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Luxembourg, January 1987

A PRELIMINARY ASSESSMENT OF THE RADIOLOGICAL IMPACT OF THE CHERNOBYL REACTOR ACCIDENT ON THE POPULATION OF THE EUROPEAN COMMUNITY

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National Radiological Protection Board

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ABSTRACT

Following the Chernobyl accident the Commission of the European Communities asked the National Radiological Protection Board to carry out a preliminary assessment of the radiological consequences of the accident on the population of the European Community (EC). The aim of the study was to review information on the environmental contamination measured in member states of the EC; to make a preliminary assessment of individual and population doses for each country; to make an estimate of the resulting health impact and to indicate the effects of the various countermeasures taken by member states in terms of the reductions in both individual and population exposure which they produced.

All of the main pathways by which people have been and will be exposed to radiation as a result of the accident were included in the assessment. The impact estimate is based on environmental measurements made during the month after the accident, and on calculations made using mathematical models of radionuclide transfer through the environment.

The calculated effective doses to average individuals in EC countries from exposure over the next 50 years range from 0.3 μSv (in Portugal) to between about 300 and 500 μSv (in the FRG, Italy and Greece). The total collective effective dose to the population of EC countries, integrated over all time, is estimated to be about 80 000 man Sv. This may be compared to the collective effective dose from natural background radiation of about 500 000 man Sv every year. In some countries, the restrictions placed on consumption of some foods are estimated to have been effective in reducing doses to the most exposed individuals; the reduction being up to about a factor of 2. Throughout the EC, however, countermeasures are estimated to have reduced the collective effective dose by about only 5%.

There are significant uncertainties in parts of the assessments and in the future improved assessments of the radiological impact of the Chernobyl accident will be made. The results presented in this paper should therefore be regarded as preliminary.

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The Appendices to this report are in a separate volume which is currently being prepared.

1. INTRODUCTION

The accident at the Chernobyl Unit 4 reactor in the USSR, in April 1986, resulted in large quantities of radioactive materials being released into the atmosphere over a period of several days. During this time a complex set of meteorological conditions occurred which dispersed and deposited these materials over large areas of Europe. Levels of radioactivity in the environment were monitored by national authorities, and in some countries countermeasures were introduced in order to reduce the radiation exposure of individuals in the population.

Several papers have already been published in the scientific literature reporting environmental measurements made by various institutions and assessing the implications of these measurements in terms of predicted radiation doses to exposed individuals. These studies have tended to be for specific countries and are, by their very nature, only first estimates. The aim of the study described in this report is to review the environmental contamination measured in member states of the European Community (EC); to make a preliminary assessment of individual and population doses for each country; to make an estimate of the resulting health impact and to indicate the effects of the various preventive measures instigated by member states in terms of the reductions in both individual and population exposure which they produced.

This report summarises the main conclusions of the study. The detailed scientific and technical information that support these conclusions are presented in a separate volume of appendices to the main report. The uncertainties in some parts of the assessment are large, and the authors therefore wish to stress the preliminary nature of the results.

2. GENERAL DESCRIPTION OF THE ACCIDENT

The accident at Unit 4 of the Chernobyl nuclear power station occurred on the 26th April 1986 during a test of the ability of one of the turbines to supply the reactor's power requirements should a power failure ever occur(1). However, a series of human errors, whereby safety systems were deliberately switched off and operating rules were ignored, brought the reactor into an unstable condition. A rapid increase in power occurred at 0123h local time on the 26th (2123h GMT on the 25th), followed by a steam explosion which shifted the top cover off the reactor. After 2-3 seconds, a second explosion occurred and hot pieces of the reactor were ejected from the destroyed reactor building. A mixture of radioactive gases and particulate matter was carried to heights exceeding 1200m(1).

The release of radioactive material to the atmosphere continued over a period of about 10 days with two peaks in release rate, on the first day (26th April) and on the 9th day (5th May) during which time mitigating actions by the Soviets brought the reactor into a state where further major releases were unlikely(1).

Figure 1 shows estimates of the areas of land covered by the main body of the plume at various times during the release. The figures are based on trajectories calculated by the UK Meteorological Office(2) assuming that the release of material to atmosphere started on Saturday, 26th April and continued until Monday, 5th May. Figure 1(a) shows that on Saturday, 26th, the day of the accident, only areas to the north of Chernobyl were affected by the plume, but that by Monday (Figure 1(b)) areas of Scandinavia and north-east Poland were affected. Radiation readings on the central and eastern coast of Sweden were 14 times normal, indicating that a plume of radioactivity had reached Scandinavia, and alerting the international community that a large accident had occurred. By Wednesday (Figure 1(c)) the wind direction at the site had changed leading to a plume of material travelling to the south and east. At this time also a complex frontal system developed over Europe. A high pressure system caused the contaminated air mass to split, spreading activity over other regions of Europe.

By Friday the 2nd May (Figure 1(d)) the initial contamination had reached as far as the UK, while contamination now emanating from Chernobyl was moving southwards over Greece. By Saturday 3rd May (Figure 1(e)) the area of contaminated air extended from north-western Europe to south-eastern Europe. On Monday 5th May, the main contaminated air mass lay over southern Germany, Italy, Greece and eastern Europe, with the remains of the initial contaminated air mass dispersing over the Atlantic. By Tuesday, 6th May the rate of release from the damaged reactor had fallen to relatively low levels. Where there had been rainfall during the time of plume passage, radioactive material was washed out from the cloud and deposited on the ground at levels that were high relative to neighbouring areas where it did not rain. This was particularly the case in parts of Italy, Greece, the Federal Republic of Germany and the British Isles.

Following the initial alert by the Swedish authorities, monitoring for radioactive contamination was increased by all countries in Europe and others elsewhere. Initially attention was given to measuring radiation dose-rate and the concentration of various radionuclides in air and on the ground. The most important nuclide as far as health consequences to the population were concerned was correctly identified in the early stage of the incident as iodine-131. The group in the population which was most at risk was identified as young children drinking fresh milk from animals grazing contaminated pastures. Other foods, such as leafy green vegetables and fruit, were identified as possible sources of exposure. Depending on the level of contamination found and also on the radiological criteria being applied, a range of countermeasures were instigated by national authorities to limit radiation exposure. These countermeasures included, for example, changing grazing animals' diet from pasture to uncontaminated stored feed, instructing people to wash fruit and vegetables before eating them, advising people against drinking undiluted rainwater, and, in countries where the levels were particularly high, the withdrawal of fresh milk and vegetables from public consumption. These countermeasures remained in place for various lengths of time, ranging from a few days to a month in some places, again depending on the radiological criteria being adopted by the particular member state and on the environmental levels found.

As the levels of the short-lived iodine-131 (half-life 8 days) fell over the next few weeks attention moved to the longer lived isotopes of caesium. In some cases additional countermeasures were introduced to limit the long term intake of caesium radioisotopes. Concern about fresh milk and vegetables became reduced but other foods, such as meat and milk products, became of increased importance. A range of radionuclides have been detected in various environmental materials in all countries since the Chernobyl release. In all cases the most important radionuclides are iodine-131, caesium-134 and caesium-137; other fission product radionuclides were found including tellurium-132, ruthenium-103 and ruthenium-106. The actinides have been detected but at very low levels; compared to the other radionuclides found these levels are of small radiological significance.

Figure 2 shows the variation in the total accumulated deposit of iodine-131 throughout Europe. The highest levels of deposition occurred where there was heavy rainfall during the passage of the radioactive plume. Of the EC member states the highest levels of iodine-131 contamination were seen in southern Germany, followed by Greece and Northern Italy. Similar patterns of deposition of caesium-137 were found, as illustrated in Figure 3. However, there are some differences, due to the differing behaviour of the two radionuclides. Figures 2 and 3 are based on the available environmental data for each country, which varied in the degree of detail provided, and inevitably judgement was used in producing these figures. They are thought to be a fair representation of the general situation in each country or region but areas within each region could have higher or lower depositions depending on local factors.

3. THE DOSE ASSESSMENT PROCEDURE

Following the release of radionuclides to atmosphere people will be irradiated via a number of different routes. While the cloud is overhead people will be exposed to external irradiation from material in the cloud and internal irradiation following inhalation of the material. Radioactive material is removed from the cloud during transit and transferred to the ground. This results in the exposure of people by other routes notably: external irradiation from the deposited material, the inhalation of resuspended material, and the transfer of material through the terrestrial environment to foods consumed by people. In this preliminary assessment only those pathways which are likely to give rise to significant radiation exposure have been considered. These are: external irradiation of the whole body from the cloud and from deposited material, and internal irradiation from inhalation of the material in the cloud and from ingestion of contaminated foodstuffs. Resuspension of deposited material has been shown to be a minor contributor to radiation exposure following accidental releases to atmosphere containing predominantly iodine and caesium radioisotopes(3). Pathways leading solely to exposure of the skin, and the resulting risk of contracting skin cancer, have not been considered in this preliminary study.

In this study doses are assessed only for the EC countries. No account is taken of the consumption of foods imported from non-EC countries and doses to individuals travelling to non-EC countries have not been evaluated. In general, these omissions are not likely to lead to under estimation of doses in each member state. A possible exception to this would be for countries with relatively low levels of contamination where omitting to include imports of food from more contaminated areas could lead to a slight underestimation of the radiation doses received.

Because the radionuclides released from Chernobyl have half-lives ranging from a few hours to many years, the dose is not delivered to individuals uniformly as a function of time. Typically the dose-rate is highest in the first few days following the arrival of the radioactive plume, falling to a much lower level which then persists for many years. In order to give some impression of how the radiation exposure varies with time, the doses delivered in the first year and those received in subsequent years are calculated and presented separately in this study.

