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RADRUE METHOD FOR RECONSTRUCTION OF EXTERNAL PHOTON DOSES TO CHERNOBYL LIQUIDATORS IN EPIDEMIOLOGICAL STUDIES

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Abstract

Between 1986 and 1990, several hundred thousand workers, called “liquidators” or “clean-up workers”, took part in decontamination and recovery activities within the 30-km zone around the Chernobyl nuclear power plant in Ukraine, where a major accident occurred in April 1986. The Chernobyl liquidators were mainly exposed to external ionizing radiation levels that depended primarily on their work locations and the time after the accident when the work was performed. Because individual doses were often monitored inadequately or were not monitored at all for the majority of liquidators, a new method of photon (i.e. gamma and x-rays) dose assessment, called “RADRUE” (Realistic Analytical Dose Reconstruction with Uncertainty Estimation) was developed to obtain unbiased and reasonably accurate estimates for use in three epidemiologic studies of hematological malignancies and thyroid cancer among liquidators. The RADRUE program implements a time-and-motion dose reconstruction method that is flexible and conceptually easy to understand. It includes a large exposure rate database and interpolation and extrapolation techniques to calculate exposure rates at places where liquidators lived and worked within ~70 km of the destroyed reactor. The RADRUE technique relies on data collected from subjects’ interviews conducted by trained interviewers, and on expert dosimetrists to interpret the information and provide supplementary information, when necessary, based upon their own Chernobyl experience. The RADRUE technique was used to estimate doses from external irradiation, as well as uncertainties,

to the bone-marrow for 929 subjects and to the thyroid gland for 530 subjects enrolled in epidemiologic studies. Individual bone-marrow dose estimates were found to range from less than one μGy to 3,300 mGy, with an arithmetic mean of 71 mGy. Individual thyroid dose estimates were lower and ranged from 20 μGy to 507 mGy, with an arithmetic mean of 29 mGy. The uncertainties, expressed in terms of geometric standard deviations, ranged from 1.1 to 5.8, with an arithmetic mean of 1.9.

Keywords

external dose; Chernobyl; liquidators; dose reconstruction; bone marrow; thyroid

INTRODUCTION

The accident at the Chernobyl Nuclear Power Plant (ChNPP) in northern Ukraine on 26 April 1986 was followed by a phase of cleanup and recovery, which officially lasted until the end of 1990. This effort involved a large number of clean-up workers, the so-called “liquidators.” About 400,000 liquidators took part in cleanup and recovery activities within the 30-km zone around the ChNPP in 1986–1987 (the years of largest radiation hazard and highest intensity of cleanup operations); most of them were from Ukraine, the Russian Federation and Belarus (WHO 2006). The Chernobyl liquidators were mainly exposed to external whole-body photon (i.e. gamma and x-rays) doses that depended primarily on their work locations and on the time after the accident when the work was performed. Unfortunately, for a number of reasons, individual doses were monitored inadequately or were not monitored at all for the majority of liquidators (Chumak 2007). There were also problems with the registration and archival of the results of dosimetric monitoring. Therefore, the available estimates of individual dose are insufficient in terms of both scope and quality. At the same time, demand for reliable dosimetric information is high because of the need for a realistic assessment of the radiation doses received by this population group and requests from studies of health effects of the Chernobyl accident.

On-going epidemiological studies on Chernobyl cleanup workers critically depend on the availability of unbiased and accurate individual dose estimates for all study subjects. The International Agency for Research on Cancer (IARC) initiated two case-control studies of (a) hematological malignancies and of (b) thyroid cancer to evaluate the radiation-induced risk of these diseases among the Chernobyl liquidators. The primary goal of these studies is an evaluation of the effects of protracted exposure and radiation type in the low-to-medium dose range (0–500 mGy). The study population comprises liquidators from the Baltic countries (~15,000), Belarus (~66,000), and the Russian Federation (~65,000), who worked in 1986–1987 and who were either registered in the Chernobyl registries (in Belarus and Russia) or included in established cohorts (in Estonia, Latvia and Lithuania). A total of 70 patients with hematological malignancies, 107 with thyroid carcinoma, and 710 control subjects were included in the main data set (Kesminiene et al. 2008). The subjects of the hematological study were all males, while 38% of the subjects of the thyroid study were females.

In addition, a collaborative case-control study of leukemia and other blood diseases in Ukrainian male liquidators is being conducted by the Research Center for Radiation Medicine of the Academy of Medical Sciences of Ukraine (RCRM) and the U.S. National Cancer Institute (NCI) (Romanenko et al. 2008a). The study population includes approximately 110,000 persons who worked as liquidators between 1986 and 1990. For the first analysis, a total of 71 leukemia cases and 501 controls were identified as study subjects (Romanenko et al. 2008a and b, in press).

To satisfy epidemiologic study requirements, individual dose estimates were needed for all subjects (some of whom are deceased) included in the three studies. The main requirements for dosimetry of the study subjects are (i) uniform quality of dose estimates, to be achieved via application of a single universal method of dose assessment, (ii) ability to estimate doses for all of the dose levels, and (iii) applicability of dose-estimation process to all subjects, including those deceased. The third requirement is particularly significant for the leukemia studies, as this disease has large probability of lethality and many of the cases had already died before the study began.

None of the available methods of retrospective dosimetry or the existing dosimetric data sets could meet all these stringent criteria. The dose values recorded in the state registries of liquidators are called official dose records (ODR). In the state registries of Belarus, Ukraine, and Russia, ODR are available for only about 20, 50, and 60% of registered liquidators, respectively (UNSCEAR 2000). In the Baltic States, the ODR were drawn from official documents confirming participation in the clean-up activities and are available for 82% of the members of the Chernobyl liquidator cohorts in Estonia and Latvia, and for 69% in Lithuania (Rahu et al. 2006; Kesminiene et al. 1997). Further, as was demonstrated elsewhere (Chumak et al. 2007a), the ODR are usually biased upward. Advanced retrospective biodosimetry techniques like EPR (Electron Paramagnetic Resonance) dosimetry with tooth enamel (Chumak et al. 1999) or FISH (Fluorescence In Situ Hybridization) applied to lymphocyte chromosomes (Edwards 2000) are limited by labor intensive analysis, insufficient availability of samples (EPR), or inadequate sensitivity threshold (FISH). Both techniques are only applicable to live subjects; *post mortem* extraction of teeth for EPR analysis is feasible in principle but, for ethical reasons, it is not considered in epidemiologic studies in which a large number of samples are required. Besides, with both techniques, it is impossible to separate the Chernobyl exposure from any other unknown pre- or post-Chernobyl exposure (occupational, natural, dental, or medical). In addition, leukemia patients are frequently treated by methods that cause chromosome translocations and hence may invalidate the results of FISH.

In the Chernobyl context an alternative method, called analytical dose reconstruction (ADR), was developed soon after the accident by the Institute of Biophysics^{†††} in Moscow for the retrospective assessment of doses received by ChNPP personnel during the first days after the event (Illichev et al. 1996). The work histories of the ChNPP staff were reconstructed on the basis of free-flow interrogation, the results of which had to be confirmed by eye witnesses. A conservative ‘radiation protection’ philosophy was used to estimate the doses. The method used a time and motion approach in which both the dose rates and the exposure times tended to be overestimated. Fuzzy-logic algebra was used for uncertainty propagation (Kryuchkov et al. 1998). An independent verification of the ADR dose estimates by EPR dosimetry demonstrated, as expected, that the ADR doses were overestimated by a factor of at least two (Chumak et al. 2005). In addition, the application of the ADR method was limited to the highly skilled and knowledgeable personnel of the ChNPP who were able to recall and describe their actions and movements in detail, and whose work histories could be confirmed.

It was suggested that a modified version of the ADR approach could be applied to a broader population of liquidators. Four main revisions were considered: (i) use of ‘realistic’ rather than conservative parameter values in the dose-estimation process, (ii) simplification of the interview process and use of a standard validated questionnaire, (iii) development of software that allows description of movements of a person with the help of a geographic map, and (iv) application of stochastic simulation for the assessment of uncertainties. The result of this modification was named RADRUE–Realistic Analytical Dose Reconstruction with Uncertainty Estimation. Description of the formalism of the RADRUE methodology and

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discussion of particular solutions and features of the computer-aided dose calculations are presented in this paper.

MATERIALS AND METHODS

The basic principles of the RADRUE technique and the main aspects of its implementation are discussed in subsections that follow. The basic equation employed and the issues of radiation quantities and units are discussed first, followed by discussion of (i) the input data for the calculations, (ii) the database of measured exposure rates and interpolated values, and (iii) the uncertainties in the procedure of dose estimation.

