

Overview of the Chernobyl accident and its consequences

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Searches

We searched, along with our own peer-reviewed data and personal files, PubMed for English-language articles, references of relevant articles and textbooks published during the period from the Chernobyl accident, 1986, including those appeared in the former Soviet Union official sources, through October, 2010, with the search terms “Chernobyl and thyroid”, “thyroid cancer”, “radiation-induced thyroid cancer”, “liquidators and Chernobyl”, “radiation risk”, and “radiation dose and ¹³¹I and Chernobyl”. We also searched websites of the international organizations including the WHO, UNSCEAR, IAEA, UNICEF, UNDP and IARC. In addition, we used Russian or country-specific language sources such as published articles, proceedings of the official scientific conventions, textbooks and websites of the government-owned institutions in Belarus, Russia and Ukraine.

Conflict of Interest

The authors declare no conflict of interest.

Abstract

The accident at Chernobyl nuclear power plant (CNPP) was the worst industrial accident of the last century that involved radiation. The unprecedented release of multiple different radioisotopes led to radioactive contamination of large areas surrounding the accident site. The exposure of the residents of these areas was varied and therefore the consequences for health and radioecology could not be reliably estimated quickly. Even though some studies have now been ongoing for 25 years and have provided a better understanding of the situation, these are yet neither complete nor comprehensive enough to determine long term risk. A true assessment can only be provided after following the observed population for their natural lifespan.

In this article, we review technical aspects of the accident and provide relevant information on radioactive releases that resulted in exposure of this large population to radiation. A number of different groups of people were exposed to radiation: workers involved in the initial clean-up response, and members of the general population who were either evacuated from the settlements in the CNPP vicinity shortly after the accident, or continued to live in the affected territories of Belarus, Russia and Ukraine. Through domestic efforts and extensive international cooperation, essential information on radiation dose and health status for this population has been collected. This has permitted the identification of high-risk groups and the use of more specialized means of collecting information, diagnosis, treatment and follow-up. Since radiation-associated thyroid cancer is the one of the major health consequences of the Chernobyl accident, a particular emphasis is placed on this malignancy. The initial epidemiological studies are reviewed, as are the most significant studies and/or aid programs in the three affected countries.

Key words: Chernobyl, radioactive contamination, radiation thyroid dose, thyroid cancer, radiation risk of thyroid cancer

Introduction

The accident at Chernobyl nuclear power station (CNPP) that occurred 25 years ago on 26th April 1986 was the worst industrial accident involving radiation in the 20th century. Before this, the only experience of radiation exposure to a large population was the atomic bombings of Hiroshima and Nagasaki in 1945. The nature of the radiation exposure after Chernobyl was very different from that in Japan: protracted versus acute single dose, mostly internal versus external irradiation, involvement of different spectra of isotopes, irregular and patchy radioactive contamination of the environment, and radiation exposure of a population on millions of people of all ages. That is why many consequences, both related to health and society, could not be anticipated from what had been learnt from the radiation exposure to the Japanese population in 1945.

In this article we review some technical aspects of the accident and provide information on the radioactive releases that caused contamination of large areas in the former Soviet Union countries, Belarus, Russia and Ukraine, particularly those in the immediate vicinity of the accident site. We also describe the major groups of the population affected by the accident and consider the information available on the radiation dose received by this population. In a separate subsection we highlight epidemiological and medical studies from the early stages to demonstrate the importance and necessity of international cooperation in large-scale disasters.

Accident and radioactive releases from CNPP

The Chernobyl Nuclear Power Plant is located in the north of Ukraine close to the junction of the borders of three states, Ukraine, Belarus and Russia. The accident at Reactor Number 4 took place shortly after midnight on April 26, 1986. A number of accounts of the accident, some giving a minute by minute sequence, have been published. According to USCEAR [1], the course of events could be summarized as follows. Due to some reactor design

flaws and human error during experimental operations immediately preceding the accident, overheating of the fuel rods and fragmentation in the active zone led to the rapid transfer of excessive heat to the coolant water and induced a shock wave breaking the primary coolant system pipeline joints. The leaking water instantaneously turned to steam - this first explosion caused displacement of the reactor core during which the remaining cooling water was driven out of the system. Without coolant, part of the nuclear fuel vaporized as a result of the increased temperature and this eventually resulted in a large explosion that destroyed the reactor and the building surrounding it dispersing reactor debris and radioactive materials to the CNPP, the immediate vicinity and more widely into the environment. The initial fires that occurred after the major explosion were brought under control by the end of the night of the accident. However, fuel materials remaining at the meltdown site grew hot, ignited combustible products formed in the disrupted core milieu and caused an explosive fire. Tremendous efforts were made to extinguish it, including dumping of various fission- and fire-control materials from helicopters, but the radioactive releases continued for approximately 10 more days [2,3].

There were 7 deaths during the first night of the accident: two staff members and five firemen involved in fire fighting actions. Among 237 firemen and CNPP employees examined within several next days for acute radiation sickness, manifestations of varying degrees of severity were found in 134 individuals. Despite the intensive therapy provided, including 13 bone marrow transplantations, 28 patients died within 4 months after the accident for various causes of death. Myelosuppression was the major cause of death, but 19 more deaths were registered up to 2004, and in these cases bone marrow failure was unlikely the underlying cause [4].

The estimated release of radioactivity from the destroyed reactor reached a total of approximately 13 EBq (1EBq = 10^{18} Bq) [1,5,6]. The main radionuclides released are listed in Table 1; ^{131}I and ^{137}Cs are most significant for dose received by the exposed population.

Radioactive emissions from CNPP were characterized by a wide spectrum of physicochemical forms and composition: gaseous, steam aerosol, aerosol mixtures, fuel particles, mineral particles with entrapped radionuclides, aggregates of different mineral particles, and organic compounds. The composition varied from mono-element noble gases and atomic iodine or ruthenium, to multi-element compounds and aggregates, fuel components, graphite, silicates and others, each with different radionuclide proportions [5].

Over 90% of ^{90}Sr , $^{141,144}\text{Ce}$, and isotopes of Pu and ^{241}Am were released in the form of fuel particles measuring 10 μM and less [5]. 75% of ^{137}Cs contamination within the exclusion zone (the 30-km zone around CNPP) could also be attributed to this physical form. At longer distances, contamination of the territories in European countries was due to steam-aerosol and gaseous mixtures, and to the particles of submicron size, containing $^{103,106}\text{Ru}$, $^{131,133}\text{I}$, ^{132}Te , $^{134,137}\text{Cs}$ and radioactive noble gases. The same isotopes were also detected in Pacific and Atlantic Oceans, and even in the Americas and Asia, emphasizing the global scale of the accident. Following the completion of a sarcophagus around the destroyed reactor and building in November 1986, active emissions into the environment were no longer observed [1,2].

