Health Effects of Reactor Accidents with Special Regards to Chernobyl —A Review Paper

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In the history of the world nuclear industry there were four major accidents of operating nuclear reactors, i.e., at plutonium production facility in Windscale, UK, 1957; at NPP Three Mile Island, USA, 1979; at Chernobyl NPP, USSR, 1986; and at Fukushima-1 NPP, Japan, in 2011. The Chernobyl accident was the most severe, causing a huge release and deposition of radionuclides over large areas of Europe. Only after this accident there were real health effects caused by radiation, including carcinogenic effect among the population of the adjacent areas of Belarus, Russia and Ukraine. In this paper, same-type basic radiological characteristics are presented for four reactor accidents with more detail presented for the Chernobyl accident. The latter include mean radiation doses incurred by various groups of inhabitants of the three more affected countries, Belarus, Russia and Ukraine. Those who were children at the time and drank milk with high levels of radioactive iodine received high thyroid doses. Since early 1990s there was dramatic increase in thyroid cancer incidence among those exposed to radioiodine at a young age. Apart from this kind of health effects there was no clearly demonstrated increase in the somatic diseases due to radiation. The paper discusses the reasons why the Chernobyl accident had severe radiological consequences.

KEY WORDS: radiation, environmental release, nuclear accident, effective dose, thyroid dose, Windscale accident, TMI accident, Chernobyl accident, Fukushima-1 accident, health effect, thyroid cancer.

Table of contents:
I Introduction: History of major nuclear reactor accidents
II Human exposure pathways and potential health consequences
III Fire at the reactor for Pu production at Windscale, UK, in 1957
IV Core melting at the NPP Three Mile Island, USA, in 1979
V Explosion of the reactor at the Chernobyl NPP, USSR, in 1986
VI Core melting of three reactors at Fukushima-1 NPP, Japan, in 2011
VII Discussion and conclusions

I INTRODUCTION: HISTORY OF MAJOR NUCLEAR REACTOR ACCIDENTS

Experts realized the danger of nuclear reactor accidents for human health and developed measures of prevention and response since the 1950s. In subsequent decades, dozens of local accidents at critical assemblies and research reactors contributed to increased attention to reactor accidents. Many of them led to the death of workers or detriment to their health.

The danger of an accident at an operating nuclear reactor is due, on the one hand, to the presence in it of a huge activity of nuclear fission and neutron activation products, and on the other —the possibility of a rapid increase in power or insufficient heat elimination, up to an explosion.

Quantitative risk assessment for both workers and members of the public was necessary in order to develop measures of prevention and response in case of a reactor accident. The major achievement in that field was the US AEC/NRC report WASH-1400 ‘Reactor Safety Study’, 1975, unofficially called ‘The Rasmussen report’. This report quantified risk of radiological consequences of a reactor accident including acute and stochastic health effects.

The first accident of a nuclear reactor, which was accompanied by a significant release of volatile radionuclides into the environment, occurred at a plutonium production plant in the UK, Windscale, in 1957. Although the risks of exposure of workers and the public in such cases were generally understood since 1975 and preventive measures have been taken, three more major reactor accidents occurred in the following four decades: at Three Mile Island NPP in Pennsylvania, USA, in 1979, at the Chernobyl NPP in the Kiev region, USSR, in 1986, and at Fukushima-1 NPP in the Fukushima prefecture, Japan, in 2011. In the most severe of them, the Chernobyl accident, there were significant health consequences, even lethal, among workers, as well as remote stochastic consequences for workers and the population of the
surrounding area.\(^3\)

This review article will briefly compare the radiological consequences of four major nuclear reactor accidents (in chronological order) in terms of radioactive releases and exposure levels of the general public, as well as present an overview of the health consequences of the Chernobyl accident for the population of Belarus, Russia, and Ukraine, which were observed during the past 30 years.

II HUMAN EXPOSURE PATHWAYS AND POTENTIAL HEALTH CONSEQUENCES

When an accident of a nuclear reactor leads to a significant release of radioactive substances into the environment, the population may be exposed to radiation through several pathways. The contribution of each exposure pathway to the total dose depends on the type of accident, the extent and isotopic composition of the release, environmental transfer, lifestyle and dietary habits of the population.

