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# Dose Estimates from the Chernobyl Accident

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## DISCLAIMER

# Dose Estimates from the Chernobyl Accident

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ABSTRACT

The Lawrence Livermore National Laboratory Atmospheric Release Advisory Capability (ARAC) responded to the Chernobyl nuclear reactor accident in the Soviet Union by utilizing long-range atmospheric dispersion modeling to estimate the amount of radioactivity released (source term) and the radiation dose distribution due to exposure to the radioactive cloud over Europe and the Northern Hemisphere. In later assessments, after the release of data on the accident by the Soviet Union, the ARAC team used their mesoscale to regional scale model to focus in on the radiation dose distribution within the Soviet Union and the vicinity of the Chernobyl plant.

## Introduction

Measurements of airborne radioactivity over Europe, Japan and the U.S. indicated that the release from the Chernobyl reactor accident in the Soviet Union on 26 April 1986 contained a wide spectrum of fission and activation products up to heights of 7 km or more within a few days after the initial explosion. This high altitude presence of radioactivity would in part be attributable to atmospheric dynamics factors other than the thermal energy released in the initial explosion. Indications were that two types of releases had taken place—an initial powerful explosion followed by days of a less energetic reactor fire.

The Atmospheric Release Advisory Center (ARAC) (Dickerson, Gudiksen and Sullivan 1983) at the Lawrence Livermore National Laboratory utilized three-dimensional atmospheric dispersion models to determine the characteristics of the source term (release) and the evolution of the spatial distributions of the airborne radioactivity as it was transported over Europe and subsequently over the Northern Hemisphere. This paper

describes the ARAC involvement, and the results of the model calculations and their integration with radiological measurements made within Europe, Kuwait, Japan and the U.S. to estimate the quantity of specific radionuclides released. Then the unmitigated inhalation and immersion dose distributions due to direct cloud exposure throughout Europe and the Northern Hemisphere were calculated. Close in calculations were made with the models to obtain results in the vicinity of the reactor (30 km radius) which were compared to radiological data from the USSR. The most important radionuclides of global concern were $^{137}$Cs, $^{134}$Cs and $^{131}$I because of their relative abundance as well as their radiological and chemical characteristics. $^{131}$I and $^{137}$Cs measurements were used to estimate the source term in the absence of such data from the USSR at the time.

The radiological measurements used in this work were acquired from numerous informal reports prepared by various scientific organizations in Denmark, Finland, France, Japan, Kuwait, Netherlands, Norway, Sweden, United Kingdom, United States, and West Germany as well as from the World Health Organization (WHO) and the International Atomic Energy Agency (IAEA) data tabulation reports.

The units in this report are based on the international SI standards. In order to help the reader to translate them into more conventional units, some practical equivalents are given below:

1 mGy = .1 Rad

1 Bq $\approx$ 27 pCi

## The ARAC Transport and Dispersion Models

The Atmospheric Release Advisory Capability (ARAC) project is a Department of Energy (DOE) sponsored emergency response service available for use by both federal and state agencies in case of a potential or actual atmospheric release of nuclear material. During the past decade the ARAC has responded to over 100 real-time situations, including exercises. The most notable responses include the Three Mile Island (TMI) accident and

the subsequent venting of the Kr-85 from the containment, the Titan II missile accident in Arkansas, the re-entry of COSMOS-954 into the atmosphere, the Sequoyah Facility accident in Oklahoma, and most recently the Chernobyl reactor accident in the Soviet Union. The Chernobyl accident consequences, being on a global scale, were the most difficult challenge to the ARAC to date.

The Chernobyl source term estimations and the European and hemispherical inhalation dose estimates were computed with the three-dimensional sequential puff transport and diffusion model PATRIC (Lange 1978a) that was adapted to the hemispheric troposphere from its original purpose to assess the global transport of the stratospheric radioactivity cloud generated by Chinese atmospheric nuclear weapons tests. It is a simplified version of the ADPIC model (Lange 1978b) which was used to calculate the higher resolution, close-in inhalation dose for a 200 and 30 km radius around the Chernobyl reactor.

Both models are based on the particle-in-cell concept. This technique involves the generation of a large number of marker particles to represent the radioactivity distribution. These particles are injected as a sequence of puffs at the source point and subsequently transported within a three-dimensional Eulerian grid mesh by means of a transport velocity applied to each particle. This transport velocity consists of a wind velocity provided at each grid point and a diffusion velocity based on Gaussian diffusion in PATRIC, and on gradient diffusion in ADPIC. In addition, gravitational settling and dry deposition velocity vectors as well as radioactive decay may be applied to the particles, as appropriate. For Chernobyl effects of terrain and wet deposition due to precipitation scavenging, however, were not available and were not included. Summing the resulting distribution of particles over the grid mesh volumes allows determination of the three-dimensional concentration distributions that are needed for dose estimations.

The PATRIC calculations were based on a computational mesh covering the Northern Hemisphere. The mesh, consisting of 46 × 50 × 14 grid cells with 381 km horizontal resolution and a 750 m vertical spacing, was positioned over a flat polar stereographic

projection of the Northern Hemisphere at 60 degrees north latitude. In order to better resolve the concentration distributions, a particle sampling grid was also placed over the European area with a grid dimension of one third the size of the computational grid. The Northern Hemisphere wind fields used by the model were supplied by the U.S. Air Force Global Weather Central (AFGWC). These gridded wind fields contained values at seven pressure levels ranging from 1000 to 250 mb. The rate of diffusion was calculated assuming a neutral to slightly unstable atmosphere. The particles were assumed to be 1$\mu$m in radius and to have a dry deposition velocity of 0.001 m/s except for particles representing iodine which were given a 0.003 m/s velocity.