Radioactive contamination of territories

The dynamic meteorological conditions, including the wind, cloudiness, temperature, humidity and precipitations together with varying physicochemical characteristics of the radioactive materials released at different times after the reactor destruction defined the heterogeneous pattern of the ground contamination [7,8,9]. Figure 1 demonstrates reconstructed plume traces over the part of Europe.

Further monitoring of the territories permitted a contamination pattern to be established based on average ^{137}Cs deposition densities (this isotope is easy to measure, has a long half-life and is radiologically significant) as shown in Figure 2, for the territories around Chernobyl, and

for the whole of Europe in Figure 3. The highest density of contamination is observed in the vicinity of the CNPP. However the levels exceeding the expected background could be detected as far as up to 3000 km from the accident site.

Territories of Belarus, Russia and Ukraine were affected by the accident most heavily, as specified in Table 2. From the total ^{137}Cs activity of about 64 TBq (1.7 MCi) deposited in Europe in 1986, Belarus received 23%, Russia - 30% and Ukraine - 18% resulting in radioactive contamination of approximately 3% of the European part of the former Soviet Union [10]. There were also contaminated areas in Austria, Finland, Germany, Norway, Romania and Sweden (Figure 3).

The radioactive isotopes of iodine ($^{131,132,133,135}\text{I}$) which are short-lived radionuclides belonging to the group of light volatile substances played a key role in the contamination of the environment. It is worth mentioning, however, that only ^{131}I has a high radiological significance. Among other isotopes, only $^{133,135}\text{I}$ increased the general exposure dose, especially for the thyroid, but due to their short half-lives their effect is restricted to the areas within the immediate vicinity of the CNPP.

Because of the rapid decay of ^{131}I , collection of a large number of samples for detailed analysis was difficult [11]. However, the results of model calculations based on the limited number of measurements and determinations of ^{131}I to different radionuclides ratios, especially ^{137}Cs (which varied 5-60-fold in different measurements), allowed reconstruction of contamination density maps [1,5,12]. The most contaminated areas are in Belarus, the 3 regions in the east and south-east: Brest, Gomel and Mogilev; in Russia the 4 south-western regions: Bryansk, Kaluga, Tula and Orel; and in Ukraine the 6 northern regions: Cherkassy, Chernigov, Kyiv, Rovno, Volyn and Zhitomir regions (refer to Figure 1). The refined ^{131}I contamination maps are expected to be published by UNSCEAR in 2011. This will enable the more accurate

estimation of thyroid dose that are essential for radiation epidemiology and public health assessment of the health consequences of the accident.

Most radionuclides released by the accident have already decayed. Attention over the next few decades is most likely to be centered on ^{137}Cs and ^{90}Sr ; the latter being more important in the areas closest to the CNPP [5].

Groups radiologically affected by the accident

There are three major groups of individuals for whom estimation of radiation health effects after Chernobyl is particularly important. These are the workers involved in the actions during the accident or in the mitigation of the aftermath, those individuals who lived close to the CNPP site and were evacuated following the accident, and those who continued to reside in the contaminated areas further from the CNPP. All were exposed to radiation at different times after the accident, under different circumstances and to different spectra and amounts of radioactive elements. Thus, accumulated effective doses are quite different among the groups and furthermore there are large uncertainties in dose estimates.

Liquidators

The first category is further subdivided into those who were at CNPP during the first day of the accident and took part in emergency measures, and those who were engaged in recovery operations from 1986 to 1990. In the literature the second group is often referred to as “liquidators”, the term officially introduced by the former Soviet Union. There were about 600 emergency workers at CNPP during May 26, and about 600,000 liquidators including both civilians and servicemen until 1990. Estimated external doses in the 134 emergency workers with symptoms of acute radiation sickness ranged between 0.8-16 Gy, being markedly higher than internal doses calculated to be between 0.021 and 4.1 Gy for the thyroid in the 23 firemen who died of bone marrow failure [13]. It was suggested that the lower thyroid doses might have

been brought about due to the stable iodine pills taken by emergency workers. Among the liquidators, the average effective doses ranged from 15 mSv to 170 mSv with individual variations from <10 mSv to >500 mSv in 1986-87 [1]. Internal exposures to the thyroid may have ranged from < 0.15 Gy to 3 Gy with an average of 0.21 Gy in those who took part in the activities in and around CNPP during the first few months after the accident [14]; the short-lived radioiodine isotopes decayed rapidly after that.

Evacuated residents

There was mass evacuation of residents of the settlements nearest to the CNPP, depending on the radiological situation and their distance from the power plant [15-18]. On April 27, about 50,000 people were evacuated from the town of Pripyat located 3 km from the CNPP. This is where most employees at the CNPP and their families resided before the accident. During the 10 days after the accident, through May 7, 1986, a similar number of people who lived inside the 30-km zone surrounding CNPP were evacuated from areas in Ukraine and Belarus. Active evacuations continued until September, 1986 and involved a total of about 116,000 people, mostly from areas in Ukraine and Belarus. Estimates of external effective doses reconstructed for approximately 30,000 residents of the 30-km zone indicate the dose range have been from 0.1 mSv to 380 mSv with an average of 17 mSv [19]. Mean thyroid doses from ^{131}I , based on about 5,000 direct measurements and about 10,000 questionnaires collected from Ukrainian evacuees were 0.11-3.9 Gy in children, 0.066-0.39 Gy in adolescents and 0.066-0.40 Gy in adults [20,21]. In Belarusian evacuees the estimates are 1-4.3 Gy, 1 Gy and 0.68 Gy, respectively [22]. These investigations demonstrated an important inverse correlation between thyroid dose and age at exposure.

General population

Reconstructed maps of soil contamination with ^{137}Cs (Figure 2) taken together with

demographic data for Belarus, Russia and Ukraine indicate that the population of contaminated territories (i.e. with ^{137}Cs levels exceeding 37 kBq/m²) was above 5 million at the time of accident, comprising around 1 million children (<15 years old) and approximately 200,000 adolescents. Since the number of residents of contaminated territories is substantially greater than in the two categories of clean-up workers described above, and also because the residents include individuals of all ages who might have been exposed to diverse radiological conditions at different geographical locations, dose estimates in them are more complicated and are intrinsically associated with large uncertainties. This is of particular note in the differences observed in the estimates of average collective and individual doses. Models of accumulated dose from external sources are based on soil ^{137}Cs contamination levels and are normalized to isotope deposition density. Estimates of external dose range from 11 $\mu\text{Sv}/\text{kBq}/\text{m}^2$ to 24 $\mu\text{Sv}/\text{kBq}/\text{m}^2$ in 1986 for contaminated territories of the three countries; the doses were higher in rural and lower in urban areas [1]. Study of external doses in one contaminated settlement in Russia in 1987 found individual doses to be within 2-13 mGy range with a mean of 5 mGy [23]. Internal doses for the thyroid rely on direct thyroid measurements (several hundred thousand were taken cumulatively after the accident), individual questionnaires and computer modeling. Estimates indicate that the doses varied in a wide range from <0.05 mGy to >2 Gy in Belarusian, Russian and Ukrainian individuals of all age groups with averages of <0.3-0.7 Gy in children and individual doses up to 10 Gy [24-30]. Thyroid doses exceeding 2 Gy were observed almost exclusively in younger children aged less than 4 years [30] and they usually were higher in the residents of rural than in urban areas with similar contamination level [29].

