Update of Impacts of the Chernobyl Accident: Assessments of the Chernobyl Forum (2003-2005) and UNSCEAR (2005-2008)

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Abstract

The accident at the Chernobyl NPP in Ukraine in 1986 was the most severe in the history of the nuclear industry, causing a huge release of radionuclides over large areas of Europe. Its radiological consequences were recently revisited by the UN Chernobyl Forum (2003-2005) and UNSCEAR (2005-2008).

For the first time environmental impacts were considered in detail, including radioactive contamination of terrestrial and aquatic environments, application and effectiveness of countermeasures and effects on biota. Updated dosimetric data were presented for more than half a million of emergency and recovery operation workers, about 100 million inhabitants of the three most affected countries, Belarus, the Russian Federation and Ukraine, and for 500 million inhabitants of other European countries. The average effective dose of the emergency and recovery operation workers was estimated to be about 0.12 Sv. An exception is a cohort of several hundred emergency workers who received high radiation doses; of whom 28 persons died in 1986 due to acute radiation sickness.

The majority of the six million residents of the ‘contaminated areas’ in Belarus, Russia and Ukraine received relatively minor radiation doses which are comparable with the natural background levels. However, those who were children at the time and drank milk with high levels of radioactive iodine received during the first few months after the accident particularly high doses to the thyroid. Since early 1990s there was the dramatic increase in thyroid cancer incidence among those exposed to radioiodine at a young age. Also in 1990s there was some increase of leukaemia in most exposed workers.

Apart from those two health effects revealed in the two different population cohorts as the result of 20-year epidemiological observations there was, until 2007, no clearly demonstrated increase in the somatic diseases due to radiation. There was, however, an increase in psychological problems among the affected population, compounded by the social disruption that followed the break-up of the Soviet Union. In particular, the UN Chernobyl Forum concluded that after a number of years, along with

reduction of radiation levels and accumulation of humanitarian consequences, severe social and economic depression of the affected regions and associated psychological problems of the general public and the workers had become the most significant problem to be addressed by the national authorities.

Introduction

The Chernobyl accident was the most severe in the history of the world nuclear industry. At night of 26 April 1986, Unit 4 of the Chernobyl nuclear power plant, located 130 km to the north-east of Kiev, the capital of Ukraine[1], was destroyed by two powerful explosions in the reactor core. The Chernobyl NPP was equipped with four RBMK reactors with a graphite moderator, a thermal power of 3200 MW and an electrical power of 1000 MW each. The explosions were caused by gross breaches of the operating procedures by staff and technical inadequacies in the safety systems (INSAG 1993). As a result of the explosions, highly radioactive core fragments were ejected onto the site. The hot graphite exposed to air caught fire and burned for 10 days.

During that time period, radioactive substances were ejected from the burning reactor and spread by winds under changing weather conditions over Europe, principally Belarus, Ukraine and Russia. No more than 20% of the radioactive discharge spread beyond Europe (De Cort et al. 1998).

More than 400,000 emergency and recovery operation workers, including army, power plant staff, local police and fire services, were involved in containing and cleaning up the accident in 1986-1987. Later, the number of registered "liquidators" rose to about 600,000.

About six million people live in areas of Belarus, Russia and Ukraine that are 'contaminated with radionuclides' due to the Chernobyl accident (above 37 kBq m^{-2} or 1 Ci km^{-2} of ^{137}Cs)[2]. Amongst them, about 400,000 people lived in more contaminated areas – classified at the time by Soviet authorities as 'areas of strict radiation control' (above 555 kBq m^{-2} or 15 Ci km^{-2} of ^{137}Cs). Of this population, 115,000 people were evacuated in the spring and summer of 1986 from the area surrounding the Chernobyl power plant (designated the "Exclusion Zone") to non-contaminated areas. Another 220,000 people were relocated in subsequent years (UNSCEAR 2000).

The consequences of the Chernobyl accident were widely discussed at the Kiev conference in 1988 (IAEA 1989), pursuant to the results of the IAEA Chernobyl project (IAG 1991), and at the conferences marking its 10^{th} anniversary (Karaoglou et al. 1996; IAEA 1996). The health consequences were analysed comprehensively by UNSCEAR in its 1988 and 2000 reports (UNSCEAR 1988, 2000). In 2005-2008 UNSCEAR has undertaken further assessment of the Chernobyl environmental and health consequences and recently published the resulting report (UNSCEAR 2010).

Because of continued contradictions in the interpretation of the Chernobyl accident consequences, the IAEA initiated in early 2003 establishing the Chernobyl Forum

[1] Up until 1991, Belarus, Russia and Ukraine were parts of the USSR.