## Source Term Estimation

It is difficult to quantify the magnitude of the release of specific nuclides to the atmosphere, especially when they are caused by catastrophic events. The Soviets reported discharge of the core inventory of 20% of $^{131}$I and 13% of $^{137}$Cs based on material deposited in the near- field inside the USSR. Investigators in Western Europe estimate approximately another 20% of these volatile nuclides were transported to their region in addition to the Soviet data. In addition to these far-field data from Western Europe, analysis of upper level atmospheric concentrations made by aircraft indicate that as much as an additional 20% of the core inventory of these radionuclides found their way into the rest of the northern hemisphere as far away as Japan and the United States (Goldman et al. 1987). Altogether, estimates range from 40% to 60% of the core inventory of iodine and somewhat smaller percentages of cesium were released to the atmosphere.

Estimates of a source term based on numerical models and limited measurements are also subject to considerable uncertainty, especially considering the large distances involved in the Chernobyl accident. The evolution of the radionuclide plume in time and space is dominated by nonlinear and discontinuous processes in the atmosphere acting on a broad spectrum of spatial scales. In addition, terrain and the change in the physical

and radiochemical composition of the plume introduce uncertainties in model predictions. Using the available measurements, the long-range transport model PATRIC was able to estimate a source term for the Chernobyl release that is likely to be within a factor of two to three of the actual amount released. (The estimates were prepared prior to the release of the Soviet report (USSR, 1986) but still hold).

Some features of the release suggested that the source term was divided into two phases: an early explosion-like phase, with up to 50% of the total release injected to heights of several kilometers; and a later, longer burn phase that injected smaller amounts of material at lower heights. The PATRIC source estimation iterative process focused on $^{131}I$ (corrected to total radioiodine when only filter samples were available) and $^{137}Cs$. It was based only on air-concentration samples to avoid the highly localized nature of wet deposition patterns, and it reconciled model results with surface and upper-air concentration measurements (Gudiksen and Lange 1986). Approximately 80 radiological measurements were acquired from informal reports prepared by various scientific organizations in Denmark, Finland, France, Japan, Kuwait, the Netherlands, Norway, Sweden, the United Kingdom, the United States, and the Federal Republic of Germany, as well as from the World Health Organization (WHO) and the IAEA data tabulation reports and various U.S. aircraft flights.

Measurements of airborne radioactivity over Europe, Japan and the United States detected the presence of fresh fission products up to heights of about 7 km within a few days after the initial explosion. Highly increased particulate $^{131}I$ and radiocesium activities were reported over northeast Poland on April 30 between the ground level and 3 km with comparatively low activity between 6 and 12 km, and in increased levels at 15 km. Jaworowski and Kownacka (1986), based on Polish aircraft measurements, suggest that 50% of the released activity was injected to an altitude of about 7 km. These results suggested that some radionuclides released by the explosion and the subsequent fire within the reactor core must have been transported to heights well within the middle troposphere.

This may have been due to a variety of factors, such as the thermal energy associated with the release, rapid atmospheric mixing due to the presence of thunderstorms in the vicinity of the Chernobyl area, or the possible uplifting of the radionuclides over a warm front situated between Chernobyl and the Baltic Sea. Therefore, the source term designed for PATRIC consisted of an upper- and a lower-level cloud of radionuclides. The upper-level cloud was assumed to be due to the initial explosion and uplifting and to contain the major fraction of activity that was released during the first day. The lower-level cloud was assumed to be the result of the hot fire that continued to cause radioactive emissions during a 6-day period following the initial explosion.

In order to match observations, it was assumed that the upper-level cloud was centered at 4500 m, with a vertical extent from 1500 to 7500 m, which included one-half of the total activity released. It was also assumed that the lower-level cloud, which contained the other half of the amount released, was centered at 1300 m and extended from the surface to 1500 m.

This source-term configuration, along with the initial ARAC estimates that $1.5 \times 10^{18}$ Bq of $^{131}I$ and $1.1 \times 10^{17}$ Bq of $^{137}Cs$ were emitted during the 6-day release period, served as a first basis for the PATRIC model to calculate the three-dimensional activity distribution as a function of time for two grid scales: one over Europe, the other over the Northern Hemisphere. By forcing to zero the mean relative error between measured and computed concentrations, a more refined source term for PATRIC was derived, namely a total release of $1.7 \times 10^{18}$ Bq of $^{131}I$ and $8.9 \times 10^{16}$ Bq of $^{137}Cs$. Most $^{131}I$ air concentrations were obtained by gamma-spectrometry of air filters. Since radioiodine is generally fractionated among the particulate, gaseous iodine, and methyl iodide forms, the particulate fraction represented only 20 to 50% of the total iodine, with a most likely value of about 33%. Therefore, all iodine filter measurements were multiplied by a factor of three for use in estimating the total iodine release.

Source terms for radionuclides other than $^{131}I$ and $^{137}Cs$, as used in the PATRIC code, are indicated in Table 1. To acquire release estimates for the fission products, activity ratios relative to $^{137}Cs$ were derived from measurements of airborne radioactivity. To minimize the effect of isotope fractionation due to precipitation scavenging, the data used for this purpose were mainly limited to measurements in Sweden and Finland. The activity ratios often varied over a considerable range. However, selective averaging yielded the activity ratios shown in Table 1 for the principal fission products, along with the estimated corresponding total activity released.

