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Risks of potential accidents of nuclear power plants in Europe

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32-60	Reserve-exemplaren

TABLE OF CONTENTS

SUMMARY

Over 200 nuclear power plants for commercial electricity production are presently operational in Europe. The 1986 accident with the nuclear power plant in Chernobyl has shown that severe accidents with a nuclear power plant can lead to a large scale contamination of Europe. This report is focussed on an integrated assessment of probabilistic cancer mortality risks due to possible accidental releases from the European nuclear power plants. For each of the European nuclear power plants the probability of accidental releases per year of operation is combined with the consequences in terms of the excess doses received over a lifetime (70 years). Risk estimates are restricted to cancer mortality and do not include immediate or short term deaths in the direct vicinity (< 5-10 km) of the plants. Countermeasures to reduce radiation doses are not considered. Location specific risks are presented in maps of Europe. The excess mortality risk due to the combined operation of the European nuclear power plants is estimated to be about 10 x 10^{-8} per year in Western Europe. Going East the risks increase gradually to over 1000 x 10^{-8} per year in regions of the former Soviet Union, where reactors of the Chernobyl type are located.

The nuclear power plants in the East European countries dominate the estimated risk pattern and contribute at least 40-50% to the average risk in the West European countries. Improving the reactor safety in eastern European countries could lead to considerable reductions in estimated excess mortality risks. In western Europe the mortality risk might be reduced by a factor of two, and in eastern Europe by a factor of 100 to 1000.

SAMENVATTING

In Europa zijn momenteel meer dan 200 kerncentrales voor commerciële electriciteits produktie operationeel. Het ongeval met de kerncentrale in Tsjernobyl heeft aangetoond dat een ernstig ongeval met een kerncentrale kan leiden tot een grootschalige radioactieve besmetting van Europa. Deze studie is gericht op het schatten van de probabilistische sterfterisico's die het gevolg zijn van mogelijke ongevallen met Europese kerncentrales. De waarschijnlijkheid van een ongevalslozing is voor elk van de Europese centrales gecombineerd met de gevolgen in termen van toegevoegde levenslange (70 jaar) blootstelling aan ioniserende straling en het daardoor toegevoegd sterfterisico door kankerinductie. Acute slachtoffers die uitsluitend kunnen voorkomen bij zeer grote lozingen en in de directe omgeving van de reactoren (< 5-10 km) zijn niet in de beschouwing betrokken, en maatregelen om blootstelling te beperken zijn niet beschouwd. De sterfterisico's worden gepresenteerd door middel van een risicokaart van Europa.

Het blijkt dat het extra sterfterisico in West-Europa ca. 10 x 10^{-8} per jaar bedraagt. In oostelijke richting loopt dit op tot ongeveer 1000 x 10^{-8} per jaar in delen van de voormalige Sovjet Unie, waar zich reactoren van het 'Tsjernobyl' type bevinden.

De Oost-Europese reactoren domineren het risicopatroon over het Europese continent, en dragen ten minste 40-50% bij aan het gemiddeld risico in West Europese landen. Indien de Oost-Europese centrales op het West-Europese veiligheidsniveau gebracht worden, kan het geschatte extra sterfte risico met een factor 2 in West Europa en met een factor 100 tot 1000 in Oost-Europa gereduceerd worden.

1 INTRODUCTION

The control and reduction of risks related to environmental pollution is the primary aim of environmental policies. Risk-oriented policies require integrated risk assessments. The risks related to possible accidents with nuclear power reactors are a major environmental concern. The accident at the nuclear power plant in Chernobyl in 1986 has shown that large scale accidents with nuclear power plants can lead to the contamination of an entire continent. Over 200 nuclear power plants for commercial electricity production are presently operational in Europe. The question rises to what extend possible accidental releases imply a risk for the European population. Various studies have adressed the estimation of possible accidental releases from specific nuclear power plants. Such studies mainly focus on the direct vicinity of a particular plant, and do not consider the overall risk due to the combined use of all European nuclear power plants. The purpose of this study is to provide an evaluation of the location dependent risks over the European continent due to the combined use of all European nuclear power plants. This study focuses on the estimation of excess mortality risks due to longterm stochastic radiation effects. Immediate or short term deaths due to very high radiation exposure, which can only be expected in the close vicinity of the nuclear power plants (within a distance of less than 5-10 km) are not included in the evaluation.

In this report a brief summary of the approach and results are given, focussing on the policy aspects and implications. Detailed information on the method used and the results obtained are provided in Slaper *et al.* (1993). In order to certify a large comparability with assessments for continuous releases, the modelling methods and parameter choices closely related to the approaches and recommendations provided in the MORIS-study (Blaauboer *et al.*, 1992).

The risk evaluation is based upon a probabilistic evaluation of the environmental chain from sources to effects and risks. An outline of the method applied is given in chapter 2, and involves the characterization of the accident and release probabilities for the sources (sections 2.2 and 2.3), the atmospheric dispersion and deposition of released nuclides (section 2.4), the transfer of nuclides to soil, plants, animals and foodproducts, leading to subsequent radiation exposure of the population (section 2.5). Excess mortality risks are expressed per year of operation of all nuclear power plants considered. Baseline estimates are provided for a rural population with a high food intake. In order to obtain the risk of an accidental release the lifetime (70 year) follow up dose and risk is calculated.

The results of the risk evaluations are provided in chapter 3, where the location dependent excess mortality risks due to possible accidental releases to the atmosphere are presented in maps of Europe. In Chapter 4 a discussion of the results and uncertainties is presented and suggestions for further research are proposed.

2 METHOD

2.1 Introduction

The method provides a probabilistic evaluation of the chain: source-emission-dispersion-exposure-effect-risk. Figure 2.1 gives a schematic presentation of this chain and the major elements in the risk assessment modelling. A total of 217 nuclear power plants were involved in this evaluation (see section 2.1).

The estimation of accidental releases requires an evaluation of accident probabilities and subsequently released fractions from the reactor core of all the nuclear power plants. Detailed safety analyses for many of the European power plants are not available. Therefore, a categorization of these power plants, based on the reactor safety characteristics and design was obtained from Eendebak *et al.* (1992). For each reactor type accident probabilities (section 2.2) and probabilistic releases (section 2.3) are estimated.