In the most general case of airborne release, there are several pathways whereby humans can be exposed to radioactive materials — Fig. 1.\(^4\) The main pathways are listed below in the approximate time sequence within which the doses would have been received.

1. External radiation direct from cloud;
2. Internal dose from inhalation of radioactive materials in the air;
3. External dose from radioactive materials deposited on the ground; and
4. Internal dose from eating and drinking radioactive materials in food and water.

Under most exposure conditions for members of the general public the two more important pathways are items three and four above, i.e. exposure to radiation from the decay of radionuclides deposited on the soil and other surfaces and from the ingestion of contaminated food and water. If persons would have been evacuated quickly after passage of the initial cloud, then the more important pathways would have been the first two items because the latter two pathways would have been prevented.

The spectrum of health consequences of a nuclear reactor accident for the population of the territory exposed to radiation from a passing cloud and from fallout is extremely wide. In the early period after the accident, doses can be high (above 0.5 Gy) and, under adverse circumstances, cause deterministic health effects up to radiation sickness.\(^2,\ 3\) Depending on the levels and conditions of irradiation, these can be harmful effects in the red bone marrow, lungs, thyroid gland, lens of the eye, etc. However, in practice, such effects in the population have not been observed in any of the above listed accidents. As a result of the Chernobyl accident, the deterministic effects were possible because of high radiation levels, for example, in the closely located town of Pripyat, but the residents were timely evacuated.\(^3,\ 4\)

In the entire dose range, starting with low dose, radiation can cause stochastic health effects in the population.\(^1–3\) Depending on the extent and composition of the release, these can be tumors of the thyroid gland and leukemia, especially in children, as well as solid cancers in other organs. Historically, after accidents in nuclear reactors, only an increase in thyroid cancers in children in the Chernobyl affected zone was observed, see below.

III FIRE AT THE REACTOR FOR PU PRODUCTION AT WINDSCALE, UK, IN 1957

Chronologically, the first accident of a nuclear reactor with the release of a significant amount of radionuclides into the environment was a fire at a plutonium production plant in Windscale, UK, that happened on October 10, 1957. The cause of the fire, which lasted about half a day, was overheating of the fuel and graphite moderator during its planned annealing.
Emissions of volatile radionuclides occurred during the day through a stack 120 m high under changing weather conditions. The main fallouts occurred in northwest England; however, fallout traces were also detected in continental Europe.\textsuperscript{5,14} The total emission of the most radiologically significant \(^{131}\text{I}\) was estimated at 600–740 TBq,\textsuperscript{1,2} but later this estimate was increased to 1,800 TBq,\textsuperscript{9} taking into account a larger number of measurements in the environment. Along with \(^{131}\text{I}\), a comparable amount of \(^{132}\text{Te}\) was released, as well as about 180 TBq of \(^{137}\text{Cs}\) and 42 TBq of \(^{210}\text{Po}\).\textsuperscript{9} The retrospective assessment of the radiological significance of the accident in Windscale, 1957, was given at a level of 5–6 out of a possible 7 International Nuclear and Radiological Event Scale (INES) levels.\textsuperscript{6,7}

The main exposure pathway of the population of England, especially of children and adolescents, was the consumption of milk contaminated with \(^{131}\text{I}\) through environmental chain. At the insistence of experts, the consumption of locally produced milk was prohibited for about a month in an area of about 500 km\(^2\) around the enterprise.\textsuperscript{5,12}

Taking into account the measured \(^{131}\text{I}\) concentrations in milk and air and especially its activity in the thyroid gland of about two dozen adult residents of Leeds and London, the average doses in the adult thyroid were estimated at about 2 mGy in the 100 km radius, about 1 mGy to 200 km radius in the south-east direction and less than 1 mGy throughout the rest of England.\textsuperscript{5} The average thyroid doses in children of different age groups could be 1.5–7 times higher than in adults.\textsuperscript{13} Effective doses, mainly due to \(^{131}\text{I}\) intake with food and \(^{210}\text{Po}\) inhalation, were estimated by CRICK and LINSLEY by an order of magnitude lower than the thyroid dose in adults.\textsuperscript{5} Thus, both the thyroid doses and the effective doses in the population of England turned out to be small.