Basic principles

The main idea of dose calculation by the RADRUE technique is very straightforward and is based on calculation of external dose as a product of the exposure rate and irradiation time, with shielding taken into account. It should be noted that at the time of the Chernobyl cleanup work in 1986–1990, all the radiation measurement devices used for monitoring were calibrated in terms of exposure rate (R h^{-1} , mR h^{-1}) and it is therefore convenient to use exposure rates (in those units) in the retrospective dose calculations. Mathematically the external dose D , (mGy), absorbed during a liquidator's work can be inferred from the summation of the products of exposure rate, duration, and location factor during each time interval when the person was exposed to radiation:

$$D = \sum_{i=1}^n C_i P[x(t_i), y(t_i), t_i] \Delta t_i L_i, \quad (1)$$

where C_i is the conversion coefficient from exposure to the dose to tissue (e.g., red bone marrow or thyroid) of interest (mGy h^{-1} per mR h^{-1}); $P[x(t_i), y(t_i), t_i]$ is the exposure rate (mR h^{-1}) at the location $[x(t_i), y(t_i)]$ and at time t_i , where and when the liquidator was present; Δt_i is the time interval during which the liquidator performed a relatively brief task under stable conditions of exposure at that location; L_i is the location factor for the working conditions (sometimes called “location factor”); and n is the number of (usually unequal) time intervals considered in the calculation. The RADRUE method includes both point estimates of dose and the uncertainties in the dose estimates caused by uncertainties of the input parameters. Any time that a liquidator spent traveling, sleeping, or resting during a mission is also included in the analysis.

Implementation of the RADRUE method requires information on the work histories of the liquidators, exposure rates at the locations visited by the liquidators, location factors for protection equipment that reduced the liquidators' exposures, and appropriate exposure-to-dose conversion coefficients, which depend on workplace environment. The methods used to obtain the relevant information and associated uncertainties are described below.

Work histories of liquidators

Information about a liquidator's work history is obtained from personal interviews using a standard questionnaire, which is complemented by maps, photographs and other information designed to help the liquidator remember his/her activities in the Chernobyl area. The interviewers use a questionnaire designed jointly by the researchers from Belarus/Baltic/Russia/IARC and Ukrainian-American studies. The questionnaire has two parts: the first deals with demographic information, occupational history, and other potential risk factors for the diseases under study, including the medical history of the subject; while the second part focuses on factors related to radiation dosimetry. The dosimetric part of the questionnaire includes

many detailed questions regarding (a) liquidator's routes to and from his/her work place(s) in the 30-km zone, (b) details about the work he/she performed, including duration and special shielding from radiation, and (c) locations of residence and rest quarters during her/his mission. Answers to these questions form the basis for the dose calculations. The complexity and duration of participation in the Chernobyl cleanup work were different for different liquidators. In some cases the task was as simple as driving a truck from outside the 70-km zone to the industrial site to deliver equipment or supplies. In other cases, the person lived in a village in proximity of the ChNPP for an extended period of time and commuted daily to perform a variety of tasks at a variety of locations.

In the epidemiological studies conducted by investigators from the IARC, interviews were performed by trained interviewers; in the ongoing study of Ukrainian liquidators, all interviewers, in addition to being trained, were experienced liquidators themselves. To obtain information for a deceased liquidator two types of proxies were interviewed. The first was the spouse or next-of-kin of the subject, who provided demographic and medical history data; this person also nominated a colleague-proxy. The second type was a co-worker or colleague of the subject, who, ideally, worked together with the subject at Chernobyl or participated in the cleanup work at the same time in a similar role. When proxy interviews were conducted, the information received about the routes followed and the work performed was inherently more uncertain.

Database of exposure rates

Information about exposure rates was needed for the many locations where the liquidators worked, traveled, or rested during the time interval from the date of the accident to the end of December 1987 (for the Belarus/Baltic/Russia/IARC studies) or to the end of December 1990 (for the Ukrainian-American study). Most of the locations of interest are within the 30-km zone, shown in Fig. 1, although eligibility criteria for the status of liquidator in Belarus allowed working in a larger area, called the 70-km zone, where the rest quarters for most liquidators also were located. The 30-km zone contains four smaller areas, each described by a base map and characterized by similar values of the exposure-rate gradient. As shown in Fig. 2, these areas, which are designated in this paper as “base-map area, decrease in size as the accident site is approached, starting with (a) the so-called “4-km zone”, which is located near the center of the 30-km zone (see Fig. 1), (b) the ChNPP industrial site, which contains the buildings housing the four units of the ChNPP, and (c) the roofs of the buildings near the destroyed Unit 4 reactor

Available environmental radiation data—The RADRUE database of exposure rates is based on two types of available environmental data: radiation-exposure rates and the isotopic composition and amounts of radioactivity deposited on the ground surface. The exposure-rate measurements were made by about 20 organizations in different places and at different times between 26 April 1986 and the end of 1987 (Kryuchkov et al. 2008). Exposure-rate measurements inside the building housing Units 3 and 4 were made by three organizations during 1986–1988.

The environmental exposure-rate data obtained in 1986 for the Ukrainian parts of the 30- and 70-km zones, including the ChNPP industrial site and the ChNPP main buildings, were collected from different sources and verified by the ChNPP radiation-protection service in 1990–1992 in cooperation with the Sosnovy Bor Branch of the Radium Institute. The break-up of the USSR and subsequent events made it impossible to accomplish the data collection for 1987. As for the Belarusian parts of the 30- and 70-km zones, the Moscow Institute of Biophysics obtained and verified an electronic database of measurements (Savkin 1993). Altogether the compiled databases contain results of 23,003 exposure-rate measurements. The

numbers of measurements used to describe the radiation fields in different base map areas are shown in Table 1.

In 1989, there was a campaign to measure ground-deposition densities of radionuclides near the site of the accident. Soil samples were collected from a total of 312 locations between 5 and 35 km from the damaged reactor. The samples were analyzed by gamma spectrometry to determine the activity fractions for longer lived nuclides like ^{137}Cs , ^{134}Cs , ^{106}Ru , and ^{144}Ce . The results of these measurements were used to estimate exposure rates at the sampling locations at the time of sampling.

Procedures for interpolation and extrapolation—The available measurements do not provide complete and evenly distributed coverage for all areas in the base maps. For the purpose of interpolation, each base map area was subdivided using a 100 by 100 rectangular grid, and the goal was to have a database of exposure rates for every node of this grid for each time period of interest. The dimensions of the cells are 1400 m x 1400 m for the 70-km zone, 600 m x 600 m for the 30-km zone, 70 m x 70 m for the 4-km zone, 15 m x 8 m for the industrial site, 6 m x 1.3 m for units 1 and 2 of the ChNPP, 4.5 m x 2 m for units 3 and 4, and 1.8 m x 1.5 m for ChNPP roofs. To complete the descriptions of the radiation fields, a kriging interpolation method and extrapolation techniques were used. In base-map areas with high gradients of exposure rates, like the ChNPP roofs, there is more spatial resolution of the radiation-field grid than in base-map areas further from the reactor, with low exposure-rate gradients and larger grid spacing.

Radiation-exposure rates changed with time from 1986 through 1990 due to radioactive decay, clean-up activities, and vertical migration of radionuclides into deeper layers of soil. To address the effects of these changes over time, a series of exposure-rate grids were prepared for each base-map area. Values of exposure rates at grid points within each base-map area are estimated separately, but the condition of continuity requires that the exposure rates near the boundaries of the base-map area be similar to those at the nearest points of the adjoining base-map area. The RADRUE database of exposure rates was derived with use of several methods of interpolation in space and time. A detailed description of the methods that were used is given in the Appendix.

Because the radiation-exposure rates changed with time, a set of exposure-rate grids was prepared for each base-map area; each covered a different segment of the overall time period of interest for calculations of doses to liquidators. Fig. 3 illustrates the spatial variation in the 30-km zone around the ChNPP of the exposure rates that were estimated for the dates of 15 May 1986 and 15 May 1988.

Location factors

The exposure rates measured at particular locations or calculated for grid points do not apply to the liquidators if they were shielded from the radiation source, for example, by wearing a lead apron or by being in a car or armored vehicle. The exposure rates provided by the database are therefore multiplied by a location factor that depends on the conditions of exposure. Table 2 shows the location factors that were used to reflect most conditions of exposure. Liquidators were frequently shielded from the radiation fields at places where they lived, traveled through, and worked, although there were circumstances under which temporary sources of radiation led to higher exposure rates. Some situations of this type are indicated by location factors larger than one, which are based on experience gained after the accident. Some factors, such as those related to residence type, were applicable to many liquidators, whereas others were required only for very specialized tasks undertaken by a few workers. Shielding of local sources to reduce high exposure rates in particular work locations was not considered in a generic way

because the opportunities for such shielding and its effectiveness varied according to the particular conditions encountered.