The atmospheric dispersion of the accidental release of radionuclides is calculated applying a statistically based approach, accounting for a variety of weather conditions,

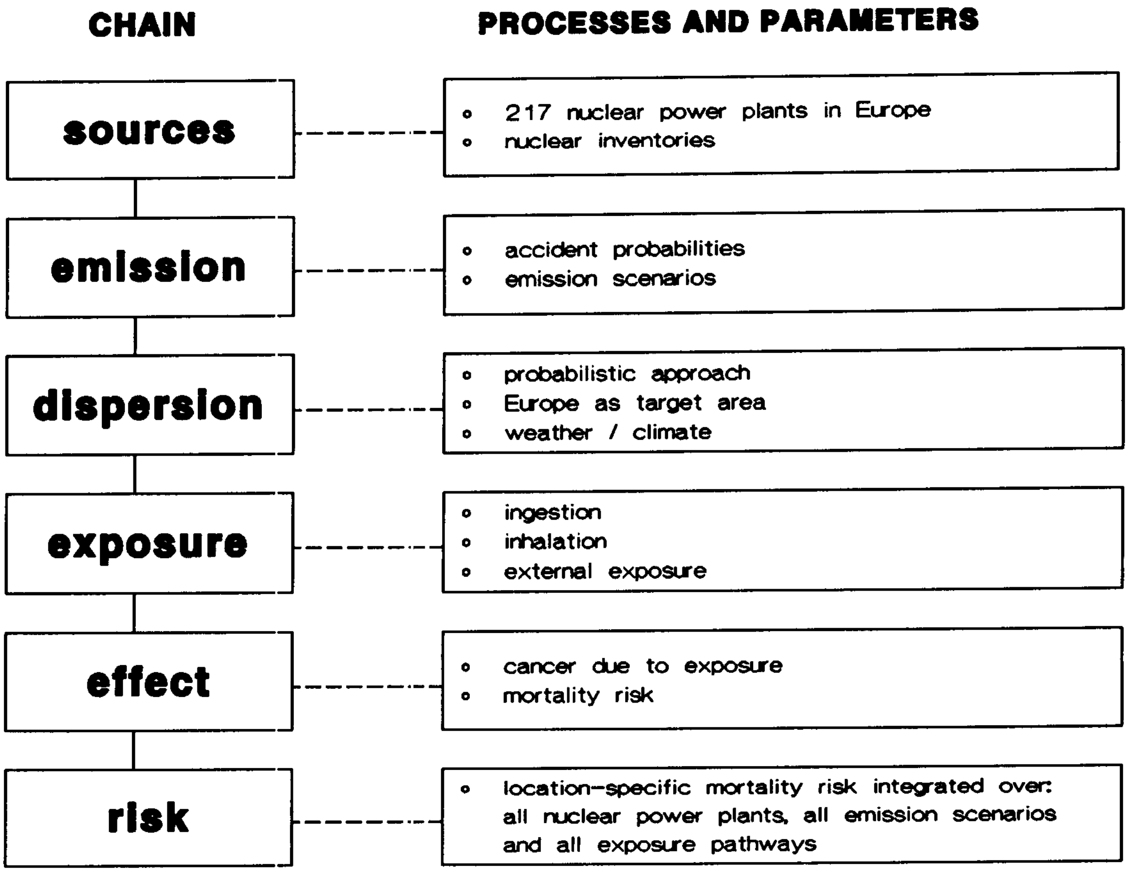

Figure 2.1 Schematic presentation of the source-to-effect(-risk) chain and the main processes and parameters involved in this study

with Europe as target area (section 2.4).
Following an accidental release external exposure, inhalation and ingestion contribute to the overall radiation dose received. The exposures due to an accidental release are not restricted to a short period after the accident. External exposure and ingestion of deposited nuclides with long half lifes can contribute to the radiation dose received over a considerable period in time. The dose to the population is calculated for a lifetime follow-up period of 70 years. Countermeasures are not considered. The total dose is attributed to the time of the accident. The method of exposure evaluation and some results regarding the relative contribution of the various pathways are provided in section 2.5.
For a large number of locations in Europe the probabilistic dose contribution is calculated for all nuclear power plants, and summed to obtain the total probabilistic location dependent dose (see section 2.6). Using the calculated doses an estimated excess cancer mortality risk per year of combined operation of all nuclear power plants is obtained.

2.2 The plants and their source terms

All European nuclear power plants operational on July 1st, 1992 and producing electrical power in excess of 50 MW were selected (Kernkraftwerke, 1992). The so obtained 217 nuclear power plants were divided into nine different reactor types, according to a categorisation by Eendebak *et al.* (1992). The reactor types used are (numbers in parentheses indicate the number of operational plants):

- six types of light water reactors:
  - (89) PWR (pressurized water reactor) of Western design, with a containment;
  - (23) BWR (boiling-water reactor) of Western design, with a containment;
  - (10) PWR-V230 (the oldest pressurized water reactor) of Russian design, lacking a containment and redundancy in safety systems;
  - (16) PWR-V213 (improved version of PWR-V230 of Russian design) limited containment and limited redundancy;
  - (18) PWR-V1000 - Russian-designed reactor, similar to some of the Western European reactors;
  - (19) LWGR (light water graphite-moderated reactor) of Russian design (the 'Chernobyl-type') no containment and limited redundancy of safety systems;
- two types of gas-cooled reactors
  - (24) GCR (graphite-moderated gas (CO_2)-cooled reactor) reactor core enclosed by a steel or concrete pressure vessel;
  - (14) AGR (advanced gas-cooled reactor), an improved version of the GCR;
- (4) FBR (the fast breeder reactor)

The locations and types of all the selected plants are given in Figure 2.2 .