It is worth noting that organized administration of prophylactic or thyroid-blocking doses of stable iodine was not common. According to some surveys, from 1% to about 25% of the residents of contaminated territories reported taking KI pills shortly after the accident but the recall rate was low [29,31]. In part this was due to poor preparedness for large-scale accidents

such as one that happened at CNPP, and in part to inappropriate information from the authorities. An official announcement in the mass media appeared only on April 28th, i.e. two days after the reactor was destroyed. The delay was caused initially by insufficient understanding of the scale of the accident as well as apprehension of possible massive panic within the exposed population. It might be expected that if clear instructions on essential safety measures had been delivered swiftly and timely (e.g. taking KI pills, not consuming fresh milk and vegetables grown in the open plots, not going outside, etc.), health consequences, at least for the residents of contaminated territories, would be less dramatic. Cost-benefit analysis performed in Belarus for 2,566 thyroid cancers in children and adolescents diagnosed and treated during 1990-2005 showed that if potassium iodide prophylaxis had been provided, budget expenditures would have decreased by \$400,000 per 100,000 of population [32].

It is also of note that after the Chernobyl accident, several laws regulating the dissemination and handling of ecological information were brought in within the former Soviet Union countries. In Russia, for instance, information on emergencies and ecological, meteorological, demographic and sanitary-epidemiologic data of importance for safe industrial operations and for individual and public safety have been decreed to be open and non-restricted [33].

Major medical and epidemiological studies of the Chernobyl accident

The scale of the accident and the number of people affected by it were unprecedented; therefore initially it was very difficult to predict possible health consequences. In 2002, S.Nagataki, evaluating state of knowledge about Chernobyl, designated the major post-accident periods as follows: 1986-1989 information difficult to obtain; 1990-1991 exchanges with other countries initiated; 1992 case reports: childhood thyroid cancer; 1992-1994 period of

ascertainment; 1995 ascertainment and search for causes; 1996-present investigations carried out that will continue into the future [34].

The first health screenings in the most contaminated areas around Chernobyl were started shortly after the accident, mostly organized through local medical authorities. Only from 1990, after the request from the Government of the former Soviet Union in October 1989, were international efforts initiated that still persist today.

The first important collaboration was the International Chernobyl Project coordinated by IAEA. During 1990-91, 200 experts from 25 countries examined the health status of the population, including hematological, cardiovascular and thyroid disease, radiogenic cataract, cancer prevalence, fetal abnormalities and mental health for possible radiological consequences. The study involved a total of 825,000 people from 2,225 settlements in the three affected states [35]. One of the purposes was also to evaluate the mitigation measures undertaken and to develop health-related advice for the population residing in contaminated areas. The major findings of this project generally confirmed the previously established surface contamination levels; the whole body lifetime doses were estimated not to exceed 160 mSv and were several times lower than initial estimates of about 350 mSv. Actual thyroid doses were difficult to confirm. Stress and anxiety in the population were significant but apparently not radiation-related; no increase in leukemia or solid cancers was observed at that time and thyroid dose estimates in children were suggestive of the possible increase in thyroid cancer incidence in the future. The extent of population evacuation that had occurred, and the foodstuff restrictions that had been put in place appeared to be sometimes excessive.

In February 1990, the Government of the former Soviet Union appealed to the Sasakawa Memorial Health Foundation (SMHF) of Japan to provide assistance, specifically to the population of the contaminated territories. SMHF in collaboration with the Japan Shipbuilding Industry Foundation (now the Nippon Foundation) created a 5-year program initially entitled the

“Chernobyl Sasakawa Health and Medical Cooperation Project”. According to the report of experts who evaluated the situation in the areas close to Chernobyl, the major concerns were fear and anxiety among the residents, poor dissemination of information, and insufficient understanding of health problems in the population. Therefore, the provision of a direct health examination, particularly in children, was identified as the highest priority task [36]. In May 1991, health examination of children began in five centres established in Gomel and Mogilev (Belarus), Kiev and Zhitomir (Ukraine), and Bryansk (Russia) with a special focus on direct thyroid dose measurement, thyroid examination and blood tests (also including hormone and antibody measurements) according to an agreed, unified protocol. To implement the project, SMHF donated to each centre five mobile units equipped with whole body counters, ultrasound machines and blood analyzers, 10 buses for patients’ transportation as well as other medical and diagnostic equipment, computers, supplies and medicines. 158,995 children aged 0-10 years at accident had been examined by April 1996. The project also supported training in Japan and on-site, visits of experts to the five centers, and educational materials and lectures for the residents. Among 120,605 screened patients, 585 (4.85%, range 1.01-17.69) patients with thyroid nodules and 63 (0.52%, range 0.22-1.92) with thyroid cancer were identified, with the highest rate to be among the residents of the most heavily contaminated Gomel region in Belarus who were aged 0-3 years at accident [37]. The prevalence of goiter was 18-54% but there was no correlation with whole body ^{137}Cs count or the level of ^{137}Cs contamination at the settlement of residence [38]. The frequencies of hematopoietic malignancies, abnormal hematological parameters and thyroid autoimmunity also did not correlate with whole body ^{137}Cs count or the level of ^{137}Cs contamination [39]. The results of the project, which was the most reliable study at the time, indicated a link between thyroid cancer in children and the Chernobyl accident, and pointed at the need for further investigations.

In view of a high importance of the results obtained in 1991-96, SMHF extended the project for 5 more years focusing on Gomel region of Belarus. A comparative study of thyroid diseases in children born before and after the accident was designed to involve 21,601 persons screened between February, 1998 to December, 2000 using the approaches established during the first project. [40]. A total of 32 thyroid cancers (equating to 0.15% of the children screened) were diagnosed of which 31 were in the group of 9,720 children born before the accident, one in a child born during April 27 - December 31, 1986 (i.e., possibly exposed in utero) while no thyroid cancers were detected in the group of 9,472 children born after the accident. The estimated odds ratios of the frequency of thyroid cancer in the group born before the accident compared to in utero exposed group were 11 and 121 compared to those born after the accident. The conclusion regarding the likelihood of a causal link between direct external or internal exposure to short-lived radionuclides including ^{131}I and ^{133}I was drawn.