Conversion coefficients from exposure rates to organ dose rates

Conversion coefficients were selected on the basis of available measurements for locations inside Unit 4, documentation from ICRP (1996), and expert judgment (VK, LA). The conversion coefficients were obtained as the products of the conversion coefficients from air kerma rate to organ dose rate (mGy h^{-1} per mGy h^{-1}) and from exposure rate to air kerma rate (mGy h^{-1} per mR h^{-1}). The organ dose rates per air kerma rates vary according to the geometry of exposure and the energy spectra of the photons that characterize the radiation fields, whereas the ratio of air kerma rate to exposure rate is a constant equal to $8.7 \cdot 10^{-3} \text{ mGy h}^{-1}$ per mR h^{-1}). Irradiation geometries varied with location and were in many cases a mixture of anterior-posterior (AP), rotational (ROT), and isotropic (ISO) geometries. The ROT geometry was considered to be the most representative for working conditions on the roofs, while mixtures of AP, ROT, and ISO geometries were used for all other areas. The photon energy spectra varied from one location to another and from one time period to another, but were generally centered between 0.15 and 0.4 MeV (Kochetkov et al. 1992); in that energy range, the variation of the conversion coefficient to bone marrow or thyroid dose is relatively small. As shown in Table 3, for both red marrow and thyroid, the estimated mean values of the conversion coefficients were highest for work on the roofs, with somewhat lower values used for other work locations; the conversion coefficients for thyroid in general were larger and more variable than those for bone marrow.

Uncertainties

Uncertainties of doses estimated by the RADRUE technique can be divided into two categories, referred to as “intrinsic” and “human factor” uncertainties (Chumak et al. 2008 Chumak et al. in press). In the first category are uncertainties in exposure-rate data and soil-contamination measurements, uncertainties in the interpolation of these data in time and space, uncertainties in factors used to characterize the effectiveness of shielding, and imprecision of data from the questionnaire (e.g., failure to recall specifically the time of a particular mission). In the second category are mistakes in responses to questions, particularly by worker proxies, the recording of a subject’s responses by the interviewers, and the interpretation of the information by the expert. Differences in analyses performed by two experts are included in the human-factor category as well.

Analysis of the intrinsic uncertainties was implemented through use of a stochastic model. The uncertainty distributions for the parameters $P[x(t_i), y(t_i), t_i]$, t_i , Δt_i , L_i , C_i were considered in the stochastic calculations as were the reported numbers of times a particular task was repeated by a liquidator. A distribution of dose estimates was obtained by repetitive calculations using eqn (1) and randomly selected values from the distributions of those parameters. When appropriate, the correlations between the parameter values were taken into account. The calculations were performed using the Crystal Ball software (Decisioneering 2000). The distribution of dose estimates reflects the intrinsic uncertainties of the input parameters used to estimate the liquidator’s dose. The relative importance of human-factor uncertainties is discussed qualitatively in a later section.

Implementation of the RADRUE technique

A flowchart of the RADRUE dose calculation is shown in Fig. 4. The five stages of work (Personal interview, Deterministic calculations, Quality control, Dose limitation, and Stochastic dose calculation) are shown in separate columns with specification of the person (Interviewer, Expert, Reviewer, Supervisor, and Operator) responsible to carry out the duties listed in each column. Results obtained in each column are transferred to another according to

the arrow's direction. The main tools of the RADRUE program are shown in grey rectangles at the bottom of each column. With the exception of the manual of interviewer, all tools are subprograms of RADRUE. The description of the main components and of the flowchart of RADRUE calculations is given below.

Personal interview—The liquidator's description of her/his work during cleanup as well as information on travel and rest were recorded by the interviewer in the dosimetric part of the study questionnaire. The interviewer split the liquidator's activities into missions and episodes and filled separate forms for each episode of each mission. Besides, the interviewer copied and collected all additional information that was provided by the interviewed liquidator: certificates, itineraries of the liquidator's transportations drawn by hand on paper maps, etc.

Deterministic calculations—An expert dosimetrist analyzed the information recorded in the dosimetry section of the questionnaire (block "*Analysis of questionnaire*"). The expert was very well aware of the local geography and knew from personal experience the history of the radiation situation in and around the ChNPP as well as the rules and regulations in force during the clean-up work in 1986–1990. The expert dosimetrist evaluated the reliability of the information provided and used his experience and knowledge to reconstruct any necessary details not reported during the interview. This stage of the RADRUE process is very important, because the liquidator's (or proxy's) recollections of events were often not sufficiently precise and consistent. Therefore, the expert's role was to check the consistency of the liquidator's report, fix possible inconsistencies, and reformulate quite general information contained in the questionnaire for entry into the computer code.

In order to prepare the data needed for dose estimation, the expert recreated the itinerary (also called "route") of the liquidator during his/her clean-up activities based on the information in the questionnaire (block "*Breakdown of itinerary by frames*"). There is a hierarchy of definitions, which were used to describe the liquidator's route. Definitions of the terms that were used are presented in Fig. 5. The first step was to verify the interviewer's separation of work into distinct mission(s) and breaking down each of the missions into episodes, which represented typically the liquidator's activities during a daily cycle of 24 hours. The episodes were further subdivided by the expert into frames during which specific tasks were conducted. The number of frames could be very small for trivial efforts or very large for others.

Three types of frames were considered: ordinary, alternative, and parallel:

- *ordinary frames* are those characterized by a relatively well defined itinerary, including exposure rates and location factors. The expert classified the itinerary for each ordinary frame with use of one of three possible approaches that depended upon the completeness of the questionnaire responses (see Fig. 5). If a precise description of the itinerary was provided, both the points on the route and the lines taken between the points were used to describe the route; and the resulting *trajectory* was used in the calculations. When the liquidator was unable to specify the itinerary and/or the order in which he worked at the locations specified, the information was entered as *points only*. In that case, the locations were known, but the sequence was not. When the liquidator did not report a definite route or specific location, the most uncertain type, as *area*, was used;
- *alternative frames* were used when the same action could be carried out in different ways. For example, a liquidator could be transferred from Settlement A to Settlement B with a bus along Road 1 or with a car along Road 2. Probabilities of using any of the considered routes were specified, the sum of the probabilities being equal to 1. All *alternative frames* for the same action had the same duration;

- *parallel frames*. In some cases a few different actions connected with radiation could happen at the same time. For example, if a liquidator was transferred in a truck along a contaminated road (ordinary frame) and there was a radioactively contaminated load in back of the truck that contributed to the radiation exposure of the liquidator, *parallel frames* were used. Usually in such frames the estimation of the additional exposure rate was done by the expert.

After splitting the liquidator's activity into its elements (in terms of missions, episodes, and frames), the expert entered all the descriptive characteristics (dates, places etc.) of the liquidator's mission(s), episode(s) and frame(s) by means of special graphical and textual (formatted entry or menu selection) procedures (block "*Description of frames*"). Textual procedures required entry of location, duration of the event, as well as identification of appropriate location factors. Intrinsic uncertainties of the itinerary (its duration, time of beginning or end, repetition factor, etc) were key entered together with the itinerary. This detailed description of the route used by the liquidator was combined with the appropriate time-dependent exposure rates that were estimated for each of the grid points in each base-map area (tools "*Location factors*" and "*Exposure rate grids*").

Finally, a deterministic estimate of the total exposure, X , (mR), was obtained by means of the following equation:

$$X = \sum_{i=1}^n P[x(t_i), y(t_i), t_i] \Delta t_i L_i, \quad (2)$$

in which all parameters are defined as in eqn (1).

Quality control—The procedures used for the estimation of the exposures require a substantial amount of information. Data-entry errors are possible during this process. Several special procedures were routinely used to check the quality of the data entry and other important steps in the calculation process.

Block "Checking of expert interpretation": All questionnaires were thoroughly checked by a reviewer. The purpose of the check was to verify the quality of the expert's work. It begins with reading of the questionnaire and ends with the quality control of data entry. Errors were detected in less than 5% of questionnaires.

Block "Standard checking": An automated system of special queries was used to check the validity of important parameters of the system. Those queries are designed to make sure that the starting and ending dates of all episodes are consistent and that the duration of all frames for each day is exactly 24 hours. These checks are very efficient for finding inadvertent mistakes made by the expert or data-entry operator. Such checks were made routinely for all dose calculations.

Block "Independent calculations": The reviewers checked about 10% of all estimates of exposure by repeating the calculations. In this method the reviewers prepared their own set of data based on the questionnaire information and their understanding of the situation during the clean-up work. Then they step-by-step compared the results of calculations based on the expert's and their own interpretation of the questionnaire.

Dose limitation—Some of the deterministic calculations of exposure yielded estimates that were unrealistically high. This occurred particularly when a liquidator reported repeatedly performing the same job in a highly contaminated area and was consequently estimated to

receive a large total exposure. Contrary to such a result, radiation-protection rules dictated that work performed on a regular basis in compliance with radiation-safety rules could not lead to exposures over the permissible dose limits. Efficient dose control and dose management (e.g., application of daily limits) were possible only for liquidators whose organizations provided routine monitoring. Such rules do not apply for many liquidators, whose doses were not monitored and who were susceptible to receive large doses of radiation. These are (i) all liquidators who worked in the first days after the accident; (ii) civilian liquidators who worked at the ChNPP in April–May 1986 without dosimeters; and (iii) liquidators who worked later, after May 1986, either alone or in small groups, and got lost in the industrial site or in the 4-km zone around the ChNPP.

