*Journal of Environmental Protection and Ecology 1, No 3, 260–266 (2000)*

*Environmental radioactivity*

# THE IMPACT OF THE CHERNOBYL ACCIDENT – MODEL CONCLUSIONS ON THE RELATED RISK IN EUROPE

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**Abstract.** The European Commission has published the "Atlas of Caesium Deposition on Europe after the Chernobyl Accident" in 1998. Greece contributed with data provided by NES/NTUA and ERL/NCSR "Demokritos". This work presents the results of a statistical analysis of the Atlas data, which allow to apply a simple model to the European territory, taking into account the locations and the power of 210 power reactors operating in 88 nuclear power plants (NPPs). The radioactive pollution risk patterns are presented by use of special mapping software, developed for this purpose. Special attention is paid to the Kozloduy NPP and its contribution to the risk for the Greek territory.

*Keywords*: radioactive pollution, "Chernobyl-level accident" pollution model, radioactive pollution risk.

## AIMS AND BACKGROUND

The prediction of the radiological impact of a major nuclear accident can be done on a purely theoretical basis. At the same time, an important EU document has been published recently — the "Atlas of Caesium Deposition on Europe after the Chernobyl Accident" (from now on — "Caesium Atlas"[1]). It contains detailed maps of the $^{137}$Cs deposition in different European countries (including those which are not members of EU). Roughly 75% of the Greek data have been provided by Prof. Simopoulos, NTUA, Athens, while the rest — by P. Kritidis, ERL. The statistical analysis of the data of the Caesium Atlas, combined with the data presented in an earlier major EU document[2], allows a rough evaluation of the radiological risk from nuclear accidents in different areas of Europe. Taking into account that the Chernobyl accident took place at almost the most unfavourable season, this evaluation is rather overestimating the impact of a future accident of this type. The data for Greece are of special interest, due to the large public concern related to the closest NPP-Kozloduy.

## RADIOACTIVE POLLUTION VERSUS DISTANCE

The experience of the Chernobyl accident proved once again that the radioactive pollution of soil and plants with $^{137}$Cs has the major contribution to the population

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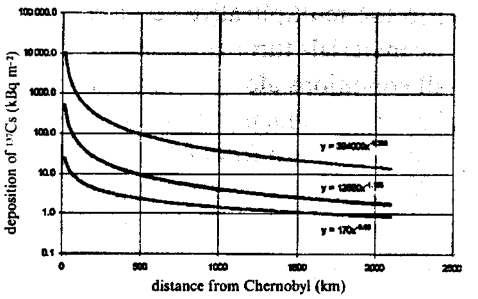

Fig. 1. Deposition of $^{137}$Cs: trends of regional minimum (lower line), maximum (upper line) and the trend of the country averages observed in different distances from Chernobyl

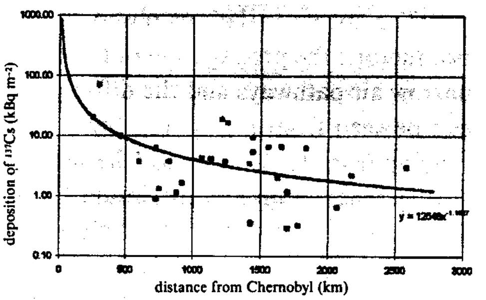

Fig. 2. Deposition of $^{137}$Cs: country averages observed in different distances from Chernobyl

in regions distant more than 100 km from the accident site. The data of the Caesium Atlas[2] have been analysed in detail to derive statistical relations of the $^{137}$Cs deposition as a function of the distance from Chernobyl. The deposition is characterised by strong variations. The trends of deposition maximum and minimum observed at different distances are shown in Fig. 1. They are compared with the trend of the average values, observed in different countries, where the distance of each country's centroid from Chernobyl has been used and the country's area has been used as weighting factor.

The observed variations with respect to the trend of the country averages start from 0.12-14 at small distances from Chernobyl and decrease to 0.5-8.3 at 2000 km. The power of the trend lines decreases from -1.34 (regional maximum) through -1.16 (country averages) to -0.69 (regional minimum).

A more detailed picture of the average deposition of $^{137}$Cs in different countries is given in Fig.2. The "average distance" refers to the country's centroid.

The country averages differ from the trend line typically within 0.25-4. The most heavily and most lightly polluted countries with respect to the trend expectation are given in Table 1.