Details of the dose assessment procedure are given in Appendix A. The main principles involved in estimating external and internal doses are briefly discussed in the following sections.

3.1 External irradiation pathways

In the calculation of radiation doses from external irradiation only penetrating gamma rays are considered. The weaker beta particles from radionuclides in the cloud and deposited on the ground give rise to doses primarily to the skin, and have not been considered. External exposure depends on the distribution of the radionuclide concentration in the plume and on the ground, the energy of the radiation emitted by each radionuclide, and the transmission of the radiation from the source through different media to the body. In calculating external exposure from the cloud, simple mathematical models were used to relate the dose to the concentration of radionuclides in air, as discussed in Appendix A. Where possible, calculated dose rates in air were compared with measured dose rates known to be due solely to the radioactivity in the plume.

External radiation exposure from deposited material varies depending on the deposition process, the nature of the surface and the shielding provided by any surrounding structure. Following deposition the dose rate above the surface will decline due to radioactive decay and the removal of material from the surface by natural weathering processes. In this study measured external gamma dose rates were used to estimate the radiation dose from deposited material in the first 30 days following deposition. For later times models were used to predict the external dose, from the total amount of activity deposited on the ground, allowing for both radioactive decay and natural weathering processes. The details of this calculational procedure are given in Appendix A. Care was taken to ensure consistency between the measured doses and those predicted by models.

In calculating external radiation doses from both routes of exposure account is taken for the attenuation of gamma radiation by buildings. Allowance is made for the time that people spend indoors and the shielding properties of buildings.

3.2 Internal irradiation pathways

In determining the internal irradiation of people it is first necessary to know the concentration of radionuclides in the environmental materials that are taken into the body, ie, air, food and water. The amount of each material ingested or inhaled is then required, so that the intake of the radionuclide of interest by this pathway can be calculated. Finally a dosimetric model is required so that the extent of internal irradiation received following the intake of the radionuclide can be calculated. Only intake by inhalation and ingestion is considered in this study; another possible route of intake is via the skin but this is comparatively unimportant in this case.

Direct inhalation of radionuclides in the cloud is modelled simply using the measured air concentration multiplied by an inhalation rate to determine the intake rate of the radionuclide. Indoor air concentrations are assumed to be lower than those outdoors and, as for the external irradiation pathways, allowance is made for the length of time people spend indoors.

Radionuclides deposited on the ground may be transferred to a number of terrestrial foods. The extent to which a particular food will be contaminated will vary depending on the characteristics of the nuclide concerned and the particular environment. The season of the year in which an accidental release occurs also has an important influence on the subsequent transfer of radionuclides through the foodchain. In this study measured concentrations of radionuclides in various foods are used where possible to predict the radiation exposure from ingestion. Terrestrial foodchain models have to be used, however, to predict how the measured concentrations in foods will vary as a function of time. Such models are also used to estimate concentrations of radionuclides in foods which have not been measured. The details of the models used and the various assumptions made are given in Appendix A. The following foods have been considered in the assessment of internal exposure from ingestion : beef, lamb, root vegetables, green vegetables, fruit, milk, milk products, grain, game and fish. Some of these foods are only taken into account when assessing the dose to a more exposed individual, rather than the average member of the population. There are a few foods that technically are not included in this categorisation scheme (eg, shellfish, mushrooms). However the omission of these extra foods is unlikely to affect the dose estimates significantly. Where possible the intake rates assumed for the various foods are those appropriate for the country of interest.

Radionuclides can also be ingested by the inadvertent consumption of contaminated soil and dust. Previous studies(4) have shown this route of intake to be insignificant compared with the ingestion of contaminated foodstuffs for those radionuclides of concern here. This pathway of exposure has, therefore, not been considered in this study.

The concentrations of radionuclides in rain-water were relatively high in some areas following the Chernobyl accident. However, because there is usually a large dilution of this water with existing uncontaminated water, the concentration of radionuclides in drinking water is rarely a large contributor to individual dose. In this assessment only doses to individuals obtaining the majority of their water supplies from undiluted rain-water have been assessed.

Unlike external irradiation, which ends if the source of exposure is removed, internal irradiation continues in time following an intake of radioactive material, even if no further intake of activity takes place. In radiological protection it is conventional practice to express doses from intakes of radionuclides as the dose received over the lifetime of an individual (usually taken to be 70 years) from intakes in a given year. This approach is adopted in this study. Thus doses "in the first year" (see Section 4) are those received over a lifetime from intakes in that year, while doses from intakes in subsequent years are those integrated over the lifetime of an individual from all intakes. For adults the integration period is taken to be 50 years, implying that all adults are aged 20 years. Therefore, doses to adults are slightly over estimated by this procedure, which takes no account of the age distribution in the population.

Once a mixture of radionuclides has been taken into the body, they can be re-distributed between the various body organs according to their chemical properties. In this way there can be widely different radiation exposure to different organs in the body. In principle, the radiation doses to each organ can be evaluated and the risk of an adverse health effect from that exposure assessed. However it is convenient to express in a single number a quantity that broadly represents the risk to health. This can be achieved by taking the doses in each of the major organs and tissues of the body and multiplying them by a weighting factor according to the risk associated with a unit dose to that organ. The sum of these weighted doses is called the "effective dose equivalent", abbreviated in this report to "effective dose". In this preliminary assessment effective doses have been evaluated for individuals in each country, and because of the pre-dominance of iodine-131 in the release, which concentrates in the thyroid gland after intake, thyroid doses have been evaluated separately.

3.3 Estimation of individual dose

The radiation dose to any given individual depends on many factors, including the fraction of their time spent outdoors, their breathing rate and diet, their body size and metabolism. Thus for any given measured level of contamination, there can be a relatively wide range of individual doses. In order to provide some idea of the likely range, doses due to the internal irradiation pathways have been estimated for three representative age-groups, namely, a 1 year old infant, a 10 year old child and an adult. This has been done by using intake rates of air, water and various foodstuffs appropriate for each age-group, and taking into account the body size and metabolic characteristics of each group. The variation with age of external irradiation doses is small and is not considered in this study. In addition, for each age group doses have been evaluated for an average member of the population, and separately for a "critical" member of the population, that is a theoretical person with habits which lead to higher than average exposure from all of the pathways considered. Thus doses were calculated for six sets of individuals in all.

Average individuals have food intake rates representative of the means for the country of interest and are assumed to eat food containing average levels of contamination. Wherever possible, intake rates recommended by each country were used. Where such information was not available, the intake rates used were those given for a country that was judged to be similar in dietary habits. In some cases the intake rates available were for 6 months old infants rather than 1 year olds; these were used in the assessment but could lead to slight under or over estimates of the doses to 1 year olds depending on the foods concerned. Individuals comprising the theoretical "critical group" are assumed to have higher than average intake rates of all of the foods, and the levels of contamination of all the foods, together with the external dose rates are taken as representative of the higher levels measured. No individual would actually consume all these types of food with above average contamination and at a high rate. Individuals in the critical group are also assumed to spend a greater part of their time outdoors than average and to live in buildings with less shielding than average. These assumptions will lead to an overestimate of doses to actual individuals and are intended to give an idea of the possible upper end of the range of doses in the population. Details of the intake rates and other habit data assumed in this study are given in Appendix A.

3.4 Estimation of collective dose

It is often useful to have a measure of the total radiation dose to a whole population. Quantities used to express these totals are called collective doses and they are obtained by adding all the individual doses in the population. In this study we have calculated both collective effective doses and collective thyroid doses, and have evaluated them separately for the populations of each member state of the European Community.

When calculating the collective doses from the ingestion of contaminated food, a problem occurs in assessing the individual doses in the population, because it is not known from what location an individual obtains his diet. Two methods of estimating collective doses can be used. In the first method we assume that people obtain all their food locally and that the distribution of food production is the same as that of the population. This method is relatively easy to apply, requiring population distribution data but no agricultural production data. However the results may not be accurate, because people do not generally obtain all their food locally. In the second method we assume that all food produced will be consumed by someone and in calculating collective doses it is not necessary to identify the individual consuming it. This method is more accurate but requires additional information on agricultural production, and cannot indicate the ranges of individual dose that make up the collective dose. In this study collective doses have been evaluated by both methods and the results of each approach are compared.

In estimating collective doses the intakes and dosimetric quantities are taken to be those of an average adult. The effect on the collective dose of treating the children in the population separately is relatively small and has not been considered in this preliminary assessment.

3.5 Environmental measurement data

Once the Chernobyl release became known national authorities in the EC member states all took steps to increase their routine environmental monitoring programmes. In all cases a large number of environmental measurements were made both during the time when the plume of radioactive material was overhead and subsequently; such measurements are continuing. The degree of detail in which such measurement data have been reported varies from country to country. In some cases full reports have been prepared and issued, detailing the various measurements and discussing their implications. In other cases the various data are still being collated and are only available in a preliminary form. In carrying out this preliminary study data were obtained from a number of sources including the Commission of the European Communities and the countries themselves; generally only those measurements made before June 1st are included.

As indicated in the previous sections there are a number of environmental measurements that are required to estimate the radiation exposure via the various routes. These are: external gamma dose rates, preferably throughout the first 30 days following the arrival of the plume; concentrations of radionuclides in air during the time the plume was overhead; concentrations of radionuclides in rain-water and in various foods; and the measured total deposit of radionuclides on the ground. The way in which these measurements are used is discussed in Appendix A. Appendix B discusses in detail the data available on a country-by-country basis, which data were used in the assessment procedure, and how they were converted for input to the assessment model.