After May 1986, only liquidators working on the industrial site, in the 4-km zone, or at the debris burial sites had the possibility to receive considerable doses during a working day. Daily doses were relatively low for all other liquidators.

With respect to the above considerations, three categories of liquidators whose activities were adequately controlled by associated radiation-protection staffs were identified: military liquidators (Ministry of Defense); staff of the ChNPP; and staff of the Administration of Construction No. 605 (AC-605) from the Ministry of Medium Machinery. Available records of daily doses to personnel in these categories during 1986 were examined and the distribution parameters were evaluated. Table 4 shows the geometric mean (GM) values and the geometric standard deviations (GSDs) for the distributions of measured daily exposures for these categories of workers in 1986. Also shown in Table 4 are the estimated GMs for daily exposures in 1987–1988 and 1989–1990; these were obtained by adjusting the 1986 result by the relative change in the permissible dose limits during the later periods. The GSD of the distribution for each worker category was assumed to be the same in later years as it was in 1986.

The decision whether dose limitation was applicable to a particular liquidator's dose estimate was made according to prescribed rules. If a liquidator did not belong to one of the eligible categories (e.g., military, ChNPP and AC-605) or if the daily work assignment was not repeated three or more times, then the dose limitation was not applicable. The practicality of dose management was also taken into account. For instance, only those military liquidators who worked in an organized group were considered for dose limitation; military personnel operating individually (e.g., drivers) were not eligible.

For a liquidator whose work met the eligibility criteria for dose limitation, the RADRUE program checked whether the estimate exceeded the appropriate daily value and, if it did, assigned the appropriate daily value and the associated uncertainty. The dose-limitation procedure was applied to about 13% (77 of 572) of the liquidators in the Ukrainian-American study and to 9% (76 of 887) of the liquidators in the Belarus/Baltic/Russia/IARC studies. For these persons, exposure estimates both with and without application of the dose-limitation procedure were saved in order to evaluate the impact of the procedure on the risk estimates.

Stochastic dose calculation—The final stage of the RADRUE program is the calculation of the individual dose estimates to thyroid and bone marrow, and of their distributions, which reflect the intrinsic uncertainties associated with the input parameters. These include (1) uncertainties in exposure-rate data and soil-contamination measurements; (2) uncertainties in the interpolation of these data in time and space; (3) uncertainties in factors used to characterize the effectiveness of shielding (4) uncertainties in the times spent performing the various activities; (5) uncertainties associated with the dose limitation procedure; and (6) imprecision of data from the questionnaire (e.g., failure to recall specifically the time of a particular mission). The human-factor uncertainties are discussed qualitatively in a later section.

Monte Carlo method was used to evaluate intrinsic uncertainty and to obtain the stochastic distribution of individual dose estimates for each study subject. According to this method, a possible dose realization was simulated by taking into account the probability distributions of the dosimetry model parameters and the route of the liquidator, which was assigned based on the questionnaire. This process was repeated 10,000 times for each study subject to generate a distribution of his/her dose estimates.

RESULTS: DOSE ESTIMATES AND UNCERTAINTIES

The RADRUE program was used to estimate external radiation doses to the 1,459 subjects (cases and controls) of the epidemiological studies related to cleanup work following the Chernobyl accident. Table 5 contains information about the worker categories and age distributions for subjects (all male) in the two leukemia studies and illustrates the variety of persons designated as liquidators. Uncertainties in the dose estimates were also assessed for all subjects.

Dose estimates for the subjects of the Ukrainian-American epidemiologic study

Table 6 contains the estimates of bone-marrow dose for the 572 subjects of the Ukrainian-American study, subdivided according to the first year of work at Chernobyl. The subjects were interviewed in 2002–2004. The average dose to liquidators who began work in 1986 was 100 mGy, that is, about two times higher than the average dose received by workers who began work in 1987 and about three times higher than the average dose to those whose work started in 1988–1990. The range of individual doses (means of stochastic dose distributions) for workers who began work in a particular year was at least three orders of magnitude. This reflects the fact that persons classified as liquidators performed a wide variety of tasks and their dose estimates correspond to those different activities. The highest doses were estimated for individuals who started their work on 26 April 1986 (the day of the accident); they are classified as witnesses or victims of the accident. More detailed information on the estimates of bone-marrow dose for the subjects of the Ukrainian-American study can be found in Chumak et al. (2008).

Dose estimates for the subjects of the Belarus/Baltic/Russia/IARC epidemiologic studies

The Belarus/Baltic/Russia/IARC studies include Chernobyl liquidators from five countries who worked on the site in 1986 or in 1987, and who were interviewed in 1998–2003. Most of these persons were from Belarus and Russia, with smaller numbers of people from the Baltic countries. Table 7 contains the mean and geometric mean estimates of bone-marrow-doses for the 357 liquidators in the Belarus/Baltic/Russia/IARC case-control study of hematological malignancies, as well as the range of doses for the liquidators from each country. The average dose for the subjects from Belarus (11 mGy) is substantially lower than comparable averages for liquidators from Lithuania and the Russian Federation (above 100 mGy) or from Estonia and Latvia (around 50 mGy). There are fundamental differences between liquidators from Belarus and those from Russia and the Baltic countries. Eighty-one percent of the liquidators from Belarus were sent by civilian organizations. One-third of them worked only in the 70-km zone, not the 30-km zone. In contrast, the majority of Russian and Baltic liquidators were military reservists who worked in the 30-km zone.

The mean and geometric mean thyroid doses from external radiation estimated for the individuals included in the Belarus/Baltic/Russia/IARC case-control study of thyroid cancer are shown in Table 8. Similar to the bone-marrow doses, the average dose to the thyroid from external radiation for the subjects from Belarus (12 mGy) is substantially lower than averages for their colleagues from Lithuania and the Russian Federation (above 100 mGy) or from Estonia (around 90 mGy) and Latvia (around 70 mGy).

Uncertainties in doses estimated by RADRUE

As indicated previously, a Monte Carlo method was used to evaluate intrinsic uncertainty and to obtain the stochastic distribution of individual dose estimates for each study subject. The distributions of the individual dose estimates were found to be approximately lognormal and were characterized by their GM and GSD; the arithmetic means of the dose estimates were also determined in the calculation process.

The GSDs associated with an individual dose estimate in the Ukrainian-American study ranged from about 1.2 to 4.5 for persons who began work in 1986, and ranges that were nearly as wide were typical of the other years. Uncertainties in individual doses for the Belarus/Baltic/Russia/IARC studies were found to be slightly lower. The overall distribution of the GSDs of the individual doses reconstructed for the 1,459 liquidators included in the three studies is shown in Fig. 6.

It should be noted that, to date, comprehensive uncertainty calculations that address both “intrinsic” and “human factor” types of uncertainty and distinguish between shared and unshared errors have not been done. However, a simplified two-step sensitivity analysis was performed to evaluate the relative importance of the shared and unshared errors in the overall uncertainties of the RADRUE dose estimates.

In a first step, a sensitivity analysis was performed in order to rank the parameters of the model according to their contribution to the overall uncertainty. Stochastic doses were calculated for two questionnaires. One of those questionnaires was rather simple and led to a small dose. The other one was rather complex and led to a high dose. For each of the two questionnaires, the variability in exposure rate contributed more than 96% to the overall uncertainty of doses, while the variability of other parameters (location factor, frame duration, episode repetition, conversion coefficient) accounted only for a few per cent of uncertainty.

The second step included an evaluation of the probability that two or more liquidators worked at the same location at the same time and what part of their doses was defined by the exposure rate shared at that location. This analysis of coincidence was performed with the help of the RADRUE query system for 434 liquidators who worked in 1986. RADRUE keeps all intermediate information that can be reached with the query system. In total 187,488 frames were compared. Most of them (150,056 or more than 80%) do not show any coincidence and only for 240 (0.13%) of frames the dose was determined by the coincidental event. It means that either two liquidators had lunch in the same canteen at the same time, or they were in the same bus during the trip to or from work from or to living quarters, etc. The result of this analysis for 434 liquidators shows that the “shared” dose caused by liquidators sharing the same exposure rate at a given location represents less than 1% of the total dose.

It is important to note that there are other sources of shared errors that have not been considered. For example, all the exposure rate measurements in the 4-km zone were made in 1986 (Table 1). At later times, the exposure rates are extrapolated and the uncertainties associated with that extrapolation are large. The doses to persons working there after August 1986 are all linked to the data set used for the extrapolation. The same comment applies to measurements made in other areas.

