Unit of Radiation and Cancer
International Agency for Research on Cancer
Lyon, France

RECONSTRUCTION OF DOSES FOR CHERNOBYL LIQUIDATORS

20 March 2003

FINAL PERFORMANCE REPORT

Principal Investigator: Elisabeth Cardis

Co-investigators: V.P. Krjuchkov, L. Anspaugh A. Bouville, V.V. Chumak, V. Drozdovich, Yu. Gavrilin, I. Golovanov, P. Hubert, S. Illychev, V.K. Ivanov, A. Kesminiene, J. Kurtinaitis, E. Maceika, I.V. Malakhova A. K. Mirhaidarov, V.A. Pitkevitch, A. Stengrevics, M. Tekkel, V. Tenet, A. Tsykalo

Grant No: R01CCR015763 – US CDC

LIST OF PARTICIPATING INSTITUTIONS AND ACRONYMS

Belarus

- Belarussian Centre for Medical Technologies, Computer Systems, Health Care Administration and Management (BelCMT), Minsk
- Research Institute for Oncology and Medical Radiology, Minsk
- Research Clinical Institute of Radiation Medicine and Endocrinology (IRME), Minsk
- Research Institute of Haematology and Blood Transfusion (RIHBT)

Russia

- Institute of Biophysics (IB), Moscow
- Medical Radiological Research Centre of Russian Academy of Medical Sciences (MRRC RAMS), Obninsk

Ukraine

- Scientific Centre for Radiation Medicine, Kiev
- Department of Dose Reconstruction, Chernobyl Nuclear Power Plant, Chernobyl

Baltic countries

- Institute of Experimental and Clinical Medicine, Tallinn, Estonia
- Vilnius University Oncology Institute, Vilnius, Lithuania
- Lithuanian Cancer Registry, Vilnius, Lithuania
- Latvian Centre of Oncology, Riga
- Latvian Cancer Registry, Riga

Outside CIS

- International Agency for Research on Cancer (IARC), Lyon, France
- Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France
- US National Cancer Institute, Rockville, MD, USA

Table of contents

List of annexes

List of acronyms

RADRUE – Radiation Dose Reconstruction with Uncertainty Estimates;
SEAD – Soft Expert Assessment Dosimetry

ADR – Analytical Dose Reconstruction

EPR- Electron Paramagnetic Resonance

ER – Exposure Rate

GSD – Geometric Standard Deviation

ChNPP – Chernobyl Nuclear Power Plant

RE – Radiation Environment

AR – Accident Remediation

DB – Database

IBPh – Institute of Biophysics

NHL - non-Hodgkin's Lymphoma

RBM – Red Bone Marrow

TG – Thyroid Gland

List of figures

List of tables

Abstract

Case-control studies of leukaemia and non-Hodgkin lymphoma (NHL) and of thyroid cancer have been carried out, nested within the cohorts of Chernobyl liquidators, the persons who were involved in the clean-up of the Chernobyl accident in 1986 and 1987 in the area around the Chernobyl nuclear power plant, under a contract from the European Commission. The leukaemia and NHL study included 70 cases and 304 matched controls, while the study of thyroid cancer included 73 cases and 309 matched controls.

The majority of liquidators in the studies were exposed predominantly to whole body radiation (from external sources and intake of ^{137}Cs), although substantial dose to the thyroid from iodine isotopes could be received by liquidators who worked in May-June 1986 and who resided in contaminated territories of Belarus.

The main objective of the current project was to develop, test and implement a detailed method for individual dose reconstruction for the subjects in these epidemiological studies. Two different approaches were considered and tested. The method adopted, RADRUE (Radiation Dose Estimation with Uncertainty Estimates), a variant of an analytical dose reconstruction method previously derived for professional radiation workers of the Chernobyl power plant, appears to work well. It is based on detailed time and motion studies, coupled with the use of very comprehensive databases of radiological data.

The development of this method has involved very extensive work to:

1. locate, collate and evaluate very large databases of gamma background measurements made by various organisations at different times on the industrial site and throughout the 30 and 70 km areas around the Chernobyl nuclear power plant;
2. bring together experts knowledgeable about working conditions in different groups of liquidators and formalise and compile their knowledge into an integrated database;
3. develop an integrated software program that allows the calculation of doses and associated uncertainties from a subject's work history;
4. carefully reconstruct itineraries of the study subjects using the information provided in the very detailed study questionnaires.

Extensive validation of the work has been carried out.

The contract also provided funds for the extension of the case-control study to further groups of liquidators in Baltic countries and Russia. This has allowed the evaluation of possible recall difficulties for a number of questions related to work as a liquidator, as the majority of Baltic liquidators had previously been included in a cohort study and had responded to asimilar questionnaire. Data from this questionnaire was obtained. Overall, there was good agreement between the answers to the two questionnaires concerning dates and places of work and type of activity performed.

Doses and associated uncertainties were estimated for all of the subjects in the case-control study. Doses to the bone marrow range from close to 0 to over 1 Gy, with a median of 20 mGy. The average geometric standard deviation was of the order of 2. Doses to the bone marrow among Belarus liquidators tended to be much lower (8 mGy) than among Russia liquidators (55). Doses to the thyroid gland ranged from close to 0 to 2 Gy, with a median of about 70 mGy. The highest doses were found for Belarus liquidators who lived and worked in areas of high contamination and are related to ingestion of I-131. For Russian and Baltic country liquidators, doses from ingestion are thought to be close to zero. Doses from inhalation of I-131 were, however, received for liquidators who worked in the first weeks after the accident.

In conclusion, this contract has permitted the development, testing and optimisation of a detailed analytic dose reconstruction method for the estimation of individual doses and related uncertainties for Chernobyl liquidators. The method has been successfully applied to the subjects included in case-control studies of leukaemia, NHL and thyroid cancer among Chernobyl liquidators from Belarus, Russia and Baltic countries. Analyses of these data are underway under a separate contract and results should be submitted for publication in late 2003.

The approach has implications for dose reconstruction in other situations, and may be adapted for populations of workers involved in clean-up of accidents in the future.

Significant findings

The work has shown that it is possible to reconstruct, with adequate precision for an epidemiological study, individual doses for workers involved in clean-up from detailed time and motion studies. This requires the development and testing of a detailed questionnaire about history and conditions of work, a set of relevant visual aids to assist the subjects in recalling their places of work, the collection and integration of all available dosimetric information and the analysis of work histories from questionnaires by experts familiar with the work and conditions of work in the clean-up areas.

The result is a fully integrated program that can be adapted to includethe following: extensive dose-rate measurements, an interface for plotting and entering information on the liquidators route and conditions of work, calculation of individual doses and simulationsdesigned to take into account dosimetric and questionnaire uncertainties. The dose reconstruction method has been tested, validated and optimized, and an approach for assessing uncertainties has been implemented. Though the method must rely on expert assessment of the questionnaires, it was shown to be sufficiently standardized to be reproducible.

Usefulness of findings

The work has the following important results:

- *The development and validation of methods for assessing individual doses and associated* uncertainties for liquidators involved the Chernobyl accident – this is essential for prediction of the consequences of the accident among liquidators, for improving radiation protection measures and emergency preparedness in the case of future accidents, as well as for estimating radiation doses to other populations of workers involved in clean-up and accidental situations in the US and elsewhere.
- *The reconstruction of individual doses and of their associated uncertainties for the subjects included in the epidemiological studies* – this is essential to ensure that the case-control studies provide valuable scientific information concerning the size and pattern of cancer risk following low dose protracted radiation exposure. This work, in addition to contributing to the understanding of mechanisms of radiation carcinogenesis, has important implications, for radiation protection of workers as well as of the general population.

Scientific report

Background

Since the 1950's, routine occupational radiation doses from external photon radiation have been relatively well monitored through the use of personal radiation dosimeters [Fix *et al*., 1997]. This is not always the case, however, when workers participate in clean-up and decontamination in the course of a nuclear accident or in environmental clean-up in general. This is illustrated by the Chernobyl accident, which happened on 26 April 1986, exposed millions of people to radiation at different dose-rates and dose levels. The majority of exposed persons received relatively low doses (Table 1).

Table 1 Estimates of collective effective doses among populations exposed as a result of the Chernobyl accident [Cardis *et al*., 1996]

Population	Number	Collective effective dose (Sv)
Evacuees	135,000	1,600
Liquidators (1986–1987)	200,000	20,000
Persons living in contaminated areas[1]:		
Deposition density of 137Cs >15 Ci km–2	270,000	10,000–20,000
Deposition density of 137Cs >1 to 15 Ci km–2	6,800,000	35,000–100,000

The populations at risk can be separated into the following groups:

1. the “liquidators” also referred to as “clean-up workers” they include persons who participated in the clean up of the accident (clean-up of the reactor, construction of the sarcophagus, decontamination, building of roads, destruction and burial of contaminated buildings, forests and equipment), as well as many others, including physicians, teachers, cooks, interpreters who worked in the contaminated territories
2. the “evacuees” those who were evacuated from the town of Pripyat and the 30 km zone around the Chernobyl reactor in April-May 1986 ;
3. the residents of the “strict control zones” (SCZ’s): those members of the general population who have continued to live in the more heavily contaminated areas (with level of 137Cs deposition greater than 555 kBq/m2), typically within a few hundred kilometers of the Chernobyl Nuclear Power Plant. Within these areas, radiation monitoring and preventive measures have been taken to maintain doses within permissible levels;
4. the general population of the contaminated territories in the three countries.

Because of their numbers, comprehensive registration and follow-up system, and because of their levels of radiation dose, the population of Chernobyl accident recovery workers or “liquidators” appears to be the most likely to be informative for the study of risks following low dose protracted radiation exposure[Cardis *et al.*, 1996; Cardis and Okeanov, 1996; Ivanov *et al.,* 1997a].

Liquidation of the Chernobyl accident consequences lasted for about three years and during that period, different tasks were carried out, such as:

[1] These doses are for the 1986–1995 time period; over the longer term (1996–2056), the collective dose will increase by approximately 50%.

- the initial localization of the catastrophe (fire fighting, closing down not affected units of the power plant)
- evacuation of the Pripyat and 30-km zone population
- decontamination inside the Chernobyl NPP buildings, roofs of the nearby buildings and nearby territories
- renovation, run up, and maintenance of the first, second and third blocks
- construction of sarcophagus
- actions to decrease the radioactive materials spread in the environment
- safe guard of the 30-km zone and settlements
- other activities in the 30-km zone (health care, ecological monitoring, servicing of the liquidators, etc.)

Different groups of liquidators were involved in these tasks; they worked under differing conditions of radiation monitoring and safety and were exposed to different types and levels of radiation. The group of the liquidators cannot be simply defined only by the type of the work they have undertaken. It is also necessary to take into account which institution sent the liquidator to the 30-km zone, the time period during whichthey worked there, the organizationto which he/she was affiliated while working in the 30-km zone, and how the dosimetric control was organized.

In all, some 600 000 liquidators from all over the former Soviet Union are thought to have participated in the clean-up of the contaminated areas around the reactor and in other areas of Ukraine and Belarus [UNSCEAR 2000]. For practical reasons, not all of these received individual dosimeters. Moreover, logistic difficulties arose in accurately recording and centralising doses for very large numbers of workers sent and monitored by different organisations. As a result, 12 years after the Chernobyl accident, only a small proportion (less than 10%) of the clean-up workers (usually referred to as "liquidators") had reliable estimates of their doses [Pitkevitch et al., 1995, 1996].

Little effort had been put, until this contract began, into the physical reconstruction of individual doses for the majority of liquidators. The exception is for staff of the Chernobyl Nuclear Power Plant (ChNPP) and a limited number of professional radiation workers from other institutions who worked on the industrial site of the plant. For these, much work has gone into the development, validation and application of methods for estimating individual radiation dose based on an analysis of factors involved in the creation and the dynamics of the radiation field at the plant site and in the immediate vicinity of the ChNPP [Illichev et *al.*, 1996].

A large proportion of liquidators involved in the clean-up of the accident were not professional radiation workers, however, but included military reservists and construction workers who worked throughout the 30-km zone around the Chernobyl reactor. Dose-reconstruction methods developed for professional radiation workers therefore needed to be modified to take into account the less precise and accurate knowledge of the place and conditions of work, different exposure conditions and different dosimetric control practices.

The funds received under this contract were for partial support of the development of these methods and for the application of the method to the reconstruction of individual doses and associated uncertainties for subjects included in the case-control studies of risk of leukemia, non-Hodgkin's lymphomas and thyroid cancer carried out among Chernobyl liquidators in Belarus and Russia in a collaborative project co-ordinated by IARC and funded by the European Commission.

To be informative for the evaluation of radiation related risks, these studies must rely on individual estimates of radiation dose. Dosimetry, however, poses an important problem. As mentioned above, official data regarding individual doses received by liquidators are not available for all liquidators; further, data available for some groups of liquidators require verification [Pitkevitch et al., 1996]. The biological techniques currently available to estimate individual radiation dose are not sufficiently reliable to derive precise and accurate estimate individual doses in the range received by the majority of liquidators [Cardis and Okeanov, 1996]. Work is actively continuing in this area in many laboratories around the world, and better methods may be available in the future. In anticipation of such developments, blood samples have therefore been obtained from consenting study subjects, lymphocytes isolated, frozen and kept at -70 ^{o}C until a biological technique exists which is demonstrated to be sufficiently reliable, precise and accurate for estimating low doses in the range of interest.

Currently, and in the foreseeable future, the most promising approach for estimating doses in epidemiological studies is through analytical dose reconstruction based on time and motion studies.

The development and validation of the current analytical dose reconstruction approach has applications for reconstructing doses to other worker populations involved in clean-up or in accidental situations where individual accurate dosimetric control may not always be possible.

Specific aims

The specific aims of the project were two-fold:

- To adapt the existing methods for assessment of doses for non-professional liquidators having worked in the zone around the ChNPP in 1986 and 1987
- To reconstruct the individual doses (and uncertainty) to the subjects included in the case-control studies of leukaemia, NHL and thyroid cancer among Belarus and Russian liquidators.

The work was divided into four tasks, as follows:

1. Compilation of data from various sources concerning radiation levels, work histories, etc.
2. Adaptation and validation of existing dose reconstruction methods for professional radiation workers on the industrial site of the Chernobyl NPP and calculation of associated uncertainties.
3. Collection of additional questionnaire data for validation of dose reconstruction method.
4. Reconstruction of dose and uncertainty for study subjects.

The methods and procedures used and the results are described for each of these tasks, below.

Task 1. Compilation of data from various sources

Work under this task involved the collection, critical review and compilation of data from many sources, including data on radiation environment (RE) measurements, dose records, work histories of liquidators' clean up activities and topological maps of the areas where clean up activities took place after the Chernobyl Nuclear Power Plant (ChNPP) accident. The detail of the information collected is provided below.

1 Data on radiation environment (RE) measurements. Verification of the data.

Available data on instrumental measurements of radiation environment for the period from the 26th of April 1986 till the 31st of December 1987 have been collected within the framework of the project. On the basis of these data, a system of interactive digital GIS maps of dose-rates for the whole period and for the territories of interest was created and incorporated into a software package specially conceived for this project. This software, called RADRUE (*Radiation Dose Reconstruction with Uncertainty Estimates)* contains all of the collected data in one integrated database, an interface to enter the details about the liquidator's work history, a "calculator" that uses the information entered as well as the data from the database to calculate a central estimate of dose and a link to a Monte Carlo simulation program for uncertainty calculations. Details of the RADRUE system are provided below under Task 2.

Several types of radiation environment data were collected: data on exposure rate (ER), surface activity and nuclide composition measurements. According to the location where the measurements of the RE were made, data is grouped into several sets, which form the so-called "base maps". The following different base maps were developed: the base map of the main buildings of ChNPP, that of the industrial site of ChNPP, the 4-km zone map, the 30-km zone map and the 70-km zone map.

The measurements compiled were made by different organizations, in different accident remediation (AR) workplaces. The list of organizations that conducted the measurements is presented in Table 2.

The discrete data on the radiation environment for the Ukrainian part of the 30-km and 70-km zones (including the industrial site and the main building of the ChNPP) were aggregated from different sources and verified by ChNPP radiation protection service, in cooperation with the Sosnoviy Bor branch of the Radium Institute. The methodology used for the collection, systematization and checking of the data is described in Sakulin *et al.* [1992].

For the Belorussian part of 30-km and 70 km zones, RADRUE used an electronic database (DB) which was aggregated and verified in the Institute of Biophysics (IBPh), Ministry of Health USSR [Savkin, 1993] by means of integration of measurements made by regional sanitary-and-epidemiological units and regional civil defense offices, as well as by the IBPh complex expedition.

Thus, the data assembled in the developed RADRUE system have been verified and computerized by the relevant organizations. The total number of original measurements for the different locations in the combined database is given in Table 3. The number of records in the table for the 30-km and the 70 km zones are for the Ukrainian and Belorussian parts of these zones.

Table 2 Location of research sites and organizations conducting RE measurements

№	Location	Name of organizations which made the measurements [References]
1	30-km zone, 70-km zone	Chemical forces of the MD[2] USSR [MD USSR, 1988] ; DMA PA "Combinat"[3] [UDK NPO "Prypiat", 1987] ; External dosimetric service ChNPP [Shteinberg, 1986] ; Sub-units of the HMSB[4] USSR [Izrael, 1987] ; CA DMD [5] №605 [US-605, 1986] ; AUSRPIET[6] [AUSRPIET, 1987] ; IBPh MH USSR[7] [Lyubchanskyi *et al.,* 1988] ; Hlopin's Radium institute [Sakulin *et al.,* 1992]
2	4-km zone	CA ChNPP[8] [US ChNPP, 1986] ; AUSRPIET [AUSRPIET, 1987] ; IBPh MH USSR [Lyubchanskyi *et al,* 1988] ; DMA PA "Combinat" [UDK NPO "Prypiat", 1987] ; Chemical forces of the MD USSR [MD USSR, 1988] ; Hlopin's Radium institute [Sakulin *et al.,* 1992]
3	The industrial site	RPD ChNPP[9] [IBPh MH USSR, 1986]; CE [10] Kurchatov's Institute [Shikalov *et al.*, 2001]; CA DMD №605 [US-605, 1986]; Chemical forces of the MD USSR [MD USSR, 1988]; Hlopin's Radium institute [Sakulin *et al.,* 1992]

[2] Ministry of Defense of the USSR
[3] Dosimetric monitoring administration of the production association «Combinat»
[4] Hydrography and Meteorology Statutory Board
[5] Construction Administration Dosimetric Monitoring Department
[6] All-Union Scientific Research and Planning Institute of the Energy Technology
[7] Institute of Biophysics, Ministry of Health USSR
[8] Chernobyl Nuclear Power Plant Construction Administration
[9] ChNPP Radiation Protection Department

№	Location	Name of organizations which made the measurements [References]
4	The rooms of Unit 1 and Unit 2 of the ChNPP	RPD ChNPP [IBPh MH USSR, 1986]; IBPh MH USSR [Lyubchanskyi *et al.,* 1988]
5	The rooms of Unit 3 and Unit 4 of the ChNPP	RPD ChNPP [IBP MH USSR, 1986], CE Kurchatov's Institute [Shikalov *et al.,* 2001], CA DMD №605 [US-605, 1986]
6	The ChNPP main building roofs	RE group of the DE USSR[11] [DE USSR, 1987], CE Kurchatov's Institute [Shikalov *et al.,* 2001], AUSRPIET [AUSRPIET, 1987], IBPh MH USSR [Lyubchanskyi *et al*., 1988]

Analysis of the completeness of measurements made in different locations and different time periods showed that information was missing for some time periods and base maps. Information for these had to be reconstructed using a combination of interpolation (which was in fact used as a basic RE reconstruction method) and the following methods: multiple linear regression from early dates after the accident to later dates, dose-rate reconstruction based on radionuclides fall-out density and a 4- dimensional interpolation method (4-D) specially developed during the project for dose reconstruction inside main ChNPP building. The details of dose reconstruction methods are given under Task 2 below.

