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Risks due to beyond design base accidents of nuclear power plants in Europe—the methodology of riskmap

Iouli Andreev [a,b,*,1], Markus Hittenberger [b,1], Peter Hofer [a,2], Helga Kromp-Kolb [b,1], Wolfgang Kromp [a,2], Petra Seibert [b,1], Gerhard Wotawa [b,1]

[a] *Institute of Risk Research, University of Vienna, Vienna, Austria*
[b] *Institute of Meteorology and Physics, Universität für Bodenkultur, Vienna, Austria*

Abstract

International treaties on liability in the case of nuclear accidents set a limit on the repair payments to be made by the operators of nuclear power plants to countries adversely affected by nuclear fall-out which is independent of the actual risk incurred by the individual countries. A map of the risk due to beyond design base accidents of nuclear power plants in Europe could give an indication which countries are likely to profit by joining the treaties and which are not. Such a riskmap for effects based on the deposition of the long-lived radionuclide Cs-137 is being developed for commercial nuclear power plants in Europe. Dispersion and deposition calculations are based on meteorological data of 1 year. The modular design allows scenario calculations for different assumptions concerning source terms and frequencies of beyond design base accidents of individual power plants or plant types as well as a sensitivity analysis of the results. © 1998 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

International treaties on liability in the case of nuclear accidents, as, e.g., the Vienna or the Paris Conventions, set a limit on the repair payments to be made by the operators

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[*] Corresponding author. Tel.: +43 1 4790094; fax: +43 1 4790095; e-mail: Risikoforschung@univie.ac.at
[1] Tel.: +43 1 470582017; fax: +43 1 470582060; e-mail: imp@mail.boku.ac.at
[2] Tel.: +43 1 4790094; fax: +43 1 4790095; e-mail: risikoforschung@univie.ac.at

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of nuclear power plants (NPPs) to countries adversely affected by nuclear fall-out. At present, these limits are set independently of the actual risk caused or incurred by the individual countries. Although the geographical distribution of fall-out after an accident is stochastic in the sense that it is the result of a coincidental combination of radioactive emissions and prevailing weather conditions, certain features are more likely to occur than others, due to climatological features, such as wind distribution and precipitation patterns.

The aim of the present study is to map the risk due to beyond design base accidents (BDBA) of nuclear power plants in all of Europe in order to: (a) provide a tool to determine which nuclear power plants pose the greatest risk to a given area to provide a basis for the setting of priorities regarding safety upgradings and phase-outs; (b) make transboundary risk visible and thus reinforce what has already been made clearly visible by the accident in Chernobyl [1]: the risk of nuclear energy production is not just an internal, national affair; (c) help in defining risk ‘exporters’ and risk ‘importers’, an aspect that international liability agreements like the Vienna and Paris Convention should take into account, e.g. in determining fair contributions of individual countries to insurance pools.

Using empirical factors to describe the influences of geography, Sinyak [2] calculated normalized damage factors for the main cities of Europe. Slaper et al. [3] calculated a map of risk of excess cancer deaths due to nuclear accidents, based on simplified models and assumptions, with restrictions as to its applicability, especially in mountainous, high precipitation areas.

The present effort will provide a flexible and more generally applicable tool of a modular structure to facilitate sensitivity analysis and scenario calculations based on a sound dispersion model and meteorological data.

2. Methodology

The risk posed by accidents in nuclear power plants is determined by the damage caused and the likelihood of occurrence. Many factors influence the two basic complexes determining possible damage, source term and atmospheric transmission, and most of these are highly complex themselves and can vary greatly for different nuclear accidents and times. Therefore, resulting risk calculations will always contain high uncertainties. Any tool that is to be of use must therefore permit to determine the sensitivity of the results on input parameters and be flexible enough to calculate a large number of scenarios to define upper and lower bounds of risks, robust features of the geographical distribution of risk, etc. Fortunately, the most time-consuming computation, the transport and deposition simulation, is linear in the sense that if the source term is changed by some factor, the deposited activities change by the same factor. Thus, it is sufficient to calculate the transport and deposition once; many different scenarios can then be generated without too much effort.