**Table 1.** Activity fraction relative to $^{137}Cs$ and estimated activity released (decay corrected to 26 April 1986).

| Nuclide | Fraction | Activity Released (Bq) |
|---|---|---|
| $^{137}Cs$ | 1.0 | $8.9 \times 10^{16}$ |
| $^{136}Cs$ | 0.2 | $2.0 \times 10^{16}$ |
| $^{134}Cs$ | 0.5 | $4.8 \times 10^{16}$ |
| $^{131}I$ | 20. | $1.7 \times 10^{18}$ |
| $^{133}I$ | 42. | $3.7 \times 10^{18}$ |
| $^{141}Ce$ | 0.1 | $8.9 \times 10^{15}$ |
| $^{144}Ce$ | 0.06 | $5.2 \times 10^{15}$ |
| $^{140}Ba$ | 0.5 | $4.4 \times 10^{16}$ |
| $^{140}La$ | 0.5 | $4.4 \times 10^{16}$ |
| $^{95}Zr$ | 0.1 | $8.9 \times 10^{15}$ |
| $^{95}Nb$ | 0.1 | $8.9 \times 10^{15}$ |
| $^{132}Te$ | 4.2 | $3.7 \times 10^{17}$ |
| $^{103}Ru$ | 0.3 | $3.0 \times 10^{16}$ |
| $^{106}Ru$ | 0.06 | $5.2 \times 10^{15}$ |
| $^{133}Xe$ | — | $6.5 \times 10^{18}$ |

## Temporal and Spatial Distribution of Radioactivity

The PATRIC results obtained with the source inventories for $^{131}I$ and $^{137}Cs$ from Table 1 contain a detailed analysis of the time-varying horizontal and vertical spatial distributions of airborne radioactivity. These indicated that the cloud became segmented during the first day, with the lower section heading toward Scandinavia and the upper

part heading in a south-easterly direction, with subsequent transport across Asia to Japan, the North Pacific, and the United States. To demonstrate the evolution of the activity distribution as modeled by the marker particles of PATRIC Figure 1 shows the calculated particle pattern spread over the northern hemisphere at days 2. 4. 6 and 10 after the initial release.

Note that by the end of April 27 (day 2) the activity near the surface had traveled in a northwesterly direction, toward Scandinavia, passing over the northeastern corner of Poland en route. The activity distribution continued its expansion into Scandinavia by April 29, at the same time moving southwesterly through Poland toward eastern and central Europe. The emissions from the reactor during this period were also transported eastward. By May 1, the surface activity had spread throughout central and southern Europe as well as east and south of the Chernobyl area. By May 5, nearly the entire northern hemisphere is engulfed with material having reached the United States. In a quantitative way, the surface air concentration patterns for $^{131}I$ over Europe at 2 day intervals between April 27 and May 3 are shown in Figure 2. The concentrations are averages over 24 hours between 0000 GMT and 2400 GMT on the day shown.

Since the emissions in the model due to the fire were assumed to be continuous until this time, the concentration levels were fairly constant, ranging generally between 1 and 100 $Bq/m^3$. Until May 3 at which time concentrations decreased to 1 to 10 $Bq/m^3$ as the cloud expanded over Europe to include the United Kingdom and the Mediterranean and eastward, over the Soviet Union. (Although the subsequently published release curve obtained from the Russians indicates a longer release period, until May 6, and showed a second peak, most measurements in Western Europe do not show such a second peak, indeed, material released after May 2 went towards the Black Sea. The calculated concentrations in the vicinity of the Chernobyl area are underestimated by several orders of magnitude because of the coarse spatial resolution inherent in these model calculations,

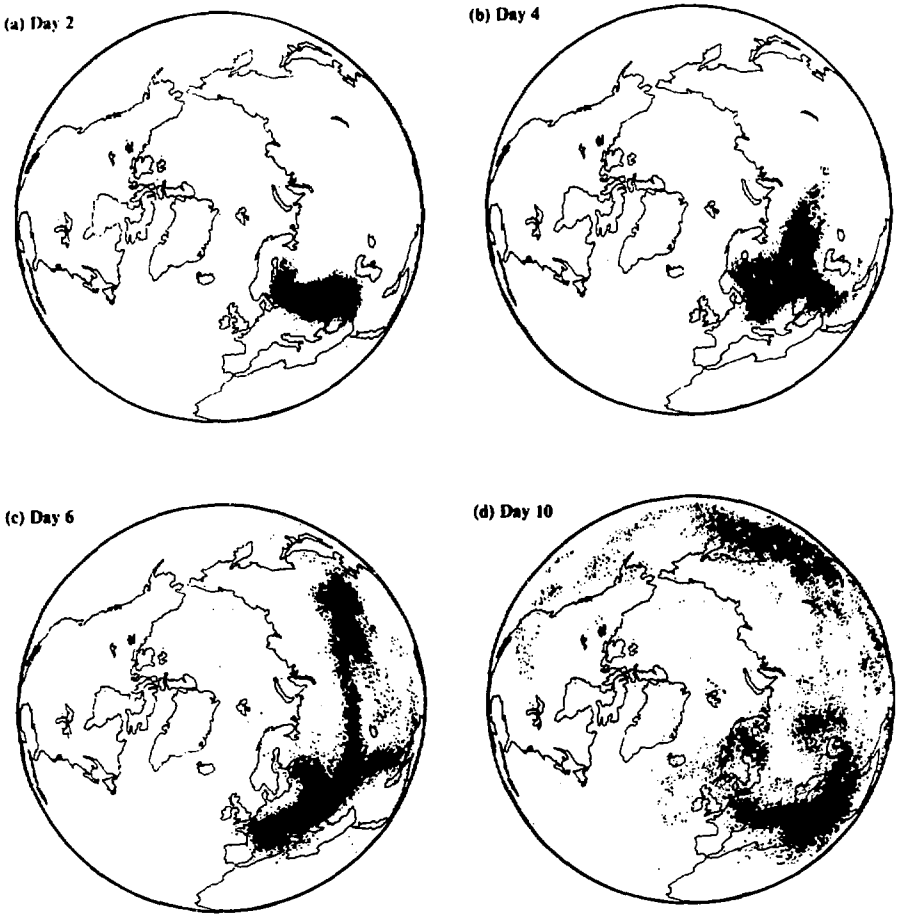


**Figure 1.** ARAC plots showing how the clouds of radioactive material spread around the Northern Hemisphere at (a)2, (b)4, (c)6, and (d)10 days after the initial explosion.

uncertainly of the time when the release actually terminated and knowledge of the actual source strength.