VALIDATION OF THE DOSE ESTIMATES

To assess the adequacy of the new dose-reconstruction method, it was desirable to apply the RADRUE technique to estimate doses to sets of liquidators having independent and reliable alternative dose estimates. Three subgroups with differing types of dose estimates were selected:

- the first group was “victims and witnesses of the accident,” meaning that they were in the immediate vicinity of the ChNPP reactor during the first hours after the accident occurred. Their doses were based on measured chromosome aberrations (dicentrics) which provide reliable estimates of the whole body (and bone marrow) dose received by those workers;
- the second group consisted of staff members of the AC-605 organization; their doses were based on official records of personal monitoring with thermoluminescent dosimeters (TLDs). Those results should give a reasonable estimate of the bone-marrow dose during the period of exposure; and
- the third group was composed of persons whose dose estimates were based on EPR of tooth enamel; it included military liquidators and those sent on a mission to the 30-km zone. The EPR doses to tooth enamel were converted to the bone-marrow doses to be compared with the doses estimated by the RADRUE technique.

In addition, it was found interesting to compare the doses obtained using RADRUE with the “official” doses found in the Registry.

Comparison of doses estimated by RADRUE and by evaluation of chromosome aberrations

Twenty patients who were sent from Chernobyl to clinics of the Institute of Biophysics in Moscow soon after the accident were selected for dose reconstruction using the RADRUE technique. All of these persons (firemen, ChNPP workers from the reactor and turbine buildings, and plant construction, security, and medical personnel) were categorized as victims and witnesses of the accident. In 1986, doses were estimated for all 20 people using the frequency of unstable chromosome aberrations (dicentrics). Those doses were estimated in specialized Clinical Hospital #6 (Guskova et al. 1988).

The medical record of each person had a very clear and well defined route list describing his activities after the beginning of the accident. This was used to establish the locations where the person’s exposure occurred. Results of exposure-rate measurements made on 26 April 1986, were used for exposure-rate reconstruction everywhere except on the roofs of the ChNPP. The radiation situation on the roofs on April 26 was extrapolated from the measurements made in September 1986.

Fig. 7 shows the comparison of the RADRUE mean-dose estimates and those derived from chromosome-aberration frequencies. The two sets of estimates are correlated ($r = 0.80$); however, the average of the ratios of the dose estimated by RADRUE to that based on chromosome aberration analysis was 0.83. This difference may be due to the fact that radiation exposure to the passing cloud of radioactive materials released during the first day of the accident is not included in the RADRUE calculation.

Comparison of doses estimated by RADRUE and official dose records based on thermoluminescent dosimetry monitoring

Forty-four employees of AC-605 were initially selected for a comparison of RADRUE dose estimates against the official doses recorded for those workers. The official doses were based upon a reliable system of worker monitoring with use of calibrated TLD badges. Five workers were later excluded from the comparison because of self-reported interruptions in dosimeter use (2 persons) or official doses inconsistent with the type of work performed (3 persons). Comparisons of dose estimates for the 39 AC-605 liquidators are shown in Fig. 8. The criteria for using the dose-limitation procedure were met by 29 of these persons.

Comparison of doses estimated by RADRUE and by EPR measurements of tooth enamel

Eighty-three liquidators have high precision dose estimates based upon EPR measurements of enamel of teeth that were extracted as the result of routine dental practice. All of the EPR-based doses exceeded 50 mGy, which is above the nominal detection limit for the RCMR EPR dosimetry protocol. All these liquidators were interviewed and the RADRUE technique was used to calculate doses for the 83 liquidators. The distribution of the 83 ratios of the RADRUE dose estimate to the EPR measurement result is shown in Fig. 9. The geometric mean ratio was 0.6. The second distribution shows the result of removing ratios for 15 subjects whose RADRUE doses were substantially lower than those based on EPR measurements.

Thorough review of the questionnaires and the data entered for the RADRUE calculations did not reveal any errors and, in fact, confirmed that low doses would be expected to result from their work at Chernobyl. It is possible that unaccounted activities, unrelated to their work at Chernobyl (occupational, medical, dental, or incidental exposure) contributed to their radiation exposure; these would not be identified when the questionnaire was administered and would therefore not be quantified. In fact, the EPR dose characterizes liquidator's exposure from the age of formation of permanent teeth, which depends on the type of tooth. To ascertain possible reasons for the discrepancies between the two sets of dose estimates, less formal interviews with these subjects were suggested. The group for additional interviews was supplemented by 15 other subjects with RADRUE dose estimates that are in good agreement with those based on EPR and interviewers were not informed of the distinction between the interviewees. The results of the follow-up interviews did not reveal the occurrence of additional exposures at Chernobyl but indicated that at least some of the subjects with EPR results exceeding those based on RADRUE had additional sources of medical exposure. There was, however, not enough information to quantify the magnitude of the associated doses.

For one liquidator there is another possible reason for the difference between the EPR dose estimate and the RADRUE dose estimate for the fraction of the dose received while working as liquidator. At other times after the accident this subject in the comparison resided in a heavily contaminated settlement. The dose received by this leukemia subject was not estimated by the RADRUE method. In heavily contaminated areas, the residential doses received during 15 years after the accident could be several tens of mGy and comparable to or higher than doses received while working as a liquidator.

Comparison of official dose records and doses estimated by RADRUE

Official dose records (ODR) are the personal records in the State Registry of Ukraine (SRU), which were entered in the course of primary registration of liquidators and are based on dose certificates available at that time. As a result, coverage with ODR in the SRU is quite limited and is lower than the percentage of liquidators possessing dose certificates today. Within the Ukrainian-American study ODRs were available for 125 subjects, while dose certificates, which were collected during interviews, were available for 219 subjects of the study (of 572); 96 have both kinds of dose records. Comparison of ODR with dose certificates revealed good coincidence (79% of dose records coincided within +5%), discrepancies were mostly due to data-entry errors, rounding effect and ambiguity in dose units. This observation allowed inclusion of data from dose certificates as ODR into comparison with RADRUE dose estimates. This comparison revealed that RADRUE dose distributions are much broader than ODR distributions for respective liquidator groups. In addition, RADRUE doses on average are much lower than those in the ODR (mean of RADRUE/ODR ratio is 0.6). This observation is in a good agreement with previous qualitative prediction (Ilyin et al. 1995) and quantitative estimate (Chumak et al. 2007b). Analysis of outliers showed that about 17% of the ODR deviate from RADRUE doses 10 and more times (both ways); in this group, the majority (95%) of ODRs are higher than respective RADRUE estimates. Case-by-case analysis of these

discrepancies revealed that RADRUE doses were higher than ODR in situations when unaccounted local exposure took place (contaminated clothes, work in contaminated vehicles), while higher ODRs were typical for some 'privileged' liquidators (like bosses, supplies specialists, secretaries), who never performed high dose activities, though high falsified doses were assigned and recorded (Ilyin et al. 1995).

EVALUATION OF THE UNCERTAINTIES RELATED TO THE INTERVIEWS

Special exercises were performed to evaluate the effects of using questionnaire responses from proxies to estimate doses to liquidators and to check the repeatability of doses estimated using the results of two interviews of the same subject.

Comparison of doses based on interviews of subjects and interviews of proxies

Because of the relatively poor prognosis of hematological malignancies, both studies included many deceased cases (Romanenko et al 2008a, in press; Kesminiene et al 2008, in press). To obtain information on their clean-up activities at Chernobyl, a proxy had to be interviewed. The proxy should be a colleague of the deceased liquidator who participated in the clean up work at the same time or, preferably, worked together with the deceased individual. To estimate the uncertainty introduced by interview of a proxy, a special sub-study was carried out. Fifty-three live cohort members were selected, and each was asked to recommend two proxies who participated in the clean-up activities at the same time. The 53 cohort members were interviewed to learn about their Chernobyl work; the proxies were interviewed and asked to describe the activities of the cohort member who recommended them. Responses to the questionnaire were obtained for all of the first proxies recommended by subjects and for 49 of the second proxies. Altogether 102 questionnaires from proxies were processed according to the standard RADRUE procedure and doses to the subjects were estimated. Those dose estimates were then compared with the ones based upon information provided by the subjects themselves.

The results of the comparisons are presented in Table 9 as ratios of doses estimated with use of the information from proxies and subjects. As indicated by the GSDs, the dose ratios cover a broad range, but the median ratios do not suggest a large bias in the dose estimates based upon proxy responses. The second part of Table 9 shows that removing four outliers from the first proxy group and two from the second proxy group substantially reduced the GSDs without greatly affecting the geometric mean ratios. Comparison of questionnaire data obtained from excluded proxies with those received from the corresponding cohort subjects showed that the proxies most likely did not know much about the work performed by the subject, mistakenly describing their own work or that of someone other than the subject. One subject reported working in a relatively low dose area in 1987, while his proxy claimed that he was working near reactor block 3 in 1986. In another case, the subject stated that he worked in river port "Pripyat" which was in Chernobyl town, but proxy claimed that the subject worked in the river port of Pripyat town.