[2] In the mapping of the deposition, ^{137}Cs was chosen because it is easy to measure long-lived radionuclide, and it is of radiological significance.

aiming to retrospectively assess the environmental and health consequences of the accident and to advise the Governments of Belarus, Ukraine and the Russian Federation on future actions, such as environmental remediation and special health care as well as research activities.

The Forum participants were eight United Nations organisations (IAEA, WHO, UNDP, FAO, UN-OCHA, UNEP, UNSCEAR[3] and The World Bank) as well as the competent authorities of Belarus, Russia and Ukraine. The Forum was created as a contribution to the United Nations' ten-year strategy for Chernobyl, launched in 2002 with the publication of *Human Consequences of the Chernobyl Nuclear Accident – A Strategy for Recovery* (UNDP and UNICEF 2002). The Chernobyl Forum and subsequent conference were chaired by Dr. Burton Bennett, Radiation Effects Research Foundation, Japan.

Forum reports on environment (IAEA 2006) and health (WHO 2006) were prepared by corresponding expert working groups and approved by consensus at the last Forum meeting in April 2005. The reports were presented and discussed during the International Conference entitled "Chernobyl: Looking Back to Go Forwards" organised by the IAEA in Vienna in September 2005 (IAEA 2008).

In November 2005, the United Nations General Assembly considered a report on efforts to promote recovery in areas affected by the Chernobyl legacy and adopted a resolution A/60/L.19 (UN 2005) in which, *inter alia*, noted consensus reached among members of the Chernobyl Forum regarding assessment of the accident consequences and future actions.

This paper presents the recent findings of the Chernobyl Forum and UNSCEAR on radiological health and environmental consequences of the Chernobyl accident.

Environmental Consequences (IAEA 2006, UNSCEAR 2010)

Radionuclide release and deposition

Major releases of radionuclides from Unit 4 of the Chernobyl NPP continued for ten days following the April 26 explosion. These included radioactive gases, condensed aerosols and a large amount of fuel particles. The total release of radioactive substances was about 14 EBq, including 1.8 EBq of iodine-131, 0.085 EBq of ^{137}Cs, 0.01 EBq of ^{90}Sr and 0.003 EBq of plutonium radioisotopes. The noble gases contributed about 50% of the total release. The most up-to-date estimates of the amounts released are similar to those of the UNSCEAR 2000 Report (UNSCEAR 2000), except for the refractory elements, which are now about 50% lower (Kashparov et al 2003).

More than 200,000 square kilometres of Europe received levels of ^{137}Cs above 37 kBq m^{-2}, (De Cort et al. 1998). Over 70 percent of this area was in the three most affected countries, Belarus, Russia and Ukraine. The deposition was extremely varied, as it was enhanced in areas where it was raining when the contaminated air masses passed. Most

[3] International Atomic Energy Agency (IAEA), World Health Organization (WHO), United Nations Development Programme (UNDP), Food and Agriculture Organization (FAO), United Nations Environment Programme (UNEP), United Nations Office for the Coordination of Humanitarian Affairs (UN-OCHA), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

of the strontium and plutonium radioisotopes were deposited within 100 km of the destroyed reactor due to larger particle sizes.

Many of the most significant radionuclides have decayed away. The releases of radioactive iodines caused great concern immediately after the accident. For the decades to come ^{137}Cs will continue to be of greatest importance, with secondary attention to ^{90}Sr. Over the longer term (hundreds to thousands of years) the plutonium isotopes and americium-241 will remain, although at levels that are not significant radiologically.

Environmental transfer

In the early months after the accident, the radionuclide levels of agricultural plants and plant-consuming animals was dominated by surface deposits. The deposition of iodine-131 caused the most immediate concern, but the problem was confined to the first two months after the accident because of ^{131}I decay. The radioiodine was rapidly absorbed into milk leading to significant thyroid doses to people consuming milk, especially children in Belarus, Russia and Ukraine. In the rest of Europe increased levels of ^{131}I in milk were observed in some southern areas, where dairy animals were already outdoors. After the early phase of direct deposit, uptake of radionuclides through plant roots from soil became increasingly important. Radioisotopes of caesium (^{137}Cs and ^{134}Cs) were the nuclides which led to the largest problems. The radiocaesium content in foodstuffs was influenced not only by deposition levels but also by types of ecosystem and soil as well as by management practices. In addition, ^{90}Sr could cause problems in areas close to the reactor, but at greater distances its deposition levels were low. Other radionuclides such as plutonium isotopes and ^{241}Am did not cause real problems in agriculture, both because of low deposition levels and poor availability for root uptake from soil.

In general, there was a substantial reduction in the transfer of radionuclides to vegetation and animals in intensive agricultural systems in the first few years after deposition, as would be expected due to weathering, physical decay, migration of radionuclides down the soil, reductions in bioavailability in soil and due to countermeasures. However, in the last decade there has been little further obvious decline, by 3-7 percent per year.