Not all of the detailed environmental data available can be used in this type of study; instead representative values have to be chosen as input to the assessment. This choice of data requires a degree of judgement which adds to the uncertainty of this preliminary dose assessment. The data were considered for each country and were then used to predict individual and collective doses for that particular country. In some cases there was a marked variation in the reported environmental levels for different regions of the country. This was generally associated with a higher degree of contamination in some parts of the country due to rainfall during the passage of the radioactive plume from Chernobyl. In these cases the country was divided into regions, within which the degree of contamination was thought to be relatively uniform for the purpose of calculating average or collective doses. As the whole of the EC was being considered in this study these regions necessarily still covered large areas and in a more detailed study smaller regions could be considered. However, it is thought that the regions chosen enable a reasonable estimate to be made of the collective dose and the range of individual doses within a country. Details of the reasons behind the choice of regions for each country are given in Appendix B. Belgium, Denmark, Ireland, Greece, Luxembourg, Netherlands and Portugal were not divided into regions as either the contamination levels were relatively uniform throughout the country or sufficient data were not available. France, Italy, the Federal Republic of Germany (FRG), Spain and the United Kingdom (UK) were divided into various regions as discussed in Appendix B. Figure 4 shows the countries and regions for which individual and collective doses were evaluated in this study.

3.6 Countermeasures taken to reduce radiation doses

Following an accidental release of radionuclides to atmosphere there are a number of possible countermeasures that can be taken to reduce radiation doses to people. In the EC countries all of the measures taken have been to reduce the exposure from the consumption of contaminated food or water. In areas of relatively high iodine-131 deposition restrictions were placed on the distribution and consumption of some fresh milk supplies (in Greece, Italy and the FRG) and some dairy products mainly from sheep and goats (Greece and Netherlands). Also people were advised at least to wash fresh vegetables and in some cases not to eat them, or supplies of vegetables, notably spinach, were withdrawn from sale (in France, Greece, Italy, Luxembourg, Netherlands and the FRG). To reduce the amount of activity reaching fresh milk in parts of Denmark, Italy, Netherlands and the FRG cattle grazing on pasture were brought indoors and given stored, uncontaminated feed. Also in the short term following the accident people in some areas, eg, in parts of the UK, were advised not to drink undiluted rain-water. In the longer term, as levels of caesium radionuclides became of concern, additional countermeasures were taken in some countries. In Greece, sales of lamb and goat meat were restricted. In some areas of the UK restrictions on the movement and slaughtering of sheep were introduced. A full discussion of the countermeasures introduced in each country and the length of time for which they were maintained is given in Appendix B.

Where possible, the effect of the countermeasures has been estimated here in terms of reductions in individual and collective doses. In principle, doses are first calculated for the countermeasures that were taken and then the calculation is repeated to estimate the dose that would have resulted had no countermeasures been applied. This was easier to do in some cases than in others. For example, where all cattle were taken indoors the measured levels of radioactivity in milk were all low and no samples of milk from cattle on pasture were available. In these cases models were used to predict what the concentrations in milk would have been if cattle had been grazing. There is obviously uncertainty associated with the use of such models and hence in the prediction of radiation exposure without countermeasures. Where restrictions were placed on the sale or consumption of certain foods it was possible to estimate the doses assuming that the foods had been eaten. The doses taking account of the countermeasure were then simply calculated by assuming that foods in an affected area, or contaminated above a given level were not consumed. Due to limitations in the available results of the model used to predict concentrations in food as a function of time, for this preliminary assessment countermeasures were assumed to be imposed for set times of 7, 30 or 100 days.

4. RESULTS OF THE DOSE ASSESSMENT

Full details of the individual and collective doses calculated for each country and region are given in Appendix C. The important features of these results are discussed in the following sections.

4.1 Average Individual Doses

The average effective doses to adult individuals in each EC country from exposure in the first year following the Chernobyl accident are shown in Table 1 and Figure 5. These doses are summed over all radionuclides and exposure pathways and were calculated taking account of any countermeasures imposed. Where different regions within a country were considered, the average dose was obtained by taking a weighted mean of the results for each region, based on population in the regions. The weighted average doses for each country range from 0.2 µSv (in Portugal) to 150-300 µSv in the FRG, Italy and Greece. Table 2 shows the contribution of the various pathways to these doses, and from this it can be seen that, in most cases, consumption of food and external irradiation from deposited material are the major contributors to doses in the first year. Differences between countries in the relative contributions of these two pathways are partly due to the countermeasures adopted and are partly artificial, arising from the uncertainties in the data used in the dose estimates rather than from a genuine difference in exposure patterns. In the case of food consumption, the average doses in the first year are mainly due to caesium-134 and caesium-137, which together contribute between about 65% and 90% of the dose, the remainder being due to iodine-131.

Average doses to the thyroids of individuals in the first year after the accident are shown in Table 3 and Figure 6. In general, the pattern of results is the same as that of effective doses, but there are small differences due to variations in the amounts of iodine and caesium radioisotopes deposited in regions and countries.

Effective doses to average adults from exposure over the 50 years following the accident are given in Table 4 and Figure 7. Comparison of these results with those in Table 1 and Figure 5 shows that exposure in the first year contributes between 45% and 75% to the total 50 year dose. Over this time period, the most important radionuclide is caesium-137.

The average effective doses may be placed in perspective by comparing them with the effective dose received each year from natural background radiation. In Europe, average individual doses from natural background are in the range 1000-2000 μSv per year. Thus average doses to individuals over the 50 years following the Chernobyl accident will be less than those received in one year from natural background radiation.

4.2 Doses to the Critical Groups

Effective doses to the theoretical critical group in the first year after the accident are shown in Table 1 and Figure 5 for each country. In Figure 5 the critical individual dose given is the highest result obtained from the calculations for each region, and in all cases is for the age group with the highest predicted doses. Differences between countries are partly a reflection of the different intake rates assumed, but are mainly due to variations in environmental concentrations between the countries. The critical group effective doses range from 4 μSv in Portugal to about 1000-2000 μSv in Italy, Greece and the FRG. The critical group of individuals consists of 1 year old infants, 10 year old children or adults depending on the country concerned, and generally there is little difference in the doses predicted for the 3 age groups. The most important exposure pathway in all cases is ingestion of contaminated food. For infants milk is generally the most important food but for the other age groups milk, lamb, green vegetables, grain and fruit all make significant contributions to the critical group dose.

Doses to the thyroids of the theoretical critical group in the first year after the accident are shown in Table 3 and Figure 6. In nearly all countries the critical group consists of 1 year old infants. The exception is Italy where 10 year olds form the critical group. These doses range from about 50 μSv to about 30 000 μSv, and are dominated by radioisotopes of iodine, taken into the body via milk.

Due to the complexities of calculating doses to individuals whose habits change with time, it has only been possible in this preliminary assessment to calculate effective doses over the next 50 years for the critical groups of adults. These results are given in Table 4. They range from 3 μSv to 3800 μSv, and between 45% and 90% of the 50 year dose arises from the first year of exposure. For children the first year's dose would contribute a larger percentage of the total dose integrated over time.

It should be noted that in calculating theoretical critical group doses, doses were not included which may have been received through drinking undiluted, contaminated rain water or through eating goats and sheep milk, fish or game meat. In general, no information was available about whether individuals are likely to have drunk rain water, nor about the time over which they might have done so. Such information was, however, available for the UK. Taking account of the advice issued concerning rain water, the effective dose to the critical group of infants from this pathway is estimated to be 320 μSv. Adding this to the effective dose in the 1st year given in Table 1 and Figure 5 would increase the total dose by about 40%. For other EC countries, calculations were also made of the doses which would have been received from consuming undiluted rain water for a day. The effective doses to the critical age group (infants) range from 100 μSv to 1000 μSv.

With the exception of Greece there was no information available on the levels of radioactivity in sheep and goats' milk or products made from these types of milk. Levels particularly of iodine-131, would have been higher than in cows' milk and depending on the relative intakes of the different types of milk could have led to slightly higher doses than predicted here. However, in Greece where data are available, including the consumption of sheep and goats' milk does not substantially change the estimated doses due to the restrictions introduced on the supply of these products.

There is little information on levels of contamination in aquatic foods eaten in the EC, but the available data indicate that these levels are generally low. However, a few, less commonly eaten, fresh water fish monitored in the UK have been found to be more highly contaminated. The effective dose to a theoretical critical group of adults from consumption of these more highly contaminated fish is estimated to be about 300 μSv in the first year. This is about 35% of the dose to the critical group of adults from the pathways considered in this study.

Data on the concentrations of radionuclides in game meat were only available for FRG and UK. In the UK and FRG it is estimated that the effective dose to the critical group (adult) from consumption of game meat would be about 80 μSv and 360 μSv respectively, in the 1st year after the accident, which is about 10% and 20%, respectively, of the dose to the critical group of adults from other pathways.

Again these theoretical critical group effective doses can be compared with the effective dose received each year due to natural background radiation (1000-2000 μSv). In no countries is the theoretical effective dose estimated for critical groups much greater than that received in one year from natural background, and in most cases it is considerably lower.

4.3 Collective Doses

Estimates of the collective effective doses to the populations of EC countries in the first year after the accident, and the collective effective doses integrated over all time (ie the collective effective dose commitments), are given in Table 5. Table 6 shows the corresponding collective doses to the thyroid.