Comparison of doses based on repeated interviews of subjects

Repeated interviews of 29 Ukrainian subjects were performed to assess the reliability of responses given by the subjects, and bone-marrow dose calculations based on the two sets of interviews were performed. The direct comparison of the mean dose estimates based on the two sets of interviews is shown in Fig. 10. The ratios of the mean dose estimates for the two interviews are within the range 0.5–2 for 19 subjects, within the ranges 0.1 to 0.5 or 2 to 10 for 7 subjects, and either <0.1 or >10 for the other 3 subjects, while the median of the ratios for the 29 subjects is about 1. The highest ratio, ~20, was due to a subject initially reporting that his mission to the ChNPP occurred in April 1987, but in the second interview giving the

date of May 1986 for this event. One of the lowest dose ratios (0.075) was due primarily to a difference in exposure rates assigned by two different experts and entered into the calculation. This is perhaps the most extreme effect of differing expert assessments, but it does clearly raise the issue of the influence of the experts in the dose-assessment process. The differences in the responses given during the repeated interviews and the differences between experts are two of the more important sources of “human factor” uncertainty associated with liquidator doses. The GSD of the distribution of the ratios of the doses from repeated interviews is about 4, which is smaller than the GSD of about 4–6 obtained for the ratios of the doses between proxies and subjects, but higher than the typical value of 2 estimated for the “intrinsic” uncertainty. Because the “human factor” uncertainties are based on results obtained for relatively small samples of subjects, and also because additional work is needed to decide how to take them into account at the individual level rather than at the group level, they have not been incorporated into individual-dose uncertainties in this paper. It is recognized that they might be the largest source of uncertainty for most subjects and deserve further investigation.

CONCLUSIONS

Modification of the time-and-motion dose reconstruction method developed for ChNPP personnel soon after the Chernobyl accident has produced an external dose-estimation procedure, called RADRUE, that is flexible. It can provide dose estimates for epidemiologic studies of liquidators as long as experts are available who have the in-depth knowledge of the work that took place after the accident. The RADRUE method employs a large exposure-rate database and interpolation techniques that can be used to calculate exposure rates at places where liquidators lived and worked within ~70 km of the destroyed reactor. The RADRUE technique relies on data collected from interviews conducted by well-trained interviewers and on expert dosimetrists who interpret the information and provide supplementary information, when necessary, based upon their own substantial experience.

Comparisons of doses estimated by RADRUE with those based on chromosome-aberration frequencies in victims and witnesses of the accident showed generally good agreement between the two sets of dose estimates. Another comparison with the official dose totals for a group of AC-605 workers whose exposures were reliably and continuously monitored using thermoluminescent dosimeters also indicated good agreement between the doses calculated by the RADRUE technique and those measured for the AC-605 liquidator group.

The results of RADRUE dose calculations for liquidators for whom doses were also estimated using EPR measurements on enamel of extracted teeth showed less consistency between estimates. It must be remembered, however, that the EPR measurements reflect radiation doses accumulated over a longer time period and from multiple sources, while the RADRUE estimates cover only the doses received during work performed during the Chernobyl cleanup.

The RADRUE technique was used to estimate external radiation doses to the 1,459 persons who participated in the cleanup following the Chernobyl accident and were the subjects of three epidemiologic studies (one Ukrainian-American and two Belarus/Baltic/Russia/IARC studies). Preliminary analysis of those results showed that the RADRUE doses correspond to the expected relations between them. For example, the average bone-marrow dose received by the Ukrainian subjects who began to work in 1986 was 100 mGy; this value is about two times higher than the average dose received by workers who began to work in 1987 and about three times higher than the average dose to those whose work started in 1988–1990; the highest doses were estimated for individuals who started their work on 26 April 1986 (the day of the accident). The average dose for the subjects from Belarus (11 mGy) is substantially lower than comparable averages for liquidators from Lithuania and the Russian Federation (above 100 mGy) or from Estonia and Latvia (around 50 mGy). This can be explained by the fact that more

than 30% of Belarusian liquidators never were in the 30-km zone, while the vast majority of Russian and Baltic liquidators were military reservists who worked in the 30-km zone. A wide range of doses was found for the study subjects, irrespective of the date work began and national identity, because of the diversity of tasks assigned to persons who participated in the cleanup. Intrinsic uncertainties in individual dose estimates for these persons were characterized by GSDs between 1.1 to 5.8; however, more than 80% of them were in the range 1.25–2.25.

Calculations of doses for study subjects using information provided by proxy respondents to the questionnaire and comparison against doses estimated on the basis of information obtained from the subjects themselves showed substantial differences. While the ratios of doses do not indicate a substantial bias in the resulting dose estimates, the uncertainty associated with the use of proxies was found to be large. Interviews of subjects identified as having life-threatening diseases should be conducted promptly, whenever possible, to avoid the need for proxies for such subjects. If proxies are needed, they should be chosen with great care and tested.

Within the framework of the Ukrainian-American epidemiological study, proxies were interviewed for 78 deceased among the 572 liquidators included in the study. Overall uncertainties in individual-dose estimates for deceased liquidators whose doses are based on interview of proxies recommended by a surviving family member are expected to be characterized by GSDs that range from 3.6 to 7.2. The mean-dose estimates for such subjects will be higher than those that would have been obtained had the subject still been alive.

Second interviews of study subjects also indicated that their later responses to questions were in some cases quite different from their earlier statements. The results of these comparisons did not indicate a bias; the median ratio of dose estimates based on the two interviews was about one. Nonetheless, pairs of estimated doses for about one-third of the subjects who were interviewed twice differed by more than a factor of two from one another and differences between the two dose estimates were more than a factor of ten in about 10% of the comparisons.

Taken all together, these comparisons showed that the reliability of the input data from the interviews is extremely important and that the human-factor uncertainties are probably the dominant ones.

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APPENDIX INTERPOLATION AND EXTRAPOLATION OF THE ENVIRONMENTAL RADIATION DATA USED IN RADRUE CALCULATIONS

Exposure rates at locations of interest changed significantly during 1986–1990 due to radioactive decay of the deposited radionuclides, their migration into the deeper soil layers, decontamination activities, and weathering. To reflect these changes, the radiation fields for every base map are described by multiple grids that cover discrete time periods. The larger blocks of time and methods used to define the exposure-rate grids for those periods are shown in Table A.1. Every base map is divided into a grid of 10,000 cells (100 by 100), so the spatial resolution of the exposure-rate field changes according to the base map size. The exposure rate in each cell is derived by interpolation and extrapolation of the available measured and calculated environment exposure rates. In total there are 77 grids related to the six base maps used for the RADRUE Chernobyl dose calculations.

Analysis revealed that the number of exposure-rate measurements available for interpolation was insufficient for all time periods and for all grid maps. Therefore, in addition to kriging interpolation, which was the main method of reconstruction of radiation-exposure rates, other methods were used. These included multiple linear regression used for extrapolation from

measurements made in the early days following the accident to later dates; exposure-rate reconstruction based on radionuclide-fallout deposition density; and a 4-dimensional (4-D) interpolation method specially developed for dose reconstruction inside the ChNPP main building.

The methods used to construct exposure-rate grids for the six base maps during different time periods are presented in Table A.1. A lognormal distribution of the reconstructed exposure rates has been assumed for the uncertainty model in all cases; thus, the uncertainties are expressed as geometric standard deviations (GSDs). The uncertainties depend on the radiation-field model, the area covered by the base map, and the time period. Table A.1 shows that the uncertainties in exposure-rate estimates vary from a GSD of 1.7 for the 30-km zone during the last trimester of 1986 to a GSD of 4.8 for the interiors of the ChNPP buildings at times after the end of 1986. Each of the methods is described below.

Kriging

Smoothing kriging proved to be the best method for the interpolation of the logarithms of the exposure-rate measurements when compared to other interpolation methods (inverse distance to a power, polynomial regression, radial basic function and modified Shepard's method) (Golden Software 2007). It was used as the main method for spatial interpolation and the creation of exposure-rate-grid maps when sufficient data were available. The frequent use of kriging is illustrated in Table A.1.

Several kriging variogram models (Golden Software 2001) were applied for interpolation in different areas: linear model with the inclination of 1.0 and no anisotropy for the all grid-map; nugget model with an empirically derived error of 0.3 for the interpolation of the logarithms of exposure rates on the industrial site of ChNPP; nugget model with an empirically derived error of 0.1 for all other places (ChNPP roofs, 4-km zone, 30- km zone, and 70-km zone). Interpolation procedure was performed using the Surfer 7.04 program (Golden Software 2001).

Exposure-rate reconstruction based on fallout-deposition densities

The number of exposure-rate measurements was insufficient for interpolation in the 30-km zone after early September 1986 and in both 30-km and 70-km zones after the start of 1988. Exposure rates were reconstructed based on radionuclide deposition density measurements. The Institute of Biophysics database, which contains 312 records, was used. The database contains deposition densities (as of June 1989) for gamma-emitters ^{106}Ru , ^{137}Cs and ^{144}Ce measured in the radial directions within 5–37.5 km from the ChNPP. The initial (26 April 1986) deposition density of ^{134}Cs at any location was assumed to be 0.5 times the measured value for ^{137}Cs at that location (Izrael et al. 1990). These radionuclides were the main contributors resulting in external exposure in the period from the end of 1986 till the end of 1990.