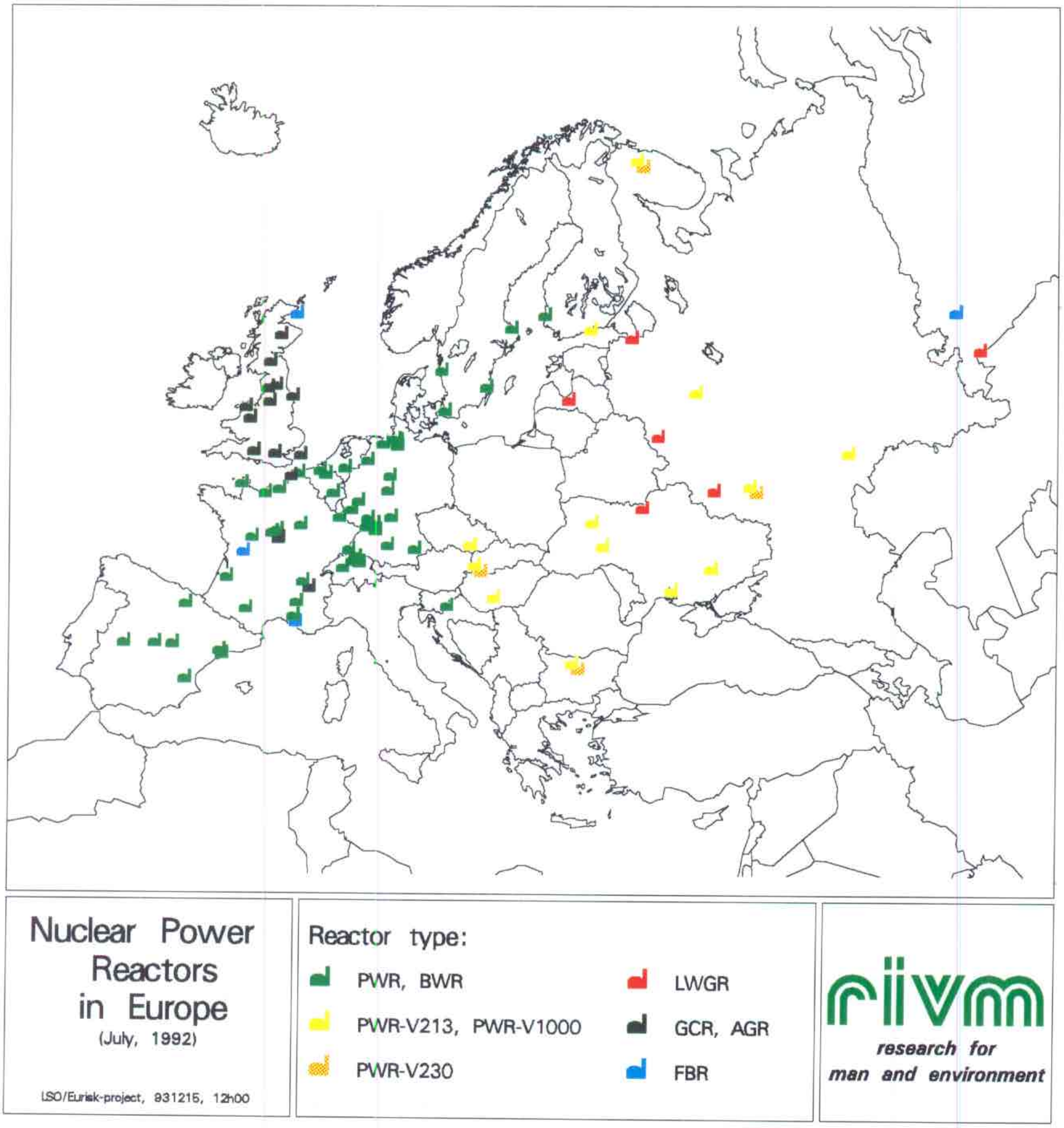

Figure 2.2 Locations and reactor types of the 217 European nuclear power plants operational on July 1st 1992, producing an electrical power in excess of 50 MW

The estimation of possible source terms for the various reactor types is based upon a literature review and expert interpretation provided by Eendebak *et al.* (1992). The probabilistic release is related to:

- the probability density that the reactor core is heavily damaged (this section)
- the probability that, following severe damage to the reactor core, a fraction of the reactor core is released to the atmosphere (conditional release probability; see section 2.3)
- the reactor inventory (section 2.3)

The probability density of a core melt (p - per reactor year) and consequent emission depend on different factors like reactor design, conditions of safety systems, the presence of containments, etc. Based on reactor design and redundancy of safety features Eendebak *et al.* (1992) assigned each of the nuclear power plants in one of four accident probability classes for severe damage to the reactor core. The reference probability class is 10^{-4} per reactor year, implying a probability of one accident with severe core damage in 10000 years of reactor operation. If a safety analysis for a particular plant clearly indicated a substantially lower risk, the plant was placed in a lower risk class. Because of the absence of a containment and a limited redundancy of safety systems the 19 LWGR and 10 PWR-V230 reactors were placed in a high risk class of 10^{-3} per reactor year. Apart from the 29 plants in the highest risk class of 10^{-3} per year, 146 plants were placed in the 10^{-4} per year class, 39 in the 10^{-5} per year risk class and 3 in the 10^{-6} per year class.

Using the above classification the average probability of damage to the reactor core amounts to 2×10^{-4} per reactor year. This figure compares well with an estimate of 3.3×10^{-4} per reactor year based upon reactor history: two core damage accidents (Three Miles Island and Chernobyl) on a total of 6000 operational reactor years worldwide.

2.3 Emission of radioactive material

Following a core meltdown the release depends on the quality of the containment and the reactor inventory. Eendebak *et al.* (1992) considered four accidental release scenarios for each of the reactor types. They provided the (conditional) probabilities for the occurrences of each of the four scenarios for the various reactor types, provided that severe damage to the reactor core had occurred. Each accident scenario is associated with certain release characteristics in terms of the fraction of nuclides released, energy content of the release and time of release. The release scenarios considered are:

- an early release, due to a failure of the containment;
- a bypass of containment, through improper closure of the ducts through the containment;
- a late release, due to a failure of the containment following very high pressures and temperatures or a melt of the reactor; and
- a 'no containment failure', with very limited releases (as was the case in the accident

at Three Miles Island).
Figure 2.3 illustrates the various release scenarios.

The results of NUREG-1150 (USNRC, 1987 and 1989) were used to estimate release fractions for nine nuclide groups from the reactor core for the various accident scenarios. A total of 54 nuclides were distinguished in the nine nuclide groups.
For each of the accident scenarios i the accidental release for nuclide n ($L_{i,n}$ in Bq) is calculated, by multiplying the release fraction for nuclide n ($f_{i,n}$) with the reactor inventory for nuclide n (A_n): $L_{i,n} = f_{i,n} \times A_n$.
The average release expected if severe core damage occurs (probabilistic conditional release (L_n, in Bq), is calculated by a probabilistically weighted summation over the various accident scenarios: $L_n = \sum_i (p_i \times L_{i,n})$, where p_i is the probability that severe damage to the reactor core leads to accident scenario i.
The probabilistic release rate is then calculated multiplying L_n with the probability rate p (per year) of the occurrence of severe damage to the reactor core: $p \times L_n$. The so obtained probabilistic release rate is used in the dispersion calculations (see section 2.4).

The nuclear inventory is given by Eendebak *et al.* (1992) for the three main types of power plants (light water reactors, gas cooled reactors and fast breeder reactors). For the light water reactors inventories are calculated from data of the German reactor, Biblis B. Comparison with data from other LWRs showed a maximum deviation of 20%. For the graphite-moderated reactor, data from the LWGR-1000 in Chernobyl are used. The data for the fast breeder reactor come from calculations of the European Fast Reactor. The inventories given are for a 'reference' power plant with a thermal power of 3000 MW. A thermal power of 3000 MW is assumed to correspond to an electrical power of 1000 MW. The inventory of each individual power plant was scaled lineairly with the electrical power of the particular plant.