The calculation of the health risk to the population of England from exposure to radioactive emissions of the Windscale accident was made by CRICK and LINSLEY in 1982–1984\textsuperscript{4,9} and continued by R. CLARK in 1990.\textsuperscript{14} In these papers, it was predicted that radiation would eventually cause about 100 fatal cancers (largely lung cancers due to inhalation of \(^{210}\text{Po}\)) and another 100 of non-fatal thyroid cancers resulting from intakes of \(^{131}\text{I}\); these predicted effects would occur throughout England over many years.\textsuperscript{5,12,14} Therefore, the detection of these effects above spontaneous morbidity is unlikely.

Nevertheless, a large-scale epidemiological study of the incidence of thyroid cancer in the period 1974–2012 was carried out in the North West of England.\textsuperscript{15} This ecological study revealed a significant increase in the incidence rate (by a factor of 1.3 relative to the rest of England) for those aged less than 20 years in 1958 living in Cumbria. However, for final judgment on the radiogenic origin of this effect, further analytical investigation is necessary.

### IV CORE MELTING AT THE NPP THREE MILE ISLAND, USA, IN 1979

The second major nuclear reactor accident with the environmental release of radioactive substances occurred on March 28, 1979, at the 2nd PWR type unit at the NPP Three Mile Island, Pennsylvania, USA. The cause of the accident was a combination of equipment malfunctions, design-related problems and worker errors that led to loss of core coolant and subsequent TMI-2’s partial meltdown.\textsuperscript{1,8}

Despite the fact that the integrity of the containment building was not compromised, volatile radionuclides of inert gases and iodine leaked into the atmosphere through a pipe 160 m high. The \(^{131}\text{I}\) release lasted about a month and amounted to about 0.6 TBq; the release of inert gases, mainly \(^{133}\text{Xe}\), lasted shorter and amounted about 90 PBq.\textsuperscript{8} The retrospective assessment of the radiological significance of the accident at TMI-2, 1979, was given at a level of 5 out of a possible 7 INES levels.\textsuperscript{5}

Despite the technical severity of the TMI-2 NPP accident and its significant economic and socio-psychological consequences, its radiological consequences are negligible. The risk to the health of the residents of the adjacent territory, caused by the radiation levels described above, is negligible.

| Event, country, year | Inert gases, mostly \(^{133}\text{Xe}\) | \(^{131}\text{I}\) | \(^{137}\text{Cs}\) | \(^{134}\text{Cs}\) | \(^{90}\text{Sr}\) |
|----------------------|-----------------|----------|---------|---------|---------|
| Windscale, UK, 1957  | 26               | 1.8      | 0.2     | –       | < 0.001 |
| Three Mile Island, USA, 1979 | 90            | < 0.001 | –       | –       | –       |
| Chernobyl, USSR, 1986 | 6,500          | 1,800    | 85      | 47      | 10      |
| Fukushima-1, Japan, 2011 | 7,300         | 120      | 15      | 15      | –       |
| Nuclear weapons tests, worldwide, since 1950s | NA           | 675,000 | 948     | –       | 622     |
V EXPLOSION OF THE REACTOR AT THE CHERNOBYL NPP, USSR, IN 1986

Event

The Chernobyl accident, the most severe in the history of the world nuclear industry, happened at night of 26 April 1986. Unit 4 of the Chernobyl NPP, located 130 km to the north east of Kiev, the capital of Ukraine, was destroyed by two strong explosions in the reactor core. The Chernobyl NPP was equipped with four RBMK reactors with a graphite moderator, a thermal power of 3,200 MW and an electrical power of 1,000 MW each. The explosions were caused by gross breaches of the operating procedures by staff and technical inadequacies in the safety systems.16)

Release and deposition

As a result of the explosions, highly radioactive core fragments were ejected onto the site. The red-hot graphite exposed to air caught fire and burned for 10 days. During that time period, radioactive substances were released from the destroyed reactor and spread by winds under changing weather conditions over Europe, principally Belarus, Ukraine and Russia. About 20% of the radioactive release spread beyond Europe.17)

The releases included radioactive gases, condensed aerosols and a large amount of fuel particles. The total release of radioactive substances was about 14,000 PBq, including most radiologically significant 1,800 PBq of 131I, 85 PBq of 137Cs and 10 PBq of 90Sr —see Table 1. The noble gases contributed about 50% of the total release. The retrospective assessment of the radiological significance of the Chernobyl accident, 1986, was given at the highest level 7 of 7 INES levels.7)

More than 200,000 km² of Europe received levels of 137Cs above 37 kBq m⁻².17) Over 70 percent of this area was in the three most affected countries, Belarus, Russia and Ukraine —Fig. 2. The deposition was extremely varied, as it was enhanced in areas where it was raining when the contaminated air masses passed.