The collective effective dose commitment to the whole population of the EC is estimated to be 78 000 man Sv. The highest collective effective doses are those to the populations of the FRG (30 000 man Sv) and Italy (27 000 man Sv), because contamination levels in these countries were relatively high and their populations are relatively large. The main pathways contributing to the collective effective dose are consumption of contaminated food and external irradiation from deposited material. In the first year food consumption is the dominant pathway, but in later years external irradiation from deposited material increases in relative importance. For both pathways, caesium-137 is the most important radionuclide.

The total collective thyroid dose to the EC population is estimated to be 170 000 man Sv. The dominant radionuclide in this instance is iodine-131 and since this has a relatively short radioactive half-life (8 days), a large fraction of the dose has been received within a few weeks of the accident. For thyroid doses, ingestion is the most important pathway.

The estimated collective effective dose in the EC from the Chernobyl accident in the first year after the release is less than 10% of the collective effective dose from natural background radiation in a single year (500 000 man Sv).

As discussed in Section 3.4, two methods were used to calculate the collective doses from ingestion; the one using only population data and the other using data on agricultural production. The results presented in Tables 5 and 6 are those obtained using the agricultural production method. The results obtained using the two methods were generally in good agreement although the production data method tended to give slightly higher results than the population data method. For example, in Denmark and Ireland, the collective effective doses predicted by the production data method were a factor of two higher than predicted by the other method. This is because these countries produce a large amount of agricultural products relative to their population size. If a significant fraction of their agricultural products is exported the collective doses estimated would not all be delivered within the country of origin.

4.4 The effect of countermeasures

The introduction of countermeasures will, in general, have the greatest impact on the radiation exposure of the critical groups in the population. Table 7 shows the effective doses estimated for theoretical critical groups in the first year following the accident, calculated with and without taking account of the introduction of countermeasures. Also shown is the percentage of the dose saved by the countermeasures. The largest calculated reductions in dose are for Greece and Italy, where restrictions on the consumption of milk and green vegetables were introduced. It is estimated that these restrictions could have led to a factor of two reduction in the dose received by critical groups. Significant reductions in the individual effective doses are also estimated for the FRG, the Netherlands and to a lesser extent the UK. It should be noted that for the UK the reduction in doses due to the introduction of restrictions on sheep was probably higher because the general model for the transfer of activity to sheep used in this assessment underestimates the dose saved in a few areas affected by the restrictions. As discussed in section 4.2 the consumption of sheep and goats' milk, and rain water, have not been included in the calculation of critical group doses. For Greece the effective dose to the critical group (child) from the consumption of sheep and goats milk in the first year would have been 3500 μSv. The three month ban on the consumption of these products effectively reduced the dose received to that estimated without including sheep and goats milk. For the UK the effective dose saved by the restrictions on drinking rain water is estimated to be 160 μSv for the critical group of infants which is about 20% of the theoretical dose estimated for this group.

The calculated reductions in thyroid doses to theoretical critical groups are also shown in Table 8. The reduction in the thyroid dose is generally greater than the reduction in the effective dose. This is because the thyroid doses are mainly due to iodine-131 and are received in a relatively short time. In most cases, countermeasures introduced for short periods were effective in reducing the dose from iodine-131 but had less influence on the effective doses which are mainly due to the caesium radioisotopes and which will be delivered over longer time periods.

Table 9 shows the total collective effective dose commitment and the collective dose commitment to the thyroid calculated with countermeasures, and the calculated reductions in collective dose. Throughout the EC countermeasures are calculated to have reduced the collective effective dose by about 5% and the collective thyroid dose by about 26%. The countermeasures are estimated to have had slightly more effect on the collective doses in the FRG, Greece and Italy.

5. THE HEALTH IMPACT ON THE POPULATION OF THE EUROPEAN COMMUNITY

5.1 Scientific background

If individuals are exposed to very high levels of radiation, serious injury and even death can occur within a matter of weeks. The radiation doses received by even the critical individuals in the EC as a result of the Chernobyl incident were well below those at which these early, acute effects of radiation would be manifested. In predicting the health impact on the EC population it is therefore only necessary to consider incidence of longer term health effects. In this preliminary assessment estimates are made of the total number of cancer fatalities which may occur in the exposed population and because of the importance of iodine-131 concentrating in the thyroid gland, the predicted incidence of fatal and non-fatal thyroid cancers.

The fundamental processes by which cancer is induced by radiation are not fully understood, but a greater incidence of various malignant diseases, cancers for short, has been observed in groups of people who were exposed to various high doses of radiation years previously, pre-eminently the survivors of the atomic bombings in Japan. Studies of patients who have been exposed to radiation for the treatment of non-malignant conditions or for diagnostic purposes, of people exposed to intense nuclear fallout in the Marshall islands, of uranium miners, and of workers in the radium luminising industry, have also provided data which broadly corroborate those from the Japanese bomb survivors. These studies can be used to derive "risk factors" which express the predicted excess numbers of various cancer types in a group of exposed individuals that may be attributed to the radiation doses received by that group. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)(5) reviews all the information on risk factors periodically, and has provided estimates of risk factors for cancers as a result of irradiation of various tissues at moderately high doses. Based on these factors and interpolating between the observed effects and zero, an excess of 100 thyroid cancers would be expected in a population receiving a collective dose to the thyroid of 10 000 man Sv, and of these 5 would be expected to be fatal. In a population receiving a collective effective dose of 10 000 man Sv the total number of cancer fatalities expected would be 125. These risk factors have been used in this assessment because they are based on a worldwide scientific consensus.

5.2 Results

The collective doses, both effective and thyroid, are presented in Tables 7 and 8 for each member state of the EC. Using the risk factors given above, estimates can be made of the numbers of non-fatal and fatal thyroid cancers (from collective thyroid doses) and total numbers of fatal cancers (from collective effective doses) which would be statistically expected in the EC following the Chernobyl accident.

In this way, the expected number of additional thyroid cancers occurring within EC countries due to Chernobyl is estimated to be some two thousand, of which about 5% are expected to result in fatality. The number of additional fatalities from cancers of all types due to Chernobyl is expected to be in the region of a thousand. These extra cancers are predicted to occur spread out in time over a few decades following the accident.

The estimates need to be seen against the background of cancers that would occur in the population even if the Chernobyl release had not happened. Over the next fifty years about thirty million people in the EC countries are expected to die from cancer of one type of another(6); the additional number of cancer fatalities due to Chernobyl, which are expected to occur over roughly that same time period, is about a thousand. Similarly, the number of thyroid cancers expected in EC countries over the next fifty years, even if the Chernobyl release had not happened, is of the order of three hundred thousand, whilst the accident itself is expected to give rise to a further two thousand over the same period.

Since members of the EC population are also subject to continuous irradiation from natural radiation sources, for example, cosmic rays, terrestrial radiation, and irradiation from naturally-occurring materials in the diet, it is possible to make an estimate of this contribution to the natural cancer fatalities in the EC population using the same risk factors. A typical annual effective dose from natural sources is about 2000 µSv; this corresponds to approximately eight thousand cancer fatalities per year in the EC due to natural radiation sources, or nearly half a million over a fifty year period, which is nearly five hundred times greater than the excess cancer fatalities predicted to result from the Chernobyl accident.

6. DISCUSSION

In carrying out this preliminary assessment of the radiological impact of the Chernobyl accident it has been necessary to make various judgements and to adopt certain assumptions. We have used available environmental monitoring data where possible and in general consider that these data are reliable. However, in a number of cases it has been necessary to extrapolate from the available data, using judgement and models of environmental transfer processes.

In this study individual and collective doses were calculated taking into account any countermeasures taken following the accident. In some cases this required a considerable amount of judgement as to exactly how the countermeasures were implemented and how effective they were. There is a possibility that in some cases people managed to avoid following the countermeasure, eg by ignoring advice not to consume certain foods. It is likely that some people took their own additional precautions, further reducing their radiation doses. It is not possible to take account of such individual variations, which are likely to have little effect on the predicted average individual and collective doses.

The uncertainties in the average individual doses are thought to be of the order of a factor of 2-3 and are mainly due to uncertainties in food intake rates. The uncertainties in the estimates of collective doses are probably similar to those of the average individual doses.

The estimates of theoretical critical group doses required more assumptions than the estimates of average individual or collective doses and have a greater uncertainty associated with them. However, due to the cautious assumptions adopted the theoretical estimates of critical group doses are likely to be overestimates. It should also be recognised that as well as individuals in the population receiving an above average dose, as represented by the theoretical critical group doses, some individuals will receive doses well below the average.

7. SUMMARY AND CONCLUSIONS

1. The assessment described in this report is a first attempt to estimate the radiological impact of the Chernobyl reactor accident on the populations of all the European Community (EC) countries. The impact estimate is based on environmental measurements made during the month after the accident, and on calculations made using mathematical models of radionuclide transfer through the environment. Full details of all the input data for the study, the calculations and the results are given in a separate volume of appendices to this report.

2. In the study, estimates were made of average doses to individuals in EC countries, of doses to theoretical critical groups of individuals and of doses to the population as a whole. All the main pathways by which people have been and will be exposed to radiation as a result of the accident were included. From the collective doses, estimates were made of the numbers of radiation-induced health effects which may occur over the next few decades. In addition, the effects of the countermeasures taken in the various countries (for example, imposing bans on the consumption of some foods) were evaluated in terms of the reductions in doses which they produced.

3. The calculated effective doses to average individuals in EC countries from exposure over the next 50 years range from 0.3 μSv (in Portugal) to between about 300 and 500 μSv (in the FRG, Italy and Greece). For perspective, these may be compared with the average effective dose to an individual from natural background radiation, which in EC countries is between 1000 μSv and 2000 μSv every year.