Currently, ^{137}Cs activity concentrations in agricultural food products are generally below national and international action levels. However, in some limited areas with high radionuclide deposition (parts of the Gomel and Mogilev regions in Belarus and the Bryansk region in Russia) or poor organic soils (the Zhytomir and Rovno regions in Ukraine) milk may still be produced with ^{137}Cs activity concentrations that exceed national action levels of 100 Bq kg^{-1}. In these areas countermeasures and environmental remediation may still be warranted.

The uptake and retention of ^{137}Cs has generally been much higher in semi-natural ecosystems than in agricultural ecosystems, and the clearance rate from forest ecosystems is extremely slow. The highest levels in foodstuffs continue to be in mushrooms, berries, game and reindeer.

Levels of radionuclides in rivers and lakes directly after the accident fell rapidly and are now generally very low in water used for drinking and irrigation, although the radiocaesium levels in the water and fish of some closed lakes have fallen only slowly. Levels in seawater and marine fish were much lower than in freshwater systems.

The deposition in urban areas could have initially given rise to a substantial external dose. However, due to radioactive decay, wind, rain and human activities, including traffic, street washing and cleanup, surface contamination by radioactive materials and air dose rate has been reduced significantly in inhabited and recreational areas since 1986, Fig. 1.

At present, in most of the settlements subjected to radioactive contamination as a result of Chernobyl, the air dose rate above solid surfaces has returned to the background level predating the accident. But the air dose rate remains elevated above undisturbed soil in gardens and parks in some settlements of Belarus, Russia and Ukraine.

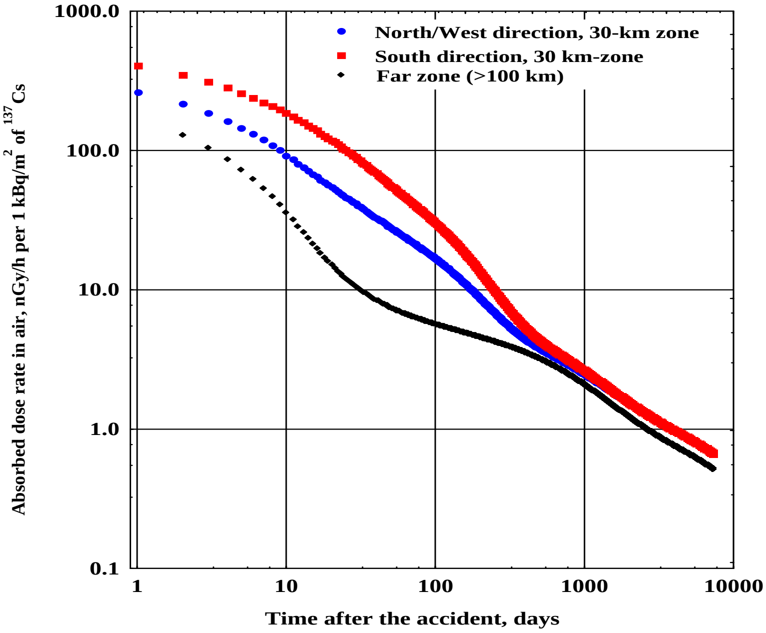

Fig. 1. Dynamics of standardised dose rate in air over undisturbed soil after the Chernobyl accident in different geographical areas (Golikov 2006).

Environmental countermeasures

The Soviet authorities introduced a wide range of short- and long-term environmental countermeasures to mitigate the accident's consequences. The countermeasures involved huge human, financial and scientific resources.

Decontamination of settlements in the affected regions of the USSR during the first years after the Chernobyl accident was successful in reducing the external dose when its implementation was preceded by proper remediation assessment. However, the decontamination has produced a disposal problem due to the considerable amount of low-level radioactive waste that was created.

In the first few weeks, management of animal fodder and milk production (including prohibiting the consumption of fresh milk) would have helped significantly to reduce the doses to the thyroid due to radioiodine. However, wide implementation of early countermeasures in the former Soviet Union was flawed, because timely advice was lacking, particularly for private farmers. Many European countries changed their agricultural practices and/or withdrew food, especially fresh milk, from the supply chain, and, in Poland, iodine prophylaxis was promptly organized; these actions generally reduced thyroid doses in those countries to negligible levels.

Over the months and years after the accident, the authorities of the former Soviet Union introduced an extensive set of agricultural countermeasures. These helped to reduce the long-term exposures from the long-lived radionuclides, notably radiocaesium. During the first few years, substantial amounts of food were removed from human consumption because of concerns about the radiocaesium levels, especially in milk and meat. In addition, pasture was treated, and clean fodder and caesium binders were provided to livestock, resulting in considerable reductions in dose.

In addition, countermeasures were instigated to reduce exposures from living and working in forests and using forest products. They included: restrictions on access; restrictions on harvesting of forest foods, such as game, berries and mushrooms; restrictions of the gathering of firewood; and alteration of hunting practices.