The damage caused by a nuclear accident is considered to be represented by the ground contamination with the long-lived radionuclide Cs-137 (half-life 30.2 a). Further effects, such as contamination with other long-lived radionuclides (Sr-90, Pu isotopes) or short-lived radionuclides (I-131, etc.), dose calculations, inclusion of mitigation measures, etc., are beyond the scope of this study.

Two different levels of damage are defined in accordance with the accident management strategies at the Chernobyl accident [4]: above a level of 5 Ci km^{-2} (185 kBq m^{-2}) Cs-137 ground contamination, measures for the improvement of the living conditions in those areas have to be taken. If the Cs-137 ground contamination exceeds 40 Ci km^{-2} (1480 kBq m^{-2}), the population has to be relocated.

2.1. Source terms and release parameters

The amount and nature of radioactive substances released into the atmosphere and the conditions under which they are set free are described by the source term. It is determined by the sequence of events leading to the release. The accidents of interest here are the so-called beyond design base accidents (BDBA), leading to very large releases. The source terms chosen for the present study are taken from a comprehensive review of accident scenarios for pressurized and boiling water reactors and their uncertainties [5]. For British graphite reactors (GCRs, AGRs) and the Soviet designed RBMKs (Chernobyl type) the source terms were taken from HPAC [6].

Considerable uncertainties are inevitable for the effective release height as well. However, while results can easily be adjusted to changes in source terms, release heights must be determined before transmission calculations are made, as they—at least initially—determine the height in which the radioactive cloud is transported, and especially whether this is within the boundary layer or above it. In view of the uncertainties, emissions are assumed to be released between 50 and 200 m above ground with equal distribution in this interval.

2.2. Frequencies of BDBA

There is no consensus on the likelihood of occurrence of beyond design base accidents (BDBA), as the technology is too young to have sufficient empirical data for reliable statistics [7]. Therefore, different scenarios for the frequency of BDBA will be considered in the present study: the IAEA safety target for existing NPPs postulates that the frequency of large off-site releases should be below 10^{-5} reactor yr^{-1} [8]. Other scenarios are taken from a broad spectrum of data published in WASH-1400 [9], the German Risk Study [10] and Sdouz et al. [5]. For WWER reactors in eastern Europe the reviews of existing probabilistic safety analyses by Höhn and Ledermann [11]. Kromp-Kolb et al. [12], Wenisch [13] and Slaper et al. [3] were consulted. Like the source terms, release frequencies do not influence transmission calculations and can therefore be taken into account at the end of calculations.

2.3. Dispersion

Transport and diffusion in the atmosphere are calculated with the Lagrangian particle model FLEXPART [14] on the basis of analysed fields from the European Centre for Medium-Range Weather Forcatsing (ECMWF). Some adaptions and simplifications were made in the model to speed up the calculations. Two different grids ($1^\circ \times 1^\circ$ and $0.5^\circ \times 0.33^\circ$) allow for higher resolution near the reactor sites, where deposition varies strongly within short distances. Results within one grid distance of NPPs are not evaluated. The model domain covers Europe and the eastern Atlantic. The release is tracked for a maximum of 10 days, until it leaves the domain or until the remaining airborne mass is less than 0.5% of the initial release—whichever occurs first. Any mass that is still airborne at this time is deposited proportional to the previous deposition in each cell.

Dry deposition is linked to land use inventories to take care of the effect of different surfaces. Wet deposition strongly depends on precipitation amounts. Therefore, special attention was paid to the analysis of the precipitation field: instead of fully using short term ECMWF forecasts, the precipitation was analysed using synoptic station data in areas with sufficient station density.