Effective doses to the theoretical critical groups in the the first year after the accident are estimated to be about 1000-2000 μSv in Italy, Greece and the FRG.

4. The total collective effective dose to the population of EC countries, integrated over all time, is estimated to be about 80 000 man Sv. This may be compared to the collective effective dose from natural background radiation of about 500 000 man Sv every year. Approximately three quarters of the 80 000 man Sv will be received in the FRG and Italy.

5. In some countries, the restrictions placed on consumption of some foods are estimated to have been effective in reducing doses to the most exposed individuals. Doses may have been reduced by about a factor of 2 in a few instances. Throughout the EC, however, countermeasures are estimated to have reduced the collective effective dose by about only 5%.

6. Over the next fifty years about thirty million people in EC countries will die of 'natural' cancers. The theoretical number of extra cancers predicted due to the Chernobyl accident is of the order of 1000. It will therefore be impossible to detect the health impact of the accident.

7. Over the coming months and years, improved assessments will be made of the radiological impact of the Chernobyl accident on the populations of the EC, and other countries. The results presented in this report should therefore be regarded as preliminary.

8. ACKNOWLEDGEMENTS

We would like to thank the UK Meteorological Office for providing the plume trajectories presented in Figure 1, and the Commission for the European Communities, who provided funding for the project and supplied many of the data on contamination levels in member states. In addition we gratefully acknowledge the assistance given to us directly by many of the member states, in particular from organisations in FRG, Greece, Ireland and the UK. We would also like to express our grateful thanks to Andrew Walmsley, Arthur Jones, Lisa Goodchild, Alison Reed, Anantray Sanghani, Julia Dionian, Joy Full and others at NRPB who contributed to this project.

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Table 1

Average Adult and Critical Group Effective Doses in the First Year[1]

Country	Effective Dose (μSv)	
	Critical Group[2]	Average Adult
Belgium	430 (I)	44
Denmark	400 (I)	55
France[3]		39
East	970 (I)	110
West	340 (I)	21
FRG[3]		150
North	430 (I)	46
South	1900 (I)	380
Greece	1300 (C/A)	300
Ireland	520 (A)	97
Italy[3]		160
North	1100 (A)	200
Central	830 (A)	120
South	760 (A)	120
Luxembourg	400 (I)	47
Netherlands	380 (A)	60
Portugal	3.6 (I)	0.2
Spain[3]		0.9
East	70 (I)	3.9
West	4.2 (I)	0.2
UK[3]		32
Cumbria, N. Wales and S.W. Scotland	840 (I)	190
rest of England	260 (C)	20
rest of Wales	370 (A)	29
rest of Scotland	590 (C/A)	83
N.Ireland	520 (A)	97

Notes

1. The results are given to two significant figures to avoid rounding errors in subsequent calculations, and this degree of accuracy is not implied.

2. For critical group, I = 1 year old infant, C = 10 year old child, A = Adult.

3 For the average adult doses are averaged across all the regions considered, and are also given for each region separately.

Table 2

Contribution by Pathway to Individual Effective Dose in the First Year

A) Main Pathways

Pathway	Approximate percentage of the effective dose in the first year[1] Average Adult	 Critical Group
Inhalation	<1-20	<1-10
Ingestion	60 - 85	70 - 97
Deposited Gamma	10 - 30	1 - 25
Cloud Gamma	< 0.3	< 0.3

B) Contribution of Individual foods to Dose

Food	Approximate percentage of the effective dose in the first year[1,2] Average Adult	 Critical 1 year old infant[3]
Milk	30 - 60	40 - 90
Milk products	1 - 10	<1 - 15
Grain	5 - 50	<1 - 15
Lamb	<1 - 15	<1 - 5
Green vegetables and fruit	5 - 30	1 - 30
Beef	1 - 20	<1 - 20

Notes

1. These percentages are approximate, and intended to illustrate the relative significance of pathways, only.

2. The most important foods vary between countries. Those given here are the ones which are generally important throughout the EC, but all the ranges may not be directly applicable in some member states.

3. Because eating habits vary considerably between age groups, the contributions of foods for 1 year old infants with extreme habits is given.

Table 3

Average Adult and Critical Group Thyroid Doses in the First Year[1]

Country	Thyroid dose (μSv) Critical group[2]	 Average adult
Belgium	10 000	290
Denmark	9300	450
France[3]		280
East	23 000	590
West	9300	200
FRG[3]		540
North	10 000	280
South	30 000	1100
Greece	6500	530
Ireland	6100	370
Italy[3]		810
North	4700	840
Central	3800	550
South	4700	910
Luxembourg	9200	370
Netherlands	5500	370
Portugal	50	0.7
Spain[3]		6.8
East	2000	30
West	68	0.9
UK[3]		200
Cumbria, N. Wales and S.W. Scotland	11000	640
rest of England	5500	180
rest of Wales	4100	130
rest of Scotland	7600	300
N.Ireland	6100	370

Notes

1. The results are given to two significant figures to avoid rounding errors in subsequent calculations, and this degree of accuracy is not implied.

2. The critical group is a 1 year old infant for all countries except Italy where the critical group is a 10 year old child.

3. For the average adult, doses are averaged across all the regions considered, and are also given for each region separately.

Table 4

Average and Critical Adult Effective Doses in 50 years[1]

Country	Effective Dose (μSv) Average	Critical
Belgium	82	440
Denmark	95	480
France[2]	76	
East	220	1100
West	39	250
FRG[2]	360	
North	85	440
South	950	3800
Greece	530	2100
Ireland	170	830
Italy[2]	310	
North	400	1900
Central	230	1400
South	210	1100
Luxembourg	86	410
Netherlands	100	570
Portugal	0.3	2.7
Spain[2]	1.2	
East	4.7	25
West	0.3	3.3
UK[2]	46	
Cumbria, N. Wales and S.W. Scotland	270	1200
rest of England	25	290
rest of Wales	37	450
rest of Scotland	150	900
N.Ireland	170	830

Note

1. The results are given to two significant figures to avoid rounding errors in subsequent calculations, and this degree of accuracy is not implied.

2. For the average adult doses are average across all the regions considered, and are also given for each region separately.

Table 5

Collective Effective Doses

Country	Collective Effective Dose (man Sv)[1]	
	First year	All time
Belgium	480	940
Denmark	650	1100
France	3000	5600
FRG	14 000	30 000
Greece	5200	8500
Ireland	660	950
Italy	17 000	27 000
Luxembourg	22	42
Netherlands	720	1200
Portugal	1.4	2.3
Spain	45	57
UK	2100	3000
TOTAL	44 000	78 000

Notes

1. The results are given to two significant figures to avoid rounding errors in subsequent calculations, and this degree of accuracy is not implied.

Table 6

Collective Thyroid Doses

Country	Collective Thyroid Dose (man Sv)[1]	
	First year	All time
Belgium	2700	3100
Denmark	2300	2700
France	16 000	19 000
FRG	36 000	52 000
Greece	8300	11 000
Ireland	1900	2200
Italy	57 000	67 000
Luxembourg	130	150
Netherlands	4900	5400
Portugal	6.8	7.7
Spain	330	340
UK	11 000	12 000
TOTAL	140 000	170 000

Notes

1. The results are given to two significant figures to avoid rounding errors in subsequent calculations, and this degree of accuracy is not implied.

Table 7

The Effect of Countermeasures on the Effective Dose to the Critical Group[1]

Country[2]	Age group[3]	Effective dose to the critical individual in the first year (μSv)[4] Theoretical estimate without countermeasures	With countermeasures	% dose saved
France	I	1100	970	12
FRG	I	3000	1900	37
Greece	A	1700	1300*	24
	C	2200	1300*	41
	I	2500*	1000	60
Italy	A	1100	1100*	-[5]
	C	1200*	970	19
	I	1200*	590	51
Netherlands	A	440	380*	14
	I	500*	330	34
UK	A/C	1100*	820	25
	I	890	840*	6

Notes

1. The results are given to two significant figures to avoid rounding errors in subsequent calculations, and this degree of accuracy is not implied.

2. No countermeasures were considered for the critical group for Belgium, Denmark, Ireland, Luxembourg, Portugal and Spain, see Appendices A and B.

3. For age group I = 1 year old infant, C = 10 year old child and A = adult.

4. Where doses for a country are given for more than one age group an asterisk* denotes the dose to the critical group.

5. After implementing countermeasures the reduction in the dose was small.

Table 8

The Effect of Countermeasures on the Thyroid Dose to the Critical Group[1]

Country[2]	Age[3] group	Thyroid dose to critical individual in first year[4] (µSv)		% dose saved
		Theoretical estimate without countermeasures	With countermeasures	
France	I	28 000	23 000	18
FRG	I	64 000	30 000	53
Greece	I	53 000	6500	88
Italy	I	29 000*	3300	89
	C	9900	4700*	53
Netherlands	I	11 000	5500	50
UK	I	12 000	11 000	8

Notes

1. The results are given to two significant figures to avoid rounding errors in subsequent calculations, and this degree of accuracy is not implied.
2. No countermeasures were considered for the critical group for Belgium, Denmark, Ireland, Luxembourg, Portugal and Spain, see Appendices A and B.
3. For age group I = 1 year old infant and C = 10 year old child.
4. Where doses for a country are given for more than one age group an asterisk* denotes the dose to the critical group.

