-	-	-	-	0.02

3.3. The reference section

The reference and information section of the Atlas includes supporting maps on population density, soil type, elevation and vegetation for Europe, at scales of 1:15-20M.

3.4. The meteorological section

Deposition patterns depend largely on the wind fields and precipitation patterns. Meteorological data, (daily precipitation and twelve hourly wind fields) during, and for two weeks after, the initial release are presented on 1:40M scale maps.

3.5. Technical appendices

Technical appendices to the Atlas consist of a description of the methods used for soil sampling, remote and laboratory measurements of caesium-137 contamination density together with the procedures used to process the data and compile the maps.

4. The map compilation procedure

One of the important elements of this project is the use of a Geographic Information System (GIS) for the preparation and production of the maps showing the density of caesium-137 deposition across Europe. A GIS is a set of software tools designed to efficiently capture, store, update, manipulate, analyze and display all forms of geographically (or spatially) referenced information. Certain complex spatial operations that would be very difficult, time consuming or impracticable in traditional database or computerized drawing packages are possible only with a GIS [1]. Individual datasets can be stored as separate layers which can then be combined with each other as required allowing relationships, trends and patterns to be visualized. The GIS being used in this project is ARC/INFO, version 6.1., a powerful software developed by ESRI Inc. of California. ARC/INFO includes a relational database interface for integration with commercial database management systems (DBMSs) and a fourth generation macro language for developing customized applications.

The cartographic detail for the European and Country scale maps is provided by information contained in the Digital Chart of the World (DCW). The DCW, produced by the US Defense Mapping Agency [2], is an established dataset of assorted digital cartographic features for the world at a scale of 1:1M. This provided a common base from which all the maps within the Atlas could be produced. Where necessary, the DCW data have been supplemented by additional information from the Lovell Johns 1:5M European Digital Database and the European Commission's Eurostat GISCO Database. Some digitizing was undertaken in order to add further geographical detail to the larger scale maps (e.g. to add localities in order to improve the visualization of the large scale maps). Substantial editing of the DCW was necessary prior to its effective use in the Atlas.

The information on radioactive deposition from the collaborating laboratories came in the form of point data, geographically located by a latitude and longitude coordinate. This information is stored in the GIS which creates a 'point' coverage (or theme) of the sampling locations for the area of interest whereby each point is tagged with a unique identification code. Additional information, such as caesium level and any other attribute information, can then be attached directly to the location through the point's identification code. The deposition sampling points are then transformed to a suitable equal area map projection (in this case the Lambert Azimuth Projection). Once the data have reached this level, cartographic data (e.g. coastline) can be overlaid for checking the locational accuracy of the sampling point coordinates. This primary analysis of the data includes also the analysis of the relation between different layers: e.g. the meteorological parameters and the elevations have been compared to the spatial distribution of the contamination; the display of the cities could explain in certain cases the lower deposition levels in those areas as the heat generated by the cities can be an obstacle to the radioactive deposition.

The next stage in the project requires the generation of maps that display isolines of deposition. This task, depending on the density of the points and the requested degree of resolution of the map, requires a degree of interpolation and generalization of the radiation data. More details on the methods used can be found in the Atlas.

In case of densely distributed points, the inverse distance weighted interpolation method has generally been used. In other cases, deeper and more complex investigations were necessary and have required external software like GEOEAS [3], GSLIB [4], VARIOWIN [5] and basic statistical packages. The very general steps of such analysis were finding the populations which were presenting different spatial distribution of the contamination, finding models which would describe these distributions and finally interpolate these data on the base of these models. The result of these interpolations are new point coverages with regular structures and with data generated at the unsampled places. This data can then be contoured and represented with isolines.

5. Conclusions

By collecting more than 500,000 data related to the spatial distribution of caesium-137 in Europe after the Chernobyl NPP accident, the Atlas has clearly shown the importance of such a dataset. For the first time it is possible to provide a comprehensive map of European contamination after the Chernobyl accident, useful for scientific community and also enable layman to better appreciate the extent of the contamination and its relative impact. Since the Atlas was fully electronically prepared the data could be made available on CDROM, useful for further scientific study. Taking into account the radioactive decay for caesium-137, the user of the Atlas can estimate the radioactive levels in the future over all Europe. Further onwards, the data generated by interpolation during the preparation of the Atlas can be used as a reference to which scientists can compare new measurements in order to analyze the contamination in time, and this for different regions and for different conditions. Further to these conclusions, it is hoped that this study can be expanded to other long-lived (e.g. strontium-90, plutonium-238, -239, -240, and americium-241) and short-lived (e.g. I-131) radionuclides.

Acknowledgments

The Atlas was compiled under the Joint Study Project (JSP6) of the CEC/CIS Collaborative Programme on the Consequences of the Chernobyl Accident, implemented into the European Commission's Radiation Protection Research Action.

The authors gratefully acknowledge the invaluable contribution to this project by all the collaborating and participating institutes in terms of the supply of data and in the constructive comments that they have provided, as well as Gregoire Dubois for his important efforts in introducing and applying spatial analysis techniques for the deposition interpolation procedures.

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