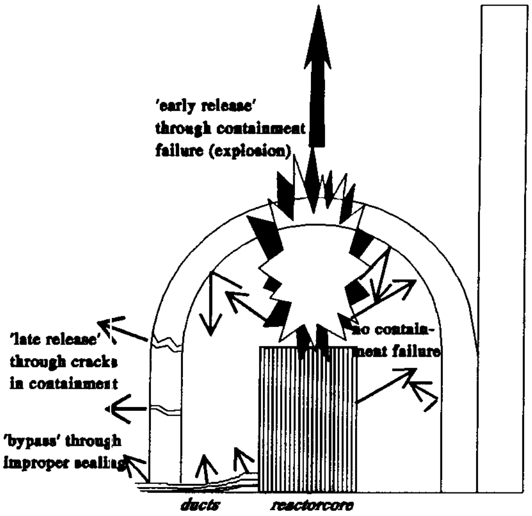

Figure 2.3 Illustration of the four different release scenarios (see text)

2.4 Dispersion of the radioactive cloud

An accidental release from a reactor can occur at any time. We assume that the probability density of an accident is independent of the weather conditions and equal over time. The probabilistic consequences in terms of dispersion and deposition of nuclides need to be based on a statistically time averaged dispersion and deposition calculation. We applied the Operational atmospheric transport model for Priority Substances (OPS, Van Jaarsveld, 1990). The OPS model calculates average air concentration and deposition on a grid basis in the Netherlands for continuous releases. The use of this model requires two considerations:

- can a model for continuous releases be applied to obtain an average dispersion for accidental releases, and
- can weather characteristics for the Netherlands also be used for the entire European continent.

We will briefly go into the argumentation on the above issues (see Slaper *et al.* 1993 for further details). A continuous release is characterized by an average release rate (L' for instance in Bq/yr). A probabilistic approach of accidental releases implies that the probability of an accidental release is considered over a certain time-period. A release can occur at any time with a constant probability density (p, probability per year). The probabilistic estimate of the accidental release per unit time equals the multiplication of the accident probability density p (per unit time) and the accidental release L (in Bq). Assuming that accidental releases are independent of the weather conditions, the product p*L can be considered as the expected accidental release rate at any moment in time. This situation is fully equivalent to a constant continuous release rate of L'=p*L. This result is in line with previous conclusions from BIOMOVS evaluations of modelling of milk contamination with steady state and dynamic models (Köhler *et al.*, 1991).

The OPS model has already been used for modelling on a European scale, for acid deposition due to NH_3, SO_2 and NO_x emissions (Van Jaarsveld, 1989; Asman en Van Jaarsveld, 1990; Erisman, 1991). The modelling results agree very well with the experimental results that were obtained from several sites in Europe. Confidence, that the extrapolation to Europe is not a source for large errors (less than a factor of 3) is further gained, from comparative calculations with deposition data from the Chernobyl accident (Slaper *et al.*, 1993). Large deviations however might occur in, for example, mountainous regions with heavy rainfall.

The OPS model provides air concentration and deposition estimates on a grid-basis. The grid-data were interpolated by means of user defined functional relationships describing the modelling results in relation to the distance from the source and the wind direction (generalized to four major directions; see Slaper *et al.* (1993)).

2.5 Exposure model

The exposure model is used to calculate the accumulated lifetime dose due to the passage of a radioactive cloud and the deposition of radioactive material on vegetation and soil. The exposure pathways considered are inhalation, ingestion and external exposure (Figure 2.4). The reference group considered is an adult rural population, spending 30% of the time outdoors, and with a high food consumption of locally harvested fresh foodproducts (see Slaper *et al.* (1993) for details). The dose received was calculated for a person remaining at the same location for a period of 70 years.

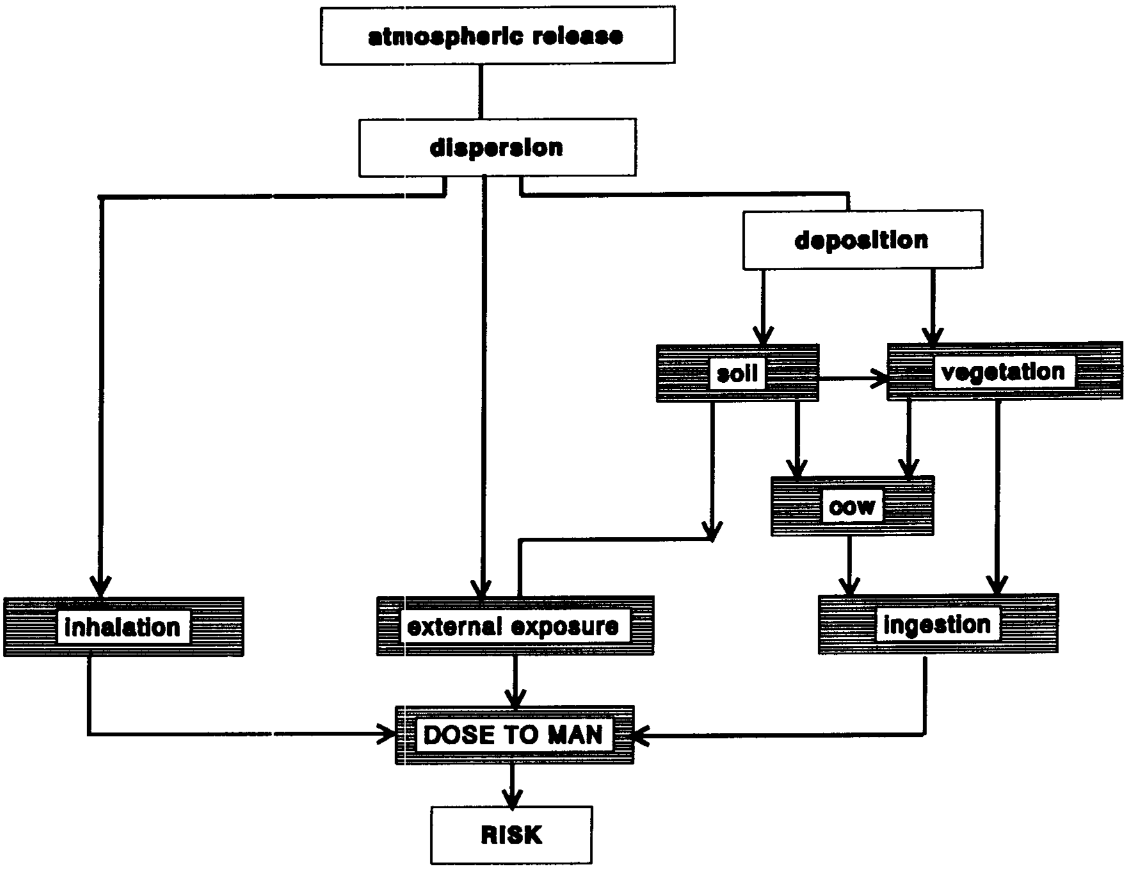

Figure 2.4 Pathways considered in exposure modelling; gray boxes indicate modules in exposure assessment calculations

2.5.1 *Inhalation*

Inhalation of nuclides is modelled according to the method described by UNSCEAR (1988), with the following major parameter choices: indoor air concentration is equal to outdoor air concentration, a breathing rate of 23 m^3 per day (ICRP, 1975) and dose conversion factors according to Nosske *et al.* (1985).