A database of fall-out density measurements was also created, based on the information from the database of IBPh. This DB includes 312 records. All of these records correspond to June 1989. The DB contains fall-out density values for gamma-emitters ^{106}Ru, ^{137}Cs and ^{144}Ce, which were the main contributors to the radiation background for the period from the end of the year 1986 till the end of year 1987.

Table 3 Electronic DB on RE description for different zones of AR.

№	Zone of AR	Number of records	Distance from the Unit 4
1	70-km zone around ChNPP	14091	2 km-168 km
2	30-km zone around ChNPP	8203	2 km – 43 km
3	4-km zone around ChNPP, including Pripyat	461	350 m – 4700 m
4	ChNPP - industrial site	3126	20 m – 1120 m
5	ChNPP - main building	3463	14 m – 930 m
6	ChNPP roofs	1364	40 m – 140 m

The data collected on the experimental measurements on RE in combination with values obtained by regression and interpolation, permit the estimation of dose-rate for each location of interest within the zone of 70-km radius around Unit 4 of ChNPP, at any moment of time during the period from the 26th of April 1986 till the end of year 1987 (the period of interest for the epidemiological study of cancer risk among liquidators, for which this dose reconstruction method was developed). The data on RE was included into the integrated database of the RADRUE software and is used

[10] Complex Expedition
[11] Radiation Exploration of the Department of Energy and Electrification of the USSR

automatically by the program in the process of the external exposure dose reconstruction for the liquidators within the study.

2 Collected visual information about clean up activities of the liquidators in ChNPP (photographs, videotapes).

Collected photographs and topographical schemes of the main buildings of the ChNPP, ChNPP industrial site, 4km zone, 30 km zone and 70km zone have been digitized and integrated into the RADRUE software as images in the interactive GIS dose-rate maps. They served as a visual interface for the RADRUE users to facilitate the indication and drawing of the locations and itineraries of each liquidator's activities during his/her missions. The images of digital maps used in the program are presented in Figures 1-7.

Videotapes and photographs reflecting different cleanup activities after the accident were collected and were used for the training of the interviewers and during interviews of the liquidators. Some of the photographs were also included into the Booklet (Annex 3) used by the interviewers to assist the liquidators in describing their work history in the epidemiological study.

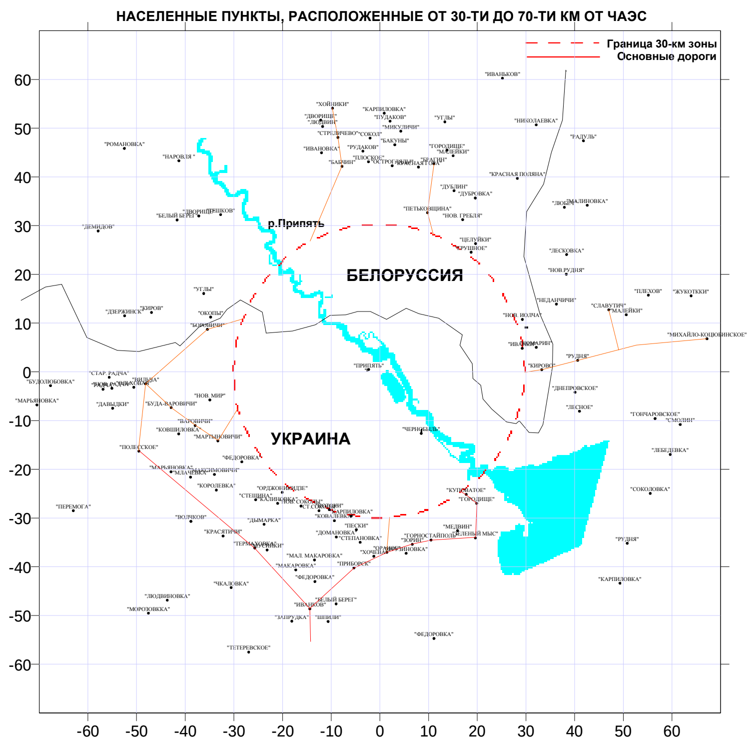


Figure 1 70-km zone around ChNPP

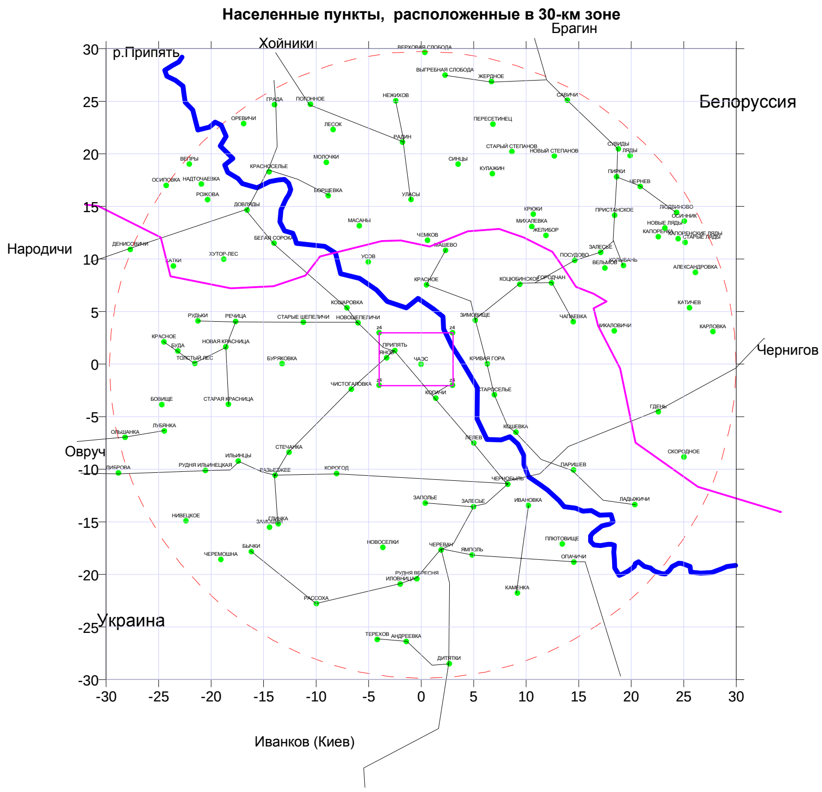


Figure 2 30-km zone around ChNPP

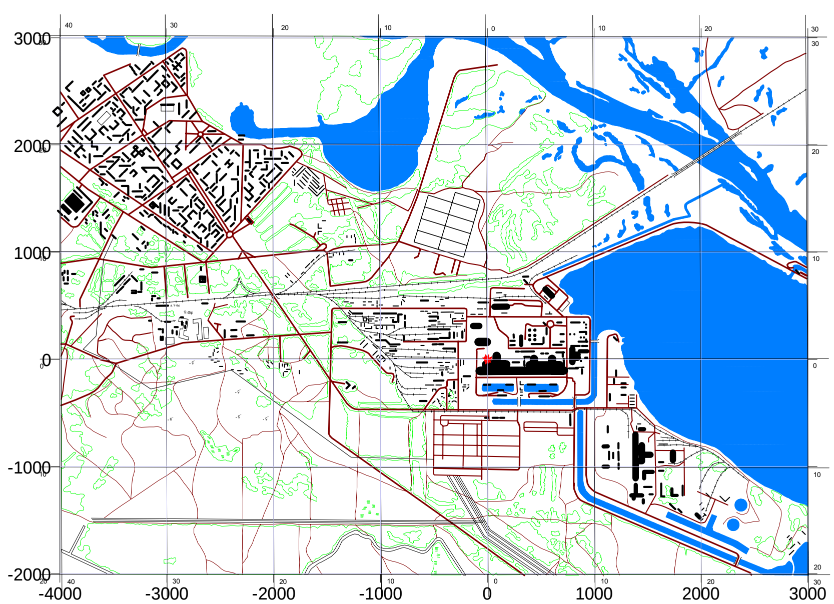


Figure 3 4-km zone around ChNPP

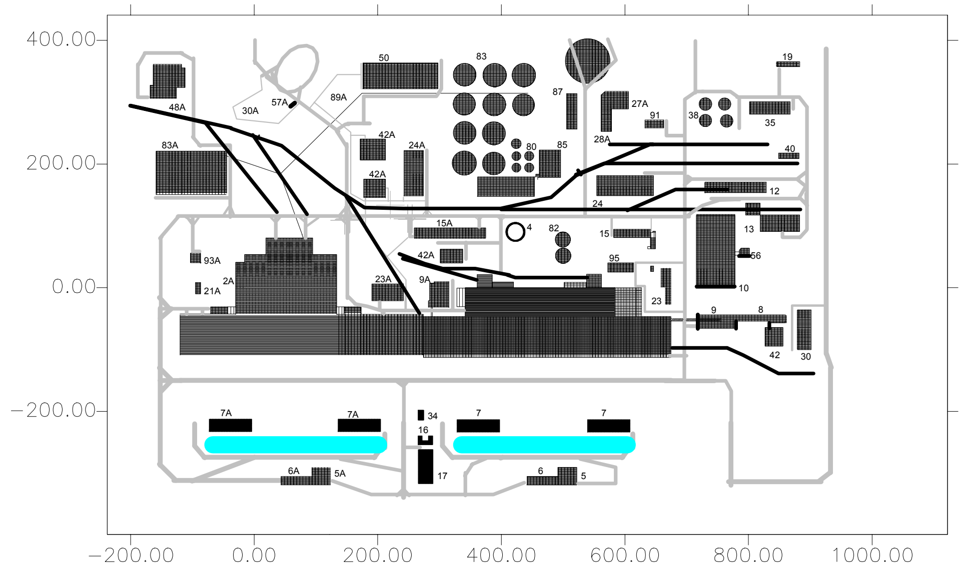


Figure 4 ChNPP industrial site

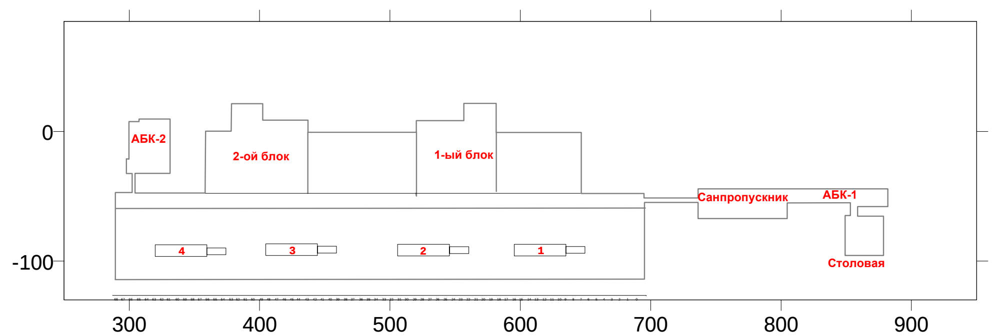


Figure 5 The rooms of Unit 1 and Unit 2 of the ChNPP

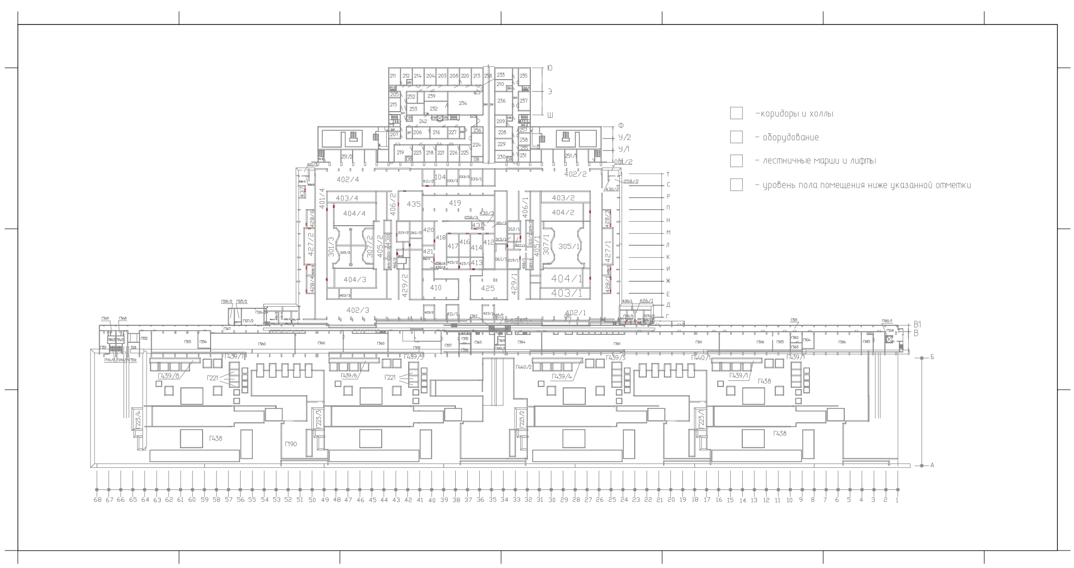


Figure 6 The rooms of Unit 3 and Unit 4 of the ChNPP

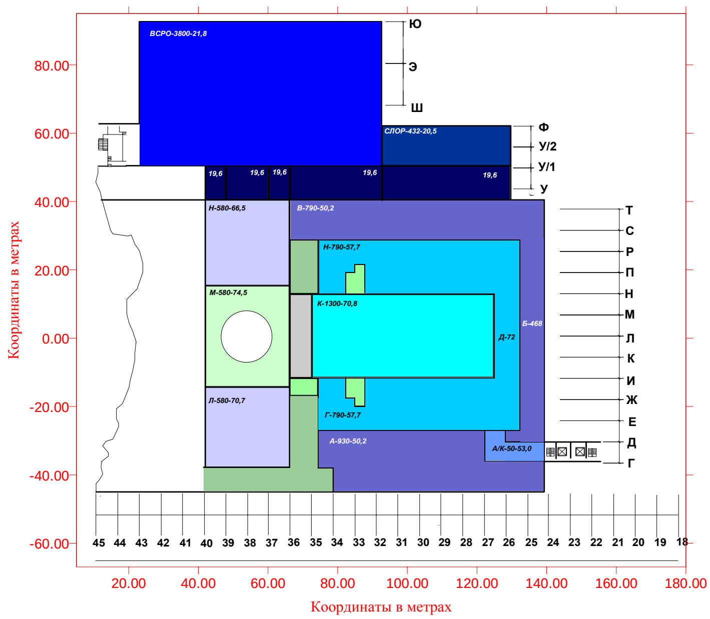


Figure 7 The ChNPP main building roofs

3 Data on individual dose records of liquidators.

A very large set of individual dose measurement records for liquidators was collected from organizations which had carried out dosimetric measurements and all information was systematized.

In addition to previously available data, the data of the Specialized State Construction Company US-605, hereafter called US-605, consists of individual dose records for 35 000 liquidators from 1986-1987 from all republics of the former USSR. These data, which have been computerized, include an identification number of the individual (the time card number), the date and time of beginning and end of work and the dose received during this period. Data on several hundreds of these liquidators have been crosschecked with information from the IBPh database on professional liquidators and appear to be correct.

Data on the individual dose records was used to derive dose distributions for the different contingents of the liquidators, which were implemented in the SEAD (*Soft expert Assessment Dosimetry*) program (see Task 2). A summary of the distribution of dose measurements for the different categories of the liquidators is presented in table 4.

Table 4 Parameters of empirical dose distributions for different groups of liquidators.

Dbf-files (without exclusions)	Number of entries	<D>, cGy	σD	<lgD>	σlgD
Witnesses of accident	658	55.2	41.7	1.61	0.36
Early liquidators	326	11.5	16.93	0.62	0.74
Personnel of ChNPP-86	2358	8.69	12.9	0.65	0.54
Personnel of ChNPP-87	4498	1.54	2.92	-0.005	0.44
Detached to ChNPP-86	608	5.74	9.03	0.27	0.73
Detached to ChNPP-87	3453	0.86	1.89	-0.41	0.55
Detached to the 30 km zone-86	29866	2.52	5.30	-0.16	0.72
Detached to the 30 km zone-87	33620	0.87	1.31	-0.42	0.56
Military liquidators and MIA-86	13791*	20.0	8.65	1.25	0.265

Dbf-files (without exclusions)	Number of entries	<D>, cGy	σD	<lgD>	σlgD
Military liquidators and MIA-87	14368*	10.8	5.92	0.957	0.315
Civil personnel of US-605 in 1986	8351	6.99	8.04	0.42	0.72
Civil personnel of US-605 in 1987	4086	3.75	5.18	0.116	0.70
Military builders from US-605 in 1986	4790	10.8	9.48	0.75	0.63
Military builders from US-605 in 1987	1352	5.92	6.30	0.44	0.64
Combinat personnel in 1987	6281	1.01	1.12	-0.16	0.39
Belarussian liquidators- 86	4956	6.41	5.16	0.64	0.44
Belarussian liquidators- 87	1822	2.53	2.30	0.26	0.35

* Doses for these groups of liquidators are given in Roentgens.

4 Data on operative exposure dose-rate measurements (bank of standard episodes)

Information on operative exposure dose-rate measurements made before assignment of work in different locations is available from dosimetric journals of the Chernobyl NPP and was verified by officials of ChNPP Dosimetry Service. It includes measurements of exposure dose-rate taken in work sites before the conduct of specific tasks; organization (name, address) to which liquidator was affiliated during cleanup work; type of work; specialty of the liquidator; place of work; dates of work and, in some cases, evaluated average dose per episode. Information on 437 different episodes of work have been computerized and previously used in the reconstruction of dose to professional liquidators.

For the case-control study, the data collected were used in RADRUE to assign doses for liquidators who had performed one of these “standard” work episodes. A special databank of “standard episodes” incorporated into RADRUE ensured the systematization of dose assignment for liquidators by the different experts reviewing the questionnaires.

Task 2 - Adaptation and validation of existing dose reconstruction methods for professional radiation workers

1 Development of methods for external exposure dose reconstruction for the liquidators.

Two approaches were considered for estimating individual external exposure dose for the liquidators in the case-control study:

- RADRUE (Radiation Dose Reconstruction with Uncertainty Estimates);
- SEAD (Soft expert Assessment Dosimetry).

As explained below, RADRUE was selected as the main method for the external exposure doses assessment. RADRUE was developed and formalized within this contract on the basis of the previous analytical dose reconstruction (ADR) method that had been developed and used earlier for evaluation of the dose of liquidators who were professional radiation workers at the ChNPP [Illichev *et al.,* 1996]. That initial ADR method was modified, with the purpose of:

- obtaining more reliable dose estimations through verification and smoothing of the radiation environment data;
- automating dose estimations to decrease the influence of subjective factors (experts influence on outcomes of doses estimation);
- integrating calculation of uncertainties of dose estimations.

Another, more crude method, SEAD, was also developed within the framework of the current project. Based on the results of the validations described below, it was decided not to use it as the main method for dose reconstruction among liquidators as it has a tendency to regress all doses towards the mean of the doses for a particular type of liquidator. It was, however, used to assign doses for a very small number of liquidators in the case-control study, for whom the data collected by questionnaire was insufficient to calculate their doses analytically with RADRUE. For such subjects individual external exposure doses, and ranges of the uncertainties, were assessed using SEAD and later were entered directly into the RADRUE software. Such possibility of direct entry of pre-assessed doses and uncertainties was foreseen in RADRUE software.

2 Development of the RADRUE method

During this contract, the procedure for external dose reconstruction using RADRUE was developed and formalized. It is described in the following.

Main terms and definitions used in RADRUE system

The first step of the dose reconstruction procedure in RADRUE is the analysis of the questionnaires in the case-control study and the transfer of information from the questionnaire to the RADRUE software. This step is performed by a small number of experts from the dosimetry services in Ukraine and Belarus, who are very familiar with the dosimetry, radiation protection and working conditions of liquidators from various organizations in different areas of the 30 and 70 km zone. The experts review thoroughly the information collected in the dosimetry part of the questionnaire, and reconstruct the so-called “liquidator's route” (itinerary).