**Table 1.** Most heavily and most lightly polluted countries with respect to the trend expectation

| Country | Actual deposition to trend expectation | Country | Actual deposition to trend expectation |
|---|---|---|---|
| Austria | 5.9 | Netherlands | 0.13 |
| Slovenia | 5.3 | Denmark | 0.13 |
| Belarus | 4.3 | Latvia | 0.15 |
| Finland | 3.5 | Belgium | 0.15 |
| Norway | 3.1 | Poland | 0.23 |
| Switzerland | 2.9 | Estonia | 0.24 |
| ..... | ..... | | |
| Greece | 2.0 | | |

The strong variations observed are due to the multiplicative contribution of two factors: the propagation of the radioactive materials through certain relatively narrow air pathways and the different rainfall conditions along these pathways. It can be seen from Fig. 1 that the combination of these factors lead in variations ranging from 1:120 close to Chernobyl to 1:20 at 2000 km from Chernobyl. Note that the maximum and minimum for given distance do not refer to the same region. If one considers a relatively small region (e.g. some prefecture of Greece), the local variations are smaller, as they reflect now only the rainfall variations under relatively constant air concentrations of the radioactive pollutants.

## THE "CHERNOBYL-LEVEL ACCIDENT" POLLUTION MODEL

We can define the "Chernobyl-level accident" as an accident, which results in the release of the same percentage of $^{137}$Cs in the environment as this from the Chernobyl-4 reactor during 1986. In addition, it leads to radioactive pollution depending on the distance according to the trend functions derived from the Chernobyl accident. In this case, the expected average deposition $D_{ij}$ of $^{137}$Cs in a point $j$ as a result of accident in reactor $i$ equals

$$D(i,j) = (W_i \,/\, W_c)\, C(R_{ij}),$$

where $W_i$ is the MW power of the reactor $i$; $W_c$ is the MW power of the Chernobyl-4 reactor (1000 MW); $R_{ij}$ is the distance between the points $i$ and $j$; $C(R)$ is the trend function derived from the Chernobyl data.

Based on this simple model, we can obtain two different estimates related to the radiological risk in any point $j$:

a. The maximum Caesium deposition $D_{\max}(j)$ expected from the "worst" accident related to $j$:

$$D_{\max}(j) = \mathrm{MAX}_i\,(D(i,j))$$

b. The total annual Caesium deposition $D_{\mathrm{tot}}(j)$ expected from accidents in all the (European) reactors:

$$D_{\mathrm{tot}}(j) = \mathrm{SUM}_i\,(P_i\, D(i,j))$$

where $P_i$ is the annual probability of a "Chernobyl-level accident" in reactor $i$.

The above estimates have different and complementary meanings. $D_{\max}(j)$ estimates the Caesium pollution in $j$ given that a nuclear accident has occurred in the most unfavourable reactor for $j$. $D_{\mathrm{tot}}(j)$ estimates the total risk for point $j$ due to the operation of all the reactors. The existing reactors can be further grouped to obtain estimates of partial contributions, e.g. the contribution of the Western Europe reactors, this of French reactors, this of Kozloduy 1-4, etc.

Prior to the demonstration of model's applications, we have to stress its great simplicity, especially in the following points:

a. The presumption of isotropic distribution of the deposition *D*. In fact, *D*(*R*) depends on the co-ordinates of *i* and *j* also through the expectancy function of air transfer from *i* to *j*. This function differs also from season to season. This could modify considerably the picture in the simple case of one source/one target ($D_{max}$). In the case of $D_{tot}$, applied to Europe, with 88 sources (NPPs) and a lot of highly populated areas, this would not change qualitatively the picture, but only the location of the most risky areas. For example, a distribution with maximum to the south direction in Central Europe would decrease the risk estimate for Luxembourg, but increase this for Brussels.

b. The seasonal dependence goes deeper if one considers also the role of rainfalls for the radioactive deposition and the role of the agricultural period (basic plants exposed to the pollutants).

To defend the use of the model we must note, that the Chernobyl accident happened during a very unfavourable season and it lasted 10 days, during which the air masses propagated through a large variety of pathways and climatic conditions. This "good statistics" supports the application of the model, at least for very rough evaluations and conclusions.

## APPLICATION OF THE MODEL IN THE CASE OF EUROPE

The model has been applied by use of NPP data of the Argonne National Laboratory INSC Database[3]. The locations of the NPPs are known with accuracy higher than 2 km. The map of Europe, in rectangular coordinates, has been composed by the data from the XEROX PARC database[4]. A special mapping software has been developed in order to visualise the results.