2.5.2 *Ingestion*

The contamination of vegetation and crops occurs through two pathways: direct interception of nuclides deposited during cloud passage and uptake of nuclides deposited from the soil. After cloud passage the soil remains contaminated, although due to nuclear decay and transfer processes the concentration in the upper soil layer will decrease. Radionuclides in food can be ingested either directly by consumption of contaminated crops or indirect by consumption of milk and meat from animals consuming contaminated grass and soil. Five major food categories are distinguished in the ingestion modelling: vegetables, cereals, roots/tubers, and milk and meat from cows. Modelling is based on IAEA (1982), and in line with Blaauboer *et al.*, (1992). Transfer factors are obtained from Köster *et al.* (1989) and Baes *et al.* (1984) for soil-plant transfer and from Bundesanzeiger (1990) for milk/meat transfer.

2.5.3 *External exposure*

External exposure from cloud passage and deposited radionuclides was estimated according to a method described by UNSCEAR (1988) for the evaluation of the Chernobyl accident. Dose conversion factors for all 54 nuclides were obtained from Kocher (1983). Shielding due to penetration of nuclides in the ground was considered as in UNSCEAR in three different time intervals: in the first month there was no reduction, from 1 month to 1 year reduction was 50%, and in the period beyond 1 year reduction was 63%. Indoors, shielding is considered to reduce doses due to external exposure from cloud passage by 30% and external exposure from deposited nuclides by 70%.

2.5.4 *Results of exposure modelling*

The total dose to humans is calculated by summing the contributions of inhalation, external exposure and ingestion. The relative contribution of the pathways is illustrated in

Figure 2.5 for the probabilistic release of the light water reactor. Ingestion and external exposure from deposited nuclides are the major dose contributing pathways. This implies that deposition related exposures contribute to around 85% of the total dose. Similar results were obtained for the other probabilistic source terms (see Slaper *et al.*, 1993).
For the adult population 70% of the 70-year follow-up dose is received in the first year.

The various source terms have been evaluated to obtain the major dose contributing nuclides. The two major dose contributing nuclides are I-131 and Cs-137, together contributing 60-80% of the total dose of all 54 nuclides considered. In addition Cs-134 contributes approximately 12-25%; each other nuclide contributes less than 5% and all other nuclides together contribute no more than a maximum of 25%. Because of the

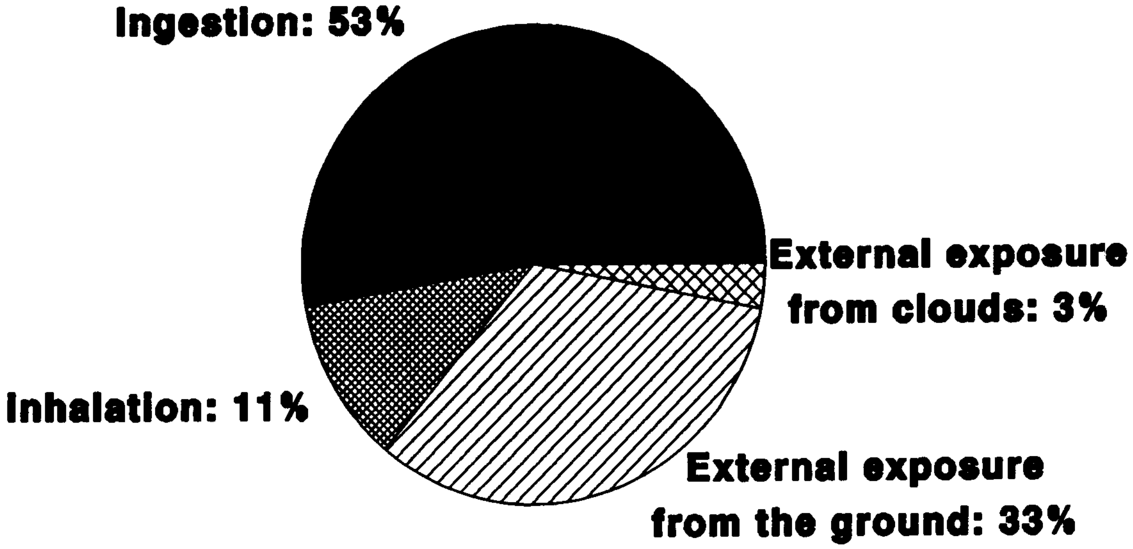

Figure 2.5 Relative importance of the four dose contributing pathways for the LWR probabilistic release

dominating role of I-131 and Cs-137 the dispersion evaluations are based on these two nuclides. Contributions of all other nuclides are accounted for by means of multiplicative factors: all contributions from iodine nuclides are attributed to I-131, and all contributions from non-iodine nuclides are attributed to Cs-137 (see Slaper *et al.*, 1993).

2.6 The risk calculations

Applying the above described methodology we calculated risks due to possible accidents with European nuclear power plants for a large number of receptor locations in Europe. The following computational scheme was applied:

- for each operational plant:
    - the time-integrated air concentrations and depositions at the receptor location are calculated for I-131 and Cs-137
    - (70-year follow-up) doses are calculated on the basis of the probabilistic air concentration and deposition
- contributions to the dose due to all nuclear plants are summed to obtain an overall dose for a person at a specific receptor location
- the resulting dose is multiplied by a mortality risk factor of 2.5% per sievert, providing the probabilistic mortality risk due to stochastic effects of doses received in the 70 years following a probabilistic accidental release for the population group considered (VROM, 1991).