Table 9

The Effect of Countermeasures on the Collective Effective Dose Commitment and the Collective Thyroid Dose Commitment[1]

Country	Collective effective dose commitment (man Sv)		Collective thyroid dose commitment (man Sv)	
	Dose received	Dose saved by countermeasures	Dose received	Dose saved by countermeasures
Belgium	940	—[2]	3100	—[2]
Denmark	1100	—[2]	2700	—[2]
France	5600	—[2]	19 000	—[2]
FRG	30 000	2000	52 000	30 000
Greece	8500	600	11 000	12 000
Ireland	950	—[2]	2200	—[2]
Italy	27 000	<1000	67 000	10 000
Luxembourg	42	1	150	50
Netherlands	1200	100	5400	1100
Portugal	2.3	—[2]	7.7	—[2]
Spain	57	—[2]	340	—[2]
UK	3000	< 100	12 000	< 1000
TOTAL	78 000		170 000	

Note

1. The results are given to two significant figures to avoid rounding errors in subsequent calculations, and this degree of accuracy is not implied.

2. No countermeasures were considered for this country, see Appendices A and B.

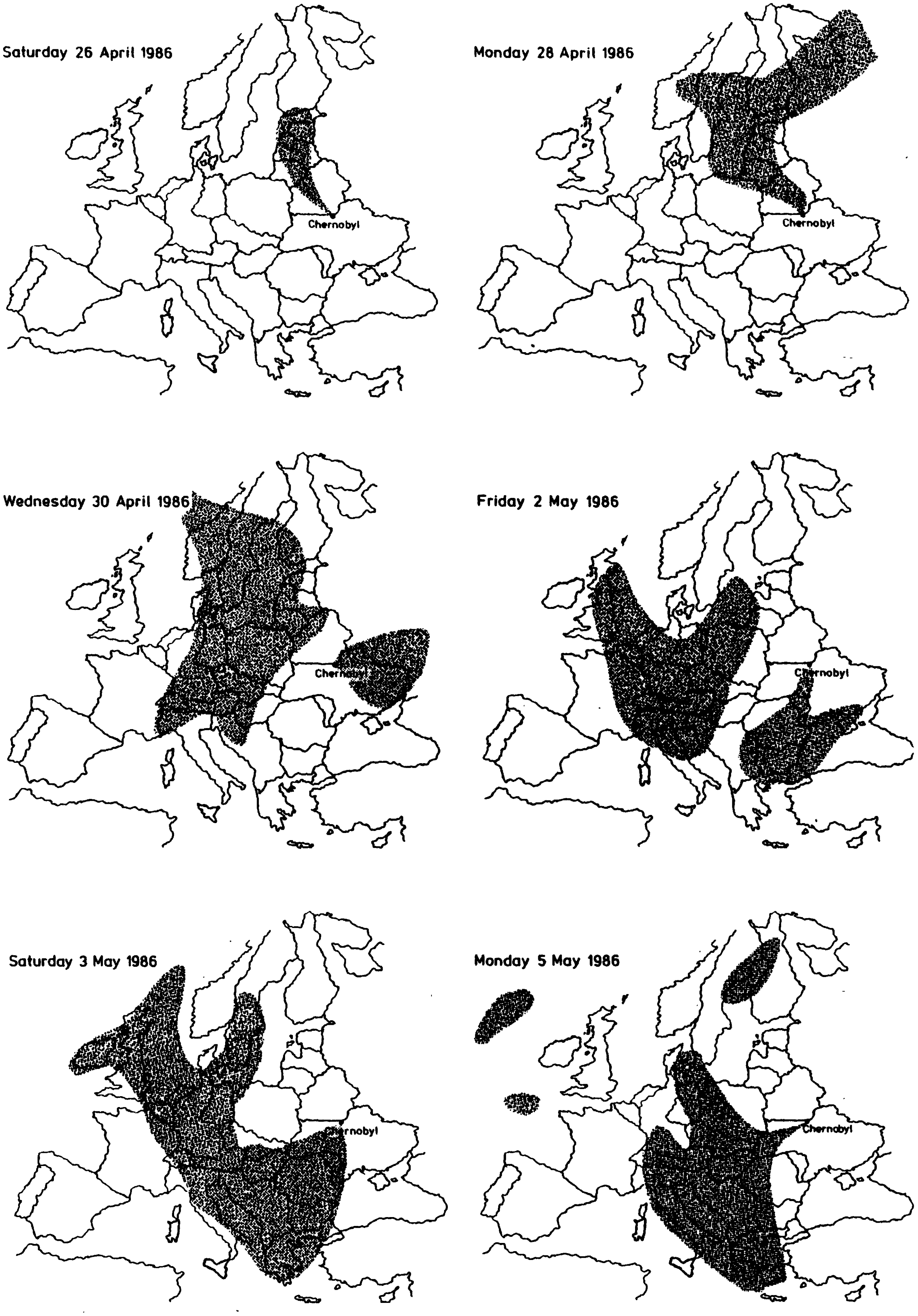


Figure 1 Areas covered by the main body of the cloud on various days during the release

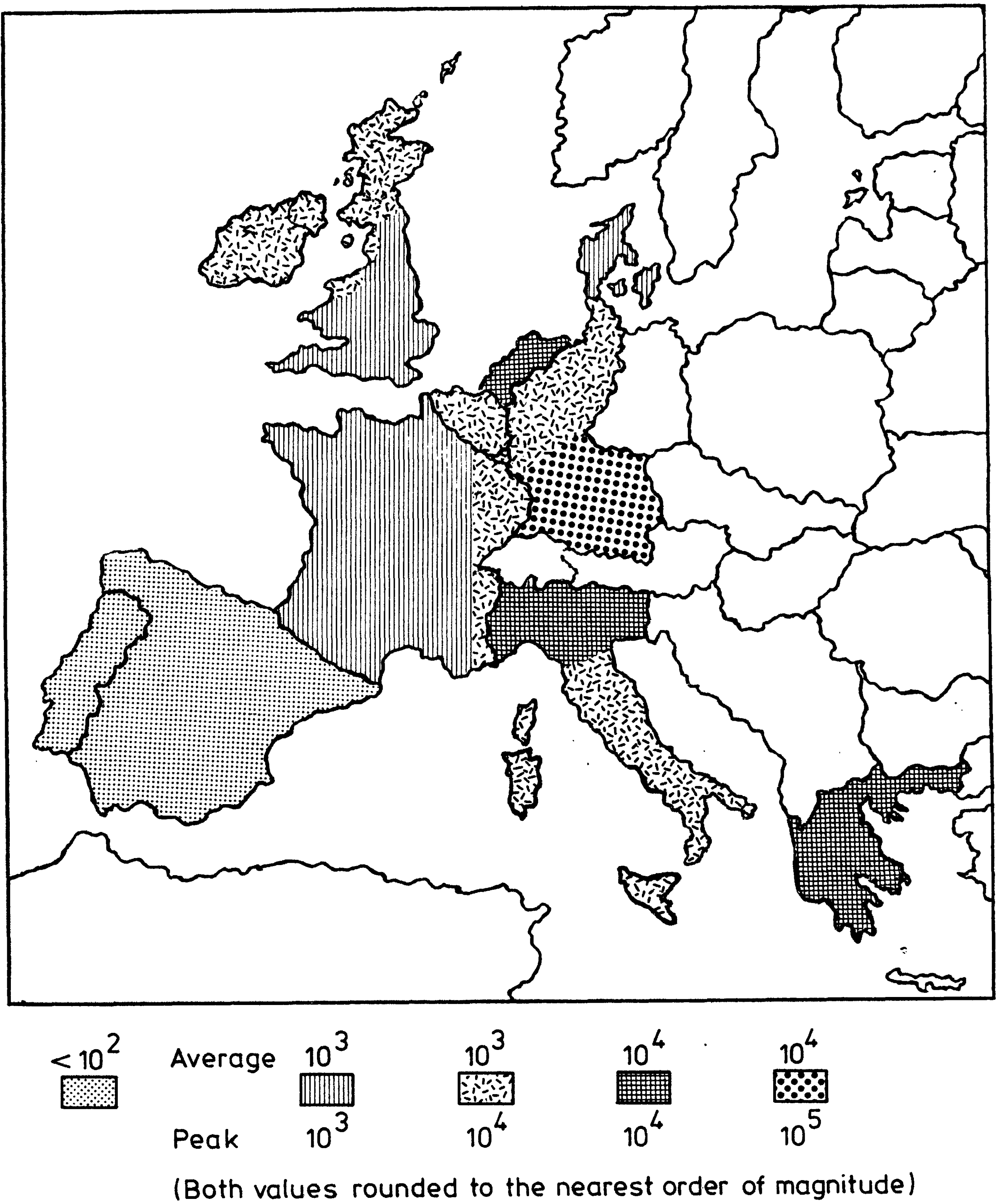
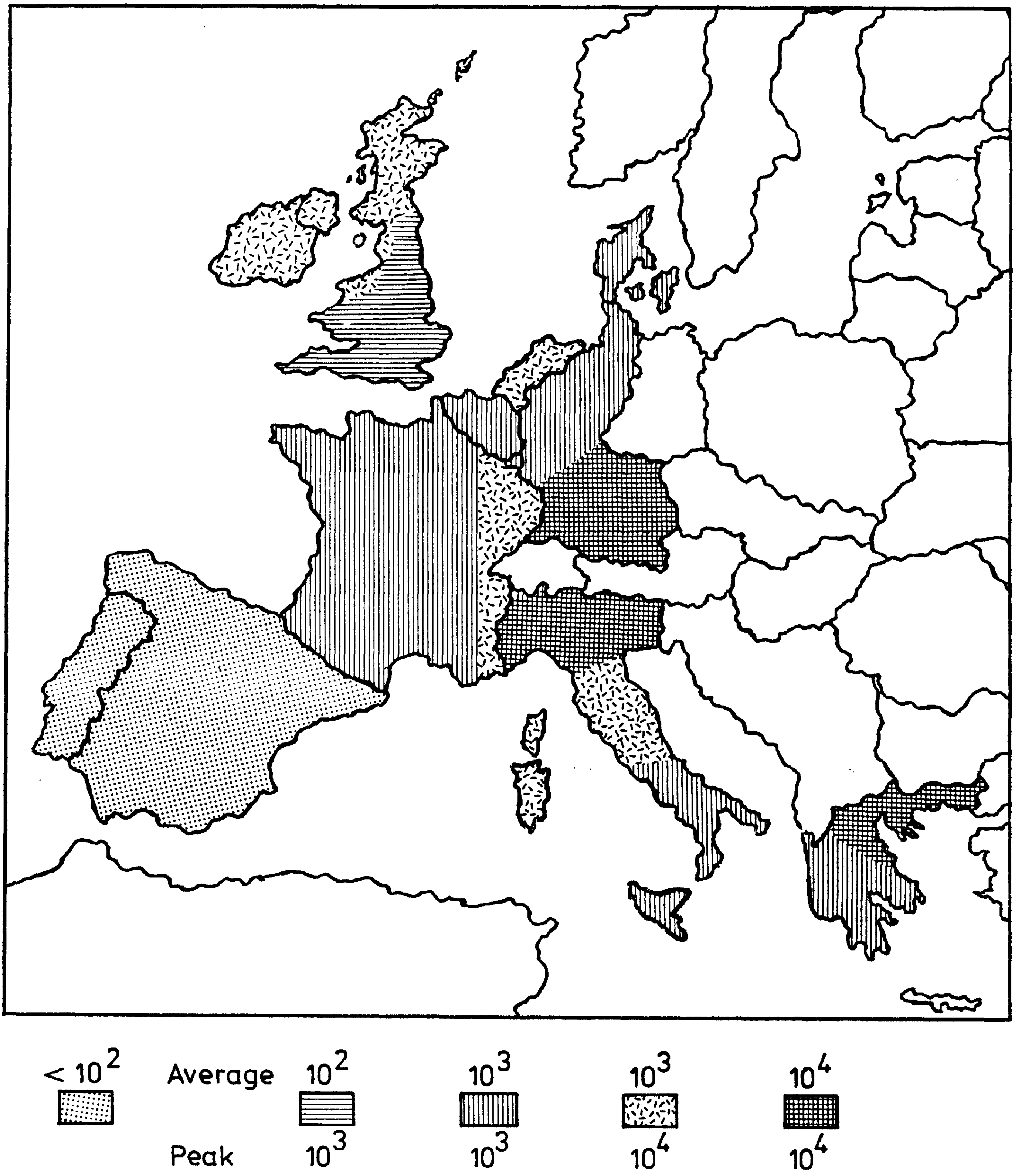