The liquidator's route is the sum of movement patterns of the liquidator, including indications of the movement speed (staying at the same place is considered as a movement with a zero speed). Once reconstructed, the liquidator’s route is input into the computer (by means of the graphic interface made on the basis of the Surfer 7.0, computer program). The graphic interface allows the representation of the liquidator's movement patterns on the base maps (Figures 1-7), with indication of the trajectory's attributes (including movement speed, time of beginning and completing of movement, type of transport used) in the special form view, and also all attributes of uncertainties (when the exact date, duration or place is unknown or uncertain). The data entered appear in the RADRUE frame dialog window (see example in Figure 8). RADRUE then calculates the liquidator’s dose automatically, from the data thus entered.

Analysis of the questionnaire and characterization of the route is not a simple task, however. While developing questionnaires for liquidators and the RADRUE method, a series of terms was identified; these are used to describe the liquidator's route in RADRUE:

- mission
- episode
- event
- frame
- subframe

There is a hierarchy of routes in the RADRUE system. The highest is the ***mission***. A mission is the sum of movement patterns, which completely characterizes the collection of operations of the liquidator during one trip to Chernobyl region (at least within the 30-km or 70-km zone around the reactor). Most liquidators had only one mission, but some of them may have had several missions. In an interval between two missions, the liquidator would have returned home.

The next level of organization is the ***episode***. An episode is a route that completely characterizes one of liquidator’s operations due to which one of the mission targets is achieved. Usually one episode corresponds to one day in Chernobyl region. One of the reasons for defining the term “episode” is that different liquidators may have had exactly the same episodes; thus, once the episode is described, the same description can be used repeatedly for other liquidators. The episode has a certain logical completeness and due to this may be repeated. The episode cannot be described as a sum of two or more episodes. The same episode can be frequently repeated for one liquidator. Examples of episodes include: the trip along the route Chernobyl - Pripyat – Chernobyl for liquidators who were truck drivers, or cleaning the reactor debris from the roof of the Units 3-4 turbine hall. The RADRUE system considers the participation (mission) of the liquidator in AR as a sum of separate episodes.

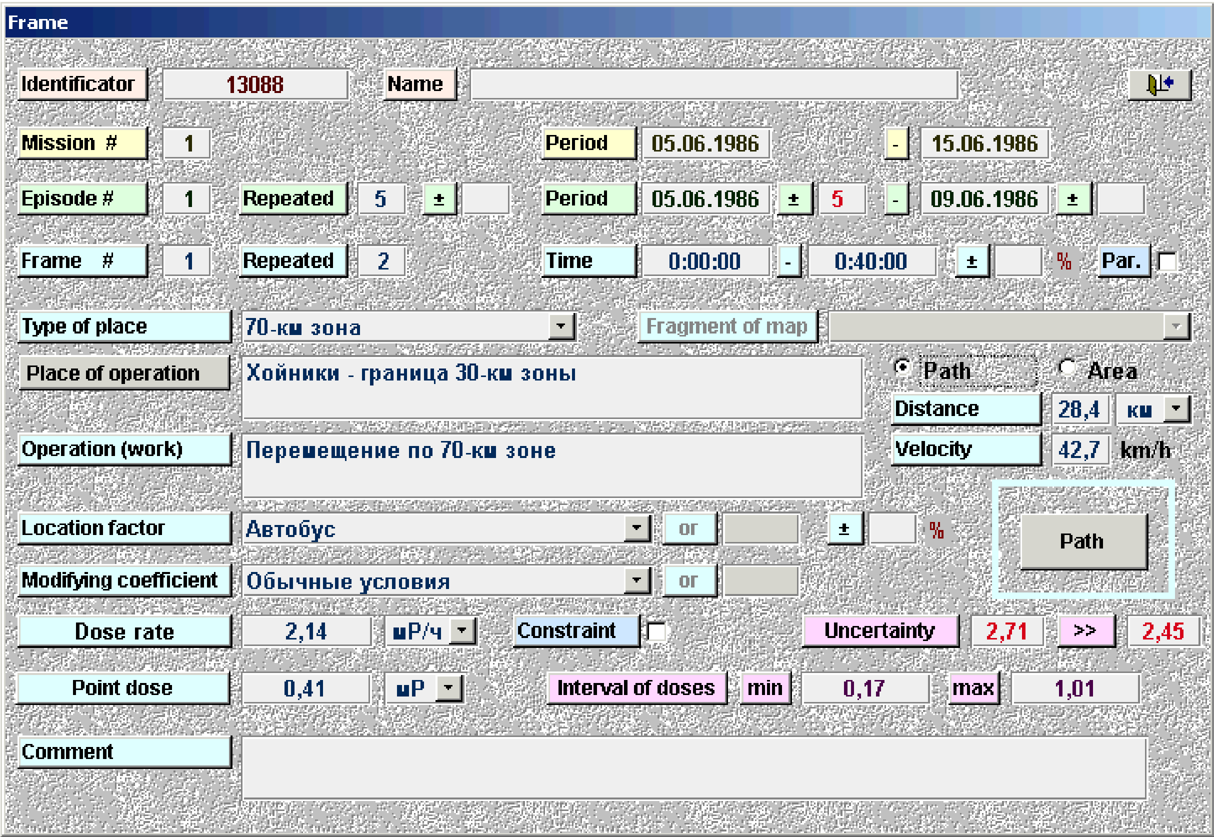


Figure 8 An image of the RADRUE frame dialog window

Any episode can be described as a series of ***events***, which are the following:

- transportation (from the place of residence to the place of work or vice-versa, from one workplace to other),
- changing of clothes,
- instructions period, where appropriate,
- walking to a workplace,
- the work (on the spot or in motion),
- resting at workplace or waiting for an assignment,
- lunch,
- resting at place of residence during AR.

The reason for defining the term "event" is the high events frequency in questionnaires.

The RADRUE system uses a number of base maps, and one event connected with transportation may occur on one, two and more base maps. That's why in RADRUE system the concept of "***frame***" has been introduced. The frame depicts the sum of a person's movement patterns within one base map as well as their attributes. If movement parameters vary, the frame is broken into two so that each frame is associated with constant attributes. Each episode of each mission of a liquidator is represented as the sum of a number of frames. If the person's movement pattern is located within only one base map and if the movement attributes are constant, then "the event" will correspond to one frame. In other cases, the event will be broken down into several frames. Unlike a logically completed episode the frame is characterized by invariability of base map and attributes.

The final term used is the ***subframe***. This term is invisible for the RADRUE computer program user but very important for understanding the uncertainty estimations. For every base map in RADRUE system there are several grids of dose-rates. One grid works within a given time interval. For each frame the appropriate grid is chosen according to frame's attributes. Each base map and grid is divided into 10,000 cells (subframes) (100×100). The dose-rate within one cell is a constant value for one grid. The computer uses the values of dose-rates that correspond to the cells of the appropriate grid the trajectory passes through. Together with the grids, the RADRUE system uses other means to describe radiation environment like analytic formulas, for example. It is important to understand that the term "subframe" is connected not only with grids but also with all other means of description.

The event and ***frame*** are the basic terms in RADRUE system. The first term describes some elementary liquidator's action from the logical point of view, and the second – from the point of view of RADRUE computer program. The discrepancy of elementary actions from these two points is the result of using several local base maps instead of one universal base map. Creating the event's template can eliminate this discrepancy. In this case the frames are used only while creating the event's template, and then the initial data is inputted to computer in parts that correspond to the events, but not to frames.

The events usually follow each other. The same thing is with frames. But there are two important exceptions to general rules.

1. In case the exact route is unclear, it is possible to enter **alternative events" –** the RADRUE program will then have, for the same event, two different descriptions. Example: liquidator could have gone from Pripyat to Kopachi using either road #1 or road #2. The liquidator could take only one of these roads, but the expert is unsure which one it was. Both events are therefore entered and given a probability (see the Operations Manual in Annex 1).
2. If there were two sources of radiation at the same time – for example the liquidator was driving a contaminated car in the 30-km zone around ChNPP. He was then being exposed by two irradiation sources at the same time - radionuclides dispersed on the ground and on the surface of the car. Two frames are then used to describe that liquidator's exposure. The first frame describes the ground surface effect, the second the effect of the surface contamination of the car. The duration of the first frame is used in the calculations that ensure that the 24 hours in the day are accounted for (between work, transport, meals and rest). The second frame, however, is a "parallel frame" and its duration is not taken into account in the 24 hours calculations.

The RADRUE method makes it possible to manually input the dose-rate in case the expert does not agree with ER value offered by the program. The expert must however include a comment to identify this and justify his reasons.

Evaluation of the person's external exposure dose

A person's **exposure dose**, X, for a frame is calculated as follows:

$$X = n \times \dot{X} \times t \ , \qquad (1)$$

where n denotes the repetition factor (i.e. the number of times the frame was repeated within the episode, unitless), $\dot{X}$ the average-exposure dose-rate for that frame (in mR h^{-1}) and t the time spent to accomplish the activity described within the frame (in hours). A person's **total exposure** can be thought of as a sum of all frames defined for that person, although the actual process of "summing" the total exposure is more complicated due to the Monte Carlo simulation that is used to define uncertainties and to derive this sum. A person's dose is then defined in terms of **air kerma**, *K*, as:

$$K = C \times X \quad , \tag{2}$$

where C is a constant equal to 0.00875 mGy mR^{-1}. Based upon assumptions on the energy spectrum of the field, values of *K* can be converted to other quantities such as effective dose or dose to the red bone marrow. Air kerma is also the agreed upon standard to be used for the comparison of calculated doses versus those derived from electron paramagnetic resonance measurements of teeth or bone (one of the approaches used to check the adequacy of the RADRUE estimation process).

Exposure dose-rate reconstruction for the RADRUE base maps

As mentioned under Task 1 above, the RADRUE system uses the following base maps:

- From 30-km to 70-km zone around ChNPP,
- From 4-km to 30-km zone around ChNPP,
- From industrial site boundary to 4-km zone around ChNPP,
- ChNPP industrial site,
- The rooms of Unit 1 and Unit 2 of the ChNPP
- The rooms of Unit 3 and Unit 4 of the ChNPP
- The ChNPP main building roofs

Reconstruction of the RE for the locations and itineraries of a liquidator is done automatically by the RADRUE program and independently in each of the 7 base maps. Each base map includes a set of files with smoothed dose-rate sub-maps, which correspond to different time periods. Those smoothed sub-maps of dose-rates were obtained from the point experimental measurements by applying several interpolation or extrapolation methods. Figure 9 summarizes the ER reconstruction methods used for different places of AR activities and for different periods following the accident.

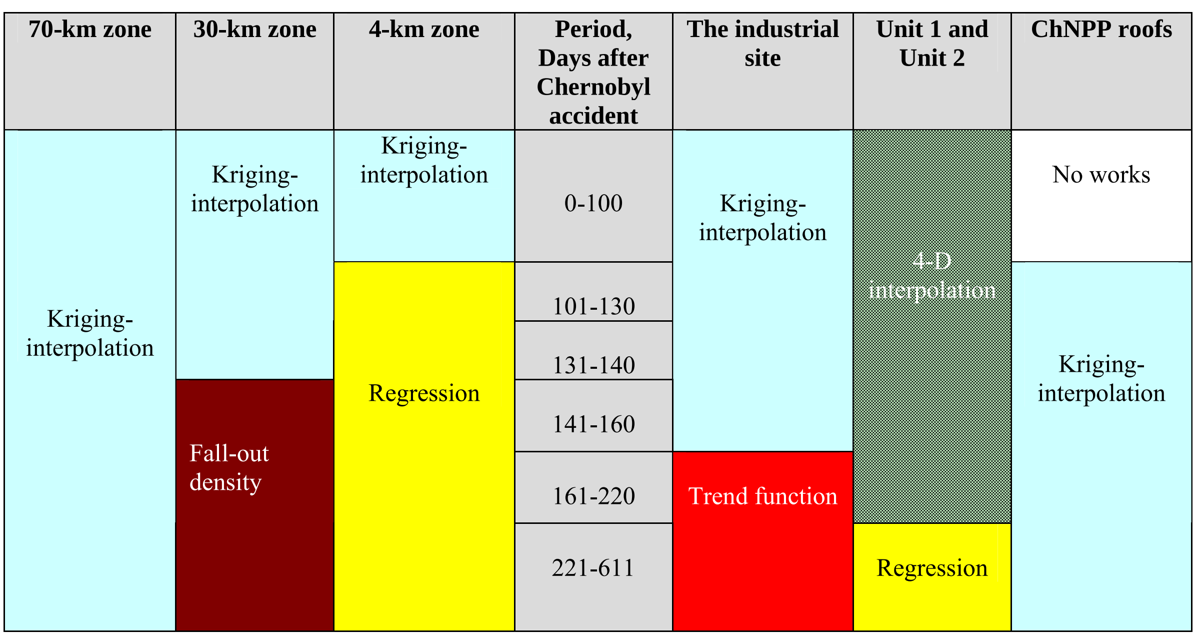


Figure 9 The ER reconstruction methods usage by different places of AR activities

Table 5 shows the list of files used for these estimations and the number of points (measurements) contained in each. Each file is made for such a time period that allows to get a sufficient number of points for interpolation/extrapolation for any site of 70-km, 30-km, 4-km zones and buildings or industrial site of ChNPP. The filename reflects the time period of the data contained.

30-km zone around ChNPP

The DB on 30-km zone that contains 8203 records is divided into 25 data files. ER interpolation was conducted by means of Surfer 7.0 application package. The Kriging method was used for interpolation. Kriging is an unbiased, minimum variance method of data interpolation that may or may not be performed on a regularly spaced grid. The smoothing Kriging version was used. The point searching method is quadrant without anisotropy. The logarithm of the ER was interpolated, notthe ER value itself. As mentioned above, this interpolation method, in comparison with ER interpolation this interpolation method gives better results in high ER gradient conditions {Illychev et al, 1996]. ER co-ordinates equal records were averaged. Linear and nugget effect models were used. The models' parameters were defined right before the interpolation. The grids were of standard sizes: 100×100 cells (in the RADRUE terms – subframes). For better adjustment of the interpolation results on 30-km zone with the results on 4-km zone, the initial data (measured ER) on 4-km zone was added to the file of initial data on 30-km zone (taking into account time periods).

Starting from the 141th day till the 615th day after the accident there were not enough ER measurements within the 30-km zone. Dose estimation for this time period was made basing on density of the quite long-living radionuclides such as ^{106}Ru, ^{134}Cs, ^{137}Cs and ^{144}Ce fall-out. The ER dynamics was calculated based on already available conversion factors, taking into account the radionuclides fall-out and ground deepening [Izrael, 1990]. The model of plane unending source screened by 1-meter air layer was used.

The Kriging method was used for the starting time period and for the later periods the exposure rates were estimated on fall-out density.

Table 5 List of files for interpolation in 30-km, 70-km and 4-km zone, on the industrial site and ChNPP roofs.

File	Period, Days	N
30-km zone around ChNPP		
0-3.dat	1-2	225
2-4.dat	3-4	252
4-6.dat	5-6	267
6-8.dat	7-8	503
8-10.dat	9-10	307
10-12.dat	11-12	219
12-15.dat	13-15	397
15-18.dat	16-18	482
18-21.dat	19-21	379
19-24.dat	20-24	439
24-29.dat	25-29	369
27-30.dat	28-30	250
30-40.dat	31-40	325
40-45.dat	41-45	138
45-50.dat	46-50	168
50-55.dat	51-55	118
55-60.dat	56-60	146
60-65.dat	61-65	167
65-75.dat	66-75	394
75-85.dat	76-85	330
85-90.dat	86-90	152
90-110.dat	91-110	461

File	Period, Days	N
110-120.dat	111-120	364
120-130.dat	121-130	512
130-140.dat	131-140	438
70-km zone		
1-10.slk	1-10	1679
10-20.slk	11-20	1736
20-30.slk	21-30	871
30-50.slk	31-50	956
50-70.slk	51-70	1165
70-90.slk	71-90	2137
90-110.slk	91-110	770
110-130.slk	111-130	1716
130-150.slk	131-150	1260
150-200.slk	151-200	1317
200-270.slk	201-270	327
270-360.slk	271-360	46
360-450.slk	361-450	48
450-600.slk	451-600	63
4-km zone around ChNPP		
bd_4km_1-9_right.dat	1-9	183
bd_4km_10-35_right.dat	10-35	190
bd_4km_35-60_right.dat	36-60	352
bd_4km_ff_60-100_right.dat	61-100	321
The ChNPP industrial site		
prom_0-1_right.dat	1	74
prom_1-2.dat	2	42
prom_2-4.dat	3-4	51
prom_4-14.dat	5-14	86
prom_14-22.dat	15-22	53
prom_22-27.dat	23-27	146
Prom_27-32-right.dat	28-32	157
prom_32-38-r.dat	33-38	238
prom_38-45-r.dat	39-45	328
Prom_45-50-r.dat	46-50	258
Prom_50-60-r.dat	51-60	529
Prom_60-70-r.dat	61-70	303
Prom_70-85.dat	71-85	446
Prom_85-90.dat	86-90	189
Prom_90-120.dat	91-120	286
Prom_120-130.dat	121-130	86
Prom_130-160_right.dat	131-160	40
Prom_350-374_right.dat	351-374	366
Prom_725_right.dat	725	306
The ChNPP roofs		
Digit_rad_09_86_right.dat	100-158	527
Digit_rad_10_86_right.dat	159-359	93
Digit_rad_20_04_87_right.dat	360-387	201
Digit_rad_05_87_right.dat	388-445	255
Roof1.dat	446-615	332

70-km zone around ChNPP

DB on 70-km zone contains 6888 recordsis divided on 14 data files. For better interpolation results the DB records on 70-km zone were combined with those of 30-km zone (8203 records). The filename reflects the time period of the contained data. Table 5 shows the list of files and the number of points contained in each. Each file is made for a time period that allows getting a sufficient number of points for any site of 70-km zone. 124 ER values from Table 5 were added to the last five ER measurements files. These values were calculated using radiation pollution density by the method described above. They were added because of the lack of ER value records for some sites of the 70-km zone. The ER interpolation was made using the Surfer 7.0 application package.

4-km zone around ChNPP

The DB on the 4-km zone contains 461 records and data from the industrial site DB. DB is divided on 4 data files. The list of files and the number of points contained in each are given in Table 5. Each file is made for such a time period that allows getting a sufficient number of points for any site of 4-km zone. Kriging interpolation method was applied. Because of insufficient data, a multiple regression has been used for time period of 101-615 days (till the end of 1987).

ChNPP industrial site

The DB on the ChNPP industrial site contains 3126 records and it is divided on 18 data files. The filename reflects the time period during which the measurements were made. The list of files and the number of points contained in each are given in Table 5. Each file is made for such a time period that allows to get a sufficient number of points for any site of the Industrial Site. Kriging interpolation method was used. The ChNPP industrial site data were directly used only for interpolation itself in the time period of 1-160 day after the accident. Starting from day 161 after the accident, there were only two short time intervals that containedlarge enough number of ER records from the industrial site. These maps have been used together with days 1-160 maps and by means of the Excel "trend-function" for estimation of ER dynamics in the period of 161-615 day after the accident (31 December 1987). Trend-function has also been used for all time intervals with the exception of the first day of accident.

ChNPP roofs

The DB on the ChNPP roofs contains 1364 records and it is divided on 5 data files. The list of files and the number of points contained in each are given in Table 5. Unlike industrial site, 4-km, 30-km, 70-km zone files, the roof files contain ER values that were measured within one workday. The records on these maps were done accordingly on 4 September and 1 October 1986, 20 April, 18 May and 15 June 1987. Kriging was used for the spatial interpolation of the dose-rates. In the current RADRUE version, the RE on the roofs is considered to correspond to discrete time periods as shown in Table 5. Trend-function has also been used for all time intervals.

The rooms of Unit 1 and Unit 2 of the ChNPP

Unlike all other base maps, ER reconstruction in the rooms of Unit 1 and Unit 2 of the ChNPP needs another approach, because Kriging and other standard interpolation methods work only in two dimensions. For the inside of the ChNPP building a simple 4-D interpolation method has been invented. This method is similar to 2-D method of inverse distance zero degree (weight dependence inversely to a distance in zero degree). There were 3463 measurements inside ChNPP main building within the 1-220 days interval after the accident. For each point for which an interpolation was needed, the 5 nearest neighbor records were taken. To find the distance between the points (x_1, y_1, z_1, t_1) and (x_2, y_2, z_2, t_2) the Mahalanobis distance (m) was used.