3 RESULTS OF RISK EVALUATIONS

3.1 Risk evaluations

Cancer mortality risks due to possible accidental releases from the 217 operational nuclear power plants in Europe are calculated for 8000 receptor locations in Europe (in a grid of half a degree latitude and one degree longitude). The risk estimates are presented on a map of Europe. Two risk maps are obtained.
The first represents the present situation (Figure 3.1). It can be seen that the highest risks occur around the location of the LWGR plants (greater than 10^{-5} per year). Going east as well as west the mortality risk reduces gradually to less than 10^{-8} in Iceland and the south-west coast of Spain. In large parts of Western Europe the mortality risk lies between 3×10^{-8} and 3×10^{-7} per year. Note that in this presentation the effect of countermeasures and the contribution of short term deaths in the vicinity of the reactors are not taken into account. Including mortality risks due to short term effects could have a significant effect in the close vicinity of the plants, however the average mortality risk over a grid cell of the presented size would most likely not be altered substantially (probably less than 20%).

Probably one of the most effective measures to reduce the excess mortality risk is an improvement in the safety measures in the 'Eastern' European reactors (in particular the LWGR and PWR-V230 reactor type). In Figure 3.2 a second risk map is presented. This represents the situation in which it is assumed that Eastern European reactor types have a safety level comparable to that of Western European reactors. Comparing the results for this latter situation with the risks shown in Figure 3.1, a large decrease in risk in eastern Europe is profound. The highest risk areas in this second situation reflect the areas with the highest density of power plants.

When averaging the mortality risks for large areas spanning mid-European latitudes (48-56 N), Figure 3.3 shows that the risk for the two situations is longitudinally dependent. These results show that the largest risk reductions would occur in Eastern Europe (more than a factor 100), whereas reductions of only approximately 50% would occur in Western Europe.

3.2 Uncertainties

The source-risk evaluation presented in this report involves many uncertainties. The largest uncertainties are related to the estimation of accident probabilities and probabilistic nuclide releases. Eendebak *et al.* (1992) indicated uncertainties of accident probabilities of a factor of 3 for Western European plants (on average) and a factor of 10 for Eastern European plants. Based on the history of accidental releases an upper estimate which exceeds the calculated best estimate by a factor of 6 can be obtained (Slaper *et al.* 1993).

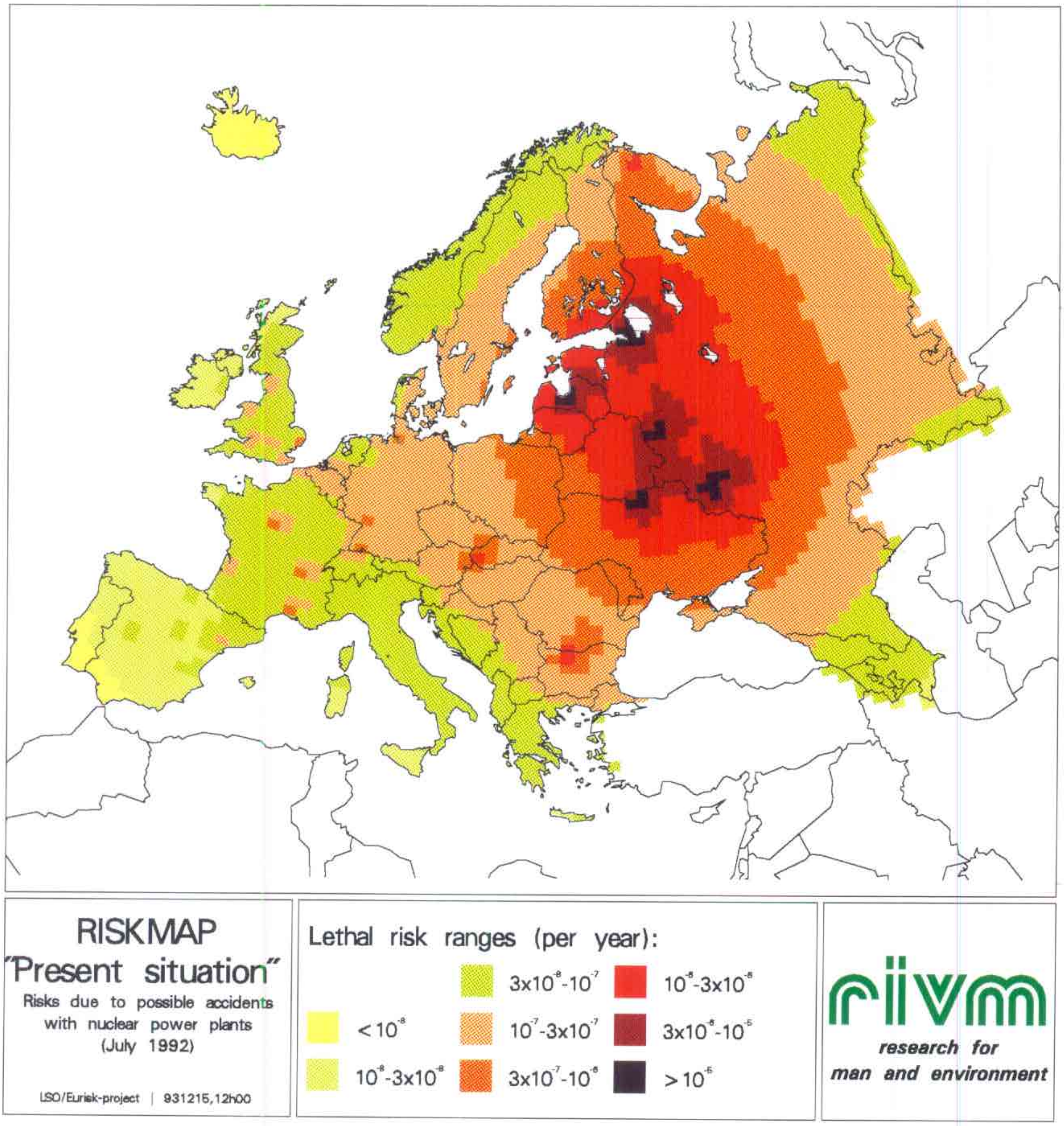

Figure 3.1 Estimated cancer mortality risk due to possible accidentally released nuclides from nuclear power plants in Europe