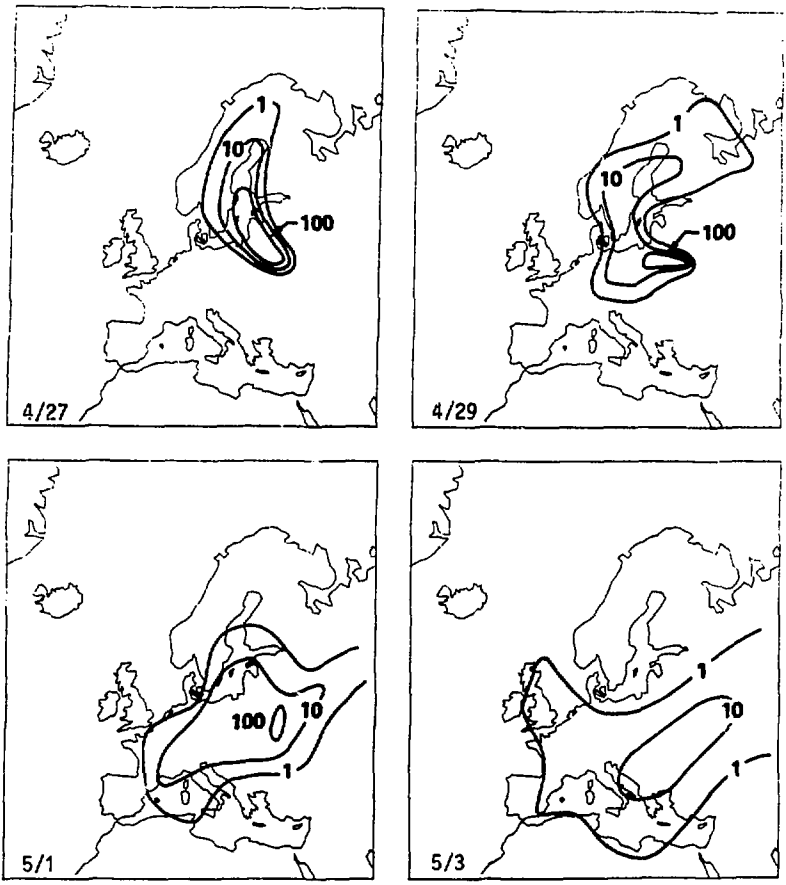


**Figure 2.** $^{131}$I surface air concentration patterns over Europe (Bq/m$^3$) based on PATRIC model for dates listed.

On the global scale, a major fraction of the activity was transported at elevated levels in the atmosphere. Figure 3 illustrates the calculated $^{131}$I activity distributions at a height of 5500 m on May 2 and 5. The radioactivity present at this level had traveled across Asia to reach Japan by May 2, and subsequently crossed the Bering Sea and the Gulf of Alaska to intercept the west coast of the continental United States on May 5. By contrast, the surface concentration patterns, also shown in Figure 3, indicate a much longer transit time,

arriving in the area of Japan about May 7 and in the United States on may 13. Since $^{131}I$ was detected in surface air samples collected in these areas 3 to 4 days prior to this, the precipitation scavenging processes or other large scale downward motion, which are not included in the calculations, could have been responsible for some of the rapid transport of the radionuclides to the surface from the higher altitudes.

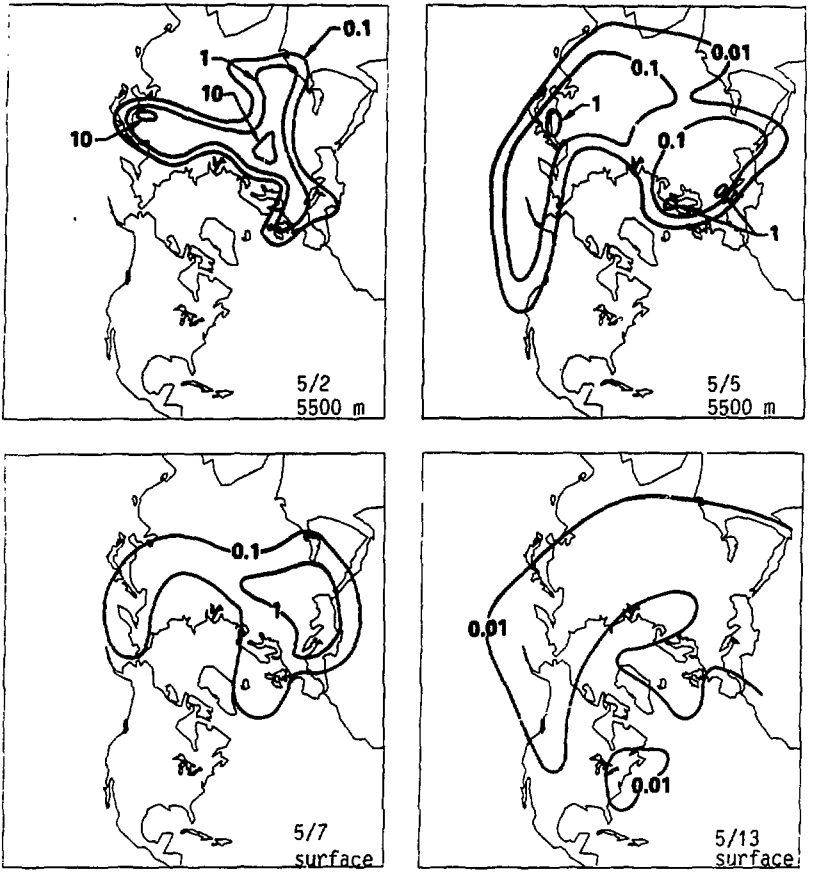


**Figure 3.** $^{131}I$ Surface and upper air concentrations over the Northern Hemisphere ($Bq/m^3$) based on PATRIC model for days shown.