A different approximation was preferable for later time periods (from 220 days after the accident -1 December 1986) on Unit 4. In this case the exposure dose-rate logarithm P at point with co-ordinates (x, y, z, t) is defined by a non-linear interpolation function with empirically fitted coefficients.

All basic maps of doses rates were reviewed by the panel of experts, guided by A.Tsykalo. Data was confirmed to be consistent with official documents, as well as with the personal notes of dose-rate measurements held by the expert.

Dose factors for conversion from air kerma to dose for red bone marrow and thyroid gland

The RADRUE calculation program estimates exposure dose. For the purpose of the epidemiological study, it was required to estimate the dose to the red bone marrow and to some other specific organs. Parameters of the distributions of air-kerma to organ-doses ratios were derived.

It was shown that the conversion ratios quasi don't depend on the time period. Therefore calculations were done for the 60th day after the accident on the Unit 4 on ChNPP. It was presumed that radionuclide composition listed in Table 6 was typical for that day. The second and the fourth columns give the radionuclide's relative activity (100% is the summary radionuclide's activity at the moment of the accident).

From [Ilyin *et al.*, 1995] it was known that the geometry of irradiation of liquidators can be considered as a combination of directed, isotropic and rotational irradiation. The contribution of each geometry depended on the concrete place of work, as well as on whether the activity of the liquidator in a given place was connected to environmental radioactivity or not. The latter means, that for the liquidator occupied with cleaning of sources of radioactivity, with radiation survey or construction of protective barriers, the main geometry of irradiation would be anterior-posterior since the liquidator is generally facing the main source. In cases when the activity of the liquidator is not connectedto radioactivity, the geometry of irradiation was assumed to be close to rotational.

Table 6 Nuclide fall-out compound on the 60-th day after the accident.

Radionuclide	Activity, %	Radionuclide	Activity, %
Ba-140	1.0	Pm-147	0.5
Ce-141	1.0	Ru-103/Rh-103M	1.0
Ce-144/Pr-144	2.8	Ru-106/Rh-106	1.7
Cs-134	0.4	Sr-90/Y-90	2.6
Cs-137/Ba-137M	0.8	Zr-95/Nb-95M	1.8
Nb-95	2.7		

Based on these considerations, and in order to simplify the calculations, it was decided to allocate two geometry of irradiation depending on whether the liquidator was on the roofs or not.

On the roofs, the geometry of irradiation was considered a combination of AP and rotational geometry; in all other cases the geometry of an irradiation was considered as mixture of rotational and isotropic. It was clear, however, that on the industrial site and on Unit 4 of the ChNPP cases of AP irradiation were possible; this was solved by postulating a distribution for the conversion factors, taking into account the likelihood of such irradiations. The chosen distributions and their parameters are given in Table 7.

Table 7 Parameters of dose conversion factors distributions

Organ	Everything, except for roofs	The roofs
RBM	normal distribution; mean=0.72; σ=0.07	normal distribution; mean=0.77;σ=0.08
Thyroid Gland	normal distribution; mean=0.80; σ=0.16	lognormal distribution; mean=0.86; β=1.34

The values and distributions of the conversion factors satisfy the following criteria, which were established after examination of experimental measurements on spatial distributions and spectrums of radiation [Kotchetkov *et al.*, 1992; Troshin *et al.*, 1992; ICRP, 1975; Jacob *et al.*, 1990]

- the values of dose conversion factors for the roofs (RBM and TG) is more than factors for other places of work,
- the standard deviation of dose conversion factors distributions should be more than 5 % for RBM and 13 % for TG,
- the average value of dose conversion factors should be in limits from 0.69 till 0.77 for RBM and in limits from 0.73 till 1.0 for TG,
- the most part of probability of values of dose conversion factors should fall in the intervals 0.69-0.77 for RBM and 0.73-1.00 for TG,
- the values of dose conversion factors for TG on the average should be greater than those for RBM,
- the standard deviation for distribution of dose conversion factors on the ChNPP roofs should be higher, than the standard deviation in other places of works,
- on average, conditions of irradiation are the closest to rotational geometry, even for roofs ChNPP,
- the value of dose conversion factor is higher in places where there was more scattered radiation.

Dose uncertainty estimation

The RADRUE system includes a program, which consists of two modules: CALCULATOR and SIMULATOR. CALCULATOR allows the description of the liquidators route, the attribution of frame describing uncertainties in non-standard situations and also provides central dose estimates. SIMULATOR automatically calculates dose uncertainties. Below are described the different dose uncertainty estimations stages.

Uncertainty in the ER estimations

A key assumption in the ER estimations is that the ER values from any liquidator workplace point are distributed according to a lognormal distribution. This assumption is right with all ER reconstruction methods: Kriging method, interpolation or extrapolation, estimation based on available radionuclides fall-out. In accordance with our assumption, the estimation of ER reconstructed values is associated with a geometric standard deviation β_g.

The GSD estimation procedure is as follows. One ER records was consecutively excluded from every file. Then the ER value for the excluded point was reconstructed. Then these reconstructed and measured ER values were compared and the difference between reconstructed ER value logarithm and measured ER value logarithm was found. The procedure was repeated for the next point until the procedure was done for all points from current file (each time only one point was excluded). So if the file contains *n* experimental points, then a subset of *n* differences is formed. For this subset, the GSD value was found and was then used as a parameter of the potential dose distribution for every point on the base map corresponding to the file used. As the uncertainty of measured ER value is much less then the uncertainty of the reconstructed ER value this procedure has been chosen quite properly. The calculated GSD values are given in Table 8. In case of Kriging interpolation there are several data files for each base map. For this case Table 8 gives average GSD values. For interpolation, regression extrapolation and 4-D interpolation there is only one file for each base map. For this case Table 8 gives exact β_g values.

Table 8 Estimates of geometric standard deviation, β_g associated with values of external γ-exposure rate for different sites where liquidators worked, rested or were transported.

Map type	β_g	Time of validity, day	Method
	2.17	3 August – 30 September 1986	Kriging
	2.25	1 October 1986 – 19 April 1987	Kriging
	2.26	20 April 1987-17 May 1987	Kriging
Roof	2.99	18 May 1987-14 July 1987	Kriging
	2.01	After 15 July 1987	Kriging
ChNPP	3.58	26 April 1986 – 1 December 1986	4-D interpolation
building	4.78	2 December 1986 – 31 December 1987	Extrapolation by Regression
	2.77	Until 2 October 1986	Kriging
Industrial Site	3.27	After 2 October 1986	Kriging+trend function
	2.98	26 April 1986 – 3 August 1986	Kriging
4-km zone			
	4.31	After 3 August 1986	Extrapolation by Regression
	2.64	26 April 1986 – 12 September 1986	Kriging
30-km zone	1.67	After 12 September 1986	Analitical Formula
70-km zone	2.71	26 April 1986 – 31 December 1987	Kriging

The uncertainty estimation for ER reconstruction through fall-out density was done in a different way. In this case the records in 30-km zone settlements were chosen at random and ER in these points was reconstructed based on fall-out density of available isotopic composition. After that, the uncertainty estimation procedure was no different from that used for the other methods.

Frames uncertainty estimations

Each subframe consists of one grid in a map. For an individual frame, there may be only one subframe, but for movements there may be many subframes. There obviously exists a spatial correlation of the exposure rate in one subframe with the exposure rate in another. For the industrial site and the 30-km zone, for example, the lengths of one of the 10,000 cells in the map grid are equal to 20 m and 600 m, respectively, and the spatial correlation between exposure rates in cells assumed to be of an exponential form:

$$\mathrm{corr}(R) = \exp\left(\frac{-R}{k}\right), \quad (3)$$

where R is the distance between points and k is equal to 500 m and 4000 m, respectively, for the Industrial zone and the 30-km zone. Thus, the coefficients of correlation for the industrial site and the 30-km zone were found to be 0.96 and 0.86, respectively. A general value of 0.9 for this coefficient has been accepted provisionally for all maps.

Let GSD for exposure rate on the current base map be equal to β_{g0} and β_{g0}=exp(σ_0). Let also the movement trajectory pass through the series of the “subframes” (grid’s cells) consisting of N subframes. At first we’ll consider some i-th grid’s cell (p_i,q_i), where (p_i,q_i) a couple of numbers, which define the position of the i-th grid’s cell, in X-direction or in Y-direction, correspondingly. Let the geometric mean of the exposure corresponding to the part of the trajectory passing through the chosen i-th cell be equal to D_{gpiqi} and the GSD value of this exposure be equal to the GSD value of the exposure rate on the current base map, i.e. β_{g0}. Then the average dose $\langle D_{piqi} \rangle$ for exposure, which liquidator receives when passing the subframe (p_i,q_i) and the standard deviation for this exposure σ_{Dpiqi} are equal to:

$$< D_{p_i q_i} >= D_{gp_i q_i} \exp(\sigma_0^2 / 2), \qquad \sigma^2_{Dp_i q_i} = [D_{gp_i q_i} \cdot \exp(\sigma_0^2 / 2)]^2 \cdot [\exp(\sigma_0^2) - 1] \tag{4}$$

Total frame average dose <D> and total frame standard deviation σ_D are calculated according to the following:

$$< D >= \sum_{i=1}^{N} < D_{p_i q_i} >, \qquad \sigma_D^2 = \sum_{i=1}^{N} \sum_{j=1}^{N} (0.9)^{\sqrt{(p_i - p_j)^2 + (q_i - q_j)^2}} \cdot \sigma_{D_{p_i q_i}} \cdot \sigma_{D_{p_j q_j}} \quad , \tag{5}$$

where (p_i,q_i) and (p_j,q_j) a couple of numbers, which define the position of the *i*-th and *j*-th grid cell, in X-direction or in Y-direction, correspondingly.

Finally (this follows directly from the form (4) while the summary frame dose consider to be a logarithmically normal value), uncertainty on the whole frame is equal to:

$$\beta_\Sigma = \exp(\sigma_\Sigma), \text{ where } \sigma_\Sigma^2 = \ln[1 + (\tfrac{\sigma_D}{<D>})^2] \quad , \tag{6}$$

where <*D*> and σ_D are calculated according to the form (5).

Uncertainty in time spent in various activities

A further source of uncertainty is the amount of time a person spent executing each task or activity (including resting and sleeping). The dosimetry subcommittee for the epidemiological study decided to assume the time spent for each task or activity could be described by a uniform distribution with the distribution centre on the value provided by the interviewed person. The lower time limit is equal to 0.9 and the upper time limit to 1.1 of the stated time (it is noted that the range of uncertainties will be broadened for some subjects, based on the level of detail available in the questionnaire - the epidemiologists are currently working on these distributions).

Note: the duration of the final activity of the day (including resting and sleeping) is not given a distribution as it is adjusted to make sure that the total duration of the day is 24 hours.

Uncertainty in location factor

For the persons traveling in vehicles or for persons who worked in lead-shielded clothing a shielding factor ("location factor") is taken into account by RADRUE in calculating the dose. This shielding factor was considered to have a normal distribution. The standard deviation was assumed to have a value equal to 0.25 from the best estimate. The location factors values used by the RADRUE system are listed in Table 9.

Table 9 Location factors values used by the RADRUE system.

Location	Factor	Location	Factor
Man on the open air	1,00	Helicopter, h=100 meters	0,04
Tent	1,00	Adobe (wooden) house	0,11
Motorcycle	1,00	ATC[1]	0,017
A man in the lead apron	0,67	ALTC[2]	0,017
Car	0,50	Country brick house (cottage)	0,07
Bus	0,29	Brick multi-storey building	0,03
Truck	0,29	Reinforced concrete multi-storey building	0,03
Helicopter, h=10 meters	0,36	EOCM[3]	0,01
Helicopter, h=20 meters	0,14	CEFM[4]	0,01
Helicopter, h=30 meters	0,11	Bathyscaph [5]	0,0005
Helicopter, h=50 meters	0,08	Demag[6]	0,0003

[1]) armoured troop-carrier,
[2]) armoured landing troop-carrier,

[3]) engineering obstacle clearing machine,
[4]) chemical exploring fighting machine,
[5]) Exploring device used for the high ER values conditions moving by means of the lifting crane «Demag».
[6])The operator's workplace on the lifting crane «Demag».

Uncertainty due to special situations

There were additional uncertainties in liquidator's dose estimations when the liquidator could not recall the dates of a mission, the location of his workplace or the number of repetitions of this or that activity when working on AR. For these cases rules were developed in RADRUE, which the experts had to obey when entering initial data into the computer. These rules are specified as experts' instruction in the Operation Manual. If the beginning work date is known roughly (with $\pm k_b$ days error) and the ending work date is known roughly ($\pm k_e$), then the SGD value β_{g0} will be increased:

$$\beta_g = 0.5 \cdot \beta_{g0} \cdot [\exp(0.02 \cdot k_b) + \exp(0.02 \cdot k_e)] \qquad (7)$$

The form (7) was found by means of the regression analysis of the ER time dependences in different 30-km zone points and was extended on all other base maps.

Correlations in RADRUE

An episode dose is a summary of separate frame doses, which are taken in RADRUE as random values.

Frame parameters can be unambiguously defied through a subset of 4 numbers (values): (N_1, N_2, N_3, N_4), where N_1- the mission number, N_2 – episode number, N_3 –frame sequence number. N_4 characterises parameter type: exposure dose-rate P, task time T or the location factor value ShF. If N_4=1, then it is equal to P, if N_4=2, then it is equal to T, if N_4=3, then it is equal to ShF. If we have two parameters subsets for two frames (N_1 ,N_2 ,N_3 ,N_4) and (N_1' , N_2' , N_3' , N_4'), then correlation coefficient for either pair of these frames $CC_{N_1,N_2,N_3,N_4}^{N_1',N_2',N_3',N_4'}$ are calculated based on the rules summarized in Figure 10.

If a person goes on more than one mission, there is generally a substantial separation in time between the missions, and typically the missions are also separated geographically. Therefore, the assumption is made that there is no correlation among the exposures received during different missions. That is, the correlation coefficient is set equal to 0.

For the performance of a single episode, there may be many frames involved. For the purpose of the simulation, it is assumed that the exposure rates in all frames except the one(s) for the resting and sleeping period(s) are perfectly correlated.

If a person performs the same episode multiple times during the same mission, then the assumption is made that the exposure rates experienced are perfectly correlated, that is, the correlation coefficient is assumed equal to 1.0. It is also assumed that the values of the shielding factors in the simulation are correlated perfectly. However, a separate simulation is performed for the duration of the activity for each day the activity was repeated.

If a person performs different types of episodes during the same mission, it is assumed that the correlation among the different types of episodes is equal to 0.

3 SEAD method

The alternative dose reconstruction method considered in this project, SEAD, relies on the use of determinant analysis, taking into account the answers of the liquidator to the questionnaire. In this method, liquidators are classified according to the period in which they worked and the institution which sent them to the Chernobyl area in order to derive more uniform groupings (categories) of individuals with similar working conditions and dosimetry control (factors which are determinant for dose formation), e.g. drivers, dosimetrists, management etc.

Then, a set of parameters (factors) which may influence the dose within the group needs to be determined. Factors to be considered include: time of beginning of clean-up activities, type of work in the Chernobyl area, organization which sent the liquidator to the zone, place and duration of work, personal perception of exposure, attitude to the performed task. The reliability of answers obtained from the questionnaire is assessed by experts familiar with the work and taken into account in this step.

The dose D received by a liquidator is determined as a function of these factors as follows:

$$\ln(\rho D) + \rho D = f_1 + f_2 + \ldots f_n$$

The parameters of this function are estimated by fitting this model to data on specific liquidators under study for whom individual dose measurements are available. Since each category of liquidators has its own peculiarities, "calibration" of the factors needs to be performed separately for each category.

Initially SEAD method was using the same weights for all of the modifying factors. Later the method was improved by allowing assigning different weights for the different modification factors. Different sets of values of the weight were assessed (see Table 10) and a new SEAD software was created.

Good agreement was initially demonstrated between SEAD with new weights and other dose estimates. This agreement, however, was based on estimation of the weights on the subjects on whom the method was being tested. Despite extensive searches, no sufficiently large and detailed databases had been found to allow the independent estimation of the importance of the different modifying factors.

Following extensive discussions, it was decided to abandon the SEAD method for two reasons:

- in its current form, the method had a tendency to regress all dose estimates towards the mean of the distribution in that group (this is normal as the distribution of doses in each "group" of liquidators was characterized and subjects are initially assigned the geometric average, and then their dose may be increased or decreased by the expert depending on a number of factors)
- absence of independent data to estimate the weights given to the modifying factors.

Table 10 Factor weights for different variations in SEAD

N	Name of variant	Factor Weights											
		1	2	3	4	5	6	7	8	9	10	11	12
1	Method of Likert	1	1	1	1	1	1	1	1	1	1	1	1
2	Automation	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12
3	Likert without psi-factors	1	1	1	1	1	1	1	0	0	0	0	1
4	ADR	0	0	0	0	1	1	0	0	0	0	0	0
5	DEA	0	0	0	0	0	0	0	0	0	0	0	1
6	Regression	1/4	0	1	0	1	0	0	0	0	0	0	1
7	Direction+Regression (1)	1/2	1/2	1	1/2	1	1/2	1/2	0	0	0	0	1
8	Direction+Regression (2)	1/4	1/4	1	1/4	1	1/4	1/4	0	0	0	0	1
9	Correlation model	1/4	1/4	1	1/4	1	1/4	1/4	0	0	0	0	1

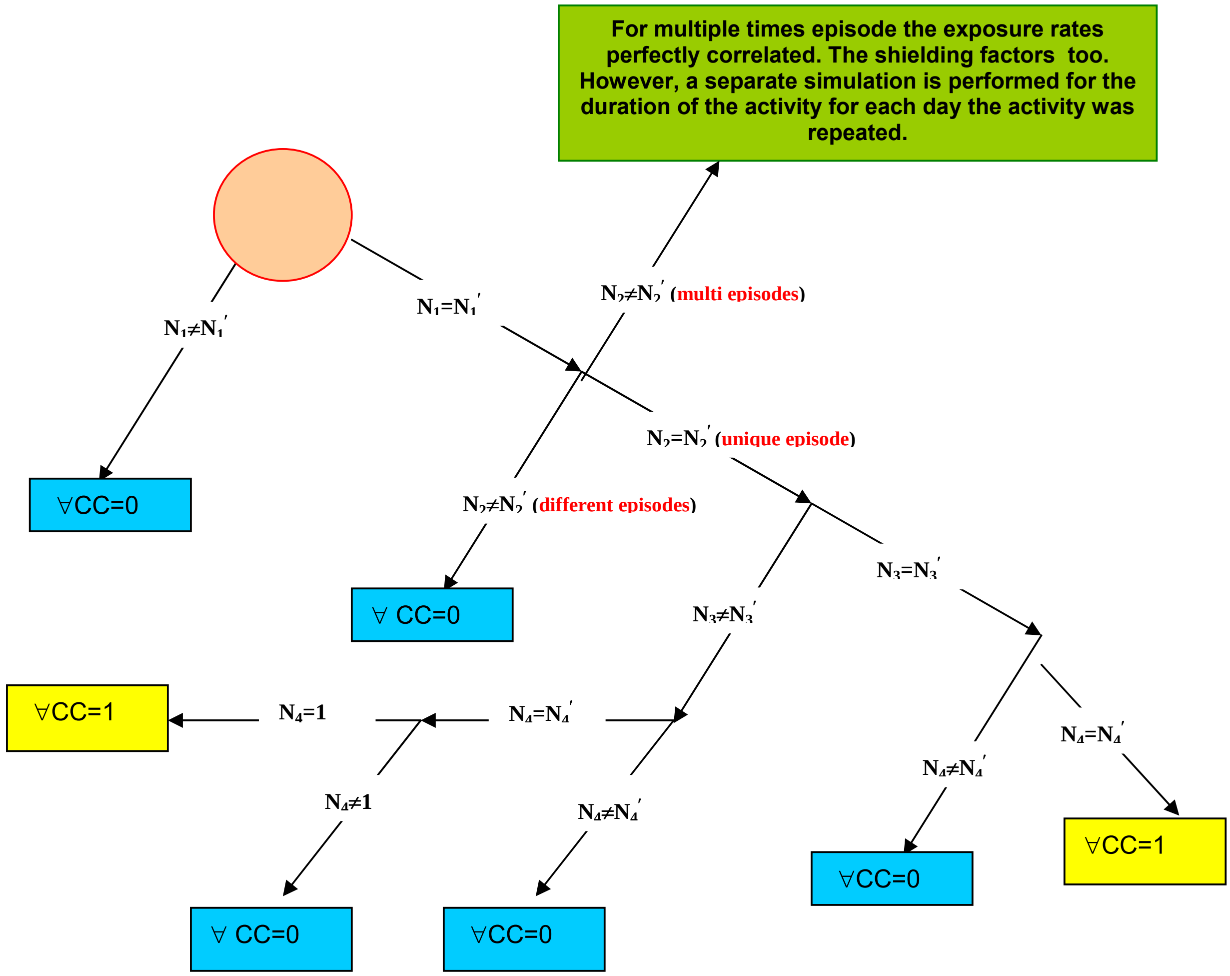


Figure 10 Rules for the correlation coefficients

4 Validation of RADRUE and SEAD methods

A number of validations were carried out to assess the adequacy of the methods, by applying them to various sets of liquidators with reliable alternative doses estimates:

These validations involved identification of liquidators with reliable dose estimates, tracing of these subjects, interviewing those willing to participate using the case-control study questionnaire and application of the initial ADR, SEAD and RADRUE methods to the calculation of their individual doses.