Human exposure pathways

For population that was not evacuated from the affected area the consumption of food, principally with milk, contaminated with radioactive iodine was of great radiological concern over first two months after the accident. For the first decade, 131I and 134Cs were of greatest importance, both with regard of external and internal (ingestion) exposure with secondary attention to ingestion of 90Sr. Over the longer term 137Cs remained of some radiological significance.3, 4)

About six million people live in areas of Belarus, Russia and Ukraine that are ‘contaminated with radionuclides’ due to the Chernobyl accident above 0.04 MBq m⁻² of 137Cs.3, 4, 18) 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 0.6 MBq m\(^{-2}\) 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 to non-contaminated areas. Another 220,000 people were relocated in subsequent years.\(^3,4\)

**Countermeasures**

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 by about 20% when its implementation was preceded by proper remediation assessment.\(^5,18\)

In the first few weeks, protective actions against consumption of food contaminated with radiiodine, including prohibiting the consumption of fresh milk, were flawed in the former Soviet Union because timely advice was lacking, particularly for private farmers. For this reason, internal exposure of the thyroid was not substantially prevented.

Over the months and years after the accident, the authorities introduced an extensive set of agricultural countermeasures. These helped to reduce the exposures from the long lived radionuclides, notably radiocaesium.

**Doses to the public**

The population categories exposed from the Chernobyl accident are presented in Table 2 along with the mean thyroid doses incurred in 1986 from intake of \(^{131}\)I and effective doses incurred over 20 years (1986–2005) from external and internal exposure, mainly to radiation of \(^{137}\)Cs and \(^{134}\)Cs.

Most of 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. For comparison, the annual world average effective dose from natural background radiation is 2.4 mSv.

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.\(^3,19\)

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 3 presents the estimated average thyroid dose to children and adolescents in 1986.\(^3\) 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, less than 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.\(^3\)

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 countries, 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 time 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.\(^3,4\)

**Early health effects**

There were no cases of acute radiation syndrome (ARS) among the general public, either among those evacuated or those not evacuated. This is consistent with the assessment of the 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.\(^3\)

**Late health effects**

Analysis of the radiation dose in the organs of evacuated persons and residents of territories with an increased level of radioactive fallout (Table 2) indicated a possible increase

| Population group                                      | Size (thousand persons) | Average thyroid dose in 1986 (mGy) | Average effective dose a in 1986–2005 (mSv) |
|-------------------------------------------------------|-------------------------|-----------------------------------|---------------------------------------------|
| Evacuees from abandoned areas of Belarus, Russia and Ukraine (1986) | 115                      | 490                               | 31                                          |
| Inhabitants of areas of strict radiation control b    | 270                      | −400                              | 61                                          |
| Inhabitants of contaminated areas c                   | 6,400                    | 102                               | 9                                           |
| Inhabitants of Belarus, Russia (19 regions) and Ukraine | 98,000                   | 16                                | 1.3                                         |
| Inhabitants of distant European countries d           | −500,000                 | 1.3                               | 0.3                                         |

a Effective dose estimates are the sum of the contributions from external and internal irradiation, excluding the thyroid dose.
b ‘Areas of strict radiation control’ were classified at the time by Soviet authorities as those with \(^{137}\)Cs soil deposition above 0.6 MBq m\(^{-2}\).\(^3,4\)
c ‘Areas contaminated with radionuclides’ due to the Chernobyl accident were classified as those with \(^{137}\)Cs soil deposition above 0.04 MBq m\(^{-2}\).\(^3,4\)
d All the European countries except Belarus, Russia and Ukraine, Turkey, countries of the Caucasus, Andorra, and San Marino.\(^3\)
place, thyroid cancer. The greatest likelihood of detecting radiation-induced cancer was thyroid cancer in children. For obvious reasons, the most attention was paid to residents of the territories of Belarus, Russia and Ukraine, where the radiation levels were larger.