Early restrictions on drinking water and changing to alternative supplies reduced internal doses from aquatic pathways in the initial period. Restrictions on the consumption of freshwater fish from some lakes also proved effective in Scandinavia and Germany. Other countermeasures to reduce the transfer of radionuclides from soil to water systems were generally ineffective.

Radiation-induced effects on plants and animals

Radiation of radionuclides released from the accident caused numerous acute adverse effects on the plants and animals living in the higher exposure areas, i.e., in localized sites at distances up to about 30 kilometres from the release point. Outside this area, no acute radiation-induced effects in plants and animals have been reported.

The response of the natural environment to the accident was a complex interaction between radiation dose, radiosensitivity and recovery of the different plants and animals. Both individual and population effects caused by radiation-induced cell death have been observed in biota inside the 30-km area as follows:

- Increased mortality of coniferous plants, soil invertebrates and mammals; and
- Reproductive losses in plants and animals.

Following the natural reduction of exposure levels due to radionuclide decay and migration, biological populations have been recovering from acute radiation effects. As soon as by the next growing season following the accident, population viability of plants and animals had substantially recovered as a result of the combined effects of reparation and repopulation from less affected areas. A few years were needed for recovery from major radiation-induced adverse effects in plants and animals.

Genetic effects of radiation, in both somatic and germ cells, have been observed in plants and animals during the first few years after the Chernobyl accident. Different cytogenetic anomalies attributable to radiation continue to be reported from experimental studies. Whether the observed cytogenetic anomalies in somatic cells have any detrimental biological significance is not known.

The recovery of affected biota in the exclusion zone has been facilitated by the removal of human activities, e.g., termination of agricultural and industrial activities. As a result, populations of many plants and animals have eventually expanded, and the present environmental conditions have had a positive impact on the biota in the 30-km area. Indeed, this area has paradoxically become a unique sanctuary for biodiversity.

Radiation doses to exposed population groups (IAEA 2006, UNSCEAR 2010)

The following population categories were exposed from the Chernobyl accident:

- Emergency and recovery operation workers who worked at the Chernobyl power plant and in the exclusion zone after the accident;
- Inhabitants evacuated from abandoned areas of Belarus, Russia and Ukraine; and
- Inhabitants of areas with radioactive fallout, who were not evacuated.

With the exception of the on-site reactor personnel and the emergency workers who were present near the destroyed reactor during the time of the accident and shortly afterwards, most of recovery operation workers and people living in the contaminated territories received relatively low whole-body radiation doses, comparable to background radiation levels accumulated over the 20 year period since the accident (Table 1). For comparison, the annual average effective dose from natural background radiation is 2.4 mSv.

Table 1. Summary of updated dose estimates for the main population groups exposed from the Chernobyl fallout

Population group	Size (thousands)	Average thyroid dose in 1986 (mGy)	Average effective dose [b] in 1986-2005 (mSv)	Collective thyroid dose in 1986 (man Gy)	Collective effective dose [b] in 1986–2005 (man Sv)
Recovery operation workers (1986-1990) [a]	530	NA	117 [a]	NA	61 200
Evacuees (1986)	115	490	31	57 000	3 600
Inhabitants of areas of strict radiation control [c]	216	NA	61	NA	13 100
Inhabitants of contaminated areas [c]	6 400	102	9	650 000	58 900
Inhabitants of Belarus, Russia (19 regions) and Ukraine	98 000	16	1.3	1 600 000	125 000
Inhabitants of distant European countries [d]	500 000	1.3	0.3	660 000	130 000

NA – Data not available.

a Effective dose estimates for the workers include only the doses from external irradiation.

b Effective dose estimates are the sum of the contributions from external and internal irradiation, excluding the thyroid dose.

c The contaminated areas were defined in the former Soviet Union as areas where the ^{137}Cs levels on soil were greater than 37 kBq/m^2 and areas of strict radiation control - where the ^{137}Cs levels were greater than 555 kBq/m^2.

d All the European countries except the three republics, Turkey, countries of the Caucasus, Andorra, and San Marino.

Compared to the UNSCEAR 2000 report: (a) dose estimates have been updated for a larger number of the Belarusian, Russian, and Ukrainian recovery operation workers (510,000 instead of 380,000), and new information is presented on the Estonian, Latvian, and Lithuanian recovery operation workers; (b) thyroid dose estimates have been updated for the Belarusian and Ukrainian evacuees, and new information is presented for the Russian evacuees; (c) the estimation of thyroid and effective doses has been expanded from 5 million to 100 million inhabitants of the three republics; and (d) thyroid and effective dose estimates have been updated for the 500 million inhabitants of other European countries.