*Worst accident impact.* A normalised pattern of the maximum deposition values ($D_{max}$) in Europe is shown in Fig. 3. The values have been normalised to the deposition of $^{137}$Cs in Athens due to the Chernobyl accident (2.1 kBq $m^{-2}$, 1986). Note that due to the rectangular co-ordinate system, the horizontal dimension appears larger as the latitude increases. The map represents correctly the real aspect ratio for the latitude of Central Greece.

The normalised values of $D_{max}$ for selected European towns are given in Table 2, together with those for the "No 2" NPP (not evident from Fig. 3). The names of the respective NPPs are quoted, where the notation "Unit M-N" means "an accident in some of the units M-N".

*Total radioactive pollution risk.* A normalised pattern of the total $^{137}$Cs pollution risk ($D_{tot}$) is shown in Fig. 4. The values have been normalised to the value for

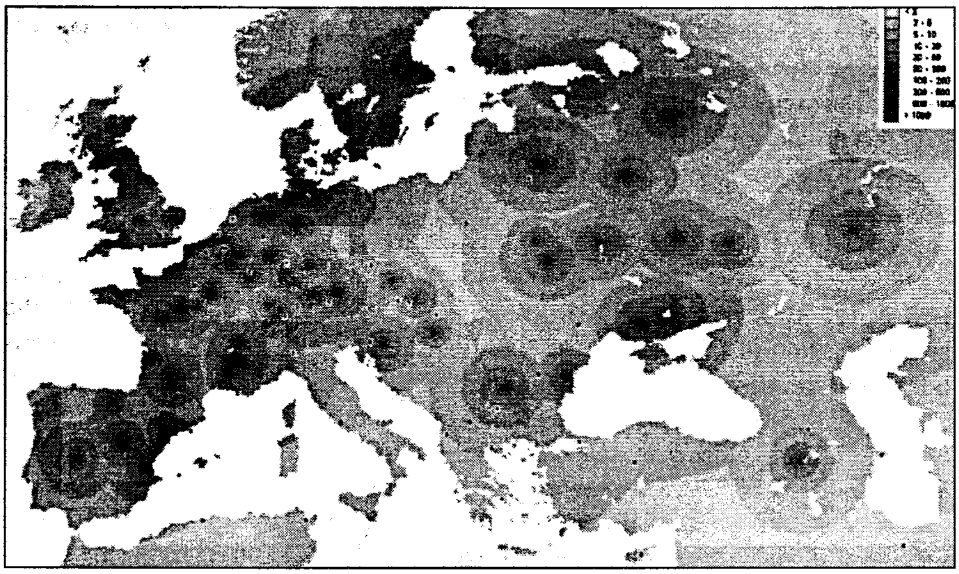

**Fig. 3.** Normalised values of $^{137}$Cs deposition due to an accident in the most unfavourable NPP for each European point. The black rectangles represent the European capitals and other important towns

Vienna. The Chernobyl-level accident probability for Kozloduy 1-4 is taken 10 times higher than that of other units.

The normalised values of $D_{tot}$ for several European towns are given in Table 3. The contribution of Kozloduy 1-4 (×10), Western Europe and former Comecon NPPs is given separately. The values have been normalised to the value for Vienna.