Exposure rates from these radionuclides were calculated by taking into account their emitted radiations, radioactive decay, and vertical migration of the deposited radionuclides into deeper soil layers. Exposure rates were calculated at the height of one meter over an infinite plane of ground contamination. The exposure rates were calculated as follows:

$$P_i = \varepsilon_i \cdot \sigma_i(t) \cdot K(L) \quad (\text{A.1})$$

in which ε_i is a conversion factor for radionuclide i ($\mu\text{R h}^{-1}$) per (kBq m^{-2}); σ_i is the deposition density of radionuclide i (kBq m^{-2}); and $K(L)$ is a coefficient defining the gamma-exposure

attenuation due to exponential deepening of the i -th radionuclide in soil with the parameter $L(t)$. The conversion factors (ϵ_i) for the radionuclides are presented in Table A.2.

The attenuation function $K(L)$ is described by the following empirically derived relationship (Izrael et al. 1990):

$$K(L) = \begin{cases} 0.63 - 0.30 \cdot \log(L(t)), & \text{if } 0.16 < L(t) < 1.6 \text{ g cm}^{-2} \\ 0.65 - 0.36 \cdot \log(L(t)), & \text{if } 1.6 < L(t) < 16 \text{ g cm}^{-2} \end{cases} \quad (\text{A.2})$$

Practically speaking, $K(L)$ does not depend on the emitted energy of photons from the radionuclides considered. The dynamic of the vertical migration of radionuclides into deeper soil layers is given in (Izrael et al. 1990) as a simple linear relationship with time t (y) after the accident: $L(t) = p + q \cdot t$. Average values of the empirical coefficients, $p = 0.4 \text{ g cm}^{-2}$ and $q = 0.27 \text{ g cm}^2 \cdot \text{y}^{-1}$, are used.

Exposure rates that were reconstructed from the radionuclide-activity measurements were interpolated using the kriging method (when possible) or were used as initial values for extrapolation to other times with use of an empirical formula.

Empirical formula

Empirically derived formulas were used for the extrapolation in time of the exposure rates for four of the six regions of interest: roofs of the ChNPP buildings, within the buildings of the ChNPP, the ChNPP industrial site, and the 4-km zone. An extrapolated exposure rates $P(t_2)$ for the time t_2 , when kriging interpolation could not be used, were calculated using the following relationship:

$$P(t_2) = \frac{K(t_2)}{K(t_1)} \cdot P(t_1), \quad (\text{A.3})$$

where $P(t_1)$ is the exposure rate derived by the kriging interpolation method for the last boundary time moment t_1 when the method is still valid; $K(t)$ is analytical correction function for particular areas; t is days. The functions for each area are given in Table A.3.

Four-dimensional (4-D) interpolation

Four-dimensional interpolation was applied to derive exposure rates in the rooms of the ChNPP buildings for the period from the start of the accident until the end of 1986. The logarithm of the exposure rate at the point of interest is calculated as a geometric mean of the logarithms of available exposure-rate measurements at the five nearest points on the 4-D space. The nearest 5 neighboring points are found by evaluation of the Manhattan (Krause 1986) 4-D distance A between them:

$$A = k_x |x_2 - x_1| + k_y |y_2 - y_1| + k_z |z_2 - z_1| + k_t |t_2 - t_1| \quad (\text{A.4})$$

where (x_1, y_1, z_1) and (x_2, y_2, z_2) are the coordinates of two locations where measurements of the exposure rates were made at times t_1 and t_2 , respectively, $k_x = 1 \text{ m}^{-1}$, $k_y = 1 \text{ m}^{-1}$, $k_z = 1 \text{ m}^{-1}$, and $k_t = 0.1 \text{ s}^{-1}$ are the empirically derived set of optimal weighting coefficients for the 4-D distance evaluation.

Extrapolation with use of equation of multiple regression

For the period from 5 August 1986 to 1 February 1987 the number of available measurements was insufficient for interpolation within the 4-km zone. Therefore, a multiple regression equation was used for estimation of exposure rates for that period. The exposure rate was calculated with use of the following empirical regression formula:

$$\begin{aligned} \log(P) = & -0.0051 \cdot t + 0.00011 \cdot x \\ & - 0.000020 \cdot y \\ & - 0.00019 \sqrt{x^2 + y^2} \\ & - 1.72 \cdot \log(\sqrt{x^2 + y^2}) \\ & - 0.59 \cdot \text{Sign}(x) \\ & - 0.084 \cdot \text{Sign}(y) + 0.00039 \cdot \log(t) + 5.68 \end{aligned} \quad (\text{A.5})$$

where $\log(P)$ is the decimal logarithm of exposure rate (R h^{-1}), x is the abscissa distance from the active zone (m), y is the ordinate distance from the active zone (m), and t is the time since the beginning of the accident (days). The function $\text{Sign}(x)$ is equal to -1 if $x < 0$, 0 if $x = 0$, and 1 if $x > 0$. The function $\text{Sign}(y)$ is similarly defined.

Deposition density and kriging

For the creation of the grid maps in the 30-km and 70-km zones for the period of 1988–1990 two methods, applied sequentially, were used. Due to lack of the exposure rate measurements for that period, exposure rates were reconstructed using the deposition-density measurements of ^{137}Cs , ^{144}Ce and ^{106}Ru at the locations where these measurements were performed in the 30-km and 70-km zones. Other exposure rates were then estimated by kriging interpolation in space to create a grid-map covering the territories of the two base maps.

Kriging and trend function

Sufficient exposure-rate measurements were not available for interpolation over the ChNPP industrial site for the periods from 2 October 1986 (date of completion of the shelter over destroyed Unit 4) to 31 December 1987. Therefore a trend function (function TREND from Microsoft© Excel) was used for extrapolation of exposure rates of grid-maps corresponding to dates before October 1986 previously created by kriging.

Table A.1

Methods used and uncertainties associated with reconstruction of radiation exposure rates for different areas and time periods.

Area of interest	Period of coverage	Method	No of grids	GSD
Roofs of ChNPP	3 August 1986–30 September 1986	Kriging	1	2.2
	1 October 1986–19 April 1987	Kriging	1	2.3
	20 April 1987–17 May 1987	Kriging	1	2.3
	18 May 1987–14 July 1987	Kriging	1	3.0
	15 July 1987–31 December 1987	Kriging	1	2.0

Area of interest	Period of coverage	Method	No of grids	GSD
The main buildings of ChNPP	01 January 1988–31 December 1990	Empirical formula	-	2.0
	26 April 1986–1 December 1986	4-D interpolation	-	3.7
	2 December 1986–31 December 1990	Empirical formula	-	4.8
Industrial site of the ChNPP	26 April 1986–1 October 1986	Kriging	17	2.8
	2 October 1986–31 December 1987	Kriging and trend function	2	3.3
	1 January 1987–31 December 1990	Empirical formula	-	3.3
4-km zone around the ChNPP	26 April 1986–4 August 1986	Kriging	4	3.0
	5 August 1986–1 February 1987	Extrapolation using multiple regression	-	4.3
	2 February 1987–31 December 1990	Empirical formula	-	4.3
30-km zone around the ChNPP	26 April 1986–12 September 1986	Kriging	25	2.6
	13 September 1986–31 December 1987	Deposition density	-	1.7
	1 January 1988–31 December 1990	Deposition density and kriging	5	1.7
70-km zone around the ChNPP	26 April 1986–31 December 1987	Kriging	14	2.7
	1 January 1988–31 December 1990	Deposition density and kriging	5	2.7

Table A.2

Exposure conversion factors for the radionuclides (Izrael et al. 1990).

Radionuclide	ε_i ($\mu\text{R h}^{-1}$ per kBq m^{-2})
$^{144}\text{Ce-Pr}$	0.022
^{106}Ru	0.10
^{134}Cs	0.79
^{137}Cs	0.29

Table A.3

Empirically derived correction functions for the extrapolation of exposure rates.

Place of work	Correction function $K(t)$
Roofs of ChNPP and industrial site	$K(t) = 0.0002302 \times \exp(8.377 \times \exp(-0.00254 \cdot t))$
4-km zone	$K(t) = 0.001532 \times \exp(6.481 \times \exp(-0.00220 \cdot t))$
Buildings of the 4 th Unit of ChNPP	$K(t) = 0.01731 \times \exp(4.057 \times \exp(-0.003016 \cdot t))$

Fig. 1.
Map of the 30-km zone around the Chernobyl accident site, including locations of some villages and some roads leading to other locations.

Fig. 2. Basemaps of a) the 4-km zone around ChNPP, b) the industrial site, and c) the roofs of the main buildings of the ChNPP. The lines on the map of the so-called 4-km zone are 1 km apart, and the dimensions of the smaller areas can be estimated on that basis.

Fig. 3. Isolines of exposure rates (mR h^{-1}) in the 30-km zone around the Chernobyl NPP: a) on 15 May 1986, and b) on 15 May 1988.