The extended SMHF project provided a good opportunity for collaboration with the Belarus/Russia/EU/IARC epidemiological case-control study (reviewed in another paper by Hatch and Cardis in this Special Edition) aimed to evaluate of the risk of thyroid cancer after exposure to ^{131}I , and to identify any risk-modifying factors. In a united effort, which initially included all individuals aged less than 15 years at the time of accident from Gomel and Mogilev regions of Belarus and from Bryansk, Kaluga, Tula and Orel regions of Russia (a total of 276 at the end of study) and at least four closely matched population-based controls (1,300 persons) were analyzed. Individual thyroid doses were reconstructed and used to estimate dose-response relationship. It was found to be significant and linear up to 1.5-2 Gy [41]. The odds ratio for thyroid cancer varied from 5.5 to 8.4 for a dose of 1 Gy according to different risk models; this was generally comparable with risk estimates for external exposures [42]. Importantly, a strong modifying effect of iodine deficiency was observed: relative risk for developing cancer was 3.2 in iodine deficient areas whereas a dietary supplementation with KI reduced the risk

approximately 3-fold (relative risk of 0.34). This study was the largest population-based investigation in young people living in Chernobyl areas; it provided a strong definitive evidence of causal association between the risk for thyroid cancer and internal exposure to radioiodine at young age. The major route of ^{131}I ingestion by residents was its incorporation into the food chains of pastured cattle, mostly cows, and consumption of fresh milk as well as from vegetables and fruits grown in open soil. Incorporation of ^{137}Cs may have contributed to dose formation. This is why both ^{131}I in the thyroid and in milk, and ^{137}Cs in soil, food and in the body are considered for dose reconstruction [43].

The World Health Organization (WHO) also played an active role in studying and managing health consequences of Chernobyl. One of the largest projects was the International Project on the Health Effects of the Chernobyl Accident (IPHECA) launched in May 1991 and completed in 1996, with international budgetary support primarily from the Government of Japan and with a contribution from the Czech Republic, Slovakia, Switzerland and Finland [44]. IPHECA included a number of pilot projects: brain damage in utero, an epidemiological registry, haematology, medical and psychological rehabilitation of Chernobyl liquidators, oral health, radiation dose reconstruction, and the effects on the thyroid. In collaboration with the SMHF project, over 210,000 children were examined. The findings were in line with the earlier SMHF projects: by the end of 1994, 565 children (333 in Belarus, 24 in the Russian Federation, 208 in Ukraine) who lived in contaminated regions were diagnosed for thyroid cancer but no significant increase in the incidence of leukemia or other blood disorders were observed [45].

In February 1999, the WHO and SMHF started the Chernobyl Telemedicine Project whose aim was to improve early diagnosis, treatment, and follow-up of patients with thyroid cancer, primarily in Gomel region of Belarus. A satellite-based telematic system was established that allowed an exchange of thyroid ultrasound and cytology images, and of related information on the patients between Thyroid Oncology Center in Minsk, the Research Center for Radiation

Medicine in Gomel and Nagasaki University School of Medicine with synchronized databases [46-49]. By September 2000, information on 330 cases was entered into the database and reviewed independently thus improving diagnosis.

Another important project was the establishment of the Chernobyl Tissue Bank (CTB) in October 1998 based on funding from the European Commission, WHO, SMHF and the U.S. National Cancer Institutes and approved by the Governments of Belarus, Russian and Ukraine [50]. This is also reviewed in a paper in this Special Edition by Thomas et al.

Even at present, when major causes of health consequences of the CNPP accident, at least with regard to thyroid cancer, are clarified, international activities continue. One of them is the Chernobyl Thyroid Diseases Study Group of Belarus, Ukraine, and the USA [51]. The study follows-up a cohort of 25,161 individuals (11,918 in Belarus and 13,243 in Ukraine) born between April 26, 1968 and April 26, 1986, with direct thyroid measurements available shortly after the accident to improve individual dose estimates and to collect health-related information based on bi-annual (or annual) screenings. The project was started in December 1996 in Belarus and in April 1998 in Ukraine.

During the first screening in 1998-2000, 45 thyroid cancers were detected in Ukraine [52]. An approximately linear dose-response relationship was found with excess relative risk estimate of 5.25 per 1 Gy. The older age tended to associate with the decreased risk of thyroid cancer. A fraction of cancers attributed to radiation was estimated to be 75% (95% CI 50-93%).

Reconstruction of thyroid doses in Belarus is now ongoing for the newly evaluation of the risk of radiation-associated thyroid cancer [53]. In Ukraine, there are extensive risk analyses of thyroid cancer and of other thyroid diseases among individuals exposed in utero to ^{131}I from Chernobyl fallout [54] as well as of that of non-cancer thyroid neoplasms [55] and autoimmune thyroiditis [56]. The results of this large-scale project are expected to further refine conclusions of the earlier, concurrent and ongoing studies.

In April 2009, a new Chernobyl program was launched by four UN agencies, IAEA, UNDP, UNICEF and WHO with financial support from the UN Trust Fund for Human Security. The objectives, primarily set in Belarus, are translation-oriented, i.e. to develop effective practical advices for the residents of contaminated territories based on the results of investigations around Chernobyl obtained so far.

Discussion

In this article we overviewed the major aspects of the accident at the CNPP, the initial response to the accident, both locally and with the involvement of international bodies, and its radiological and health consequences with a particular focus on thyroid cancer.

As a result of the large release of radioactivity, large groups of the population received radiation doses. These included clean-up workers and the general population that was either evacuated from the settlements in the vicinity of CNPP shortly after the accident, or continued to live in the territories of Belarus, Russia and Ukraine which were contaminated by fallout. Health consequences were initially difficult to forecast. Aside from the effects of acute exposure to ionizing radiation in firemen, information about the contamination levels of the affected territories, spectrum of pollutant radionuclides and doses accumulated by the residents were hard to come by. That is why, after the initial years of domestic effort, large scale international collaborations were initiated,, involving many governmental and non-governmental organizations from a number of countries and from the world-wide community. Through cooperative investigations, the health status and dosimetric data were obtained to provide grounds for assessing the consequences. First reports about the increase of thyroid cancer incidence in children and adolescents in Belarus and in Ukraine [57,58] were met cautiously by the experts because of doubts in the accuracy of diagnosis, too short period of latency (which would expected to be about 10 years as seen from A-bombings of Hiroshima and Nagasaki) and

insufficient evidence of link between Chernobyl radiation and cancer outbreak. With time, however, essential proof was found and the efforts of both health authorities in the three most affected countries and of the international parties could be better focused on the high-risk groups and using more specialized means. These still continue today.

A number of lessons have been learnt from the accident at the CNPP, for example, that a disaster in one country may affect other, that appropriate handling of vital information about the accident, and better preparedness for accidents that involve radioactive releases may result in less adverse consequences; that international collaboration even on delicate issues could be established and it can be effective. In the medical arena, a wealth of experience has been accumulated, including the recognition that there may be a relatively short period of latency for thyroid cancer after internal exposure to radioiodine, coupled with advances in the diagnosis and treatment of young patients with thyroid cancer.

Although issues of non-thyroid cancer, somatic diseases and mental consequences remained beyond of the scope of this review, these should not be forgotten too. The psychological effects of the accident are reviewed in another paper in this Special Edition by Bromet et al.