The total period for simulations encompasses the year 1995, which can be shown to be representative for the 20-year period 1977–1996 (using synoptic flow patterns after Steinacker [15]), and thus corresponds to climatological expectations. Release intervals are chosen to assure sampling of all seasons and times of day.

2.4. Risk indicators

It is impossible to cover the wide range of direct and indirect consequences on health, environmental degradation, economic loss—all strongly influenced by mitigating measures and their timing—in the risk evaluation of the present study. As mentioned, only the deposition of long-lived radionuclides will be calculated as a first step.

Even this very basic approach leaves room for discussion as to what would be an appropriate measure to identify relative risk. For example, the percentages of caesium deposited in Belarus, Russia and the Ukraine by far exceed those of other countries, yet considering these depositions in relation to the size of the individual countries, Slovenia and Austria were as much affected as the Ukraine, and more so than Russia. This becomes even clearer when considering the percentage of the area contaminated (Cs level above 10 kBq m^{-2}): Slovenia ranks first, with Austria, Bulgaria and Moldavia following. Only when higher levels of contamination are considered, Belarus again heads the list.

Regarding possible effects of contamination, it must also be kept in mind that consequences are not necessarily proportional to contamination—this is true for the level of contamination as well as for the area affected. Thus, with increasing percentage of a country contaminated, it becomes increasingly difficult to sustain it on the remaining area or economy. There is a point well below 100% where this becomes impossible. This must be taken into account when interpreting the geographical distribution of risk.

2.5. Evaluation of depositions

The deposition patterns resulting from each release on a grid covering Europe are archived and the ensemble of all the runs is the base of all subsequent statistics. Fig. 1

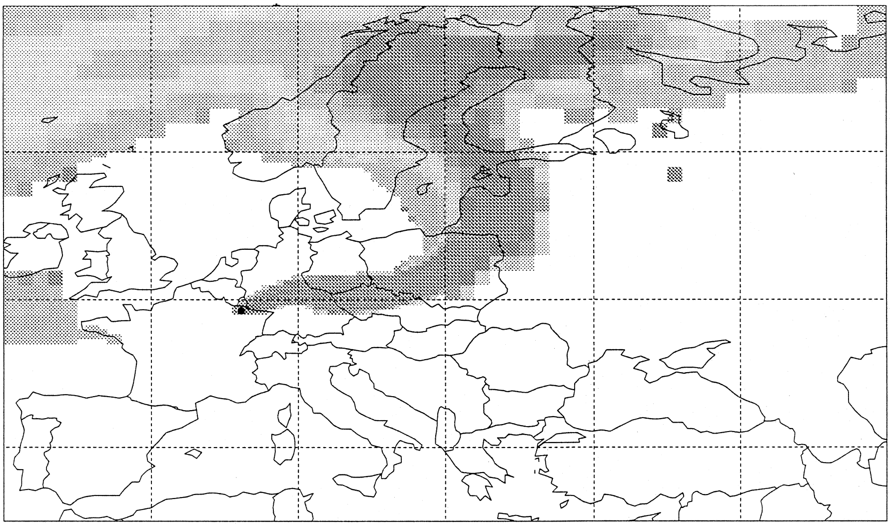

Fig. 1. Geographical distribution of the deposition resulting from a release at NPP Cattenom (relative units).

shows the deposition of one such release. At first, the deposition values are scaled with a factor corresponding to the assumed source term for each reactor. It is then checked for each release whether the contamination exceeds the two prescribed thresholds. The next step is to calculate the probability of exceedance of the threshold which has two components: the probability of the BDBA in the specific reactor, and the percentage of the meteorological situations which lead to a sufficiently high deposition. This is done for all grid elements. Finally, maps can be plotted or evaluations by country be made.

3. Summary

Riskmap is a project to develop a tool to produce maps of the geographical distribution of the risk due to beyond design base accidents of nuclear power plants in Europe. The tool is of a modular structure, allowing for scenario calculations, where uncertainties are especially high without undue demand on computer resources.

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