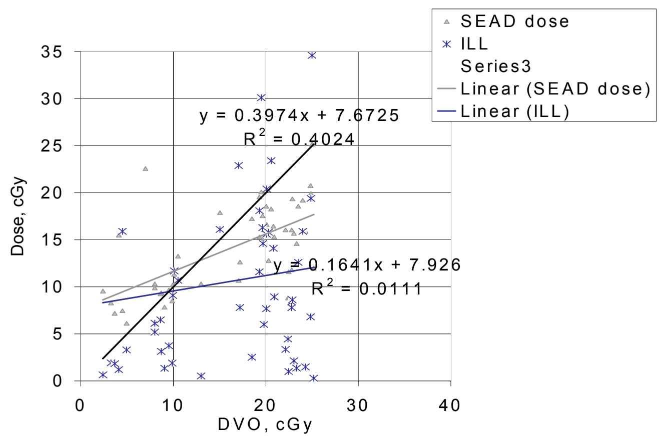
The "gold standard" used depended on the group of liquidators: official dose records or doses reconstructed by method of measuring electron spin resonance signals, induced by the liquidators' tooth enamel. The EPR method is sensitive to influence of X-rays, therefore efforts had been made to identify persons who did not have prior dental X-rays and history of occupational radiation exposures. However, high EPR doses were found for some liquidators who, on the basis of the questionnaire data provided, were unlikely to have received such doses. EPR techniques were improved by separating the enamel into buccal and lingual parts. EPR doses were then measured for both parts separately. If the doses for the two parts of the teeth were significantly different, it was an indication, that person received significant dental X-rays dose. It helped to trace liquidators with the high prior dental X-rays dose and to exclude such tooth from the analysis.

The first set of validations showed that ADR (the predecessor to RADRUE) and SEAD methods performed reasonably well for liquidators who were professional radiation workers (Figure 11). Note that this is the group of liquidators for whom the method was initially developed.

For Military liquidators, the agreement between the reconstructed doses and the official doses was not good – particularly for ADR (ILLin Fig. 12). For civilian liquidators, there was little relation between the SEAD and ADR doses and the EPR doses (Fig. 13). The EPR doses shown here were assessed without separation of the teeth to the buccal and lingual parts.

Specific cases with large differences were explored and discussed. Validation enabled to reveal and correct number of problems (for example the ADR method did not consider dose received by military personnel in places where they slept).

Figure 11 Professional: Correlation SEAD dose, ADR (ILL) dose and DVO (device measurements)



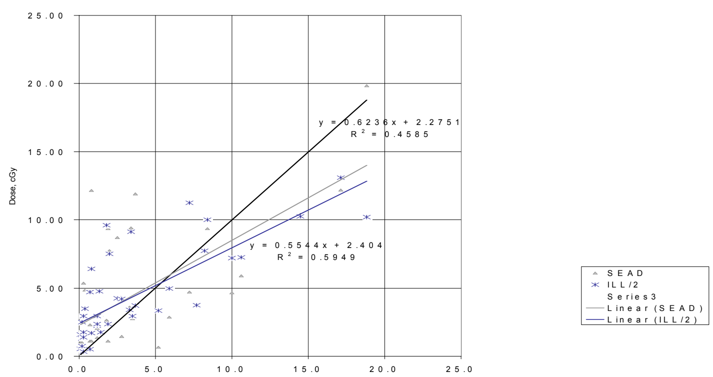
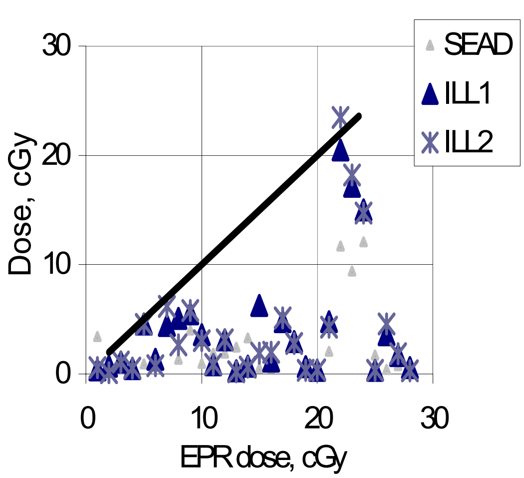


Figure 12 Military liquidators: Correlation SEAD , ADR and DVO

Figure 13 Civilians: comparison of SEAD, ADR (ILL 1 & 2) and EPR doses



When RADRUE was developed, dose estimated by this method were validated on the liquidators' with instrumental measurements as well. For a large part of the Russian liquidators official dose records were available. A comparison of RADRUE with recorded doses is presented in Figure 14.

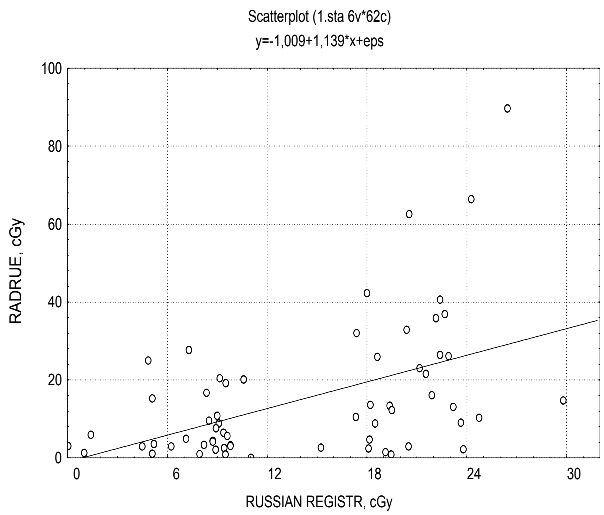


Figure 14 Comparison chart of the RADRUE and official doses from Russian registry for some of study subjects.

It can be seen satisfactory agreement between official doses from Russian registry and RADRUE estimates. RADRUE tends to overestimate high doses, compared to official dose records. It is noted, however, that the adequacy of the registered doses is under question. A system of dose constraints for the maximum daily dose was proposed to be introduced in the RADRUE estimates, reflecting the radiation protection practices at the time of the work of liquidators. This may improve the correlation with recorded doses. The rules for the application of these constraints are under development.

Further comparisons with dose estimated with EPR among Ukrainian workers are underway in a parallel project and will be available shortly. It should be noted, however, that comparisons with EPR are limited by the sensitivity of the method (sensitivity level of about 100 mGy).

Despite the absence of a satisfactory gold standard (in the range of dose under study) to validated RADRUE, it was decided that, once the internal consistency of the RADRUE was completely checked (as was done during the project – see Task 4), the epidemiological study would rely on dose estimates calculated with RADRUE, which is a logical, consistent and reproducible approach to the reconstruction of doses, based on extensive validated data on exposure rates and ER as described under Task 1.

5 Methods for thyroid dose assessment

In addition to the liquidators' external thyroid dose estimates, calculated by RADRUE, internal thyroid exposure doses were evaluated as well for the case-control study of thyroid cancer. An initial screening of liquidators was made to identify those for whom reconstruction of internal thyroid exposure doses was necessary. They were:

- Russian liquidators who took part in the clean-up in the first weeks after the accident (until June 20 1986)
- Belarussian liquidators who resided in contaminated territories of Belarus

Others were assumed not to have received a significant internal thyroid exposure dose.

Intake of KI pills and other protective measures was taken into account according to approaches described in the Operations Manual, Annex 1 [Gavrilin *et al*., 2001].

Study subjects with a potential for exposure, were further subdivided into three groups according to the main model of ^{131}I intake:

3. Liquidators who worked only at the Chernobyl NPP;
4. Liquidators who worked only in settlements located within the 30-km zone and did not work at the Chernobyl NPP;
5. Liquidators who worked in settlements located within the 30-km zone and at the Chernobyl NPP.

Liquidators who worked only at the Chernobyl NPP

For the liquidators included in this group, thyroid dose assessment is carried out according to the methodology of Styro et al [1992], assuming inhalation intake of ^{131}I. That ^{131}I intake is considered to be typical for the liquidators who worked at the Chernobyl NPP in the period from April 26 to May 5, 1986. These liquidators are thought to have little or no dose from ingestion of ^{131}I as they did not consume milk, milk products, and leafy vegetables during their work at the ChNPP.

In late April/early May 1986 and again in late May 1986, direct gamma spectrometry of the thyroid was made for approximately 700 liquidators (including workers of the ChNPP and about 100 other persons in the 30 km zone) at their temporary place of residence during the clean-up operations. In addition, about 300 direct thyroid measurements were also made in Clinic No.6 on “accident victims” (liquidators who participated in the very early emergency operations and were hospitalized in Moscow for radiation sickness). Some of the measurements were made on the same persons on different times, thus allowing a better estimation of the actual incorporated dose from iodine and other short-lived isotopes. Information on itineraries, time of work and use of stable iodine prophylaxis was obtained by questionnaire at the time of the measurement on a large number of these liquidators. Results of analyses of urinary excretion of ^{131}I are also available for some liquidators

Thyroid dose estimation for these people is based on available data on dynamics of concentration of radionuclides [Styro et al, 1992] (especially of ^{131}I) in air above the damaged reactor as well as at different directions from ChNPP at the altitudes of 200-1300m (Figure 15),

It follows from the data, presented in Figure 15 that dynamics of concentration of ^{131}I (C) in air above the reactor can be fitted by equation:

$$C = 417 \times \exp(-0.135\times t), \quad (T_{1/2}=5.13 \text{ days}) \qquad (8)$$

where t is counted from April 28, 1986.

Comparison of data in Figure 15 with available data on dynamics of concentration of ^{131}I in ground-level air at the place located at 140 km to south direction from ChNPP as well as with data on dynamics of concentration of ^{137}Cs and ^{134}Cs in ground-level air at Berezin national park of Belarus shows good agreement of peaks and minimum values of daily radionuclide concentrations at least from May 5, 1986. This agreement supports the hypothesis that contamination of ground-level air in the vicinities of the reactor since May 5, 1986 was due to radionuclides coming from upper air layers rather than from release of radionuclides from the reactor.

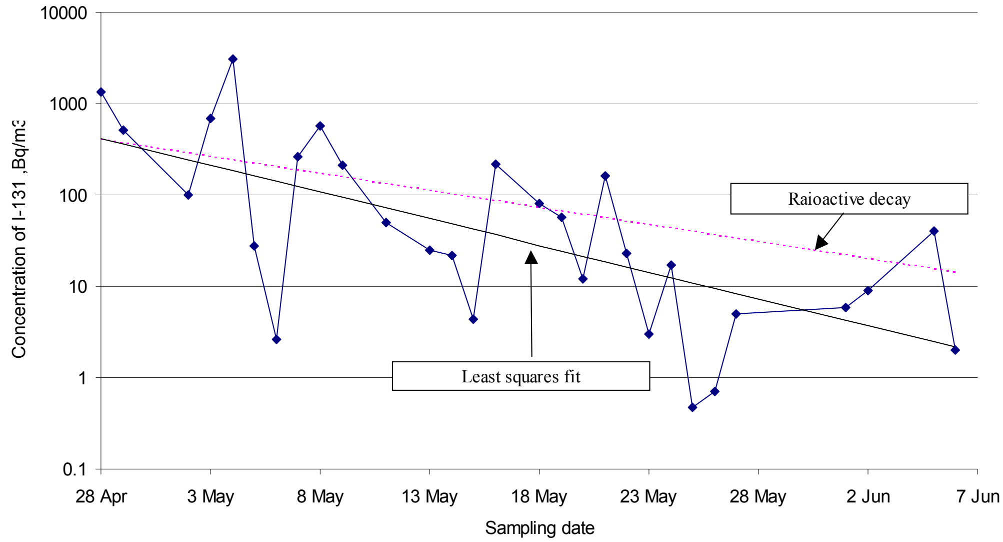


Figure 15 Dynamics of concentration of ^{131}I in air above the damaged reactor in April-June 1986.

In such case it is assumed that dynamics of inhalation intake of radioiodine to the liquidators who worked at ChNPP and around it would be correlated with (on average) the dynamics of concentration of ^{131}I above the reactor. To calculate thyroid doses it is thus assumed that the concentrations of ^{131}I in air of the rooms of ChNPP, in ground-level air in the vicinities of the reactor (10 km around the reactor) including Pripyat town since May 5, 1986 were equal to averaged values of concentration of ^{131}I ($\overline{C}$) above the reactor. Time variation is also described with equation.7.

The estimates of thyroid dose for the liquidators in this group are calculated as follows (note: this correspond to the maximum values of possible thyroid dose):

$$D = \overline{C} \times Y \times H \times S \times \nu \times F_h \times K_1 \times K_2, \quad \text{Gy} \qquad (8)$$

where Y is number of days of work in episode;
H is number of hours of work during a day;
S is number of seconds in an hour ($S=3600$ s h^{-1});
ν is breathing rate for an adult person, $\nu = 2.8\times10^{-4}$ m^3 s^{-1};
F_g is inhalation dose coefficient for an adult person, $F_g = 2.8\times10^{-7}$ Gy Bq^{-1};
K_1 is coefficient accounting for iodine prophylaxis ($K_1 \approx 0.043$ under prolonged consumption of potassium iodide pills);
K_2 is coefficient accounting for presence in the air of hardly absorbed fractions of iodine ($K_2 \approx 3$).

Insertion of K_2 is explained by the fact that only aerosol filter was used under aircraft sampling above the reactor and other territories of the former USSR. That filter does not catch hardly absorbed fractions of iodine. The use of respirators was not taken into account, because of their low efficiency, especially in case of presence in air of hardly absorbed fractions of iodine [Styro *et al*, 1992].

Liquidators who worked only in settlements located within the 30-km zone and did not work at the Chernobyl NPP

For Belarus liquidators included into this group the following procedure was used. If a liquidator worked and lived in a non-evacuated settlement, the individual thyroid dose was estimated to be the average thyroid dose for the adult population in the settlement considered.

The average thyroid dose for adult population in this settlement was estimated according to available “passport” for that settlement, or (in case such “passport” is absent) by use of a modified semiempirical model as described in the operations manual [Gavrilin *et al*, 2001]. An average consumption rate (0.7 L d^{-1}) of milk typical for adult Belarus population was accepted for dose calculation. If the liquidator worked in several non-evacuated settlements, then the total thyroid exposure was calculated as a sum of the separate doses (inhalation and ingestion), received in each settlement taking into account the length of time that the liquidator worked there.

If the liquidator served with the military or any other large organization and lived in non-evacuated settlement, but worked in an evacuated settlement, the milk consumption rate, V_{milk}, was determined as follows:

$$V_{milk} = (X/24) \times 0.7 \quad \text{L d}^{-1} \qquad (9)$$

where X is time spent by the liquidator in non-evacuated settlement.

If the liquidator served in a civilian organization (especially if such organization was small) and lived in non-evacuated settlement, but worked in an evacuated settlement, the milk consumption rate should be accepted to be equal to 0.7 L d^{-1}, assuming that he took milk with himself for his work.

If the liquidator lived and worked in an evacuated settlement, then no intake of contaminated milk is assumed. In such case total dose is a sum of inhalation doses received in each settlement where he lived and worked.

For non-Belarus liquidators included this group, the presumption is that they did not have any significant thyroid dose other than through inhalation exposure. This is because they did not come from contaminated territories, and they are presumed to have consumed clean food during their period of working within the 30-km zone. Their inhalation dose was calculated as for the first group of liquidators.

Liquidators who worked in settlements located within the 30-km zone and at the Chernobyl NPP

For the liquidators included in this group, their thyroid dose estimate was calculated to be the sum of two contributions: (1) during the work at the Chernobyl NPP, and (2) during residence and work within the 30-km zone.

Radiation dose not related to the work as a Chernobyl liquidator

Due to the wide-scale contamination of Belarusian territory following the Chernobyl accident, liquidators from Belarus have received radiation doses not only related to work as a Chernobyl liquidator but also related to their residential status. This is a peculiarity of Belarusian liquidators in comparison with subjects of study from Baltic States and Russia. Radiation doses to Belarusian liquidators were therefore estimated for the following pathways and radionuclides:

- Internal dose from ^{131}I inhalation and ingestion for Belarusian subject, applying the same method as for the liquidators who worked in settlements located within the 30-km operations manual [Gavrilin et al, 2001];
- External dose to thyroid from deposited radionuclides [Drozdovitch *et al*. 2003; Minenko *et al.* 2002].

Task 3 - Collection of data for validation of dose reconstruction method – interviews of persons with dose estimates

Information on work history was obtained for the study subjects from a detailed questionnaire covering aspects of the time, place, type and condition of work in the Chernobyl area (Annex 2). This questionnaire was prepared as a collaborative effort between dosimetrists, radiation protection experts, persons familiar with the organisation of work in the Chernobyl area and epidemiologists. It was successfully tested on 120 liquidators (half professional workers and half military) to ensure that the questions were clear and answerable and that all the information needed in principle by dosimetrists for dose reconstruction could be obtained. Specific sections (2, 3 and 4) of the history of work had to be completed respectively for each mission on which the subject was sent and for each episode of work within each mission. Spare sets of sections 2-4 were provided to the interviewer for this purpose.

The case-control studies of leukaemia and NHL and of thyroid cancer were extended to the populations of Baltic country liquidators in order to test the adequacy of the dose reconstruction method developed in Task 2. A workshop was therefore held in Tallinn (Estonia) on 15-16 May 2000 to train the interviewers for the case-control study in Estonia, Latvia and Lithuania. This workshop included interviewers, principal investigators as well as faculty from IARC and the Institute of Biophysics. Practical training of the interviewers took place on the second training day: four volunteer interviewees participated in the workshop and were interviewed by the interviewers. The completed practice interviews were then analysed by the lecturers and the results discussed with the interviewers.

Standardised description and explanation of terms used in the study questionnaire which may be difficult for some interviewees to understand were provided in an Interviewer Instructions Document, together with specific instructions related to specific questions. To assist the study subject and the interviewer in obtaining the most precise and correct information about the subject's work in the Chernobyl area, the interviewer was also provided with a Booklet (Annex 3) including detailed maps, photographs, a glossary of Chernobyl "jargon", a historical review of events which took place in the clean-up of the accident, a list of organisations involved as well as detailed lists of settlements within and outside the 30 km zone around the plant, in which subjects may have resided, worked or rested.