In conclusion, while the major health effects of the Chernobyl accident have become clearer over the past 25 years, we are still far from understanding all the consequences. Studies are still required to investigate whether the clinical course and the long-term effects of treatment of radiation-induced diseases are the same as or different from the same disorders of sporadic etiology. Investigations similar to that of the Life Span Study of Japanese A-bomb survivors and focused follow-up of patients diagnosed and treated after Chernobyl and in high-risk groups may provide essential answers to improve quality of life of those exposed to fallout from the accident, as well as to optimize radiation safety and public health systems worldwide.

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References

- [1] United Nations Scientific Committee on the effects of Atomic Radiation. Sources and effects of ionizing radiation. Report to the General Assembly, with Scientific Annexes. Volume II, Annex J: Exposures and Effects of the Chernobyl Accident. United Nations, New York, 2000.
- [2] United Nations Scientific Committee on the effects of Atomic Radiation. Sources and effects of ionizing radiation. Report to the General Assembly, with Annexes. United Nations, New York, 1988.
- [3] International Advisory Committee. The International Chernobyl Project. Technical Report: Assessment of radiological consequences and evaluation of protective measures. Vienna. International Atomic Energy Agency, Vienna, 1991.
- [4] Bennett B, Repacholi M, Carr Z (editors). Health effects of the Chernobyl Accident and special health care programmes. Report of the UN Chernobyl Forum. World Health Organization, Geneva, 2006.
- [5] National Report of Ukraine. 20 years after Chornobyl Catastrophe: Future Outlook. Kyiv, Atika, 2006.
- [6] Environmental Consequences of the Chernobyl Accident and Their Remediation: Twenty Years of Experience. Report of the Chernobyl Forum Expert Group "Environment" International Atomic Energy Agency, Vienna, 2006.
- [7] Borzilov VA, Klepikova NV. Effect of meteorological conditions and release composition on radionuclide deposition after the Chernobyl accident. In: Merwin SE, Balonov MI, editors. The Chernobyl Papers. Research Enterprises, Richland, 1993:47-68.
- [8] Izrael YU (editor). Atlas of Radioactive Contamination of European Russia, Belarus and Ukraine. Federal Service for Geodesy and Cartography of Russia. Moscow, 1998.
- [9] De Cort M, Dubois G, Fridman ShD, et al. Atlas of caesium deposition on Europe after the Chernobyl accident. EUR report nr.16733. Office for Official Publications of the European Communities, Luxembourg, 1998.

- [10] Izrael Y, Kvasnikova E, Nazarov I, *et al.* Global and regional pollution of the former European USSR with caesium-137. *Meteorol Gidrol* 1994;5:5-9.
- [11] Makhonko KP, Kozlova EG, Volokitin AA. Radioiodine accumulation on soil and reconstruction of doses from iodine exposure on the territory contaminated after the Chernobyl accident. *Radiat Risk* 1996;7:90–142.
- [12] Talerko N. Reconstruction of (131)I radioactive contamination in Ukraine caused by the Chernobyl accident using atmospheric transport modeling. *J Environ Radioact* 2005;84:343-362.
- [13] Ilyin LA. *Realities and Myths of Chernobyl*. ALARA Limited, Moscow, 1994.
- [14] Khrouch VT, Gavrilin YuI, Konstantinov YO, *et al.* Characteristics of the radionuclides inhalation intake. In: *Medical Aspects of the Accident at the ChNPP. Proceedings of the International Conference, Kiev, May 1988*. Kiev: Zdorovie Publishing House, 1988:76.]
- [15] Kholosha VI, Koval'skij NG, Babich AA. Social, economic, institutional and political impacts. Report for Ukraine. In: *One Decade After Chernobyl. Summing up the Consequences of the Accident. Proceedings of an International Conference, Vienna, 1996*. STI/PUB/1001. IAEA, Vienna, 1996:429-444.
- [16] Rolevich IV, Kenik IA, Babosov EM, *et al.* Social, economic, institutional and political impacts. Report for Belarus. In: *One Decade After Chernobyl. Summing up the Consequences of the Accident. Proceedings of an International Conference, Vienna, 1996*. STI/PUB/1001. IAEA, Vienna, 1996:411-428.
- [17] Voznyak VYa. Social, economic, institutional and political impacts. Report for the Soviet period. In: *One Decade After Chernobyl. Summing up the Consequences of the Accident. Proceedings of an International Conference, Vienna, 1996*. STI/PUB/1001. IAEA, Vienna, 1996:369-378.
- [18] Voznyak VYa. Social, economic, institutional and political impacts. Report for the Russian Federation. In: *One Decade After Chernobyl. Summing up the Consequences of the Accident*.

Proceedings of an International Conference, Vienna, 1996. STI/PUB/1001. IAEA, Vienna, 1996:379-410.

[19] Likhtarev IA, Chumak VV Repin VS. Retrospective reconstruction of individual and collective external gamma doses of population evacuated after the Chernobyl accident. *Health Phys* 1994;66:643-652.

[20] Goulko GM, Chumak VV, Chepurny NI, *et al.* Estimation of ¹³¹I doses for the evacuees from Pripjat. *Radiat Environ Biophys* 1996;35:81-87.

[21] Repin VS. Dose reconstruction and assessment of the role of some factors in radiation exposure to inhabitants, evacuated outside the 30-km zone after the Chernobyl accident. *Problems of Chernobyl exclusion zone*. Naukova Dumka Publishing House, Kiev, 1996.

[22] Gavrilin YuI. Communication to the UNSCEAR Secretariat. Institute of Biophysics, Moscow, 1997.

[23] Skryabin AM, Savkin MN, Konstantinov YO, *et al.* Distribution of doses received in rural areas affected by the Chernobyl accident. *NRPB-R277*, 1995.

[24] Gavrilin YuI, Khrusch VT, Shinkarev SM. Communication to the UNSCEAR Secretariat, 1997.

[25] Ilyin LA. Public dose burdens and health effects due to the Chernobyl accident. Paper Presented at the International Meeting Organized Jointly by Soviet and French Nuclear Societies with the Participation of the European Nuclear Society, Paris, April 1991.

[26] Ramzaev PV, Balonov MI, Kacevich AI, *et al.* Radiation doses and health consequences of the Chernobyl accident in Russia. In: *Assessment of the Health and Environmental Impact from Radiation Doses due to Released Radionuclides*. NIRS-M-102, 1994:3-25.

[27] Zvonova IA, Balonov MI. Radioiodine dosimetry and prediction of consequences of thyroid exposure of the Russian population following the Chernobyl accident. In: Merwin SE, Balonov

MI, editors. The Chernobyl Papers. Doses to the Soviet Population and Early Health Effects Studies, Volume I. Research Enterprises Inc., Richland, 1993:71-125.

[28] Zvonova IA, Balonov MI, Bratilova AA, *et al.* Methodology of thyroid dose reconstruction for population of Russia after the Chernobyl accident. In: Proceedings of the 10th International Congress of the International Radiation Protection Association, Hiroshima, Japan, May 2000:14-19.