Over the past more than 30 years after the Chernobyl accident, the incidence of the following types of cancer has been studied: thyroid cancer, leukaemia and other solid cancers than thyroid cancer.

**Thyroid cancer**

A substantial increase in thyroid cancer incidence has occurred in the three countries (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 18 years in 1986, 19,233 cases of thyroid cancer were reported between 1991 and 2015. A substantial fraction of those cases (about a quarter) was most likely caused by internal exposure of thyroids of local residents with incorporated radioiodine.

**Figure 4** demonstrates that in Belarus, after the Chernobyl accident in 1986, thyroid cancer incidence rate among children under age 10 years at diagnosis increased dramatically and subsequently declined, specifically for those born after 1986 (see 1996–2015). This pattern suggests that the dramatic increase in incidence in 1991–1995 could be associated with the accident. This increase began to appear about 5 years after the accident and persisted up until 2015. The background rate of thyroid cancer among children under age 10 y is approximately 2 to 4 cases per million per year.

Ecological observations presented above were supported with several analytical studies of thyroid cancer incidence in children (as of 1986), in which 1) clear dose dependence of cancer incidence was demonstrated, and 2) very early onset (4–5 y) of cancer incidence increase and its persistence for more than 25 y was observed. Those studies included several case-control studies, e.g., and two most informative cohort studies with about 25 thousand subjects in total, each of them with individual thyroid measurement in 1986 that substantially reduced dose uncertainty. The last two cohort studies included refined radiation risk coefficients, age at exposure and gender dependence, effect of stable iodine intake, etc.

**Leukaemia and solid cancer other than thyroid cancer**

Given the level of doses received (see Table 2), it is likely that studies of the general population will lack statistical power to identify radiation-induced risk of leukaemia and solid cancer other than thyroid cancer.

Nevertheless, there have been many post-Chernobyl studies of leukaemia and cancer morbidity in the populations of ‘contaminated’ areas in the three countries. In relation to the increase in the incidence of leukemia after irradiation *in utero* or during childhood, about ten ecological studies were carried out in three countries from 1993 to 2003, and the effect was not revealed. In five analytical studies in 2002–2016, for example, the results are contradictory. The same conclusion regarding non-thyroid cancer and breast cancer alone was made in. 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.

**Non-cancer somatic effects**

In addition, the following possible non-cancer effects of radiation in the population were investigated: cataracts, cardiovascular and cerebrovascular diseases, and malformations at birth.
The only comprehensive study conducted in Ukraine found some increase in sub-clinical posterior subcapsular lens changes in children living in ‘contaminated area’. However, individual doses were not reconstructed, and this study needs further confirmation.

The growing body of epidemiological data suggest the persistence of a cardiovascular disease effect after radiation exposure in various settings. That kind of radiogenic health effect was studied in general public in Belarus and Ukraine by local medical doctors; no convincing findings have been presented so far.

Although historical studies in Japan after the atomic bombing of 1945 did not reveal significant adverse effects of the in utero exposure to the health of the newborns, this issue was also worrisome after the Chernobyl accident. The study in Belarus by LAZJUK et al. compared pre- and post-Chernobyl accident rates of nine easily diagnosed congenital malformations among abortuses and in newborns. In the period 1983–1999, there were 12,167 congenital malformations registered — Fig. 5. There has been a slow but steady increase in congenital malformations recorded in both high and low radionuclide contaminated areas, but the increase does not show a dose-response pattern. In fact, there were significantly less congenital abnormalities in the high contamination areas compared with low contamination areas, with a RR of 0.88 (95% CI 0.84–0.91).

**Psychological consequences**

Psychological consequences of the Chernobyl accident also attracted substantial attention of scientists. Stress symptoms, depression, anxiety, and medically unexplained physical symptoms have been reported in Chernobyl-exposed populations. Many people have been traumatised by the relocation, the breakdown in social contacts, fear and anxiety about what health effects might result. The studies also found that exposed populations were more likely to report subjective poor health than were unaffected control groups.