If the case has died, the next of kin (the spouse, brother or sister or child of the liquidator) was found where possible, interviewed and asked about the name of colleagues who worked with the subject in the Chernobyl area. One of these colleagues should then have been contacted and asked to answer questions from section 2-4 of the questionnaire concerning the history and conditions of work as a liquidator. The identity of the respondent was clearly indicated.

1 Extension of the case-control study to Baltic countries

16 retrospective cases of leukaemia and NHL among liquidators from the Baltic countries were identified during a cohort study of cancer risk among the Baltic liquidators, coordinated by the National Cancer Institute, USA, and Finnish Cancer Registry (hereafter – the Baltic cohort study). The procedure was similar in the three countries – all cases diagnosed in 1990-1998 were identified through the cancer registries in Estonia, Latvia and Lithuania, which cover the three entire countries, using record linkage techniques. No prospective cases have been identified in the Baltic countries (numbers of the liquidators in these countries are very small and one-year period was too short for diseases of interest to occur in the study population).

In Estonia, two retrospective cases of thyroid cancer were detected through thyroid screening carried out in 1995 (Inskip *et al*, 1997). In Latvia and Lithuania, where specialised medical care centres for Chernobyl liquidators were set-up (in Lithuania operated until 1998), and the ultrasound examination of thyroid gland is a regular procedure of the annual health check-up, 4 thyroid cancer cases were diagnosed during their regular medical examinations**.** Two prospective cases were identified in Latvia in 2000, also during the annual health check-up. No prospective cases were identified in Estonia and Lithuania. In all, 8 thyroid cancer cases were included in the study.

To maximise the statistical power, 4 controls were interviewed for each case (hence 64 for the leukaemia and NHL study and 32 for the thyroid cancer study). In a first step, potential cases were selected at random from the roster of the study population using a random numbers generator, among all liquidators of the same age as the case (within 1 year). The controls had to be alive at the time of the diagnosis of the case to which they were matched in order to minimise selection bias. For each potential control selected, information on their names, gender, date of birth, address at the time of registration and most recent address registered were abstracted from the lists of Chernobyl liquidators rosters available in the national cancer registries in Latvia and Lithuania and at the Institute of Experimental and Clinical Medicine in Estonia. They include the current address of the liquidator, which was used for mailing questionnaires during the Baltic cohort study and obtained from all available sources - address bureaus, population registries, migration offices, Chernobyl liquidators' non-governmental organizations, local medical and social welfare institutions.

The most recent address of the cases and potential controls was available from the lists of Chernobyl liquidators (see above). When a potential study subject's address was changed, attempts were made to trace the new address through the population registry (formerly known as "address bureau"), as was previously done in epidemiological studies in Baltic countries [Tekkel *et al*, 1987].

Once the current address of the cases and potential controls was obtained, primary contact was made by letter signed by the principal investigator in the study. In Latvia and Lithuania, the interviewers contacted the majority of study subjects also by telephone, explained about the study and asked to participate. If a study subject agreed to participate then an appointment for interview was made - either at home or at the Institute of Experimental Medicine in Tallinn, the Latvian Centre of Oncology, the Lithuanian Cancer Registry or the offices of the local Chernobyl Movement Committee in Lithuania. Every effort was made to maximise the participation rate. If the subject did not answer within 3 weeks (1 week in Estonia), therefore, a reminder letter was sent. If a case refused to take part in the study, this was noted and the reason specified. If a control refused to take part in the study, he or she was replaced by another one until four controls were interviewed for each case. If any of the selected controls could not be interviewed, the reason was specified.

Information from previous questionnaire

Sixty-one liquidators from the Baltic countries included in the case-control study were previously interviewed in the cohort study of Baltic liquidators, coordinated by NCI. As some of the questions in the previous cohort study questionnaire are similar to those in the case-control questionnaire, this re-interviewing allowed the evaluation of the reliability and replicability of answers to the questionnaire. The comparison was done in the following steps:

- Identification of study subjects interviewed in both studies;
- Retrieval of information from questionnaire (duration, dates of mission, type of work, anything relevant to the mission);
- Cross-checking of the answers to the similar questions from both questionnaires using kappa test for agreement.

Biological dosimetry data

Blood samples from majority of Estonian study subjects and from part of the subjects in the Latvian and Lithuanian cohorts have been collected previously for the Baltic cohort study. Biodosimetry using two biological markers of exposure, namely, fluorescence *in situ* hybridisation (FISH) for translocation analysis and the glycophorin A (GPA) somatic cell mutation assay has been applied on a number of collected samples in several laboratories [Bigbee *et al*, 1996; 1997; Inskip *et al*, 1997]. Though overall results of the biodosimetric assays suggested that the average radiation exposure of the Baltic liquidators did not greatly exceed 10 cGy, the minimum level at which radiation effects might be detectable by the assays, it was expected that some of the individuals included in the case-control study could have received doses higher than 10 cGy. The case-control subjects, who donated their blood samples for biodosimetry during the Baltic cohort study, were identified and the results of GPA and FISH assays compared with RADRUE predictions for the same subjects.

2 Additional interviews in Russia and Ukraine

Additional information for validation was also collected from *Russia* by interviewing cases and controls within a subcohort of the professional radiation workers who were employed by the Ministry of Atomic Energy (MAE) and are registered by this Ministry. The doses of these liquidators were measured directly with the use of personal dosimeters and the dosimetric data are supposed to be included in the archives of the MAE. Twelve cases were identified from the clinics of the MAE and four controls were interviewed for each case (i.e. 48 controls), selected at random from the list of liquidators registered by the MAE. It was found out during the study, however, that the dosimetric data in the archives was incomplete and usable dose estimates could not be obtained in the framework of this project.

52 professional radiation workers with good quality instrumental dosimetry were also interviewed using the case-control study questionnaire. Both SEAD and the ADR method (the predecessor to the final RADUE) were used to estimate their dose, which was compared to the dose recorded by filmbadges and/or TLD (Figure 11 – see Task 2, above) in order to inform the choice of dose reconstruction approach.

50 military liquidators from Russia were also interviewed and their SEAD and ADR doses estimated. For these liquidators, good records on dates, place and type of work are kept by Military Registry (maintained by the Military Medical Academy in St Petersburg) and time and motion studies have been used by the military at the time of the work to estimate doses. The SEAD and ADR were therefore compared to the official military doses to inform the choice of dose reconstruction approach (Figure 12 – see Task 2, above).

Finally 50 military reservists and 41 civilian liquidators sent on mission, were also chosen at random among Ukrainian subjects for whom samples of dental enamel are available and EPR dosimetry has been carried out at the Scientific Centre for Radiation Medicine in Kiev. These liquidators, once identified, were traced and interviewed using the case-control study questionnaire. Their SEAD and ADR doses are compared to EPR in Figure 13 (Task 2, above).

3 Evaluation of reliability and replicability of answers to the questionnaire

Twenty subjects were included in the Estonian study, 65 in Lithuania, 35 in Latvia and 60 in Russia. Their distribution by case and control status is shown in Tables 11 and 12, respectively for leukaemia and NHL and for thyroid cancer.

Table 11 Distribution of subjects by country and case-control status – Leukemia and NHL

Status	Russia	Estonia	Latvia	Lithuania	Total
Case	6	2	3	11	20
Control	24	8	12	44	80
Total	30	10	15	55	100

Table 12 Distribution of cases and controls by country – Thyroid cancer study

Status	Russia	Estonia	Latvia	Lithuania	Total
Case	6	2	4	2	9
Control	24	8	16	8	36
Total	30	10	20	10	45

Out of the 145 subjects interviewed, 61 were found to have also responded to the Baltic country/NCI cohort study questionnaire.

Information on demographic variables (date of birth) shows very good agreement between the case-control and Baltic/NCI cohort study questionnaires.

Many of the questions differed slightly (in the way they were formulated and in the choice and groupings of answers) and hence comparisons are not always possible.

Table 13 summarises differences in answers between the two studies related to dates of start or ending of mission. The great majority of answers are in agreement (within one week). In some cases, information was available in the case-control study from official documents on the dates of start and stop of mission and in these cases the answer in the case-control questionnaire was in agreement with the dates on these documents. It should be noted that the duration of missions in the Baltic country cohort study was from the date the liquidator left his home to the date he returned, while in the case-control study, only the period of actual stay in the Chernobyl area was considered. This may explain some of the differences in end dates reported.

Table 13 Comparison of dates of start of mission between NCI and IARC questionnaires

	Differences between answers to NCI and IARC questionnaires (date of mission IARC- date of mission NCI, in days)						
	(-)	(-)	(-)	0	(+)	(+)	(+)
	> 1 month	1 week to 1 month	1 day to 1 week		1 day to 1 week	1 week to 1 month	>1 month
Start date of mission	2	3	9	30	9	3	4
End date of mission	2	3	4	35	7	6	2

Overall, information on the location of work in the Chernobyl area (70 km zone) agrees only partially between the two questionnaires. 7 are in perfect agreement; for 26 subjects, the agreement is partial (in the majority of cases this is due to the fact that more settlements are listed in the IARC questionnaire); for 20 subjects a disagreement is observed, but is difficult to interpret as the NCI questionnaire did not differentiate between places of work and residence. The information collected with the case-control questionnaire tends to be more detailed than in the cohort study questionnaire. This is most likely related to the much more detailed questions about work in the case-control study and to the use of maps, lists of settlements and other documents designed to assist the liquidator in reconstructing his history of work at the time. It is noted however that, in a few instances, the liquidator answered the name of a settlement in the cohort study but could not give a precise name in the case-control study; this is most likely related to the time that has passed since the accident and the greater difficulty in remembering the details in the later study (the cohort study questionnaire was administered in the period 1993-1996, depending on the country, while the case-control study interviews were carried out in 2000-2002).

Agreement is complete for the question concerning the organisation that sent the liquidator to the Chernobyl area (Table 14).

Table 14 Comparison of answers concerning organisation which sent the subject to the Chernobyl area between NCI and IARC questionnaires

IARC NCI	Regular army	Military reserve office	NIM/KGB	Other	Missing
Regular army	0	0	0	0	0
Military training ex.	0	60	0	0	0
Hired/contract work	0	0	0	1	0
Other	0	0	0	0	0
Missing	0	0	0	0	0

Out of 61 subjects who answered they had used protective measures, agreement was reasonable for use of masks (only 10 subjects reported having used a mask in one of the questionnaire but not in the other); it was less good for the use of gloves (18 subjects gave conflicting answers).

There was complete agreement concerning the activities carried out as a liquidator for 21 of the subjects; the agreement was good (but not complete) for 34 more subjects – it should be noted that the IARC questionnaire is more detailed than the NCI questionnaire and hence lists activities which are not included in the later -. Disagreement was noted only for 5 subjects (including one for whom a proxy was interviewed); in addition, one subject listed activities in the IARC questionnaire but not in the NCI one. Overall, the agreement in the main activities is quite good. Again, the case-control study questionnaire is much more detailed concerning type and conditions of work than the cohort study questionnaire.

Concerning the use of stable iodine prophylaxis, agreement was reasonable: 42 out of 53 subjects who answered the question gave the same answer in both questionnaires.

Concerning doses assigned at the time of the accident, 3 out of the 18 subjects who showed their official dose documents had reported a different dose in the cohort study. Two out of the three had a 10-fold difference in dose, probably reflecting the fact that the liquidator reported his dose in the wrong unit in the cohort study questionnaire.

For those who could not show an official dose document (forgotten or not issued), 38 out of 43 did not report a dose in the case-control questionnaire. The doses were the same for 3 out of the five liquidators who reported a dose in that questionnaire. It is noted that 12 subjects reported a dose in the cohort study questionnaire but not in the case-control study.

Biological dosimetry and RADRUE

Fifteen cases-control study subjects were identified to be MN heterozygotes and GPA assay could therefore be performed during the Baltic cohort study: on 2 liquidators from Estonia, 4 from Latvia and 9 from Lithuania. Frequency of erythrocyte variants, expressing GPA allele-loss (N/Ø) or GPA allele-loss and duplication (N/N) phenotypes, which in previous studies have been found to be correlated with radiation dose, was compared with the RADRUE doses for the same individuals (Figure 16).

Blood for translocation analyses was previously taken from 3 liquidators from Estonia included in the case-control study. Because stable types of chromosome aberrations in lymphocytes are considered to be the most relevant marker for exposure to ionising radiation, the comparison between translocation frequencies and RADRUE predictions was performed. No correlation was found between RADRUE doses and translocation frequencies.

The absence of correlation between RADRUE and GPA and FISH is not surprising and does not invalidate the use of RADRUE for dose reconstruction. Indeed, the minimum level at which radiation effects might be detectable by these assays is of the order of 100 mGy. Only two of the subjects in the case-control study for whom GPA results are available had received doses estimated to be above this level by RADUE. Even at this level, uncertainties in GPA are very large.

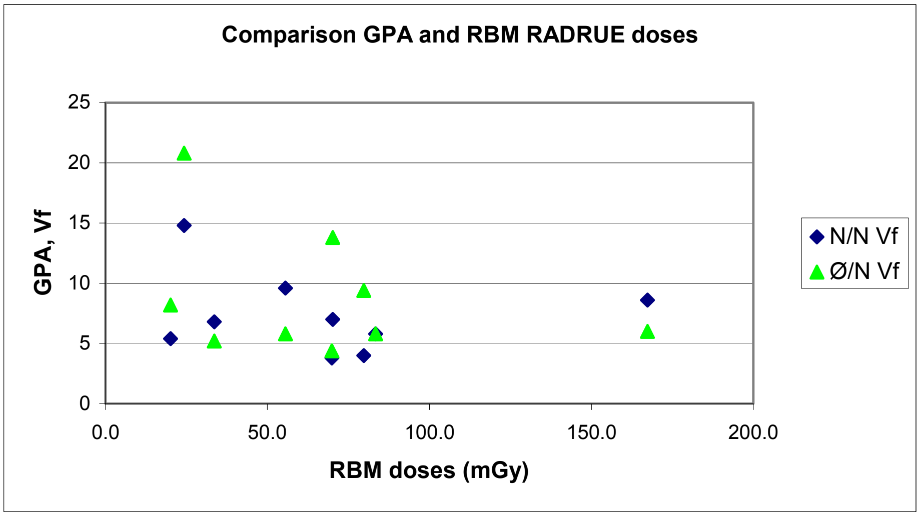


Figure 16 Comparison between RADRUE doses and GPA results.

Task 4 - Reconstruction of dose and uncertainty for study subjects

1 Processing of questionnaire data and entering of data into RADRUE software

Following the development, testing, optimization and systematization of the RADRUE method, a decision was made to base the dose calculations for subjects in the case-control studies on this method.

The dose reconstruction procedure consisted of the following steps:

a) assembling of personal file and recording it into RADRUE database: available information (primarily from the questionnaire) was analyzed by a team of experts and entered into RADRUE software for the calculations of liquidators' external exposure doses.

b) quality control of the dose calculations: a small subcommittee of experts review and check all of the dose estimates.

Data from the questionnaires in the previous European Union funded case-control studies were sent to the experts for analysis and data calculation. The data sent was in the form of computerized files, containing only the information from sections 2-4 of the questionnaire (i.e. history and conditions of work of the liquidator). No information on case/control status of the liquidator was sent to the experts.

Two experts from Ukraine (led by Dr. A. Tsykalo) and two from Belarus (led by by Dr. A. Mirkhaidarov) were chosen to analyse the questionnaires and extract information on the liquidators' routes for entry into RADRUE. The Ukrainian experts, who had previously worked for the dosimetry department of the ChNPP and were very familiar with exposure conditions on the industrial site and in the Ukrainian part of the 30 km zone around the plant, were responsible for dose calculation of liquidators from Russia and the Baltic countries. The Belarus experts focused on dose reconstruction for Belarus liquidators who, because of the proximity to their residences to Chernobyl generally worked in the Belarus part of the 30 km zone and had activities of a different nature than that of liquidators of other nationalities. In the case a Belarussian liquidator had worked on the industrial site, the questionnaire data for that part of the work was sent to the Ukrainian experts who calculated the relevant dose.

Detailed instructions were provided to these experts (see Operations Manual in Annex 1) and a number of meeting were held to review possible errors in interpretation of the questionnaire data and/or in describing the liquidators missions, episodes, frames, etc. The manual describes the rules to be applied, which all experts had to follow strictly. In cases where the experts needed to make personal decision or completely disagreed with the data in the questionnaire, they entered their best evaluation of the work conditions and were ask to document it extensively in the remarks sections of RARDUE. All such disagreements had to be reviewed and proved by the panel of experts afterwards.

The main issue of concern was the possibility that interpretation of the questionnaire data may be subjective and hence that the dose reconstruction may not be reproducible. Because of this, dose reconstruction was done independently by two (and in some cases three) experts for a 5% sample of all subjects and resulting dose estimations compared. Some of these meetings and exercised revealed features which were not clear in the RADRUE and this software was updated for clarity and user friendliness. Frequent communications took place between the experts and Dr Krjuchkov, who had developed the method, as well as staff at IARC in Lyon who reviewed the doses calculated and checked their internal consistency. During the course of the dose assessment, experts from the Institute of Biophysics in Moscow and the Ukrainian Institute for Radiation Medicine were reviewing the work of the experts and discussing errors and inconsistencies at periodic meetings held in Kiev, Gomel and Moscow.

In all, the Ukrainian team assessed doses for 310 Russian and Baltic's liquidators, and the Belarus experts for the 464 Belarusian liquidators. In the dose reconstruction all experts used the same RADRUE method and the same software.

Monte Carlo simulations were performed at IARC for the evaluation of the uncertainties of the dose estimates by the specialized computer software program. The computer program for the uncertainty evaluation was created according to methodology under Task 2.

During the course of the dose assessment, experts from the Institute of Biophysics in Moscow and the Ukrainian Institute for Radiation Medicine were reviewing the work of the experts and discussing errors and inconsistencies at periodic meetings held in Kiev, Gomel and Moscow.

As indicated under Task 2, there were a small number of liquidators for whom it was not possible to apply RADRUE due to the incomplete nature of the information provided in the questionnaire. For these, an average dose and associated uncertainty were assessed by the SEAD method and the information directly entered into RADRUE. Again, when applying SEAD, experts had strict rules to follow, which are described in the SEAD application Operations Manual.

2 Quality control and checking of the RADRUE experts work

As the process of the dose reconstruction was extensively relying on the processing of the experts (with possible data entry errors when the information was transferred into RADRUE), all the information in RADRUE for each questionnaire in the study was reviewed by one to two independent experts in Lyon.

This checking included automated checks of the internal consistency of the data in RADRUE, checks of the consistency of dates, activities, places between RADRUE and the questionnaire and manual review of all of the questionnaires and how they had been translated into a liquidator's route in RADRUE. This involved in particular checking one by one the break-down of every liquidators' missions into episodes and frames performed by the experts.

Approximately 13 500 corrections were made in RADRUE after checking, as illustrated in Table 15. About 12 500 corrections were related to the introduction of sub-frames, which appear after additional breaking-down of long episodes into shorter ones, in order to ensure that each corresponded to exactly one of the exposures rates grid maps in RADRUE. Having identified this problem, these corrections were automated, using a specially created macro program. Corrections were also made of erroneous repetition of some frames, start or end dates of the episodes, inadequate uncertainties on dates and durations of the episodes, incorrectly indicated living/work places in RADRUE, durations of the work/living/traveling, improper location factors for the frames and other mistakes and discrepancies. Many of these errors are likely to be the results of data entry errors in RADRUE. To systematize the work, extensive use of standard frames, particularly for the frames related to travel of the Russian and Baltic liquidators in the 70 and 30 km zones, was made.

Comparison charts of the dose estimates before and after verification are presented in Figure 17. The vast majority of corrections had, in fact, very little effect on the resulting dose estimates.