With the source-term configuration adjusted to optimize the overall agreement between the calculated and measured activity distributions, Table 2 shows a comparison of the calculated and measured $^{131}I$ and $^{137}Cs$ surface air concentrations and times of arrival at individual measurement sites in Europe and Kuwait. The measured air concentrations were derived by computing the average daily concentrations and subsequently averaging them over the periods given in the table.

**Table 2.** A comparison between measured and calculated surface air concentrations ($Bq/m^3$) and cloud arrival times. (Reference for Table 2 are located in Appendix A.)

| | | $^{131}I$ Concentrations | | $^{137}Cs$ Concentrations | | Cloud Arrival Time | |
|---|---|---|---|---|---|---|---|
| Location | Dates | Meas. | Calc. | Meas. | Calc. | Calc. | Meas. |
| Nurmijarvi (Finland) | 4/29–5/3 | 3.7 | 3.8 | 0.08 | 0.6 | 4/27 | 4/27 |
| Stockholm | 4/28–5/6 | 3.6 | 8.0 | 0.2 | 1.1 | 4/27 | 4/27 |
| Kjeller (Norway) | 4/28–5/5 | 6.2 | 9.5 | 0.2 | 1.3 | 4/27 | 4/27 |
| Munich | 4/30–5/6 | 7.0 | 6.5 | 1.7 | 0.9 | 4/30 | 4/30 |
| Austria | 4/29–5/5 | 3.5 | 4.2 | - | - | 4/30 | 4/29 |
| Budapest | 5/1–5/5 | 3.0 | 4.2 | 0.6 | 0.5 | 4/30 | 4/29 |
| N. Italy | 4/30–5/6 | 17 | 6.6 | 0.7 | 0.4 | 4/30 | 4/30 |
| S.E. France | 5/1–5/6 | 9.8 | 6.6 | 0.4 | 0.7 | 4/30 | 4/29 |
| Paris | 5/1–5/7 | 0.7 | 3.7 | 0.2 | 0.5 | 5/1 | 4/29 |
| S. Italy | 5/1–5/6 | 8.0 | 1.9 | 0.6 | 0.2 | 5/2 | 5/1 |
| Netherlands | 5/1–5/5 | 7.1 | 9.3 | - | - | 5/2 | 5/2 |
| Berkeley (U.K.) | 5/1–5/3 | 0.3 | 0.5 | 0.05 | 0.02 | 5/3 | 5/2 |
| Chilton (U.K.) | 5/2–5/3 | 5.4 | 4.5 | 0.9 | 0.2 | 5/3 | 5/2 |
| Athens | 5/3–5/5 | 29 | 18 | - | - | 5/3 | 5/3 |
| Kuwait | 5/4–5/9 | 0.3 | 0.1 | 0.06 | 0.03 | 5/7 | 5/5 |

The table reveals that PATRIC generally overpredicted the concentrations in Scandinavia, France, and the United Kingdom while underpredicting those measured in southern Europe and Kuwait. The overprediction in Scandinavia may be due to the uplifting of the radionuclides by a warm front that the cloud encountered during its passage to Scandinavia. The underprediction in southern Europe may be a result of improper temporal

variations in the source term, as well as terrain effects because of the Alps, and because of precipitation scavenging processes, none of which is included in the calculations. Table 2 also provides a comparison of the measured and computed cloud arrival times at each site. Agreement is excellent within Scandinavia; however, the calculated times at several sites in Western and Southern Europe lag by a day. This may in part be due to differences in which arrival times are defined by measurements.

Radionuclides were measured at various altitudes by aircraft-mounted sampling systems that collected filter samples over the Norwegian Sea, the Federal Republic of Germany, the Sea of Japan and along the west coast of the United States during a 2-week period following the accident. Table 3 provides a comparison between the measured and calculated $^{131}I$ and $^{137}Cs$ air concentrations and cloud arrival times over these areas at various altitudes. The reasonable agreement between the measured and calculated values gives credence to the existence of a high-level source term configuration suggested by the convective meteorological processes and the energetics of the explosion.

**Table 3.** A comparison between measured and calculated air concentrations ($Bq/m^3$) and cloud arrival times.

| | | | $^{131}I$ Concentrations | | $^{137}Cs$ Concentrations | | Date of Cloud Arrival | |
|---|---|---|---|---|---|---|---|---|
| Date | Location | Altitude (m) | Meas. | Calc. | Meas. | Calc. | Meas. | Calc. |
| 4/30 | Norwegian Sea | 1500 | 18. | 12. | 0.17 | 0.11 | — | — |
| 5/1 | Norwegian Sea | 750 | 0.5 | 0.7 | — | — | — | — |
| 5/1 | Norwegian Sea | 3000 | 0.07 | 0.1 | 0.09 | 0.07 | — | — |
| 5/2 | Japan Sea | 5500 | 2.7 | 1.0 | 0.07 | 0.11 | 5/2 | 5/2 |
| 5/2 | West Germany | 1500 | 11. | 13. | 1.1 | 1.3 | — | — |
| 5/2 | West Germany | 3000 | 2. | 3. | — | — | — | — |
| 5/2 | West Germany | 5500 | 1. | 1. | — | — | — | — |
| 5/4 | Japan Sea | 1500 | 0.3 | 0.2 | — | — | — | — |
| 5/4 | Japan Sea | 3000 | 1. | 1.5 | — | — | — | — |
| 5/5 | U. S. West Coast | 5500 | 0.3 | 0.1 | 0.07 | 0.04 | 5/5 | 5/5 |
| 5/5 | U. S. West Coast | 3000 | — | — | 0.003 | 0.002 | | |

## Estimation of Inhalation and Immersion Dose

In calculating a radiation dose to man from the Chernobyl accident, the major pathways are -in decreasing order of importance:

1. External gamma exposure from ground deposits of radionuclides.
2. Ingestion of radionuclides with food.
3. Inhalation of radionuclides during fallout plume passage.
4. External gamma dose from immersion during cloud passage.