![Fig. 4 Thyroid cancer incidence rate in Belarus for children under 10 years old at diagnosis.](image1)

**Fig. 4** Thyroid cancer incidence rate in Belarus for children under 10 years old at diagnosis.

![Fig. 5 Malformations at birth in four oblasts of Belarus with high and low levels of radionuclide contamination.](image2)

**Fig. 5** Malformations at birth in four oblasts of Belarus with high and low levels of radionuclide contamination.
Mothers of young children exposed to the accident remain a high-risk group for these conditions, primarily due to worries about the adverse health effects on their families. Very young children who lived in the radiocontaminated areas have been the subject of considerable research, but the findings are inconsistent. Recent comparative studies of prenatally exposed and non-exposed children point to specific psychological impairments associated with radiation exposure, whereas other studies found no significant mental health effects in exposed children grown up. 29, 30

Generally, psychological consequences of the Chernobyl accident may have outweighed its somatic effects. Renewed efforts at risk communication, based on accurate information about the somatic and mental health consequences of the disaster, should still be undertaken.

VI CORE MELTING OF THREE REACTORS AT FUKUSHIMA-1 NPP, JAPAN, IN 2011

The recent severe accident at once of three nuclear reactors occurred on the Pacific coast of Japan at the Fukushima-1 NPP on March 11, 2011. Due to an earthquake and tsunami, the power supply of the NPP was lost, and as a result of insufficient cooling of the reactors, the active cores melted in them. To this, the overheating of the rods of spent fuel in the cooling pools was added. 9

As a result of these and related events at NPP, volatile radioactive substances were released into the atmosphere for about three weeks and leaked into the ocean. According to current estimates, inert gases, iodine, tellurium and cesium were released into the atmosphere —see Table 1. 9, 10

These releases were 3–15 times less than the releases of the Chernobyl accident. Due to the carry-over of radioactive substances into the ocean, just 2 PBqS of 137Cs and 134Cs fell to the territory of East Japan, which is 20–30 times less than the Chernobyl fallout in Europe. 10 The retrospective assessment of the radiological significance of the Fukushima-1 accident, 2011, was given at the highest level 7 of 7 INES levels. 7

The population was irradiated with radioactive plumes and fallouts from the Fukushima-1 NPP accident from March 12, 2011, along all the exposure pathways described in Section 2 for aerial release. The peculiarity of internal exposure are the following factors: a) relatively small consumption of milk, in which iodine and cesium radionuclides can concentrate; b) strong fixation of cesium radionuclides in local soils and low transfer to plants and further along the ecological chain; c) a significant proportion of food imports. In addition, in Japan, protective actions were quickly taken, i.e., evacuation and sheltering, as well as rejection of contaminated food. These fast countermeasures combined with natural features contributed to reduction of internal doses. 9

To prevent external exposure, residents of municipalities close to the NPP were evacuated, partly before emissions, and partly from already contaminated areas (Iitate village and others). 9 Evacuated municipalities were thoroughly decontaminated in 2013–2017.

The higher average effective doses for the 1st year were received by residents of municipalities close to the NPP during the evacuation period, up to 10 mSv. In non-evacuated municipalities, the highest average dose in children of Fukushima city is estimated at 7 mSv. The dose for 10 years is twice as high as the dose of the first year, mainly due to external irradiation —Table 3.

The thyroid dose was also assessed higher in evacuated younger children, in the range of municipality averages from 15 to 80 mGy. Residents of non-evacuated settlements have a slightly lower estimated thyroid dose in younger children —up to 50 mGy. 9 Work on specifying the thyroid dose to residents continues due to the high social interest.

No radiation-related deaths or acute diseases have been observed among general public exposed to radiation from the Fukushima-1 accident.

According to UNSCEAR, “The doses to the general public, both those incurred during the first year and estimated for their lifetimes, are generally low or very low. No discernible increased incidence of radiation-related health effects is expected among exposed members of the public or their descendants. The most important health effect is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation.” However, “An increased risk of thyroid cancer in particular can be inferred for infants and children”. 9

Both Japanese national institutes (JAEA, QST-NIRS and others) and international organization (UNSCEAR) continue their efforts to specify radiation doses incurred by the general public in Japan and to assess radiation-related and accident-related health effects.