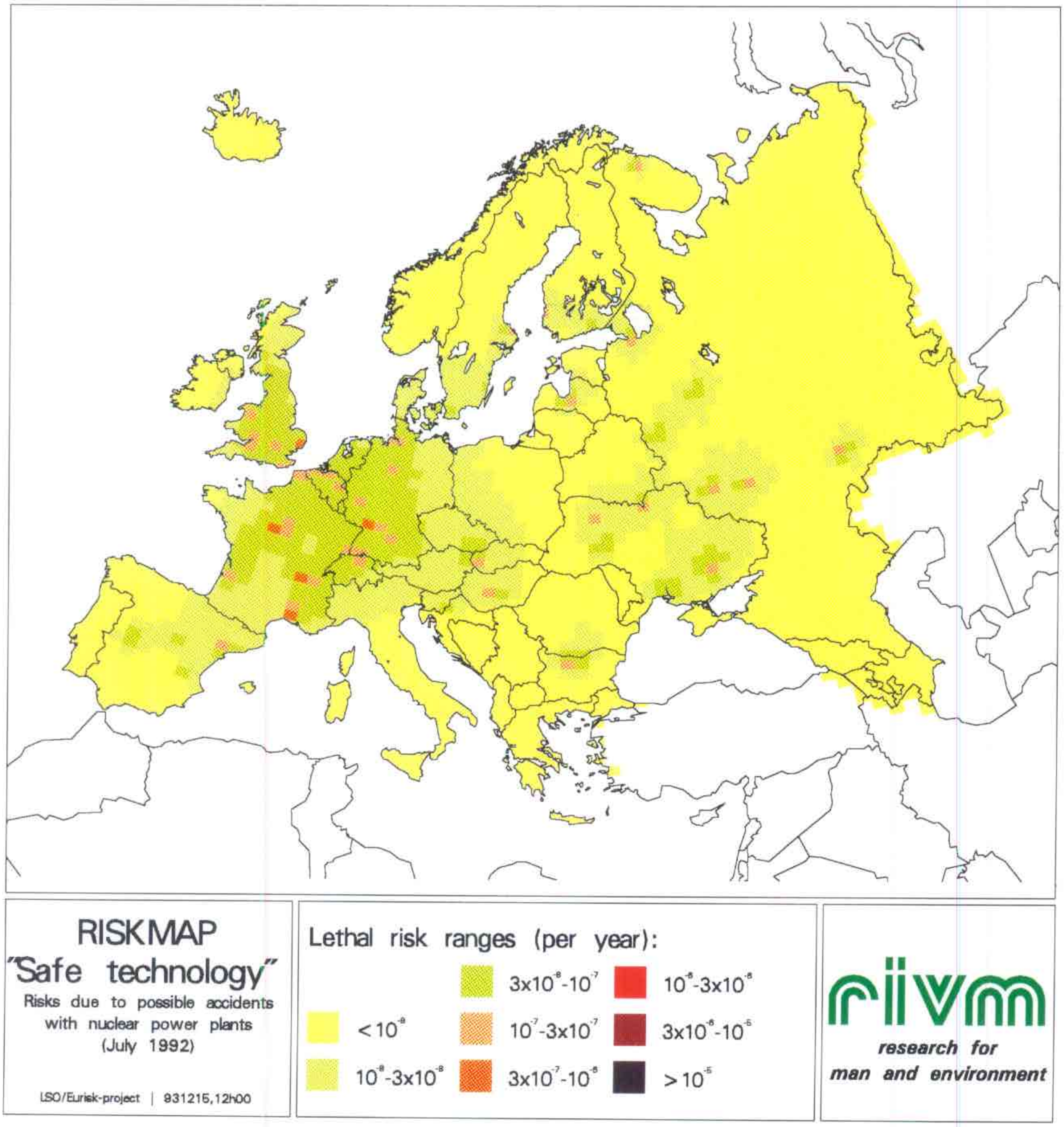

Figure 3.2 Estimated cancer mortality risk due to possible accidentally released nuclides from nuclear power plants in Europe, assuming that all Eastern European reactors involved have a safety level comparable to that of Western European reactors

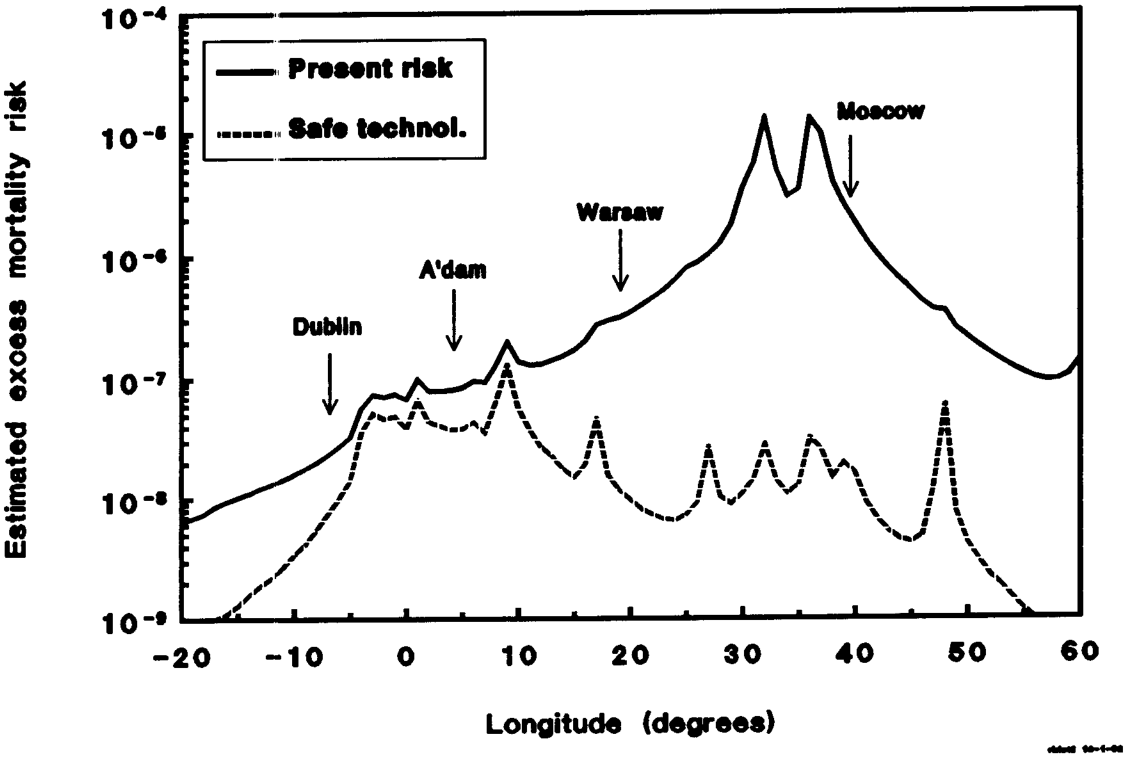

Figure 3.3 Longitudinally dependent estimated cancer mortality risk for the situations described in the risk maps and averaged over the latitudes 48° N to 56° N

In the overall estimate of uncertainties an uncertainty factor of 6 (up as well as down) in Western Europe, and of 10 in Eastern Europe was used. Applying the dispersion model to various situations has led to an estimated uncertainty factor of 4 (up as well as down). On the basis of a comparison with various other modelling efforts, an uncertainty factor of 4 was also estimated for the exposure assessment model (see Slaper *et al.*, 1993 for details). The mortality risk is the product of the various components of the chain. An indication of the overall uncertainty involved was obtained assuming that various errors in the chain are independent and lognormally distributed. The overall estimate of the uncertainty factor, is then 15 in Western Europe and 20-25 in Eastern Europe (up as well as down). These estimates must be seen as first indications of overall uncertainty.