Pathways 1 and 2 are most important, but their effect can be mitigated—sheltering, food selection, etc., while 3 and 4 are more immediate and harder to protect against. Furthermore, 1 and 2 are computed from deposition of radionuclides on the ground while 3 and 4 are obtained from air concentrations. As already mentioned, an estimate of a source term is more reliably obtained from measurements of air concentrations than from highly variable deposition patterns influenced by precipitation scavenging which can be highly localized. For this reason nuclide air-concentration patterns were estimated with PATRIC, and based on them, and the appropriate nuclide mix, inhalation and immersion doses were calculated. The PATRIC generated concentration distributions for each nuclide listed in Table 1 were integrated over the period from 26 April to 13 March to derive the 50 year *unmitigated* individual inhalation and immersion dose equivalent from exposure to the airborne radioactivity over the Northern Hemisphere, Europe, and two smaller regions of 400 × 400 km and 50 × 50 km centered on the reactor.

Figure 4 shows the isopleths of this inhalation dose committment to an adult in mGy. Figure 4a indicates a low $1\times10^{-5}$ mGy over the western United States and Canada, Japan and the eastern parts of China. The dose over Europe is shown in Figure 4b and indicates regions exceeding 0.1 mGy extending over the western USSR, northeastern Poland, and up into Sweden, while extending southward over the Ukraine and parts of eastern Europe. Most of central Europe, parts of northern Scandinavia and the remainder of eastern Europe are situated between the 0.01 and 0.1 mGy isopleths. Denmark, the U.K., Spain, and

northern Scandinavia received less than the 0.01 mGy. About 80% of these values are due to the radioiodines, while the cesium, ruthenium, and tellurium radionuclides are the major contributors to the remaining 20%. These dose estimates compare very favorably with the inhalation doses reported at a WHO meeting in the Netherlands which cited values of 0.11 mGy in northeastern Poland, 0.04 mGy within the remainder of Poland, 0.02 mGy in southern parts of Germany and Finland, and a range of 0.001 to 0.01 mGy in France, the U.K., and Italy.

Because the spatial distributions for the $^{131}I$ thyroid exposure are essentially identical to those shown in Figure 4, one may obtain the adult thyroid dose commitment by multiplying the isopleth values in Figure 4 by a factor of 23. Thus, the highest thyroid doses in Scandinavia are estimated to be about 2 mGy, approximately 0.2 mGy over central Europe, and of the order of $2\times10^{-4}$ mGy in the U.S. In a similar manner, the effective dose equivalent due to immersion in the radioactive cloud may be approximated by multiplying the isopleths in Figure 4 by 0.02. This factor, however, is spatially dependent within a factor of about 2 due to the time varying activity ratios of the radioiodines. Hence, the immersion dose is about a factor of 50 less than the inhalation dose. The relative contributions of the various radionuclides to the immersion dose are essentially the same as those for the inhalation pathway.

Due to the large spatial averaging inherent in these calculations, the radiation doses are greatly underestimated in the vicinity of the Chernobyl area. In order to acquire the spatial resolution needed to derive realistic dose estimates within this area, the ADPIC model was used to calculate the close-in dose distribution over a 400 km and a 50 km numerical grid mesh centered on the reactor site. Local meteorological data, acquired from the standard meteorological reporting stations, were received from the AFGWC. The results are shown in Figures 4c and 4d. Maximum values of the inhalation dose contours increase with the grid resolution of the model. Grid cell resolution for the innermost mesh (Figure 4d) is about 1 km, indicating doses near the reactor exceeding 100 mGy.

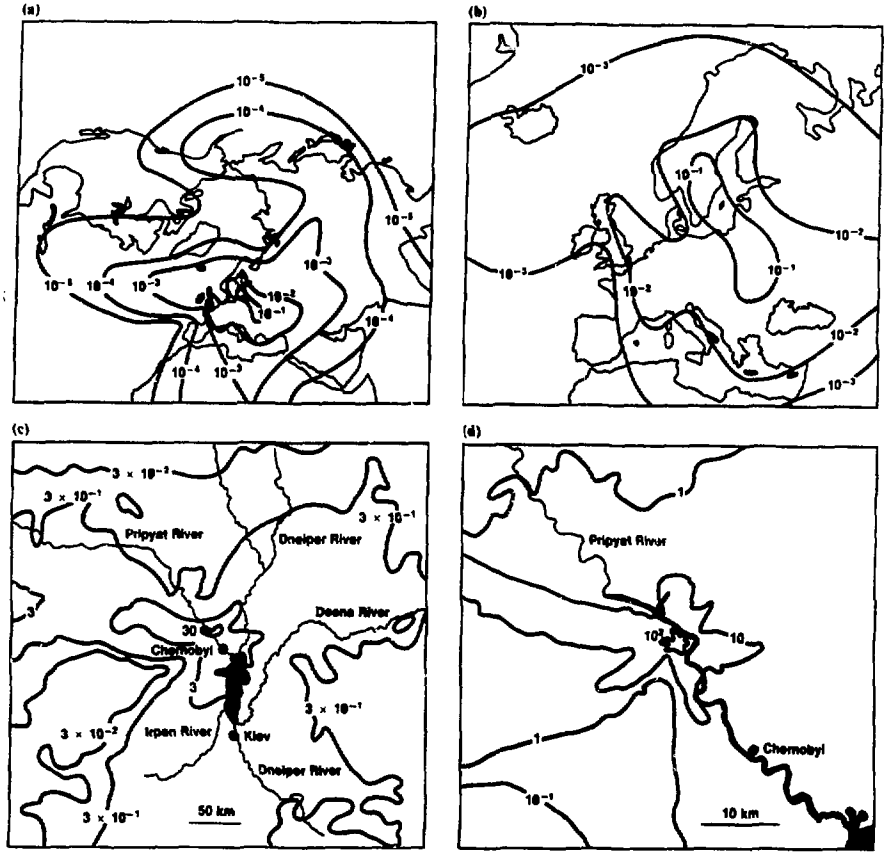


**Figure 4.** Isopleths showing the distribution of cumulative primary radiation dose (that due to breathing the contaminated air, integrated over the next 50 years). The isopleth values are given in mGy. (a)Most of the Northern Hemisphere, in a modified polar projection. (b)Europe, the Mediterranean Sea, and the North Atlantic. (c)A 400 × 400-km area around the Chernobyl reactor. (d)A 50 × 50-km area around Chernobyl. The values for the isopleths increase as the scale decreases because the computer models achieve finer resolution at smaller scales.