[29] Likhtarev IA, Gulko GM, Sobolev BG, *et al.* Thyroid dose assessment for the Chernigov region (Ukraine): estimation based on ¹³¹I thyroid measurements and extrapolation of the results to districts without monitoring. *Radiat Environ Biophys* 1994;33:149-166.

[30] Likhtarev I, Sobolev B, Kairo I, *et al.* Results of large scale thyroid dose reconstruction in Ukraine. In: Karaoglou A, Desmet G, Kelly GN, *et al.*(editors) The Radiological Consequences of the Chernobyl Accident. Proceedings of the First International Conference, Minsk, Belarus, March 1996. EUR 16544, 1996:1021-1034.

[31] Mettler FA Jr, Royal HD, Hurley JR, *et al.* Administration of stable iodine to the population around the Chernobyl nuclear power plant. *J Radiol Prot* 1992;12:159-165.

[32] Kenigsberg YaE, Kryuk YuE, Demidchik YuE. Thyroid blockage during nuclear accidents: a cost-benefit analysis of the results of Chernobyl accident. *Radiats Biol Radioecol* 2007;2:8-12.

[33] Federal Law of Russian Federation N24-F3 “On information, informatization and data protection” of 20 February, 1995.

[34] Nagataki S. Comments: lessons from the international collaboration. In: Yamashita S, Shibata S, Hoshi M, Fujimura K, editors. Chernobyl: Message for the 21st Century. International Congress Series 1234. Amsterdam-London-New York-Oxford-Paris-Shannon-Singapore-Tokyo: Elsevier, 2002:95-102.

- [35] International Advisory Committee. The International Chernobyl Project. Assessment of radiological consequences and evaluation of protective measures. Technical Report. International Atomic Energy Agency, Vienna, 1991.
- [36] Shigematsu I. Chernobyl Sasakawa Health and Medical Cooperation Project. In: Yamashita S, Shibata S, Hoshi M, Fujimura K, editors. Chernobyl: Message for the 21st Century. International Congress Series 1234. Amsterdam-London-New York-Oxford-Paris-Shannon-Singapore-Tokyo: Elsevier, 2002:3-6.
- [37] Panasyuk GD, Masyakin VB, Bereschenko AV, Cot VA. Findings of the Chernobyl Sasakawa Health and Medical Cooperation Project: thyroid nodules and cancer. In: Yamashita S, Shibata Y, editors. Chernobyl: A Decade. International Congress Series 1156. Amsterdam-Lausanne-New York-Oxford-Shannon-Singapore-Tokyo: Elsevier, 1997:59-65.
- [38] Ashizawa K, Shibata Y, Yamashita S, *et al.* Prevalence of Goiter and Urinary Iodine Excretion Levels in Children Around Chernobyl. *J Clin Endocrinol Metab* 1997;82:3430-3433.
- [39] Karevskaya IV, Fokina MM, Kozyreva EA, *et al.* Hematological findings of the Chernobyl Sasakawa Health and Medical Cooperation Project. In: Yamashita S, Shibata Y, editors. Chernobyl: A Decade. International Congress Series 1156. Amsterdam-Lausanne-New York-Oxford-Shannon-Singapore-Tokyo: Elsevier, 1997:45-58]
- [40] Shibata Y, Yamashita S, Masyakin VB, Panasyuk GD, Nagataki S. 15 years after Chernobyl: new evidence of thyroid cancer. *Lancet* 2001;358:1965-1966.
- [41] Cardis E, Kesminiene A, Ivanov V, *et al.* Risk of Thyroid Cancer After Exposure to ¹³¹I in Childhood. *J Natl Cancer Inst* 2005;97:724-732.
- [42] Ron E, Lubin JH, Shore RE, *et al.* Thyroid Cancer after Exposure to External Radiation: A Pooled Analysis of Seven Studies. *Radiat Res* 1995; 141: 259-277.
- [43] Balonov M, Bruk G, Zvonova I, *et al.* Internal dose reconstruction for the Russian population after the Chernobyl accident based on human and environmental measurements.

Presented at the Workshop on Environmental Dosimetry, Avignon, France, 22-24 November 1999.

[44] Health consequences of the Chernobyl accident. Results of the IPHECA pilot projects and related national programmes. Summary Report. Geneva: World Health Organization, 1995.

[45] Souchkevitch GN. Main scientific results of the WHO International Programme on the Health Effects of the Chernobyl Accident (IPHECA). *World Health Stat Q* 1996;49:209-12.

[46] Yamashita S, Shibata Y, Takamura N, Ashizawa K, Sera N, Eguchi K. Satellite communication and medical assistance for thyroid disease diagnosis from Nagasaki to Chernobyl. *Thyroid* 1999;9:969.

[47] Yokota K, Takamura N, Shibata Y, Yamashita S, Mine M, Tomonaga M. Evaluation of a telemedicine system for supporting thyroid disease diagnosis. *Stud Health Technol Inform* 2001;84:866-869.

[48] Yamashita S, Repacholi M. Chernobyl Telemedicine Project 1999-2004. Final report of the joint project with the WHO and the Sasakawa Memorial Health Foundation and the Republic of Belarus. Geneva: World Health Organization, 2006.

[49] Yamashita S, Carr Zh, Repacholi M. Long-term health implications of the Chernobyl accident and relevant projects of the World Health Organization. *Health Phys* 2007; 93:538-541.]

[50] Thomas GA, Williams ED, Becker DV, *et al.* Creation of a tumour bank for post Chernobyl thyroid cancer. *Clin Endocrinol (Oxf)* 2001;55:423.

[51] Stezhko VA, Buglova EE, Danilova LI, *et al.* A Cohort Study of Thyroid Cancer and Other Thyroid Diseases after the Chornobyl Accident: Objectives, Design and Methods. *Radiat Res* 2004;161:481-492.

[52] Tronko MD, Howe GR, Bogdanova TI, *et al.* A cohort study of thyroid cancer and other thyroid diseases after the chornobyl accident: thyroid cancer in Ukraine detected during first screening. *J Natl Cancer Inst* 2006;98:897-903.

- [53] Drozdovitch V, Khrouch V, Maceika E *et al.*, Reconstruction of radiation doses in a case-control study of thyroid cancer following the Chernobyl accident. *Health Phys* 2010;99:1-16.
- [54] Hatch M, Brenner A, Bogdanova T, *et al.* A screening study of thyroid cancer and other thyroid diseases among individuals exposed in utero to iodine-131 from Chernobyl fallout. *J Clin Endocrinol Metab* 2009;94:899-906.
- [55] Zablotska LB, Bogdanova TI, Ron E *et al.* A cohort study of thyroid cancer and other thyroid diseases after the Chornobyl accident: dose-response analysis of thyroid follicular adenomas detected during first screening in Ukraine (1998-2000). *Am J Epidemiol* 2008;167:305-312.
- [56] Tronko MD, Brenner AV, Olijnyk VA *et al.* Autoimmune thyroiditis and exposure to iodine-131 in the Ukrainian cohort study of thyroid cancer and other thyroid diseases after the Chornobyl accident: results from the first screening cycle (1998-2000). *J Clin Endocrinol Metab* 2006;91:4344-4351.
- [57] Kazakov VS, Demidchik EP, Astakhova LN. Thyroid cancer after Chernobyl. *Nature* 1992;359:21.
- [58] Likhtarev IA, Sobolev BG, Kairo IA, *et al.* Thyroid cancer in the Ukraine. *Nature* 1995;375:365.