We used a risk factor of 2.5% mortality probability per sievert. Implementing the new ICRP (1991) risk factor of 5% per sievert would increase all risk estimates by a factor of 2. Implementing the new ICRP (1991) dose conversion factors primarily influences the I-131 contribution, increasing inhalation and ingestion doses for I-131 by 70%. The overall doses and risks are then increased by 20-30%. Thus in completely accounting for the new ICRP changes, overall risk is increased by a factor of 2.5.

3.3 Other risk groups

The risks presented in Figures 3.1, 3.2 and 3.3 are calculated for adults of a rural population and assuming a high food consumption. This group is indicated as the reference group. Indicative calculations are also performed for other risk groups (see Slaper *et al.*, 1993 for details). Diet, the time spent outdoors, the time spent in urban areas, and the age of the exposed population are factors which influence the risk estimates. Results of calculations for various groups are provided in Table 3.1. The risk multiplication factor provides an indication of the relative change in excess mortality risks as compared to the reference group in this study.

As can be seen in Table 3.1 small children (at the time of an accident) are estimated to have 3 to 4 fold higher lifetime risk than the reference risk group. An overall mixed rural and urban population of adults with an average food consumption (ICRP, 1975) and exposure and shielding parameters as provided by UNSCEAR (1988) is expected to have 50% lower risks than given in this study. As mentioned in the previous section, full implementation of the ICRP-60 would lead to increased estimates by approximately a factor of 2.5.

Table 3.1 Risk multiplication factors for various other risk-groups, compared to the reference risk group. All estimates are based on 70 years follow-up doses.

risk group	diet	behaviour (fraction of time spent outdoor)	risk multiplication factor
adults, rural reference group in present study	extreme in the Netherlands	30% outdoor	1
adults, rural	Various other ingestion models	30% outdoor	0.6 - 3
adults, mixed (rural and urban)	Reference man (ICRP, 1975)	20% outdoor (UNSCEAR, 1988)	0.5
children (1 year), later rural	child (average and extreme) extreme adult	30% outdoor reference	3 - 4

4 CONCLUSIONS AND DISCUSSION

The aim of environmental policies is the reduction of man-made risks, both for regular releases and for accidental releases of pollutants to the environment. Risk oriented policy approaches require risk assessment methodologies. This study provides the results of an integrated source-risk evaluation for possible accidental releases to the atmosphere of nuclear power plants in Europe. The aim was to give a probabilistic estimate of the location dependent mortality risks over the European continent, related to the combined use of all presently operational nuclear power plants for commercial electricity production. Mortality risks are restricted to radiation induced cancer deaths, related to possible accidental releases. Thus, short term deaths that could occur in the direct vicinity of the nuclear power plants are not included in the presented evaluation. This implies that maximum individual mortality risks in the close vicinity of the nuclear power plants are not covered by the presented analysis. However, accounting for acute deaths is not expected to lead to a substantial alteration of the presented mortality risk maps for Europe, since the presented mortality risks are averaged over the area of the grid cells (ca. 2200-5000 km^2) and acute deaths are restricted to a limited area (probably less than 20-80 km^2). Furthermore, short term deaths can only occur under unfavourable weather conditions and very high accidental releases.

The mortality risk due to accidents of European nuclear power plants is estimated to be around 10×10^{-8} per year in Western Europe. In central Europe a large increase in the estimated risk of about 30×10^{-8} in Poland to over 1000×10^{-8} per year in Russia is observed. Approximately 50% of the mortality risk in Western Europe has to be attributed to possible accidents of Eastern European reactors.

Additional calculations were made for the situation where all Eastern European reactors are assumed to have the quality of safety measures presently found in Western European reactors. In this case the average risk in Western Europe is reduced by nearly a factor of 2 and in Eastern Europe by more than a factor of 100. Thus, reactor safety improvement can reduce risks considerably.

One of the aims in risk oriented policy approaches is to achieve a common risk oriented basis to weight the relative importance of various environmental issues. Such a common basis is only achieved if the methodology of risk analysis and the risk groups considered are comparable for various issues. The presented analysis is in close agreement with the modelling and parameter choices proposed in the MORIS-project (Blaauboer *et al.*, 1992). It was found that many of the models developed for continuous releases, could also be applied and translated to the situation of large accidental releases with a low probability of occurrence. The approach is only valid if the contamination is linearly related to the effects considered. Since this is generally assumed to be the case for cancer induction following exposure to ionizing radiation, but not for the occurrence of short term deaths, the method is restricted to the prior case.

The calculations of overall risks show a large degree of uncertainty. The main contributor to the overall uncertainty is the lack of knowledge on accident probabilities and source terms, especially for the Eastern European power plants. Estimates of accident probabilities based upon the operational and accidental history of nuclear power plants provide general agreement with the release probabilities applied in this study, and could support an indicative uncertainty range. Including the uncertainties of dispersion and exposure estimates, a preliminary estimate of the overall uncertainty of the risks is obtained: a factor of 15 in Western Europe, and a factor of 20-25 in Eastern Europe.

It should be noted that reactor safety is not a static situation, because ongoing improvements to security systems and operating procedures can contribute to lower risk levels than estimated in the present study. On the other hand, the economic recession, shortage of supplies and regional conflicts in the Eastern European countries could provide a further stress on safety features.

The results obtained in this study could aid policymakers to compare risks of regular and accidental situations. This comparison could contribute to integrated risk based policy approaches for a reduction of risks related to nuclear power generation. Furthermore the results allow for a risk comparison with other environmental issues with large scale consequences. The methodology could also be applicable to other types of atmospheric releases (accidental or regular), provided that the relationship between the amount of a release and the effect is essentially linear.

Estimates provided in this study could be improved in several of ways. A reduction of uncertainties could be most effectively achieved by an improved safety analysis of various reactor types, and especially of the Eastern European reactors. Furthermore regional estimates could be improved incorporating average regional weather conditions, topography and soil characteristics. A combination with demographic data could provide insight in the population averaged risks involved.

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