Data from the Russian report (USSR 1986) can be used to check the validity of the close-in ADPIC results (Figure 4d). In Figure 5 are shown the gamma radiation levels in a zone around the reactor site on May 29, 1986 in mR/hr as measured by the Russians. In the same report they published a curve relating the change with time of the open field

external gamma exposure rate $P(t)$ in R/hr near the Chernobyl power stations, and also the equation they used to relate gamma-exposure rate 15 days after the accident, $P(15)$, in mR/hr to a child's thyroid dose from inhalation $Dt(ICh)$ in mGy.

$$Dt(ICh) = 100P(15) \tag{1}$$

From the $P(t)$ versus $t$ curve mentioned above, one can relate $P(t)$ at 15 days to $P(t)$ at 35 days after the accident. The relation turns out to be approximately

$$P(15) = 2P(35) \tag{2}$$

Assuming that the inhalation dose for a child thyroid is approximately 120 times the adult whole body inhalation dose $D(IA)$,

$$Dt(ICh) = 120D(IA) \tag{3}$$

equations (1), (2), and (3) can be combined to compute the adult inhalation dose $D(IA)$ directly with the gamma-exposure rate $P(35)$, thirty-five days after the accident

$$D(IA) = 1.7P(35) \tag{4}$$

With equation (4) one can directly relate the measured adult inhalation dose $D(IA)$ computed from Figure 5 to values computed by ADPIC in Figure 4d. Table 4 shows such a comparison for several points around the reactor.

Table 4 indicates a systematic underestimation of the adult 50 year inhalation dose by close to a factor of three below the Russian data. Several explanations for this can be given: first, the ADPIC runs did not include the last three, significant release days because Russian source data were not yet available at the time of the ADPIC run, which was based on a back-calculated source term. Second, the ADPIC source term as described placed a large fraction of the activity at heights above 4 km. This was to simulate later uplifting

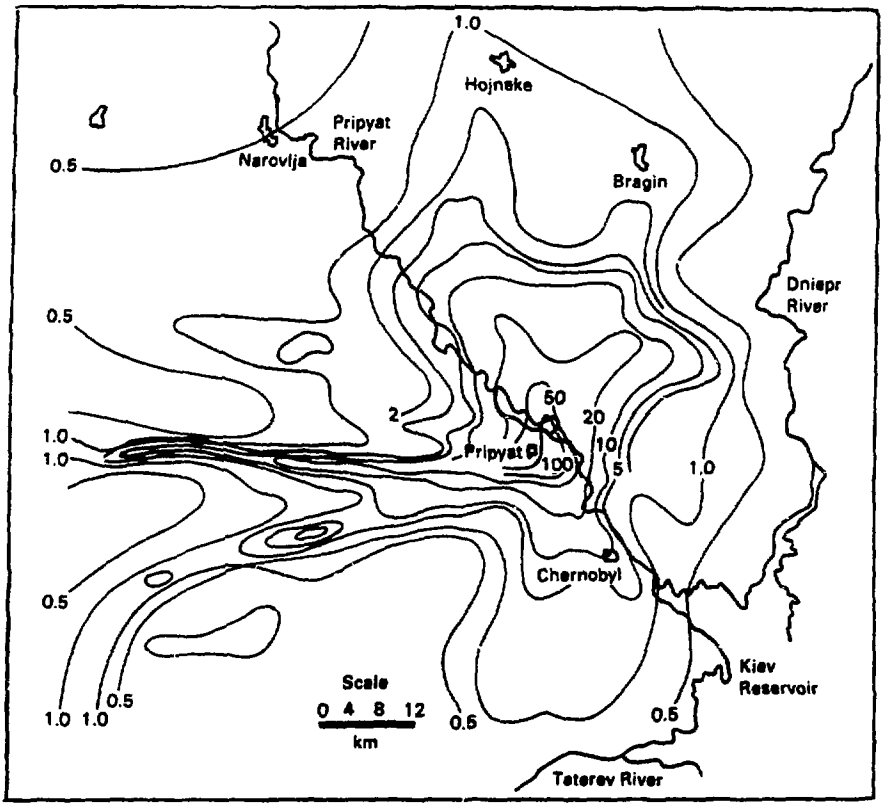


**Figure 5.** External gamma-exposure-rate levels (mR/hr) in the vicinity of Chernobyl on May 29, 1986.

of the material by atmospheric processes but underestimated the amount of radioactivity near the surface close-in. Finally, deposition close-in contained debris from larger particles and non-volatile radionuclides not included in the model source term.

It is important to realize that the dose distributions presented in this work do not reflect the impact of various mitigation measures that may have been undertaken, such as evacuation, sheltering, or the introduction of stable iodine. Such measures could have significantly reduced the estimated doses shown in Figure 4. For instance, a study performed

**Table 4.** Comparison of Adult 50 year unmitigated inhalation dose equivalent in mGy from Russian data with that computed by ADPIC for various points near the Chernobyl power plant. (From Figures 4 and 5).

| Location (Distance from Plant) | Computed from Russian Data by Equation 4 (mGy) | Computed by ADPIC (mGy) |
|---|---|---|
| Chernobyl, 20 km SE | 17 | 6 |
| 10 km SE along Pripyat River | 34 | 10 |
| 20 km NW along Pripyat River | 8 | 3 |
| 10 km North | 32 | 10 |
| 30 km West | 34 | 10 |

by Roed at the Riso National Laboratory in Denmark revealed that by staying indoors the inhalation dose due to elemental and particulate $^{131}I$ as well as $^{137}Cs$ particulates may be reduced by a factor of 2 to 4.