Fig. 4.
Chart illustrating the structure of the RADRUE method of dose estimation.

Fig. 5.
Illustration and definitions of the components of the liquidator's itinerary

Fig. 6.
Distribution of GSDs of individual doses reconstructed for liquidators.

Fig. 7.

Comparison of doses calculated using the RADRUE technique with dose estimates based upon chromosome aberration frequencies for victims and witnesses of the accident. Error bars correspond to one GSD. The line indicates perfect agreement between the two sets of estimates.

Fig. 8. Comparison of doses calculated using the RADRUE technique with dose estimates based on personal TLD monitoring of employees of the group AC-605. Error bars correspond to one GSD. The line indicates perfect agreement between the two sets of estimates.

Fig. 9. Cumulative probability distributions of the ratios of RADRUE dose estimates to those obtained from EPR measurements of tooth enamel.

Fig. 10. Comparison of RADRUE doses based on repeated interviews of subjects. The parallel lines show perfect agreement, agreement within a factor of two, and agreement within a factor of ten.

Table 1
Numbers of exposure rate measurements that are included in the RADRUE database for Chernobyl.

Area	Numbers of exposure rate measurements				
	Total	1986	1987	1988	1989-90
Between the 30- and 70-km zones	5,888	5,731	157	0	0
Between the 4- and 30-km zones	8,203	8,203	0	0	0
Within the 4-km zone ^a	461	461	0	0	0
Within the ChNPP industrial site ^b	3,126	2,454	366	306	0
Inside the ChNPP main buildings	3,961	3,460	0	501	0
On the ChNPP roofs	1,364	620	744	0	0

^aThe numbers do not include the measurements made within the industrial site, inside the main buildings, or on the ChNPP roofs.
^bThe numbers do not include the measurements made inside the main buildings or on the ChNPP roofs.

Table 2

Location factors used for dose calculations in the RADRUE program.

Location	Location Factor ^a	Reference
Work in the vicinity of a strong local source	2.5	Expert opinion
Forest husbandry	1.7	Expert opinion
Livestock farming, field-husbandry	1.5	Expert opinion
Work in the vicinity of a local source	1.5	Expert opinion
Decontamination	1.35	Expert opinion
Outside	1.0	
In a tent	1.0	
On a motorcycle	1.0	Expert opinion
In a car	0.50	Expert opinion
In a bus or truck	0.29	Expert opinion
In a helicopter, height above ground:		
10 m	0.36	Kryuchkov et al. 2008
20 m	0.14	Kryuchkov et al. 2008
30 m	0.11	Kryuchkov et al. 2008
50 m	0.08	Kryuchkov et al. 2008
100 m	0.04	Kryuchkov et al. 2008
In an armored troop-carrier or armored landing troop-carrier	0.017	Expert opinion
In an engineering-obstacle-clearing or chemical-exploring-fighting machine	0.01	Dyachenko 1996
Housing of various types		
Wooden	0.11	Bailiff and Stepanenko 1996
Brick	0.07	Bailiff and Stepanenko 1996
Brick or concrete multi-story building	0.03	Bailiff and Stepanenko 1996
In bathyscaphe, a shielded exploring device moved by the crane "Demag"	0.0005	Expert opinion
In the shielded control space for the operator of the crane "Demag"	0.0003	Expert opinion

^a Coefficients of variation for these location factors were estimated to be 0.25.

Conversion coefficients from exposure rate to the organ dose rate and their estimated uncertainties (Kryuchkov et al. 2009).

Table 3

Conversion coefficients (mGy h ⁻¹ per mR h ⁻¹) for work locations at the ChNPP						
Target organ	On the roofs of the ChNPP			All other locations		
	Distribution type	AM or GM	SD or GSD	Distribution type	AM	SD
Bone marrow	Normal ^a	0.0067	0.0006	Normal ^a	0.0063	0.0006
Thyroid	Lognormal ^b	0.0075	1.3	Normal ^a	0.0070	0.0014

^a Arithmetic mean (AM) and standard deviation (SD) are shown for the normal distribution.

^b Geometric mean (GM) and geometric standard deviation (GSD) are shown for the lognormal distribution.

Table 4

Geometric means and geometric standard deviations for liquidator groups with daily monitoring.

Liquidator group	Daily exposure ^a (R)		
	1986	1987–1988 ^b	1989–1990 ^b
Military, prior to 21 May 1986	1.6 (2.6)		
Military ^c	0.8 (2.6)	0.32 (2.58)	0.23 (2.58)
AC-605 staff ^c	0.45 (2.6)	0.18 (2.6)	
ChNPP staff ^d	0.08 (2.9)	0.016 (2.9)	0.016 (2.9)

^a Geometric mean (GM); geometric standard deviation (GSD) is given in parentheses.

^b Geometric means for 1987–1990 were scaled from those found for each group in 1986 according to the ratios of permissible dose limits that applied in different years. The GSDs, which were based on empirical results for each group in 1986, were assumed to be the same during the later periods.

^c The permissible dose limit for the military liquidators and the staff of AC-605 was 250 mSv for the period from 26 April 1986 to 28 February 1987, 100 mSv for the period from 1 March 1987 to 31 December 1988, and 70 mSv during 1989 and 1990.

^d The permissible dose limit for the ChNPP staff was 250 mSv in 1986 and 50 mSv during 1987–1990.

Table 5

Number of subjects in the two leukemia studies according to category and age

Category	Belarus/Baltic/Russia/IARC study				Ukrainian-American study			
	Age (year)				Age (year)			
	All	<35	35 – 50	>=50	All	<35	35 – 50	>=50
Victims of the accident					2		1	1
Witnesses of the accident					3	1	1	1
Military liquidators	138	70	68		220	86	126	8
Early liquidators	2	1	1		66	13	29	24
ChNPP personnel					9		4	5
Belarusian liquidators	189	63	82	44				
Sent on mission to the ChNPP	7	4	3		1			1
Sent on mission to the 30-km zone	6	5	1		181	30	84	67
Staff of AC-605	12	1	11		5	1	2	2
Staff of Combinat	1		1		4		1	3
Staff of Kurchatov's Institute					2		1	1
Mixed	2	1		1	79	18	34	27
Total	357	145	167	45	572	149	283	140

Table 6
Estimates of bone-marrow doses for subjects of Ukrainian-American study of liquidators.

First year of work	Number of subjects	Average (mGy) of estimated		Uncertainty, average GSD	Range of estimated mean doses (mGy)
		Mean doses	geometric mean doses		
1986	408	100	77	1.9	0.009–3300
1987	88	55	34	2.2	0.00004–340
Total 1986–1987	496	95	70	1.9	0.00004–3300
1988	50	27	17	2.4	0.13–140
1989	21	42	25	2.2	0.23–240
1990	5	34	16	2.5	0.04–120
All years	572	87	63	2.0	0.00004–3300

Estimates of bone-marrow doses for liquidators of years of 1986–1987, who are included in the Belarus/Baltic/Russia/IARC study of hematological malignancies.

Table 7

Home country	Number of subjects	Average (mGy) of estimated		Uncertainty, average GSD	Range of estimated mean doses (mGy)
		mean doses	geometric mean doses		
Belarus	229	11	10	1.8	0.007–123
Estonia	9	46	39	1.7	0.37–154
Latvia	15	48	41	1.7	0.09–230
Lithuania	25	139	120	1.9	6.4–587
Russian Federation	79	112	89	2.0	0.2–657
All subjects	357	45	37	1.9	0.007–657

Estimates of external thyroid doses for liquidators of years of 1986–1987, who are included the Belarus/Baltic/Russia/IARC thyroid cancer study.

Table 8

Home country	Number of subjects	Average (mGy) of estimated mean doses	Uncertainty, average GSD	Range of estimated mean doses (mGy)
Belarus	420	12	1.9	0.02–454
Estonia	9	86	1.7	2.7–322
Latvia	20	69	1.7	1.9–488
Lithuania	4	113	1.8	22.8–268
Russian Federation	77	101	2.0	0.13–507
All subjects	530	29	1.9	0.02–507

Table 9

Comparison of dose estimates for subjects based upon their own responses to the questionnaire or upon the responses given by proxies.

Dose ratio ^a	All comparisons considered ^b			Six outliers excluded ^b		
	N	GM	GSD	N	GM	GSD
D _{P1} to D _S	53	1.04	7.46	49	0.97	3.68
D _{P2} to D _S	49	0.79	4.51	47	0.76	3.41
D _{P1} to D _S	102	0.91	5.94	96	0.86	3.54

^a D_S refers to the estimated dose for the subject based upon his responses to the questionnaire; D_{P1}, D_{P2}, and D_{P1} refer to the estimated doses for the subject based upon the responses to the questionnaire from the first, second, or either proxy, respectively.

^b N is the number of comparisons, GM is the geometric mean of the ratio of doses, and GSD is the geometric standard deviation of the distribution of ratios.