The highest doses were received by emergency workers and on-site personnel, in total less than 1,000 people, during the first days of the accident, ranging up to 20 Gy, which was fatal for some of the workers. The doses received by recovery operation workers, who worked for short periods during four years following the accident ranged from less than 10 mSv to more than 1,000 mSv, although about 85% of the recorded doses were in the range 20–500 mSv, with an average of about 117 mSv.

The collective effective dose to the 530,000 recovery operation workers is estimated to have been about 60,000 man Sv. This may, however, be an overestimate, as conservative assumptions appear to have been used in calculating some of the recorded doses.

Effective doses to the persons evacuated from the Chernobyl accident area in the spring and summer of 1986 were estimated to be about 30 mSv on average, mostly from external gamma radiation, with the highest dose of the order of several hundred mSv.

The high thyroid doses among the general population were due almost entirely to drinking fresh milk containing ^{131}I in the first few weeks following the accident. Figure 2 presents the estimated average thyroid dose to children and adolescents in 1986. The average thyroid dose to the evacuees is estimated to have been about 500 mGy (with individual values ranging from less than 50 mGy to more than 5,000 mGy). For the more than six million residents of the contaminated areas of the former Soviet Union who were not evacuated, the average thyroid dose was about 100 mGy, while for about 0.7% of them, the thyroid doses were more than 1,000 mGy. The average thyroid dose to pre-school children was some 2 to 4 times greater than the population average. For the 98 million residents of the whole Belarus and Ukraine and 19 oblasts of the Russian Federation, the average thyroid dose was much lower, about 20 mGy; most (93%) received thyroid doses of less than 50 mGy. The average thyroid dose to residents of the other European countries was about 1.3 mGy.

The collective thyroid dose to the 98 million residents of the former Soviet Union was some 1,600,000 man Gy. At the country level, the collective thyroid dose was highest in Ukraine, with 960,000 man Gy distributed over a population of 51 million people. At the regional level, the highest collective thyroid dose of about 320,000 man Gy was to the population of the Gomel oblast, corresponding to an average thyroid dose of about 200 mGy.

As far as whole body doses are concerned, the six million residents of the contaminated areas of the former Soviet Union received average effective doses for the period 1986–2005 of about 9 mSv, whereas for the 98 million people considered in the three republics, the average effective dose was 1.3 mSv, a third of which was received in

1986. This represents a minor increase over the dose due to background radiation over the same period (50 mSv). About three-quarters of the dose was due to external exposure, the rest being due to internal exposure. About 80% of the lifetime effective doses had been delivered by 2005.

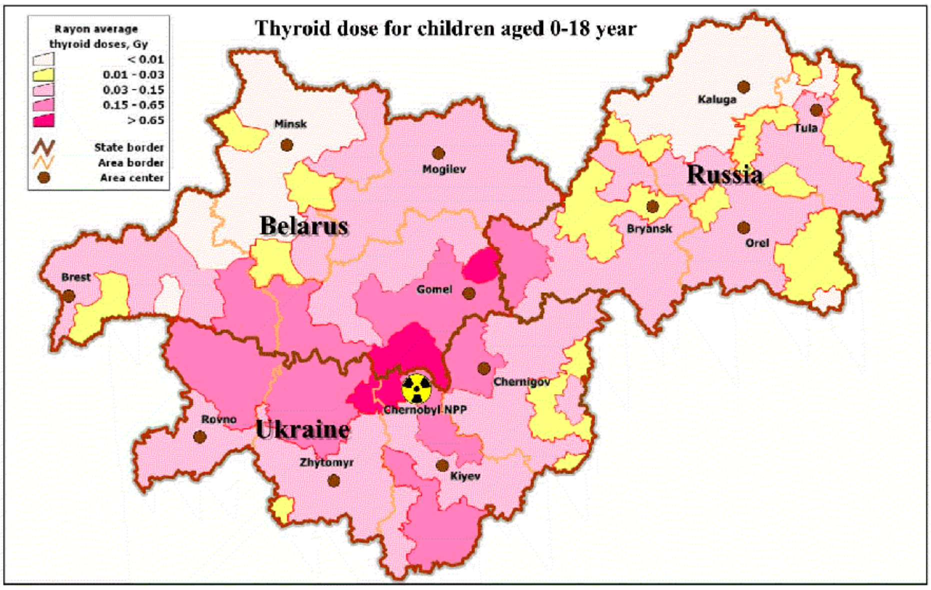

Fig. 2. The estimated district-average thyroid doses to children and adolescents living at the time of the accident in the most affected regions of Belarus, Russia and Ukraine (Russian National Medical and Dosimetric Registry 2006).

However, about 150,000 people living in the most contaminated areas received an effective dose of more than 50 mSv over the 20-year period. For the population of about 500 million in other countries of Europe, the average effective dose is estimated to have been 0.3 mSv over this period. The collective effective dose is estimated at about 125,000 man Sv to the combined populations of Belarus, Ukraine and the relevant parts of Russia, and about 130,000 man Sv to population in the rest of Europe.