In order to place the adult 50 year inhalation dose calculated in this paper in perspective to the dose burden from other pathways, Table 5 (Goldman et al. 1987) shows the calculated dose committments to adults in selected countries for the 50 year external dose due to deposition, and the thyroid and whole body dose due to ingestion, and additionally the 50 year adult inhalation dose computed by the ARAC PATRIC model.

Table 5 shows that for most European individuals the doses are generally below 0.1 mGy annually and thus represent a lifetime increment of less the 10% of natural background radioactivity, and the individual doses in the United States, Canada, China and Japan are negligible. Also added within a radius of about 30 km from the stricken reactor is the average external dose from Russian data (USSR 1986). The ratios of this to the inhalation dose from ADPIC and PATRIC is smaller than for the rest of the table entries perhaps because unlike the inhalation dose, the external dose was mitigated by evacuation of the

**Table 5.** Calculated individual dose commitments to adults in selected countries after the Chernobyl nuclear reactor accident.

| | External dose, mGy | Ingestion dose, mGy | | Inhalation dose, mGy |
|---|---|---|---|---|
| Country | 50 yr | Thyroid | Total body | 50 yr |
| Canada | 0.0020 | 0.0043 | 0.0019 | 0.00002 |
| China | 0.0044 | 0.0095 | 0.0042 | 0.00005 |
| Czechoslovakia | 0.35 | 1.3 | 0.32 | 0.05 |
| Finland | 0.43 | 1.9 | 0.40 | 0.005 |
| France | 0.11 | 0.42 | 0.11 | 0.005 |
| West Germany | 0.49 | 1.7 | 0.46 | 0.02 |
| Italy | 0.47 | 1.7 | 0.44 | 0.008 |
| Japan | 0.0051 | 0.017 | 0.0048 | 0.0002 |
| Poland | 2.2 | 9.5 | 2.0 | 0.08 |
| Sweden | 0.58 | 2.5 | 0.53 | 0.04 |
| United Kingdom | 0.13 | 0.44 | 0.13 | 0.005 |
| United States | 0.0024 | 0.0051 | 0.0022 | 0.00001 |
| Chernobyl Plant* | 120.0** | ? | ? | 10.0 |

* Average over a 30 km radius area.

** Mitigated by evacuations.

population. The effect on this population from the external and probable ingestion dose-equivalents received maybe similar to those of the Japanese atomic bomb survivers.

## Summary and Conclusions

The Lawrence Livermore National Laboratory Atmospheric Release Advisory Capability (ARAC) responded to the Chernobyl nuclear reactor accident in the Soviet Union on 26 April 1986 by utilizing long-range atmospheric dispersion modeling to estimate the amount of radioactivity released and the radiation dose distribution due to exposure to the radioactive cloud over Europe and the Northern Hemisphere. In later assessments, after the release of data on the accident by the Soviet Union, the ARAC team used their mesoscale to regional scale model to focus in on the radiation dose distribution within the Soviet Union and the vicinity of the Chernobyl plant.

The source term estimation involved an iterative process whereby an initial unit source term was used to calculate the distribution of radioactivity for comparison with measurements of airborne radioactivity of $^{131}I$ and $^{137}Cs$ at about 20 sites throughout the Northern Hemisphere. Scaling of the calculated activity distributions with those measured, lead to an estimate of the total amount of radioactivity released as a function of time and its initial vertical distribution in the atmosphere. Using this source term it was then possible to calculate the spatial and temporal evolution of the radioactive cloud over Europe and the Northern Hemisphere and the radiation inhalation and immersion dose due to cloud exposure. The source term arrived at, consisted of an upper level cloud to heights of 7 km from the inital explosion and a lower level cloud released over 6 days representing the subsequent fire. A total of $1.7 \times 10^{18}$ Bq of $^{131}I$ and $8.9 \times 10^{16}$ Bq of $^{137}Cs$ were assumed released and agreed to within a factor of 2 to 3 with later source term analyses from measurements.

Analysis of the airborne radioactivity distribution from the calculation indicated that the cloud became segmented during the first day, with the lower section heading toward Scandinavia and the upper part heading in a southeasterly direction with subsequent transport across Asia to Japan, the North Pacific, and the west coast of North America. Integrating these concentration distributions over the period 26 April to 13 May produced the 50 year unmitigated individual inhalation and immersion dose distributions due to exposure to the airborne radioactivity over Europe and the Northern Hemisphere.

Close-in (10 km) inhalation doses near the plant exceeded 10 mGy while for most of Europe doses varied from 0.1 mGy to 0.001 mGy. For the rest of the Northern Hemisphere including the United States doses were negligible. Comparison of inhalation dose to dose via the external or ingestion pathways showed it to be much smaller, as expected.

For the 130,000 evacuees from the 30 km radius area around the plant some received doses above 400 mGy, and significant health effects in terms of additional cancers, mental retardation of offspring and genetic disorders are expected. Such effects from high doses at

high dose rates have been demonstrated from studies of Japanese survivors of the atomic bombs. For most of the individuals in the European countries shown in Table 5, total individual doses are generally below 0.1 mGy annually which represents a lifetime increase of less than $10^{-7}$ of natural background radiation. For the United States, Canada, China and Japan the effect of the Chernobyl accident appears negligible. In all cases, the effect of the adult inhalation dose are significantly smaller than doses from the external and ingestion pathway.


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