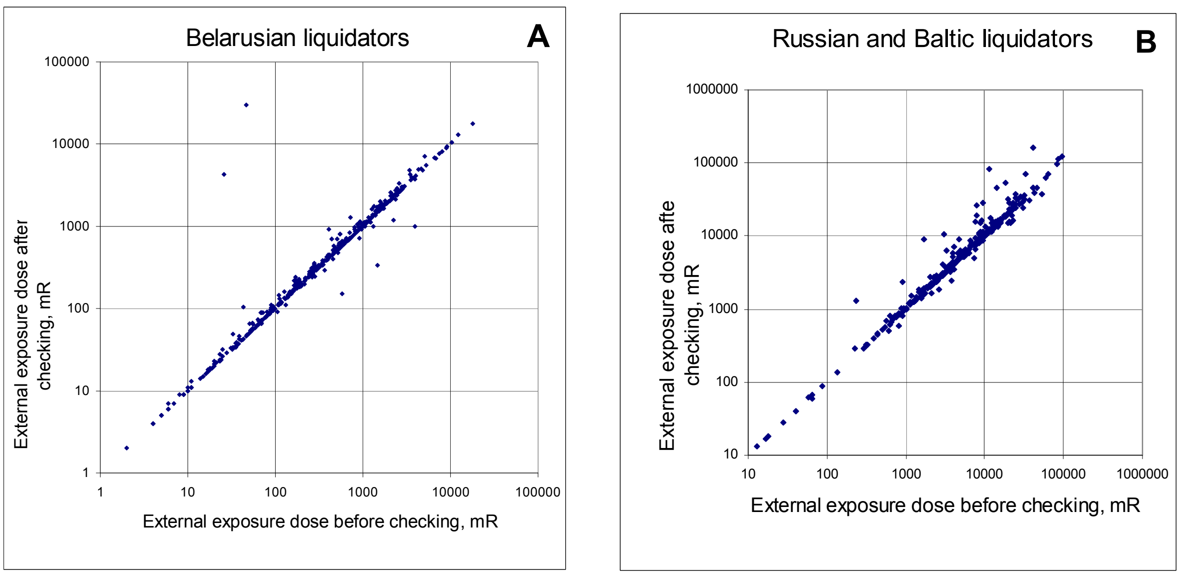


Figure 17 Correlation between RADRUE external dose estimates before and after corrections, for all subjects in the case-control studies, for Belarus and other liquidators separately.

During systematic checking of the RADRUE experts' work it was required that processed data had to fulfill the following formal consistency criteria, as follows:

- Repetition of the episode could not be more than duration of the episode in days.
- Start date of the episode could not be later than end date.
- Start of the first episode could neo be different from the start of the mission.
- End of the last episode could not be later than the end of the mission.
- Frames "contaminated cloth" had to be marked as parallel frames.
- Control of 24h/day.
- Frames with indicated uncertainties of the dates in questionnaire had to have entered uncertainties in RADRUE.
- Start of the episodes could not be before 26/04/1986 or end could not be later than 31/12/1987.
- Frames without indicated itineraries on the maps of RADRUE.
- Repetition of some specific frames (traveling, lunch) was controlled.
- Screening of very long episodes was done.
- Standard frames for the traveling of the Russian and Baltic liquidators were introduced.
- Review of the location factors on the list of all RADRUE frames, sorted by the type of action was done.

- Review of the values of velocity and location factors in the frames was done.
- Review of the description of the frames was done.

Table 15 List of the corrections made in RADRUE after the checking

Type of mistake	Number of corrections
Insufficient breakdown into frames and sub-frames for long episodes	≈12500
Introduction of standard frames	≈320
Incorrect uncertainties for the beginning and end dates of the episodes	144
Shielding factors	75
Incorrect dates of working/living episodes	43
Repetition of the episodes	43
Duration of travel	31
Incorrect or missing place of work/living in RADRUE	28
Duration of work	23
Added comments	18
Description of the frames	10
Application of the RADRUE map system	6
Balance of the 24h/day	5

3 Calculations.of external doses

Once the information from the questionnaires was entered into the RADRUE database, calculations of exposure doses were carried on automatically by the computer. The CALCULATOR module in RADRUE estimated the central estimates of the liquidators' external exposure dose in Roentgens (R).

The average and median absorbed exposure doses by the RBM and THY organs were derived by consequent running of the RADRUE SIMULATOR, as the exposure-to-organ dose conversion coefficients had probabilistic nature.

The uncertainties of the calculated doses were calculated by RADRUE SIMULATOR module as well. The simulator generated a set of 1000 point dose estimates for every liquidator, with had distribution of the values caused by the probabilistic nature of the variables (dose-rates, durations, shielding factors and etc.). Average, median and uncertainties of the organ specific dose estimates were calculated from this set of the values of point estimates for every liquidator.

4 Calculation of the internal thyroid exposure doses for the liquidators.

The internal thyroid exposure doses were reconstructed according to the methods, described under Task 2. Dates and places of residence of the liquidators were extracted from the case-control study questionnaires. The data was entered into created Visual Basic (Excel) computer program, and doses were calculated automatically by the software for the subjects. No information on individual consumption rates was available.

For the reconstruction of internal thyroid exposure doses for the Belarussian liquidators, averages of contamination levels of ^{131}I for the settlements, dates of fallouts and dates of pasture were used by the program in the calculations. Residential external doses to thyroid been reconstructed using the model for estimation of external exposure to population of contaminated areas of Belarus.

5 Distributions of doses among study subjects in the case-control study

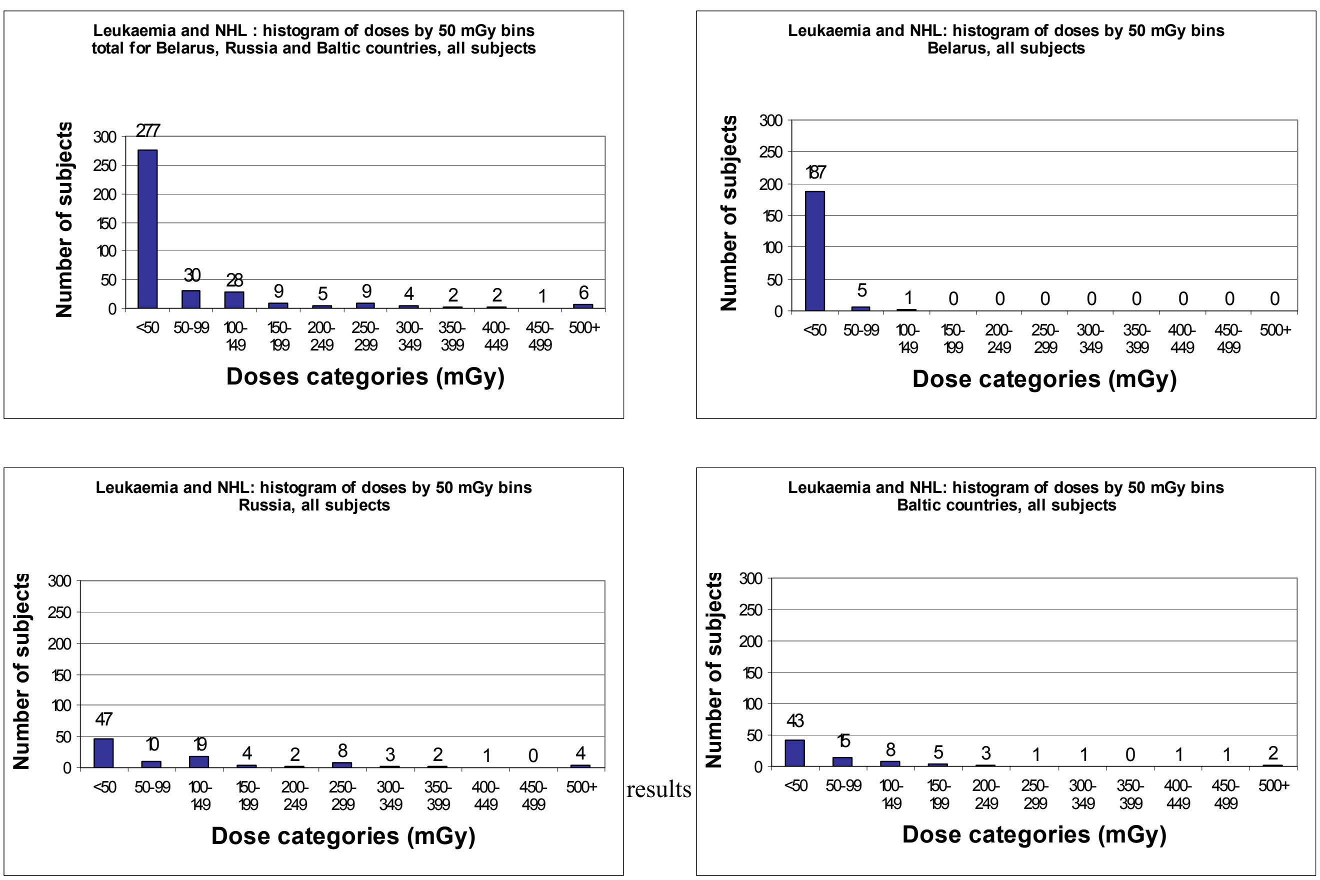
Tables 16 and 17 and Figure 18 show the distribution of bone marrow doses, by country, among the subjects included in the leukaemia and lymphoma case-control study. The median dose in Belarus is much lower than in Russia and Baltic countries (Table 17), even though doses received in their places of residence are included for Belarus subjects. If one considers only dose received working as a liquidator, the median BM for Belarus liquidators is 4.4 mGy.

The distribution of subjects by total dose to the thyroid due to external and internal exposure, and by country is shown in tables 18 and 19 and in figure 19. The majority of liquidators have received low doses to the thyroid: 60% of liquidators from Estonia, 45% from Russia and Latvia, and 40% from Lithuania belong to the lowest exposure category – below 50 mGy. A greater proportion of Belarusian liquidators was exposed to higher doses – 10% received doses above 500mGy. On average, doses in Belarus are higher than in Russia and Baltic countries (Table 19).

Table 16 Distribution of all study subjects by RBM dose[12] category and by country – Leukemia and NHL

Dose category (mGy)_	Country					
	Belarus	Russia	Estonia	Latvia	Lithuania	Total
<50	187	47	7	11	25	277
50-99	5	10	1	3	11	30
100-149	1	19			8	28
150-199		4	2		3	9
200-249		2		1	2	5
250-299		8			1	9
300-349		3			1	4
350-399		2				2
400-449		1			1	2
450-499					1	1
500+		4			2	6

Figure 18 Histogram of doses among study subjects



results

Table 17 Median RBM dose[13] and dose range by country – all subjects– Leukemia and NHL

Country	N	Median BM dose *(mGy)*	Range *(mGy)*
All countries	373	19.3	0.1 - 1 928. 3
Belarus (total)	193	7.9	0.2 - 108.0
Belarus (only as liquidator)	193	4.4	0 - 106.6
Russia:	100	55.9	0.1 - 1 928.3
Estonia	10	21.8	2.5 - 166.9
Latvia	15	20.7	0.1 - 240.1
Lithuania	55	59.2	5.0 - 1 092.5

Table 18 Distribution of all study subjects by total thyroid dose category and by country – Thyroid cancer study

Dose category (mGy)_	Country					
	Belarus	Russia	Estonia	Latvia	Lithuania	All countries
<50	69	34	6	9	4	122
50-99	70	15	3	9	4	101
100-149	16	9		1	1	27
150-199	16	5				21
200-249	22	2			1	25
250-299	17	1		1		19
300-349	2	3	1			6
350-399	20	2				22
400-449	5	1				6
450-499	3	1				4
500+	26	3				29

The median thyroid dose in Belarus is higher than in Russia and Baltic countries (Table 19).

Table 19 Median total thyroid and dose range by country – all subjects– Thyroid cancer study

Country	N	Median total dose (mGy)	Range (mGy)
All countries all subjects	382	70.845	0.13-2152.1
Belarus (all)	266	86.835	0.29-2152.1
Russia:	76	64.38	0.13-1064.57
Estonia	10	41.58	2.79-307.59
Latvia	20	55.77	2.94-273.54
Lithuania	10	61.1	21.54-200.83

The dose to the thyroid for the Belarusian liquidators was calculated taking into account the environmental exposure received in their place of residence. Due to consumption of local contaminated milk and vegetables, the median internal dose to the thyroid for Belarusian liquidators is much higher than in other countries (Table 20), while the external thyroid dose is much lower (Table 21).

Table 20 Median internal thyroid doses (I 131) by country – Thyroid cancer study

Dose (mGy)	Belarus	Russia	Estonia	Latvia	Lithuania	Total
N	160	13	6	10	1	190
Median (all)	175.1	0.6	0.6	0.5	1.4	130.7
Range	1.65-2124.4	0-8.5	0.048-2.3	0.29-1.5	1.4-1.4	0-2124.4

Table 21 Median external thyroid doses– all subjects by country – Thyroid cancer study

Dose (mGy)	Belarus	Russia	Estonia	Latvia	Lithuania	Total
N	266	76	10	20	10	382
Median (all)	2.7	64.4	41.4	55.6	61.1	6.7
Range	0-279.7	0.1-1064.6	2.8-307.2	2.9-273.5	21.5-200.8	0 -1064.6

Figure 19 Histogram of dose to the thyroid among study subjects

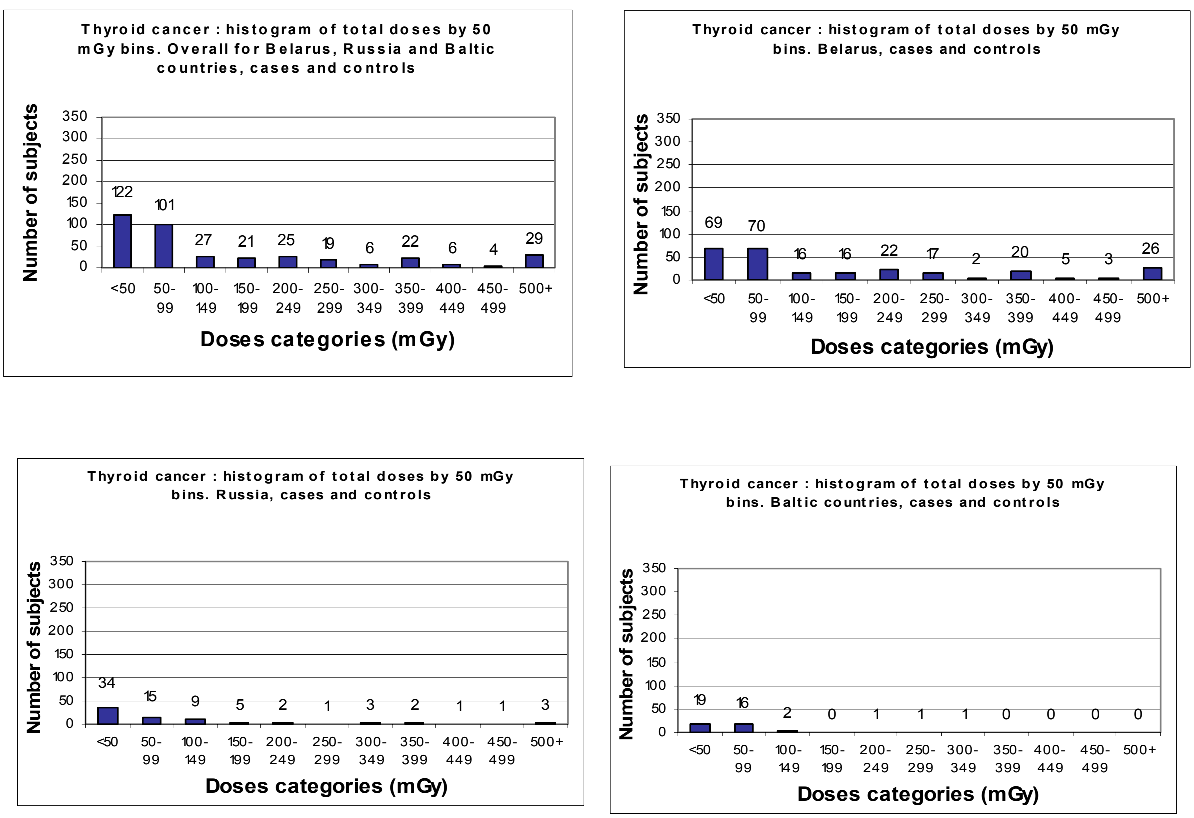


Figure 20 shows the distribution of the geometric standard deviation compared to the median dose estimate (based on 1000 simulations) for each of the subjects included in the case-control study. Although for a small number of subjects the geometric standard deviation is very large (up to 4.5, mainly for subjects with low RADRUE doses – and one subject with a high RBM RADRUE dose but a very uncertain work history), the median geometric standard deviation is of the order of 2.

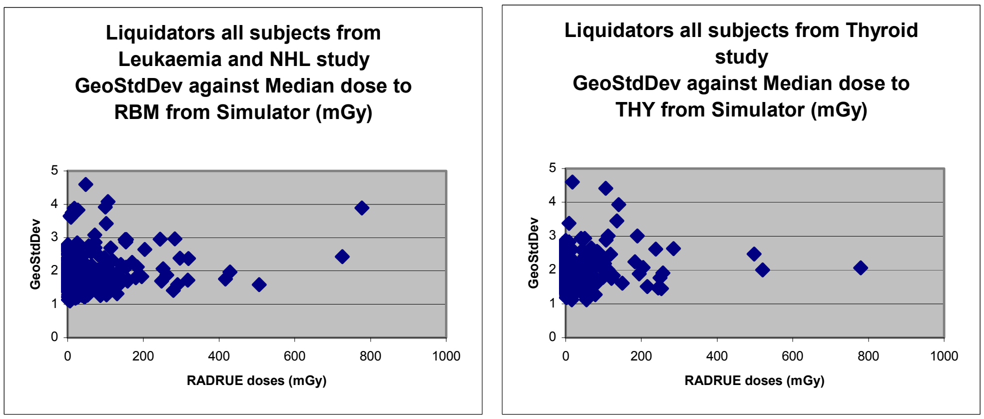


Figure 20 Distribution of Geometric Standard Deviation by the median dose estimate (based on 1000 simulations) for each of the subjects included in the case-control study

Discussion

The main objective of the current project was to develop, test and implement a detailed method for individual dose reconstruction. Two different approaches were considered and tested. The method adopted, RADRUE (Radiation Dose Estimation with Uncertainty Estimates), a variant of an analytical dose reconstruction method previously derived for professional radiation workers of the Chernobyl power plant, appears to work well. It is based on detailed time and motion studies, coupled with the use of very comprehensive data bases of radiological data.

The development of this method has involved very extensive work to:

1. locate, collate and evaluate very large databases of gamma background measurements made by various organisations at different times on the industrial site and throughout the 30 and 70 km areas around the Chernobyl nuclear power plant;
2. bring together experts knowledgeable about working conditions in different groups of liquidators and formalise and compile their knowledge into an integrated database;
3. develop an integrated software program that allows the calculation of doses and associated uncertainties from a subject's work history;
4. carefully reconstruct itineraries of the study subjects using the information provided in the very detailed study questionnaires.

Extensive validation of the work has been carried out. In particular, large groups of liquidators with instrumental dosimetry, with doses based on time and motion studies at the time of their work (military liquidators) and with EPR were identified, traced and interviewed using the case-control study questionnaire. Their doses were calculated using both of the methods initially considered for this project (ADR and SEAD) and these comparisons allowed the choice and further testing and optimisation of the main method, RADRUE. Comparisons with instrumental doses and doses from time and motion studies were generally good, while there was little correlation between reconstructed doses and EPR. The later may reflect the fact that it was not possible in the time frame of the project to exclude other exposures received by the liquidator (from UV, for example) by analysing only the lingual part of the tooth enamel. An additional validation study is currently underway in the Ukraine on a further group of liquidators. Moreover, the lower limit of detection of EPR is of the order of 100 mGy, and few of the subjects included in the study are thought to have received external doses much greater than 150 or 200 mGy.

The case-control study was extended to further groups of liquidators in Baltic countries and Russia, thus increasing the power of the initial epidemiological study. Data were available for Baltic country liquidators from a questionnaire administered in a previous cohort study and comparison of these data with those collected by questionnaire in the case-control study allowed the evaluation of possible recall difficulties for a number of questions related to work as a liquidator. Overall, there was good agreement between the answers to the two questionnaires concerning dates and places of work and type of activity performed.