Figure 2 Iodine-131 deposition, Bq m^{-2}



(Both values rounded to the nearest order of magnitude)

Figure 3 Total caesium deposition, Bq m^{-2}

A	N Ireland
B	Ireland
C	Scotland
D	SW Scotland
E	Cumbria
F	N Wales
G	Wales
H	England
I	Portugal
J	W Spain
K	E Spain
L	W France
M	E France
N	Luxembourg
O	Belgium
P	Netherlands
Q	Denmark
R	N Germany
S	S Germany
T	N Italy
U	C Italy
V	S Italy
W	Greece

Figure 4 EC countries and regions used in this assessment

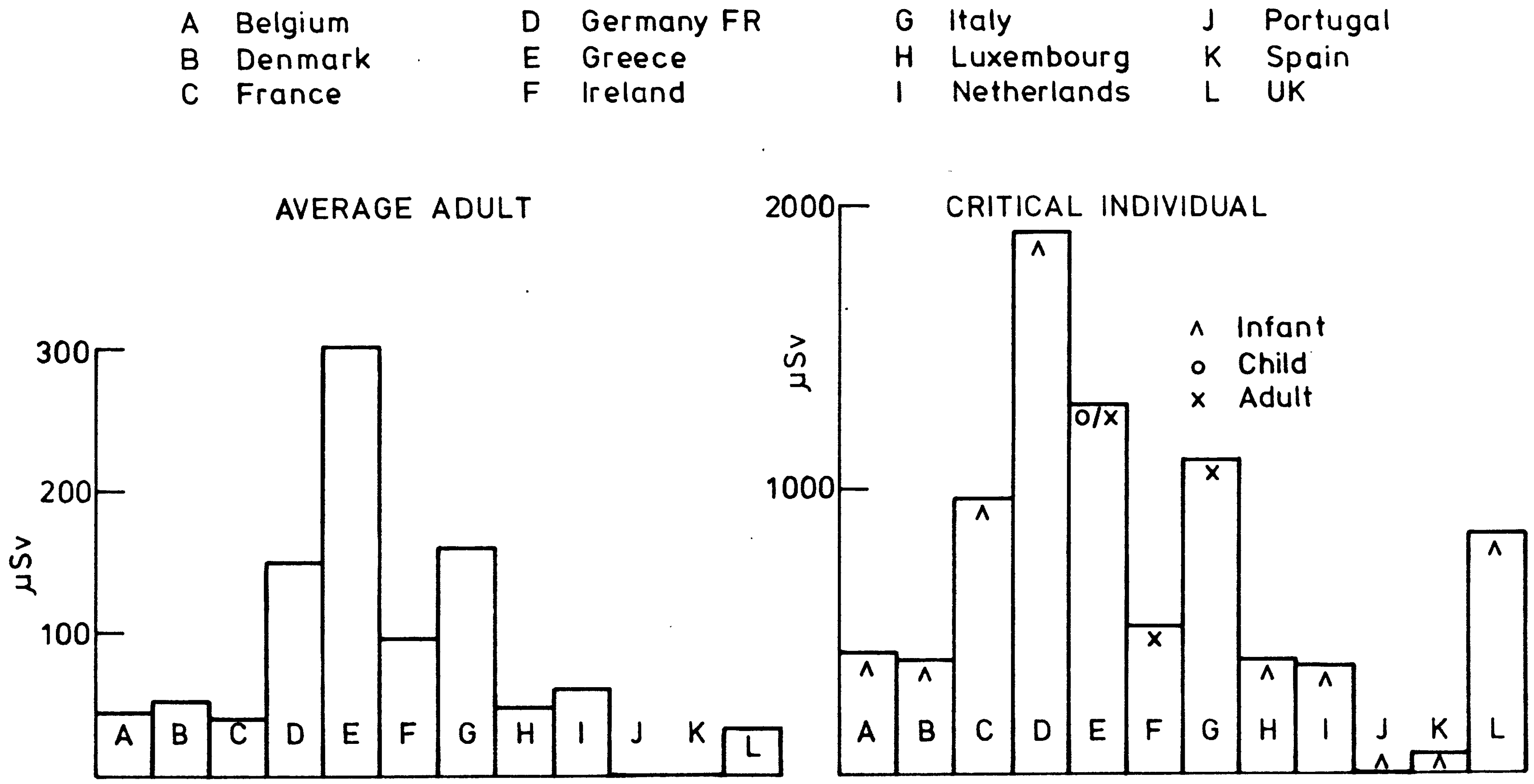


Figure 5 Individual effective dose in first year

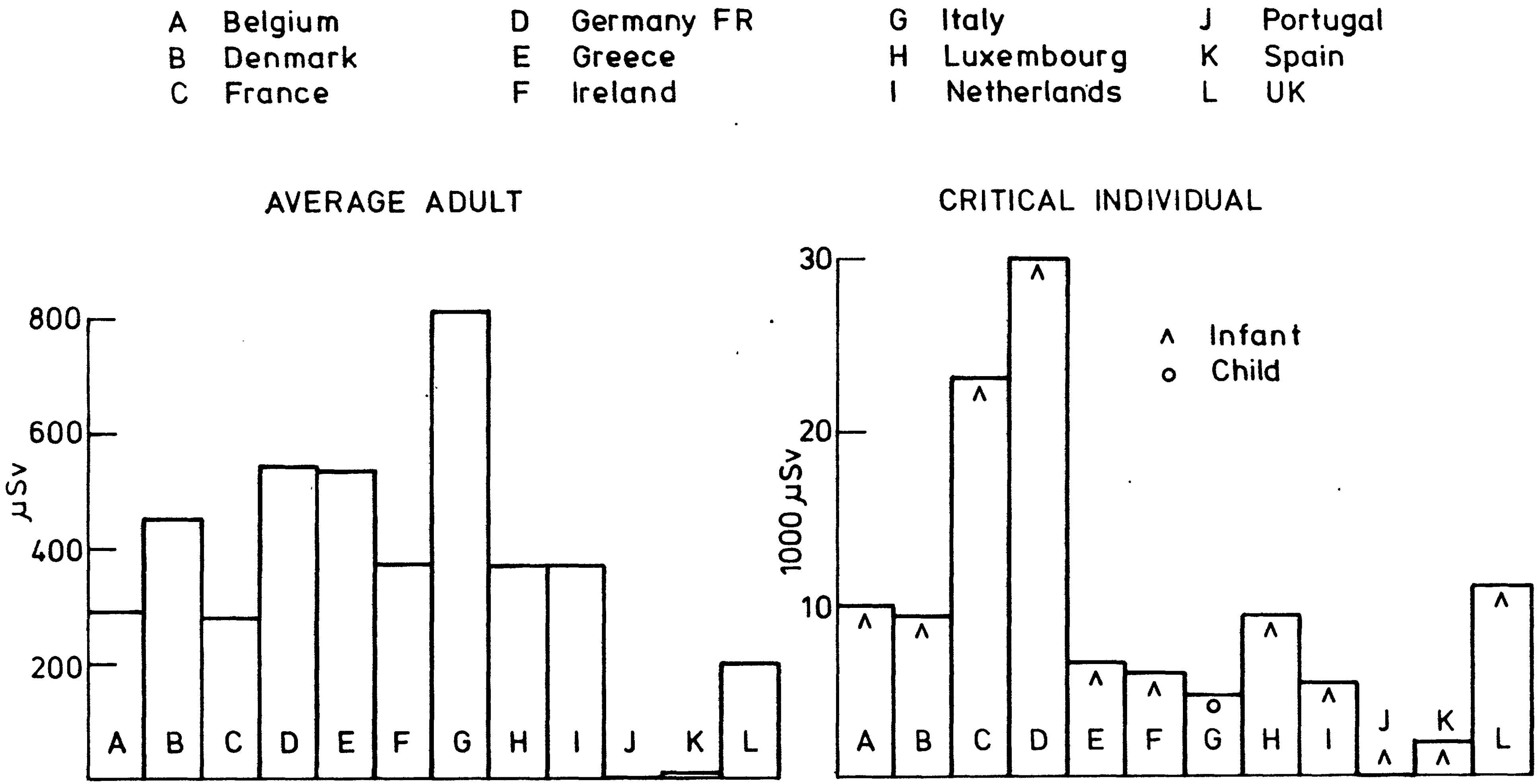


Figure 6 Individual thyroid dose in first year

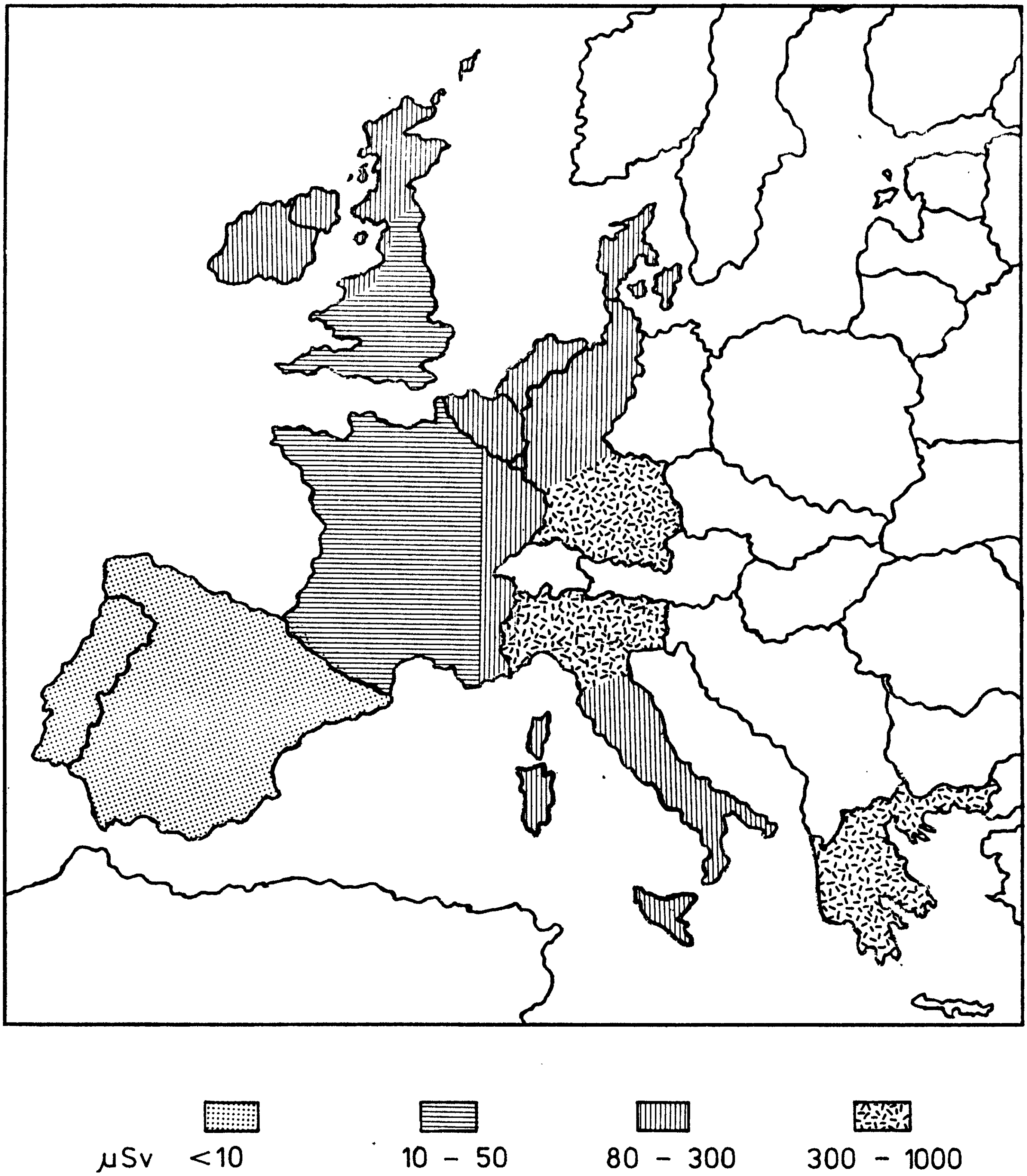


Figure 7 Average adult effective dose to 50 y within the EC

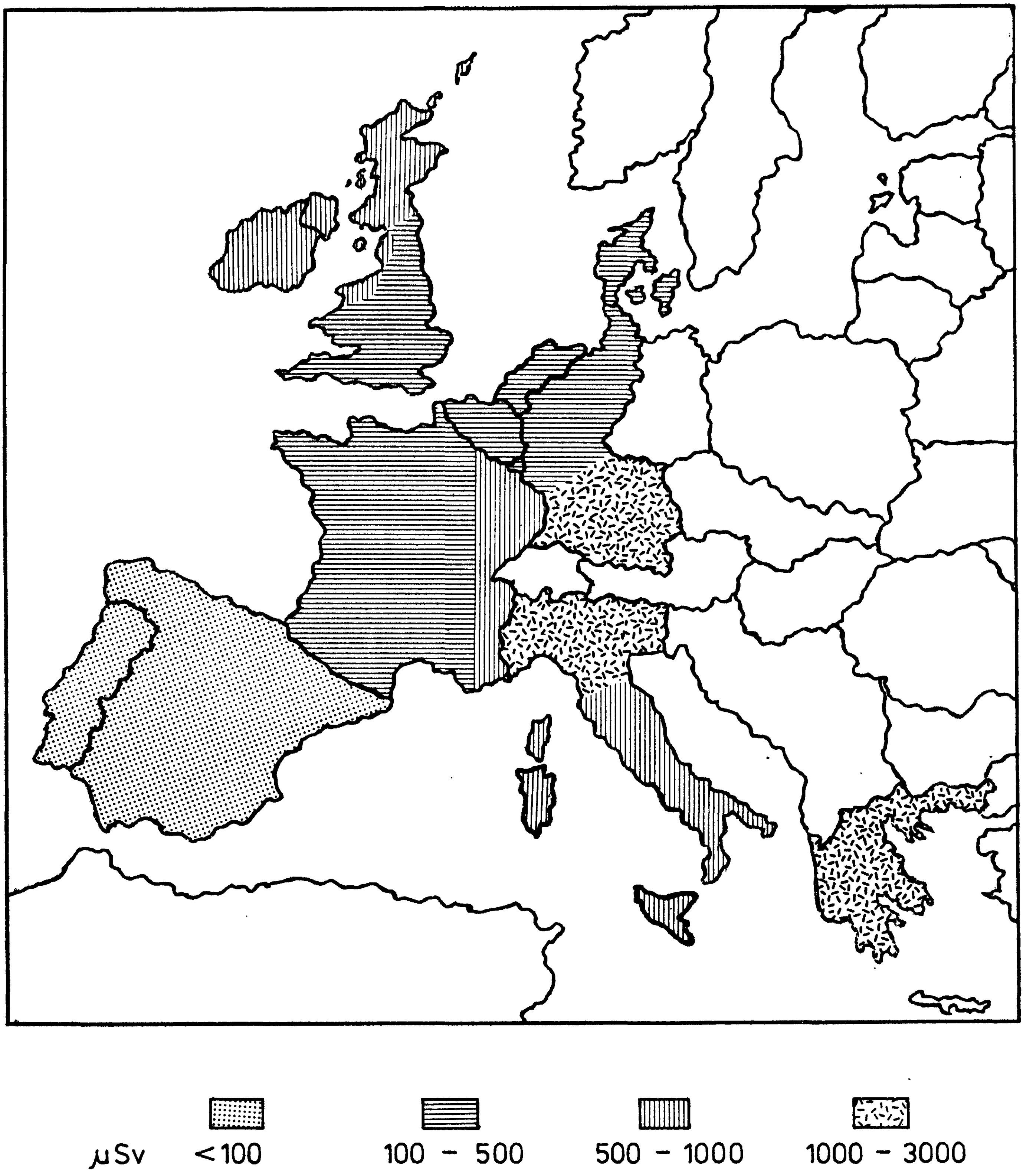


Figure 8 Critical individual effective dose in first year within the EC