Table 1. Principal radionuclides released due to the Chernobyl accident*

Radionuclide	Half life	Activity released, PBq
Noble gases		
⁸⁵ Kr	10.72 y	33
¹³³ Xe	5.25 d	~6,500
Volatile elements		
^{129m} Te	33.6 d	240
¹³² Te	3.26 d	~1,150
¹³¹ I	8.04 d	~1,760
¹³³ I	20.8 h	~2,500
¹³⁴ Cs	2.06 y	~47
¹³⁶ Cs	13.1 d	36
¹³⁷ Cs	30.0 y	~85
Elements with intermediate volatility		
⁸⁹ Sr	50.5 d	~115
⁹⁰ Sr	29.12 y	~10
¹⁰³ Ru	39.3 d	>168
¹⁰⁶ Ru	368 d	>73
¹⁴⁰ Ba	12.7 d	240
Refractory elements (including fuel particles)		
⁹⁵ Zr	64.0 d	84
⁹⁹ Mo	2.75 d	> 72
¹⁴¹ Ce	32.5 d	84
¹⁴⁴ Ce	284 d	~ 50
²³⁹ Np	2.35 d	400
²³⁸ Pu	87.74 y	0.015
²³⁹ Pu	24,065 y	0.013
²⁴⁰ Pu	6,537 y	0.018
²⁴¹ Pu	14.4 y	~2.6
²⁴² Pu	376,000 y	0.00004
²⁴² Cm	18.1 y	~0.4

* Decay corrected to 26 April 1986

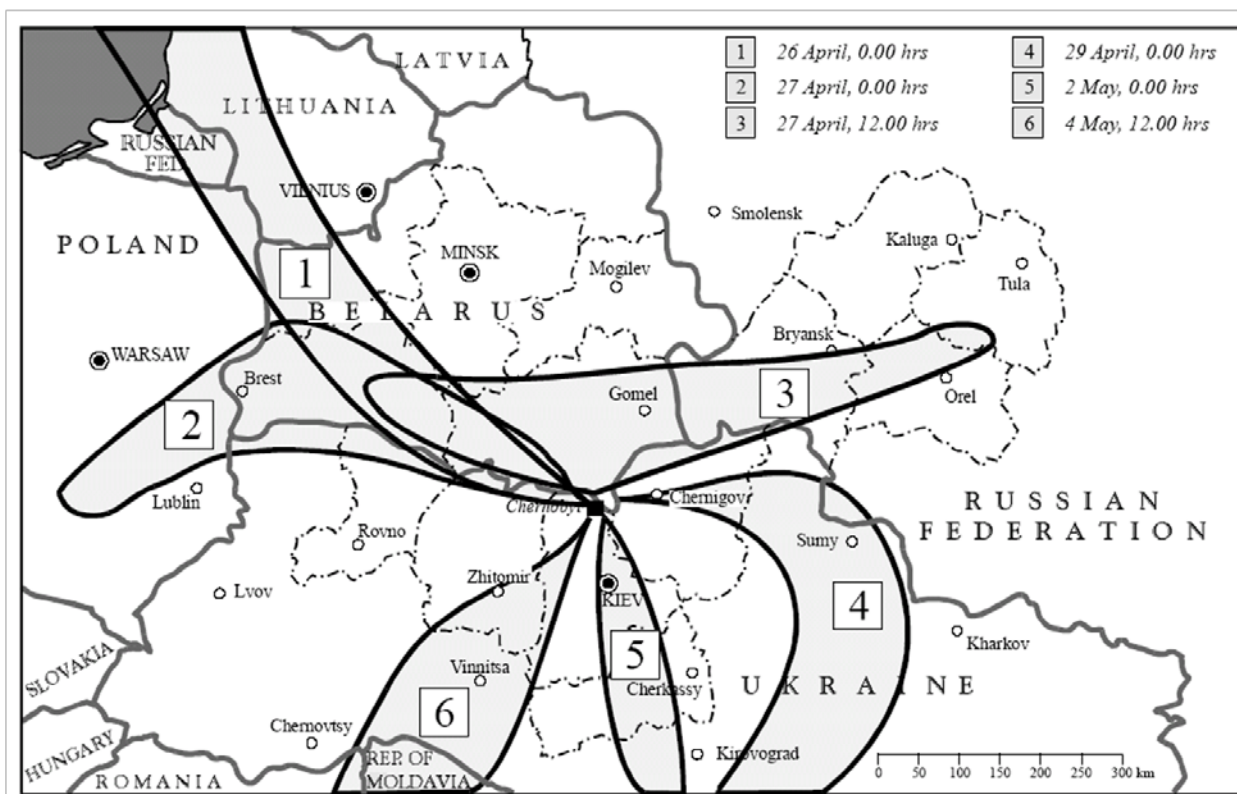
Data are inferred from refs. [2,8,16,19]

Table 2. European countries contaminated by Chernobyl fallouts in 1986*

	Area with ¹³⁷Cs deposition density range (per km²)			
	37-185 kBq/m ²	185-555 kBq/m ²	555-1480 kBq/m ²	> 1480 kBq/m ²
Russian Federation	49800	5 700	2100	300
Belarus	29900	10200	4 200	2200
Ukraine	37 200	3200	900	600
Sweden	12000	-	-	-
Finland	11500	-	-	-
Austria	8600	-	-	-
Norway	5200	-	-	-
Bulgaria	4800	-	-	-
Switzerland	1300	-	-	-
Greece	1200	-	-	-
Slovenia	300	-	-	-
Italy	300	-	-	-
Republic of Moldova	60	-	-	-