Data on a very small number of Baltic liquidators was also available for biological dosimetry (GPA and FISH). The correlation between the RADRUE estimates and the biological dose estimates is poor, as is expected in this dose range, which is below the limit of detection for individual doses for both of these biodosimetric methods.

Doses and associated uncertainties were estimated for all of the subjects in the case-control study. Doses to the bone marrow range from close to 0 to over 1 Gy, with a median of 20 mGy. Doses to the bone marrow among Baltic country liquidators tended to be much lower (8 mGy) than among Russia liquidators (55 mGy). Doses to the thyroid gland ranged from close to 0 to nearly 2 Gy. The highest doses were found for Belarus liquidators who lived and worked in areas of high contamination; these doses are related to ingestion of I-131. For Russian and Baltic country liquidators, doses from ingestion are thought to be close to zero. Doses from inhalation of I-131 were, however, received for liquidators who worked in the first weeks after the accident.

Uncertainties in the dose estimates have also been calculated, taking into account uncertainties in the input radiological data and in the answers to the questionnaires. Although for a small number of subjects the geometric standard deviation is very large (up to 4.5, mainly for subjects with low RADRUE doses – and one subject with a high RBM RADRUE dose but a very uncertain work history), the median geometric standard deviation is of the order of 2.

This contract has permitted the development, testing and optimisation of a detailed analytic dose reconstruction method for the estimation of individual doses and related uncertainties for Chernobyl liquidators and its application to an epidemiologic study of cancer risk in this population.

Conclusions

The work under this project has shown that it is possible to reconstruct, with adequate precision for an epidemiological study, individual doses for workers involved in clean-up from detailed time and motion studies. This requires the development and testing of a detailed questionnaire about history and conditions of work, a set of relevant visual aids to assist the subjects in recalling their places of work, the collection and integration of all available dosimetric information and the analysis of work histories from questionnaires by experts familiar with the work and conditions of work in the clean-up areas.

The results are a fully integrated program that can be adapted to include extensive databases of dose-rate estimates, an interface for plotting and entering information on the liquidators route and conditions of work, calculation of individual doses and simulations to take into account dosimetric and questionnaire uncertainties.

The dose reconstruction method has been tested and validated and optimized and an approach for assessing uncertainties has been implemented. Though the method must rely on expert assessment of the questionnaires, the method was shown to be sufficiently standardized to be reproducible.

Acknowledgements

In addition to the current grant, the epidemiological study of cancer risk among Chernobyl liquidators was made possible by contracts F14C-CT96-0011 and ERBIC15-CT96-0317 from the European Union (Nuclear Fission Safety and INCO-Copernicus Programmes).

The Study Group is grateful to

- Drs A.Ye. Okeanov, G. Tolochko, N. Bazoulko (Minsk), A. Konogorov (Obninsk) who participated in the feasibility study and took part in the design and start of implementation of this study,
- to Professor Ilyin, Director of Institute of Biophysics in Moscow, for support and guidance in the setting up and conduct of the dose reconstruction project
- to Professor A. Tsyb, Director of the MRRC for assistance in the organisation of the study in Russia
- to Dr V. Stzyezhko head of Department of Medicine of Catastrophe in the Belarus Ministry of Public Health and Professor N. Piliptsevitch, former Director of the BelCMT, for assistance in the organisation and conduct of the study
- to Professor E. Ivanov, former Director of the RIHBT for assistance in the identification of cases of leukaemia, the retrieval of slides and medical records for verification and the isolation and storage of lymphocytes
- to Mrs K. Rahu from the Institute of Experimental and Clinical Medicine, for technical assistance.
- to the interviewers who collected the data (Belarus: Tierekhovitch, Tatiana; Kunitskyi Dimitry, Bondarovitch Pavel, Zolotko Natalia; Estonia: Vello Jaakmees; Latvia: Kojalo Una; Lithuania: Stankevic Audrone; Russia),
- to the personnel of the regional centres of the National Radiation and Epidemiological Registry in Northwest, Volgo-Vyatsky, Central-Chernozem, North-Caucasus and Urals who participated in the organisation of the work and collection of data in the regions,
- to the Center of Occupational Diseases and Radiation Pathology (head physician Dr. E. Tchurbakova) of the RSU Clinical Hospital and the Latvian Republics Association Chernobyl for assistance in the tracing, recruitment and establishment of contact with the study subjects
- to the Chernobyl Movement of Lithuania for assistance in the tracing, recruitment and establishment of contact with the study subjects,
- to the members of the panels of pathologists and haematologists who carried out the review of the cases included in the study: Drs Yu. Sidorov, formerly of the Minsk City Oncological Dispensary, Drs E.F. Lushnikov, S. Chayt and A. Abrosimov of the Medical Radiological Research Centre in Obninsk, Dr Kaarle Franssila, former Head of Oncological Pathology at the Department of Pathology at the Helsinki University Hospital, Pr A. Svirnovsky of the Research Institute for Hematology and Blood Transfusion, Dr Lasse Teerenhovi, Helsinki University Hospital.
- to all the collaborators from the joint Baltic country/US/Finnish study cohort study of Baltic country liquidators

- to Drs Hans Storm (Danish Cancer Society, Copenhagen, Denmark). Geoff Howe (Columbia University, New York, USA) and Colin Muirhead (National Radiological Protection Board, Didcot, UK) for useful discussion and comments in the design and conduct of the study,
- and to Dr L. Stayner (National Institute of Occupational Safety and Health, USA) - for participating in modelling of impact of errors in dosimetry on risk estimates.

Bibliography

AUSRPIET: Acts on the results of the issuing certificates (passportisation) for the rooms of ChNPP. Archive of AURSPIET 1987, (in Russian)

Balonov M, Jacob P et al.: Pathways, levels and trends of population exposure after the Chernobyl accident. Proc of first International Conference of the European Commission, Belarus, the Russian Federation and the Ukraine on the radiological consequences of the Chernobyl accident, Minsk, Belarus, March 18-22, 1996, IOS Press, Amsterdam.

BEIR V: Committee on the Biological Effects of Ionizing Radiation: The effects on populations of exposure to low levels of ionizing radiation. National Academy of Sciences, Washington, DC, 1990.

Bigbee W, Jensen R, Veidebaum T, Tekkel M, Rahu M, Stengrevics A, Kesminiene A, Kurtinaitis J, Auvinen A, Hakulinen T, Servomaa K, Rytomaa T, Obrams G, Boice JD Jr.: Glycophorin A biodosimetry in Chernobyl cleanup workers from the Baltic countries. British Medical Journal 312: 1078-1079, 1996

Bigbee W, Jensen R, Veidebaum T, Tekkel M, Rahu M, Stengrevics A, Auvinen A, Hakulinen T, Servomaa K, Rytomaa T, Obrams G, Boice JD Jr: Biodosimetry of Chernobyl cleanup workers from Estonia and Latvia using the Glycophorin A in vivo somatic cell mutation assay. Radiation Research 147: 215-224, 1997

Buzunov V, Omelyanetz N, Strapko N, Ledoschuk B, Krasnikova L & Kartushin G: Chernobyl NPP accident consequences cleaning up participants in Ukraine - health status epidemiologic study - main results, 1996. Brussels, European Commission 1-871, 1996. First International Conference of the European Commission, Belarus, the Russian Federation and the Ukraine on the radiological consequences of the Chernobyl accident. Minsk, Belarus, March 18-22, 1996

Cardis E, Gilbert ES, Carpenter L, Howe G, Kato I, Armstrong BK, Beral V, Cowper G, Douglas A, Fix J, et al.: Effects of low doses and low dose rates of external ionizing radiation: cancer mortality among nuclear industry workers in three countries. Radiation Research 142: 117-132, 1995

Cardis E, Okeanov AE, Anspaugh L, et al.: Estimated long-term health effects of the Chernobyl accident. Proc of The Joint EU, IAEA and WHO International Conference One Decade after the Chernobyl Accident, Vienna, 241-271, 1996

Cardis E, Okeanov AE: What's Feasible and Desirable in the Epidemiologic Follow-Up of Chernobyl. Brussels, European Commission 1-835. First International Conference of the European Commission, Belarus, the Russian Federation and the Ukraine on the radiological consequences of the Chernobyl accident, Minsk, Belarus, March 18-22, 1996

DE USSR: Report of the governmental commission on the performed work in year 1986 Moscow: 21, 1987, (in Russian)

Drozdovitch V, Mirkhaidarov A, Shevchuk V: Uncertainty analysis of external doses used to evaluate radiological consequences of the accident on NPP. Preprint IPEP 70, Minsk, Belarus, 1-43, 2003

Fix J J, Salmon L, Cowper G, Cardis E: A retrospective evaluation of the dosimetry in an international combined epidemiological study. Radiation Protection Dosimetry 74: 39-53, 1997

Gavrilin YuI, Khrouch VT, Shinkariov SM, Krysenko NA, Skryabin AM, Bouville A, Anspaugh LR. Chernobyl accident: reconstruction of thyroid dose for inhabitants of the Republic of Belarus. Health physics 76: 105-119, 1999

Gavrilin YuI, Krjuchkov VP, Khrouch VT, Shinkariov SM: Retrospective evaluation of the individual internal thyroid exposure doses, received by the ChNPP accident liquidators. (Project of MU). Moscow: 19, 2000

Gavrilin Yu, Khrouch V, Shinkarev S: Estimation of individual internal thyroid doses due to ^{131}I intake for the subject in the case–control study in Belarus (Gomel and Mogilev Oblasts) and in Russia (Bryansk, Kaluga, Orel, and Tula Oblasts). Operations manual, Moscow, Russia, 2001

IBP MH USSR: Journals of the operative control by the service of Radiation Safety of ChNPP. Archive of IBP MH USSR, 1986, (in Russian)

ICRP: Report of the task group on reference man. A report prepared by a task group of committee 2 of the international commission on radiological protection. Pergamon Press. Oxford. New York. Toronto. Sydney. Braunschweig, 1975

Illichev SV, Kochetkov OA, Krjuchkov VP, Mazurik VK, Nosovskii AV, Pavlov DA, Snisar IV, Tsov'yanov AG: Retrospective Dosimetry of Accident Remediation Personnel at the Chernobyl Nuclear Power Plant. (eds. Kryuchkov VP, Nosovskii AV), Seda-Still, 1996

Ilyin LA, Balonov MI, Buldakov LA et al: Radiocontamination patterns and possible health consequences of the accident at the Chernobyl nuclear power station. Journal of Radiological Projection 10: 3-29, 1990

Ilyin LA, Krjuchkov VP, Osanov DP et al.: External gamma-radiation doses for liquidators of the Chernobyl issues within 1986-1987. Date of individual dosimetric monitoring and doses reconstructed retrospectively. Radiobiology and Radioecology 35: 1995

Inskip PD, Hartshorne MF, Tekkel M, Rahu M, Veidebaum T, Auvinen A, Crooks GL, Littlefield LG, McFee AF, Salomaa S, et al.: Thyroid Nodularity and Cancer among Chernobyl Clean-up Workers from Estonia. Radiation Research 147: 225-235, 1997

Inskip P, Tekkel M, Rahu M, Veidebaum T, Hakulinen T, Auvinen A, Rytomaa T, Servomaa K, Obrams G, Stengrevics A, Kesminiene A, Kurtinaitis J, Hartshorne M, Littlefield LG, Salomaa S, Tucker J, Bigbee W, Jensen R, Moloney W, Boice JD Jr.: Studies of leukaemia and thyroid disease among Chernobyl clean-up workers from the Baltics. Proc of 1997 National Council on Radiation Protection (NCRP), 1-123, 1997

Ivanov VK, Tsyb AF, Gorsky AI, Maksyutov MA, Rastopchin EM, Konogorov AP, Biryukov AP, Matyash VA, Mould RF: Thyroid cancer among "liquidators" of the Chernobyl accident. British Journal of Radiology 70: 937-941, 1997

Ivanov VK, Tsyb AF, Gorsky AL, Maksyutov MA, Rastopchin EM, Konogorov AP, Korelo AM, Biryukov AP, Matyash VA: Leukaemia and thyroid cancer in emergency workers of the Chernobyl accident: estimation of radiation risks (1986-1995). Radiation Environmental Biophysics 36: 9-16, 1997

Ivanov VK, Tsyb AF, Konogorov AP, Rastopchin EM, Khait SE: Case-control analysis of leukemia among Chernobyl accident emergency workers residing in the Russian Federation, 1986-1993. Journal of Radiological Protection 17:137-157, 1997

Ivanov VK, Tsyb AF, Petrov MA, Maksyutov MA, Shilyaeva TP, Kochergina EV: Thyroid cancer incidence among liquidators of the Chernobyl accident. Absence of dependence of radiation risks on external radiation dose. Radiation Environmental Biophysics 41:195-198, 2002

Izrael YA: Chernobyl: radioactive contamination of the natural environment, Hydrometeoizdat: 1-296, 1990 (in Russian)

Izrael YA: Radioactive contamination of natural environment in the ChNPP accident zone. Meteorology and hydrology 2: 5-18, 1987 (in Russian)

Jacob P, Rosenbaum H, Petoussi N, Zankl M: Calculation of organ doses from environmental gamma rays using human phantoms and Monte Carlo methods. Part II: Radionuclides Distributed in the air or deposited on the ground. GSF-Bericht 12: May, 1990

Kesminiene A, Kurtinaitis J, Rimdeika G: The study of Chernobyl clean-up workers from Lithuania. Acta Medica Lituanica 2: 55-61, 1997

Kotchetkov OA, Covjanov AG, Timofeev LV, Baranov IV et al.: Computational-experimental prognosis of the individual and collective exposure during the commitment of the works on the object “Sarcophagus”. Outcome report on the theme 5.2 of the contract 70-H/4. Moscow, Russia, 1992 (in Russian)

Krjuchkov VP, Osanov DP, Pavlov DA: Retrospective dose estimation of external gamma and beta radiation for liquidators of the Chernobyl nuclear power plant accident using computational method. Proc of 1994 International Symposium on Radiation Safety (ISRS), Moscow, Russia, 1-231, 1994

Likhtarev IA, Chumak VV et al.: Retrospective reconstruction of individual and collective external gamma doses of population evacuated after the Chernobyl accident. Health Physics 66:643-652, 1994

Lloyd DC, Sevan'kaev AV(editors): International scientific collaboration on the consequences of the Chernobyl accident (1991-95) - Experimental collaboration Project No.6 - Biological dosimetry for persons irradiated by the Chernobyl accident. Brussels. European Commission. EUR 16532, 1996

Lyubchanskyi EP et al. : Radiation-hygienical situation in the territory of 30-km zone and surrounding rayons. According to the materials of the examination in 1986-1987. Report of IBP MH USSR, Filial. Ref. No.401, 1988

MD USSR: Levels of the dose rates from γ- radiation in the settlements of the ChNPP 30-km zone from the 26.04.86 till 01.07.86. Directorate of the chemical military forces, Ord.566/8/08820 from December 06, 1988 (in Russian)

Minenko VF, Drozdovitch VV, Tretiakevitch SS, Ulanovsky AV: Exposure of Belarus population after Chernobyl accident: collective doses and forecast of stochastic effects. Medical and Biological Aspects of Chernobyl Accident 4:50-65, 1996 (in Russian)

Minenko VF, Ulanovsky AV, Drozdovitch VV, Shemiakina EV, Gavrilin YuI, Khrouch VT, Shinkarev SM, Bouville A, Anspaugh LR, Voilleque P: Case-control study of Chernobyl - related thyroid cancer among children in Belarus. Part II: Estimation of individual thyroid doses from long-lived radionuclides and external radiation. Health Physics, Submitted, 2002

Okeanov AE, Cardis E, Antipova SI, Poliakov SM, Sobolev AV, Bazoulko NV: Health Status and Follow-up of Liquidators in Belarus. Brussels, European Commission, 1-851, 1996. First International Conference of the European Commission, Belarus, the Russian Federation and the Ukraine on the radiological consequences of the Chernobyl accident, Minsk, Belarus, March 18-22, 1996

Osanov DP, Krjuchkov VP, Shaks AI: Determination of beta radiation doses received by personnel involved in the mitigation of the Chernobyl Accident. Research Enterprise Publication. Doses of the Soviet Population and Early Health Effects Studies, 1-313, 1993

Pitkevich VA, Ivanov VK, Tsyb AF, et al.: Dosimetric data of the All-Russia Medical and Dosimetric State Registry for emergency workers. Radiation and Risk Special Issue 2: 1-44, 1995

Pitkevich VA, Ivanov VK, Checkin S, Tsyb AF: On the problem of exposure levels for persons involved in recovery operations following the Chernobyl accident and included in the All-Russia State Medical and Dosimetric Registry. Radiation Biology and Radioecology 36: 747-757, 1996

Prisyazhniuk AE, Fedorenko Z, Okeanov AE, Ivanov V, Starinsky V, Gristchenko V, Remennik L: Epidemiology of cancer in population living in contaminated territories of Ukraine, Belarus, Russia after the Chernobyl accident, European Commission, Brussels, Belgium, 909-921, 1996

Rahu M, Tekkel M, Veidebaum T, Pukkala E, Hakulinen T, Auvinen A, Rytomaa T, Inskip PD, Boice JD Jr.: The Estonian study of Chernobyl clean-up workers: II. Incidence of Cancer and Mortality. Radiation Research 147:653-657, 1997

Sakulin SY, Rimskyi-Korsakov AA, Shuijskaya LG et al.: Report on the scientific-exploratory work “collection, analysis and systematization of the data on radiation environment in 5-km zone of ChNPP for the period from 26.04.86 till 31.12.86 (Contract No.17/86 of 12.03.92). Sosnovyi Bor, 1992 (in Russian)

Savkin MN: Particularities of ecological and hygienic radiation situation in 30-km zone of Chernobyl NPP at the late stage after the accident. Radiation and risk, Bulletin of the all-Russia Medical and Dosimetric State Registry Moscow-Obninsk 3: 94-121, 1993

Shikalov VF, Usatyi AF et al. : Radiation Environment in the object “Sarcophagus” according to the reports and protocols of 1986-1988. Institute of Kurchatov, Moscow, Russia, 2001 (in Russian)

Shteinberg NA: Report on status of the ChNPP environment within the 30-km zone one month after the accident. Executive director of the laboratory of external dosimetry Perminov VG. Pioneer camp “Skazochnyi”, 1986, proved by the chief engineer of ChNPP Shteinberg NA, 1-9, June 20, 1986, (in Russian).

Storm HH, Okeanov AE: Epidemiological investigation including dose assessment and dose reconstruction. Report, Brussels, European Commission, 1996

Styro BI, Nedvetskaite TN, Phylistovich VI: Isotopes of iodine and radiation safety. Sankt-Petersburg. Hydrometeoizdat, 255, 1992

Tekkel M, Rahu M T, Veidebaum T, Hakulinen T, Auvinen A, Rytomaa T, Inskip PD, Boice JD Jr.: The Estonian study of Chernobyl cleanup workers: I. Design and questionnaire data. Radiation Research 147: 641-652, 1997

Troshin VS, Smirnov VV, Zaycev RY et al.: Development of the method for the reconstruction of the spectral-angular distribution of the photons field base on the function of response of the dosimetrical detectors. Report for the theme N 92-3-296, 1-50, MIFI, Moscow, Russia, 1992 (in Russian)

Tsyb AF et al.: Registry material. Radiation Risk 1:67-131, 1992

UDK NPO: “Prypiat” Report on the committed work of technical department of the dosimetrical control board of PO “Kombinat” for the year 1987. Prypiat, archive of UDK NPO “Prypiat”, 1987, (in Russian)

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation): Sources and Effects of Ionizing Radiation, Report II, United Nations, No. E.00.IX.4. New York, USA, 2000

US ChNPP: Journals on the operative control of radiation environment by the service of US ChNPP radiation control for the year 1986. Archive of US ChNPP, 1986, (in Russian)

US-605: Journal of the operative control of the radiological situation by department of US-605 radiological control. Archive of US-605, 1986, (in Russian)

Annex 1

RADRUE

Operations Manual

Annex 2

Case-control studies
QUESTIONNAIRE

Annex 3

Case-control studies
INTERVIEWER BOOKLET