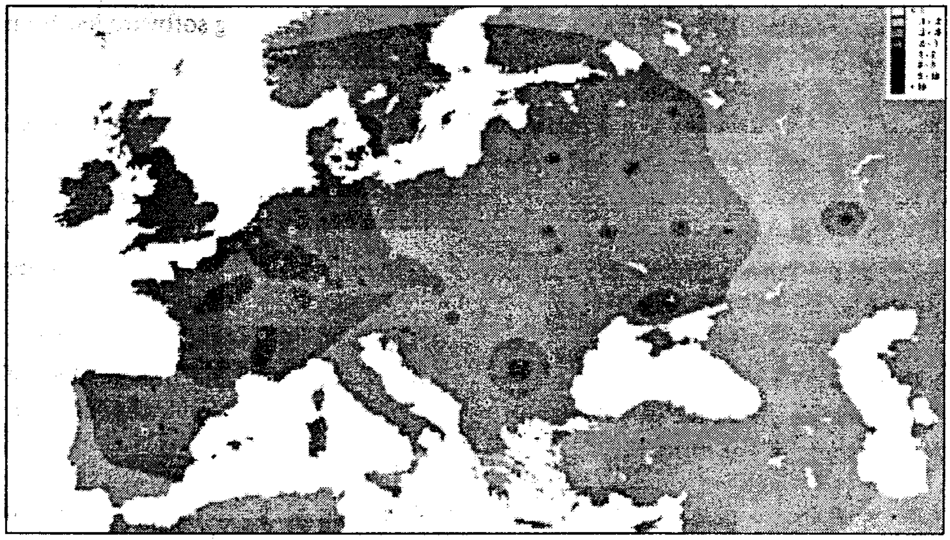

**Fig. 4.** Normalised values of the total $^{137}$Cs pollution risk ($D_{tot}$) in Europe

**Table 2.** Normalised values of $^{137}$Cs deposition due to a Chernobyl-level accident in the two most unfavourable NPPs for selected European towns

| Town | | Worst impact | | Impact No 2 |
|---|---|---|---|---|
| | value | unit | value | unit |
| Tehran | 1.0 | Medzamor 2 | 0.9 | Zaporozye 1-6 |
| Lefkosia | 1.4 | Kozloduy 6 | 1.3 | Zaporozye 1-6 |
| **Athens** | **3.1** | **Kozloduy 5-6** | **1.7** | **Chernavoda 1** |
| **Thessaloniki** | **6.1** | **Kozloduy 5-6** | **2.6** | **Kozloduy 1-4** |
| Vienna | 13 | Bohunice 1-4 | 9.6 | Dukovany 1-4 |
| London | 18 | Pauel 1-4 | 17 | Penley 1-2 |
| Sofia | 21 | Kozloduy 5-6 | 8.9 | Kozloduy 1-4 |
| Kiev | 26 | Chernobyl 11-3 | 8.2 | Chmelnitski 1 |
| Madrid | 28 | Trillo 1 | 13 | Almaraz 1-2 |
| St. Petersburg | 40 | Leningrad 1-4 | 6.2 | Kalinin 1-2 |
| Paris | 40 | Nogent 1-2 | 23 | Belleville 1-2 |
| Brussels | 47 | Chooz B1 | 41 | Doel 1-4 |
| Munhen | 47 | Isar 1-2 | 38 | Gundremmingen B-C |
| Zagreb | 50 | Krsko | 5.9 | Isar 1-2 |
| Zurich | 91 | Leibstadt | 72 | Goesgen |
| Lyon | 110 | Bugey 2-5 | 88 | Creis-Malville |
| Stuttgart | 130 | Neckarwestheim 1-2 | 46 | Philippsburg 1-2 |
| Hamburg | 170 | Kruemmel | 71 | Brokdorf |
| Luxembourg | 190 | Cattenom 1-4 | 37 | Chooz B1 |

**Table 3.** Normalised values of the total $^{137}$Cs pollution risk ($D_{tot}$) in selected towns

| | Athens | Thessaloniki | Sofia | Brussels | Luxembourg |
|---|---|---|---|---|---|
| Risk due to: | | | | | |
| Kozloduy 1-4 × 10 | 0.11 | 0.22 | 0.75 | 0.04 | 0.04 |
| Western Europe | 0.22 | 0.26 | 0.28 | 2.06 | 3.10 |
| Former Comecon | 0.11 | 0.14 | 0.22 | 0.09 | 0.10 |
| **Total risk** | **0.44** | **0.62** | **1.25** | **2.19** | **3.24** |

## DISCUSSION

The data of Fig. 3 and Table 2 characterise the Southeastern Europe and the Middle East as a real "nuclear oasis". The estimated impact of the worst nuclear accident in Lefkosia, Athens and Thessaloniki is 1-2 orders of magnitude lower than this expected in Stuttgart, Hamburg or Luxembourg. Note that this impact is related — by definition — to the personal risk level. The differences are even more dramatic at the public level, due to the large populations, living in the high-impact regions of France, Germany and Benelux.

The data of Fig. 4 and Table 3 show that that Kozloduy – even with an accident risk taken "by 10" – contributes less to the total risk in the Greek territory than the other European NPPs. On the other hand, the risk in certain regions of Central Europe, populated by tens of millions, is 5-7 times higher than this in Athens. The area around Kozloduy with $D_{tot} > 1$ equals 100 000 km$^2$, while the corresponding area of Western Europe equals 1 300 000 km$^2$. These estimations support the opinion supported by our Laboratory since many years: For Greece, the nuclear safety problem is not related to Kozloduy only, but to the safety of the nuclear power industry in general.

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*Received 19 November 1999*
*Revised 14 June 2000*