Early health effects (UNSCEAR 1988, 2010)

A total of 237 emergency workers were initially examined for signs of ARS that was verified in 134 of these individuals. Of these 134 patients, 28 died within the first four months, their deaths being directly attributable to the high radiation doses.

The dominant exposures were external irradiation of the whole body at high dose rates and beta irradiation of the skin. Internal contamination was of relatively minor importance, while neutron exposure was insignificant. Underlying bone marrow failure from the external whole body irradiation was the major contributor to all the deaths during the first two months.

Each patient with bone-marrow syndrome of Grade III–IV usually also had serious radiation damage to the skin that aggravated other conditions. Skin doses exceeded bone marrow doses by a factor of 10–30, and many ARS patients received skin doses up to 500 Gy. Radiation burns to the skin were felt to be a major contributor to at least 19 of the deaths and significantly increased the severity of the ARS, especially when skin burns exceeded 50% of the body surface area and led to major infections. After

50–60 days, if the skin was not healing, a number of patients received skin graft surgery. In addition, the leg of one patient was amputated more than 200 days after the accident, gastrointestinal syndrome was seen in 15 patients and radiation pneumonitis in 8 patients.

There were no cases of ARS among the general public, either among those evacuated or those not evacuated. This is consistent with the assessment of the radiation exposures, which showed that the whole body radiation doses to members of the general public were much lower than the well-known dose thresholds for ARS.

Late health effects (UNSCEAR 2010, WHO 2006)

ARS survivors

Among the 106 patients surviving ARS, haematopoietic recovery occurred within a matter of few months. However, recovery of the immune system took at least half a year, and complete normalization several years. Cataracts, scarring and ulceration are important ongoing problems in the ARS survivors. Between 1990 and 1996, 15 ARS survivors with extensive skin injuries underwent surgery. Most ARS survivors had suffered functional sexual disorders up to 1996; however, 14 normal children were born to survivor families within the first five years of the accident.

The major health consequences from the radiation exposure of the ARS survivors remain the skin injuries and radiation-induced cataracts. The current nature and severity of the skin injuries depend on their severity during the early period. Patients who had suffered first-degree skin injuries displayed various levels of skin degeneration, ranging from slight smoothing of the skin surface to more pronounced changes. However, over longer periods, the slight changes disappeared almost completely. With third- and fourth-degree injuries, there were areas of scarring, contractures, and radiation-induced ulcers. However, since the early 1990s, microsurgery techniques have significantly reduced the problems of radiation-induced ulcers.

Many of the patients who suffered moderate or severe ARS, developed radiation-induced cataracts in the first few years after the accident, with a strong correlation between the grade of ARS and cataract prevalence.

Over the period 1987–2006, 19 ARS survivors died for various reasons. As time progressed, assignation of radiation as the cause of death has become less clear.

The follow-up of the ARS survivors indicates that: the initial haematological depression has recovered substantially in many patients; there remain significant local injuries; there has been an increase in haematological malignancies; and the increase in other diseases is probably largely due to ageing and other factors not related to radiation exposure.

Thyroid cancer

A substantial increase in thyroid cancer incidence has occurred in the three republics (the whole of Belarus and Ukraine, and the four most affected regions of Russia) since the Chernobyl accident among those exposed as children or adolescents. Amongst those under age 14 years in 1986, 5,127 cases (under age 18 years in 1986, 6,848 cases) of thyroid cancer were reported between 1991 and 2005 (Ivanov et al 2006). A substantial fraction of those cases was caused by internal exposure of thyroids of local residents with incorporated radioiodine.

Figure 3 demonstrates that in Belarus, after the Chernobyl accident in 1986, thyroid cancer incidence rates among children under age 10 years increased dramatically and subsequently declined, specifically for those born after 1986 (see 1996–2005). This pattern suggests that the dramatic increase in incidence in 1991–1995 was associated with the accident. The increase in the incidence of thyroid cancer among children and adolescents began to appear about 5 years after the accident and persisted up until 2005. The background rate of thyroid cancer among children under age 10 years is approximately 2 to 4 cases per million per year.