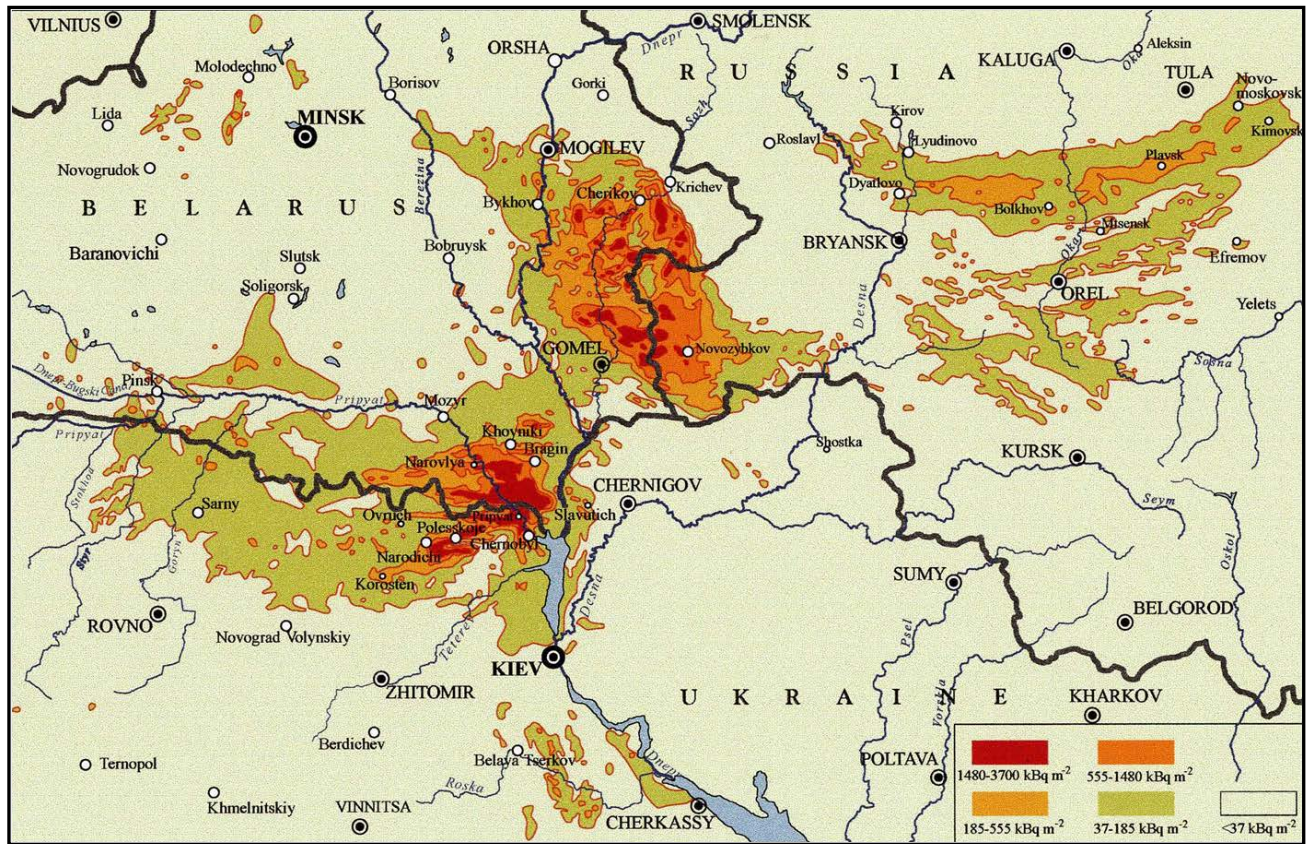
* Based on refs. [1,9]

Figure 1



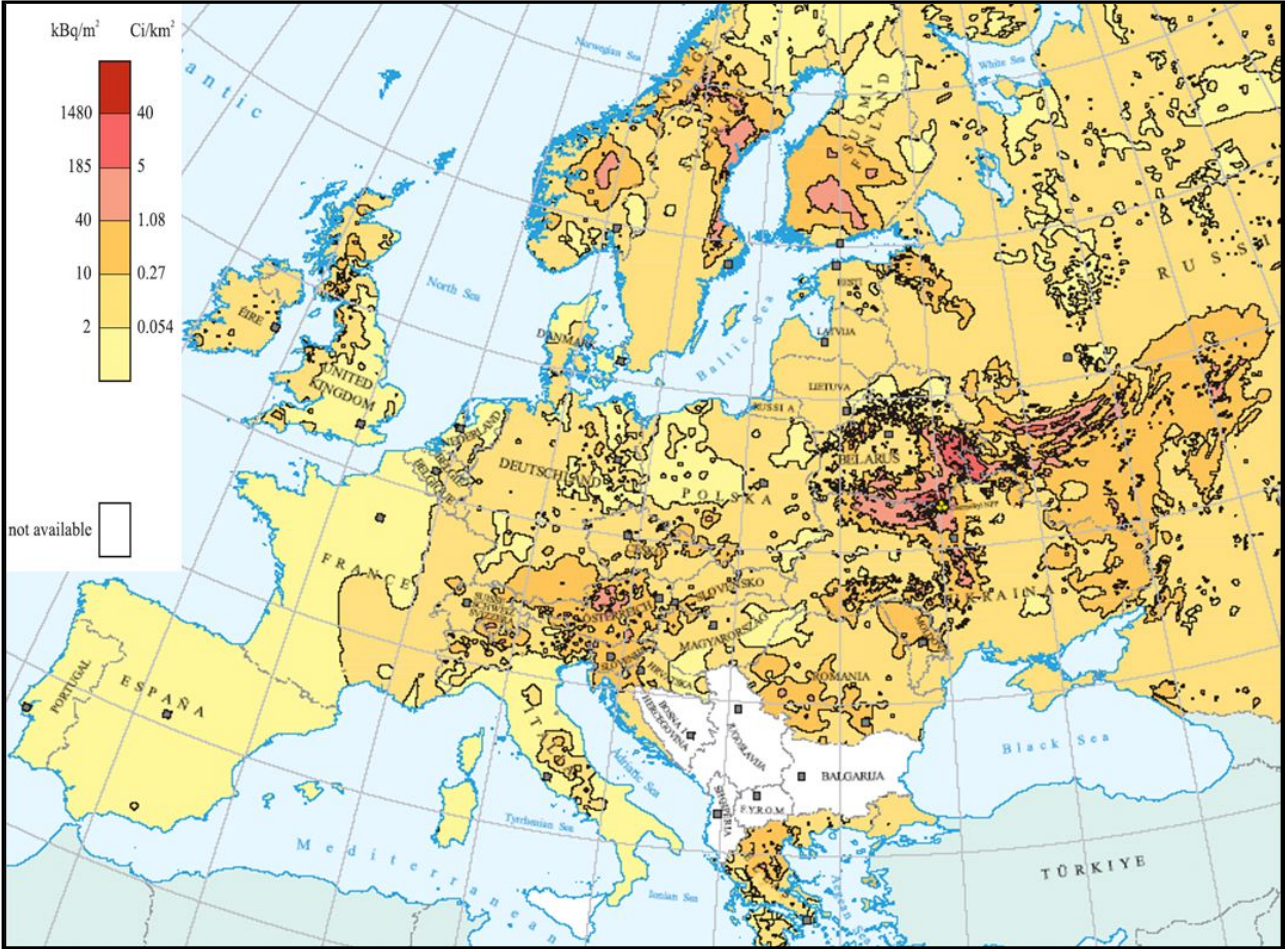
Calculated plume formation according to meteorological conditions for radioactive releases on corresponding dates just after the Chernobyl accident [7].

Figure 2



Ground deposition of ^{137}Cs in Ukraine, Belarus, and Russia around the accident site [1].

Figure 3



Ground deposition of ^{137}Cs in Europe after the Chernobyl accident [9].