VII DISCUSSION AND CONCLUSIONS

A formal comparison of the release of radioactive substances into the atmosphere (see Table 1) may lead to the conclusion that the radiological significance of global

| Table 3 | The average for a municipality or prefecture of Japan effective dose for 1 and 10 years in adults and children 1 year, mSv. 9 |
|----------|-------------------------------------------------|
| Age group (as of 2011) | Municipalities of the Fukushima prefecture | Neighboring six prefectures | The rest of Japan |
| 1st year exposure | | | |
| Adults | 1–4 | 0.2–1.4 | 0.1–0.3 |
| Children 1 y old | 2–7 | 0.3–2.5 | 0.2–0.5 |
| Ten years exposure | | | |
| Adults | 1–8 | 0.2–3 | 0.1–0.5 |
| Children 1 y old | 2–14 | 0.3–6 | 0.2–0.9 |
fallout after nuclear tests is the highest. However, most of these substances got into the high layers of the atmosphere, dispersed there, partially decayed and only gradually fell to the entire surface of the Earth. The average effective dose for the Earth population since the beginning of the tests to the present is only 1 mSv, with about half of this dose received by food ingestion. Doses to the population residing near the test sites are significantly higher due to local fallout, but this topic is beyond the scope of this article.

Among the four nuclear reactor accidents considered, the Chernobyl accident was by far the most severe because of its radiological consequences. Consider the natural, technical, and social reasons for this feature.

The first reason was the explosive nature of the destruction of the reactor, as a result of which fuel fragments were thrown out, and the hot core got in direct contact with the atmosphere. The total release of radionuclides of volatile elements (as a percentage of the reactor inventory) was 100% for inert gases, 50–60% for iodine, 20–40% for cesium, 25–60% for tellurium and 4–6% for strontium radionuclides; the release of refractory elements was about 1.5%. These release fractions are incomparably higher than in other accidents. The lack of containment in the design of the RBMK reactor also had a negative effect.

Secondly, the Chernobyl NPP is located in the depths of Europe, and most of the fallout occurred in populated areas. Not more than 20% of Cs-137 released dropped outside Europe.

Thirdly, a significant release of radionuclides lasted about 10 days under varying weather conditions, as a result of which the fallout occurred over a vast territory of most European countries.

Fourthly, in many countries of Europe, except for the northern countries, the fallout occurred during the developed vegetation period, which led to the direct contamination of plant and animal food products, especially with iodine radioisotopes.

Fifthly, internal exposure to cesium radioisotopes has made a significant contribution to the long-term exposure of the population in regions with poor agricultural sandy or organic soils, in particular, in Belarus, Russia and Ukraine.

However, the lack or delay in the use of protective actions against internal irradiation with iodine-131 played a major role in the most significant radiological consequence of the Chernobyl accident, namely in the gradual disease of several thousand children in Belarus, Russia and Ukraine with radiogenic thyroid cancer. With the exception of Pripyat, prophylaxis with stable iodine was not carried out timely. With rare exceptions, the consumption of local fresh food products and especially milk was not promptly prevented. The population of the polluted territories (about 6 million people) was not timely informed about the need for the urgent adoption of protective measures.

This happened despite the fact that the scientific basis for responding to nuclear accidents was developed; in the USSR, since 1983, there were in force criteria for making urgent decisions on measures to protect the public in case of a nuclear reactor accident. However, the huge scale of the Chernobyl accident and the slow response of the administrative system did not allow for the quick deployment of radiiodine protection measures, and after 2–3 weeks they were much less effective, since residents have already received most of the thyroid dose. This is one of the lessons of the Chernobyl accident, and these shortcomings were avoided by the Japanese authorities in 2011.

Conclusions

- Major nuclear reactor accidents may result in large radionuclide releases and subsequent adverse somatic and mental health effects of the general public.
- The health effects of the general public can be substantially mitigated with timely protective actions and environmental remediation.
- The Chernobyl accident had by far the largest radiological consequences from all the nuclear reactor accidents.
- More than 6 million people live in areas of Belarus, Russia and Ukraine with elevated radiation levels.
- The most radiologically significant exposure pathway for the public was ingestion of radiiodine with food in April–May 1986. That resulted in several thousand thyroid cancer cases in children (as of 1986).
- Further long-term external and internal exposure of the public to radiation of caesium radionuclides did not result in discernible health effects.
- Generally, psychological consequences of the Chernobyl accident may have outweighed its somatic effects.
- Vast experience of mitigation of radiological consequences of preceding nuclear reactor accidents has been successfully applied in Japan following the Fukushima-1 NPP accident in 2011.

CONFLICT OF INTEREST DISCLOSURE

The author indicated no conflicts of interest.

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