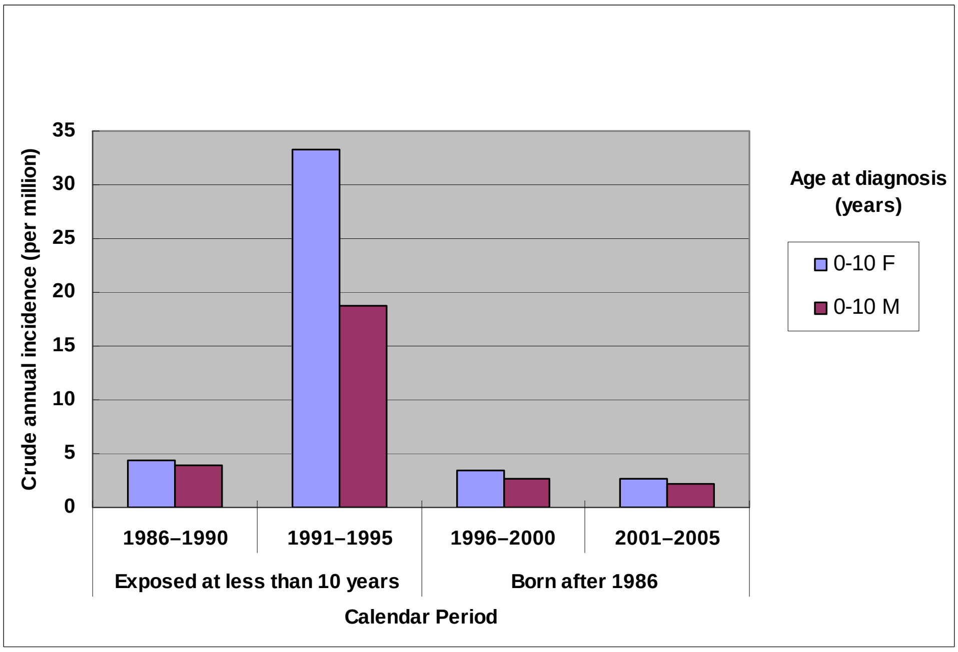

Fig. 3. Thyroid cancer incidence rate in Belarus for children under 10 years old at diagnosis

This increase has been confirmed in several case-control and cohort studies that have related the excess incidence of thyroid cancer to the estimated individual doses due primarily to the radioiodine released during the accident. There is little suggestion of increased thyroid cancer incidence among those exposed as adults in the general population.

Evidence has also emerged since the UNSCEAR 2000 Report indicating that iodine deficiency might have influenced the risk of thyroid cancer resulting from exposure to the radioactive isotopes of iodine released during the accident (Cardis et al 2005).

Leukaemia, Solid Cancers and Circulatory Diseases

Given the level of doses received, it is likely that studies of the general population will lack statistical power to identify radiation-induced risk of leukaemia, although for higher exposed emergency and recovery operation workers an increase may be detectable. The most recent studies suggest a two-fold increase in the incidence of leukaemia between 1986 and 1996 in Russian emergency and recovery operation workers exposed to external dose of more than 150 mGy. Since the risk of radiation-

induced leukaemia decreases few decades after exposure, its contribution to morbidity and mortality is likely to become less significant as time progresses.
There have been many post-Chernobyl studies of leukaemia and cancer morbidity in the populations of 'contaminated' areas in the three countries. So far, there is no convincing evidence that the incidence of leukaemia or cancer (other than thyroid) has increased in children, those exposed *in-utero*, or adult residents. It is thought, however, that for most solid cancers, the minimum latent period is of the order of 10 years or more – and it may be too early to evaluate the full radiological impact of the accident.

There appears to be some recent increase in morbidity and mortality of Russian emergency and recovery operation workers caused by circulatory system diseases. Incidence of circulatory system diseases should be interpreted with special care because of the possible indirect influence of confounding factors, such as stress and lifestyle (smoking, alcohol consumption, etc.)

Cataract

Clinically significant cataracts developed in some of the ARS survivors exposed to high radiation doses. In addition, the recently completed Ukrainian–American Chernobyl Ocular Study (Worgul et al 2007) indicates that lens opacity arising in the recovery operation workers is related to the dose received. A key finding was that the data were not compatible with a dose–effect threshold of more than 0.7 Gy, and that the lower boundary of the estimated dose threshold was close to the current dose limit for the lens of the eye, i.e. 150 mSv, although this needs to be tempered by consideration of the uncertainties in the dosimetry.

It should be noted that the main findings pertain to subclinical cataracts: 96% of observed cases were Grade I opacities. Whether or not some fraction of the radiation-associated Grade I opacities eventually progress to become more severe vision-disabling cataracts remains to be resolved.

Psychological and mental health problems (Chernobyl Forum 2006, WHO 2006)

Stress symptoms, depression, anxiety (including post-traumatic stress symptoms), and medically unexplained physical symptoms have been reported in Chernobyl-exposed populations. The studies also found that exposed populations were more likely to report subjective poor health than were unaffected control groups. In general, the social context in which the Chernobyl accident occurred makes the findings difficult to interpret because of the complicated series of events unleashed by the accident, the multiple extreme stresses and culture-specific ways of expressing distress.

In addition, individuals in the affected populations were officially categorized as "sufferers", and came to be known colloquially as "Chernobyl victims". This label, along with the extensive government benefits had the effect of encouraging individuals to think of themselves fatalistically as invalids. Thus, rather than perceiving themselves as "survivors," many of those people have come to think of themselves as helpless, weak and lacking control over their future.

Other findings of the Chernobyl Forum (Chernobyl Forum 2006, IAEA 2008)

The Chernobyl Forum also considered social and economic consequences of the Chernobyl accident that are out of scope of this paper. The Forum also elaborated practical Recommendations to the Governments of Belarus, the Russian Federation and Ukraine on health care and research, on environmental monitoring, remediation and research and those for economic and social policy that can be found elsewhere (Chernobyl Forum 2006, IAEA 2008).

Conclusions

From this paper based on 20 years of studies, it can be concluded that although those exposed to radioiodine as children or adolescents and the emergency and recovery operation workers who received high doses are at increased risk of radiation-induced effects, the vast majority of the population need not live in fear of serious health consequences from the Chernobyl accident.

Most of the workers and members of the public were exposed to low level radiation comparable to or, at most, a few times higher than the natural background levels, and exposures will continue to decrease as the deposited radionuclides decay or are further dispersed in the environment. This is true for populations of the three countries most affected by the Chernobyl accident, Belarus, the Russian Federation and Ukraine, and all the more so, for populations of other European countries. Lives have been disrupted by the Chernobyl accident, but from the radiological point of view, generally positive prospects for the future health of most individuals involved should prevail.

References

Cardis, E., A. Kesminiene, V. Ivanov et al. Risk of thyroid cancer after exposure to ^{131}I in childhood. J. Natl. Cancer Inst. 97(10): 724-732 (2005).

The Chernobyl Forum. Chernobyl's Legacy: Health, Environmental and Socio-Economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine. The Chernobyl Forum: 2003-2005. IAEA, Vienna (2006).

De Cort M, Dubois G, Fridman ShD et al. Atlas of Caesium Deposition on Europe after the Chernobyl Accident. Luxembourg: European Commission; Rept EUR 16733 (1998).

Golikov, V.Yu. In: IAEA (2006).

International Advisory Committee. International Chernobyl Project. Technical Report. IAEA: Vienna (1991).

International Atomic Energy Agency. Medical Aspects of the Chernobyl Accident. TECDOC-516, IAEA: Vienna (1989).

International Atomic Energy Agency. One Decade after Chernobyl. Summing up the Consequences of the Accident. Proceedings of an International Conference, IAEA: Vienna (1996).

International Atomic Energy Agency. Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty years of experience. IAEA: Vienna (2006).

International Atomic Energy Agency. Chernobyl: Looking Back to Go Forward. Proceedings of an International Conference. IAEA: Vienna (2008).

International Nuclear Safety Advisory Group. The Chernobyl Accident: Updating of INSAG-1. Safety Series No. 75-INSAG-7, IAEA: Vienna: (1993).

Ivanov, V.K., Ya. Kenigsberg, N.D. Tronko et al. Communication to the UNSCEAR Secretariat (2006).

Karaoglou A, Desmet G, Kelly GN and Menzel H.G., eds. The Radiological Consequences of the Chernobyl Accident. European Commission: Luxembourg, Report EUR 16544 EN (1996).

Kashparov, V.A., S.M. Lundin, S.I. Zvarich et al. Territory Contamination with the Radionuclides Representing the Fuel Component of Chernobyl Fallout. Sci. Total Environ. 317(1): 105-119 (2003).

Russian National Medical and Dosimetric Registry. District-average thyroid doses in children and adolescents in Belarus, Russia and Ukraine. Bulletin Radiation and Risk, 15 (3-4), 86-87: 2006 (in Russian).

United Nations. Strengthening of international cooperation and coordination of efforts to study, mitigate and minimize the consequences of the Chernobyl disaster. Resolution A/60/L.19 of the 60th Session of the UN General Assembly (2005).

United Nations Development Programme and the United Nations Children's Fund. Human Consequences of the Chernobyl Nuclear Accident – A Strategy for Recovery. New York (2002).

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources, Effects and Risks of Ionizing Radiation; Annexes D and G. United Nations: New York (1988).

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and Effects of Ionizing Radiation (2000 Report to the General Assembly, with Annexes); Annex J. United Nations: New York, Volume II: 451–566 (2000).

United Nations Scientific Committee on the Effects of Atomic Radiation. Health Effects due to Radiation from the Chernobyl Accident. To be published (2010).

World Health Organisation. Health Effects of the Chernobyl Accident and Special Health Care Programmes. WHO: Geneva (2006).

Worgul, B.V., Y.I. Kundiyev, N.M. Sergiyenko et al. Cataracts among Chernobyl Clean-up Workers: Implications Regarding Permissible Eye Exposures. Radiat. Res. 167(2): 233-243 (2007).