Chernobyl Accident: Exposures and Effects

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INTRODUCTION

The accident of 26 April 1986 at the Chernobyl nuclear power plant, located in Ukraine about 20 km south of the border with Belarus, was the most severe ever to have occurred in the nuclear industry. The impact of the accident on the workers and local residents has indeed been both serious and enormous. The accident caused the deaths within a few days or weeks of 30 power plant employees and firemen (including 28 deaths that were due to radiation exposure). Later on, about 240,000 workers ("liquidators") were called upon in 1986 and 1987 to take part in major mitigation activities at the reactor and within the 30-km zone surrounding the reactor. Residual mitigation activities continued until 1990; all together, about 600,000 persons received the special status of "liquidator".

In addition, massive releases of radioactive materials into the atmosphere brought about the evacuation of about 116,000 people from areas surrounding the reactor during 1986, and the relocation, after 1986, of about 220,000 people from what are at this time three independent republics of the former Soviet Union: Belarus, the Russian Federation, and Ukraine). Vast territories of those three republics were contaminated, and trace deposition of released radionuclides was measurable in all countries of the northern hemisphere. The radiation exposures of members of the public resulting from the Chernobyl accident were due initially to ^{131}I and short-lived radionuclides and subsequently to radiocaesiums (^{134}Cs and ^{137}Cs) from both external irradiation and the consumption of foods contaminated with these radionuclides.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) considered the initial radiological consequences of that accident in its 1988 Report (1). In that Report, the short-term effects and treatment of radiation injuries of workers and firefighters who were present at the site at the time of the accident were reviewed in the Appendix to Annex G, "Early effects in man of high doses of radiation", and the average individual and collective doses to the population of the northern hemisphere were evaluated in Annex D, "Exposures from the Chernobyl accident" (1). The UNSCEAR Committee now is preparing its 2000 Report, which will include an Annex on the radiation impact of the Chernobyl accident. The two main objectives of that document are (a) to review in greater detail the exposures of those most closely involved in the accident and the residents of the local areas most affected by the residual contamination and (b) to consider the health consequences that are or could be associated with these radiation exposures. Although the UNSCEAR document is still in draft form, it has been deemed useful to take the opportunity of the IRPA Congress to present its current contents and conclusions to the radiation protection community. It should be kept in mind, however, that changes may be made by the UNSCEAR Committee during its next meeting and that, in particular, numerical estimates provided in this paper may differ from those that will actually be published in the UNSCEAR Report.

CONTENTS OF THE UNSCEAR DOCUMENT

Within the last few years, several international conferences were held to review the aftermath of the accident (2-5); also, books (e.g., 6-9) and special issues of scientific journals (e.g., 10) were devoted to the Chernobyl accident. Because of the questions that have arisen about the local exposures and effects of the Chernobyl accident, the UNSCEAR Committee feels that a review of the available information at this stage, almost 15 years after the accident, is warranted. In the UNSCEAR Report, the radiation exposures of the population groups most closely involved in the accident are reviewed in detail and the health consequences that are or may potentially be associated with these radiation exposures are discussed. It is acknowledged, however, that even longer-term studies will be needed to determine the full consequences of the accident.

The populations considered are (a) the workers involved in the mitigation of the accident, either during the accident itself (including firemen and power plant personnel who received doses leading to deterministic effects) or after the accident (recovery operation workers) and (b) members of the general public who either were evacuated to avert excessive radiation exposures or who still reside in contaminated areas. The three main areas of contamination, defined as those with ^{137}Cs deposition density greater than 37 kBq m^{-2} (1 Ci km^{-2}), are in Belarus, the Russian Federation, and Ukraine; they have been designated the Central, Gomel-Mogilev-Bryansk, and Kaluga-Tula-Orel areas. The Central area is within about 100 km of the reactor, predominantly to the west and north-west. The Gomel-Mogilev-Bryansk contamination area is centred 200 km to the north-north-east of the reactor at the boundary of the Gomel and Mogilev regions of Belarus and of the Bryansk region of the

Russian Federation. The Kaluga-Tula-Orel area is located in the Russian Federation, about 500 km to the north-east of the reactor. All together, territories from the former Soviet Union with an area of about 150,000 km^2 were contaminated. About six million people reside in those territories. A large number of radiation measurements (film badges, TLDs, whole-body counts, thyroid counts, etc.) were made to evaluate the radiation exposures of the population groups that are considered. Information on the contamination levels and radiation doses in other countries is presented only if it is related to epidemiological studies conducted in those countries.

Research on possible health effects is focused on, but not limited to, the investigation of leukaemia among workers involved in the accident and of thyroid cancer among children. Other health effects that are considered are the non-cancer somatic disorders (e.g., thyroid abnormalities and immunological effects), the reproductive effects, and the psychological effects. Of particular interest are the epidemiological studies that have been undertaken among the populations of Belarus, the Russian Federation, and Ukraine that were most affected by the accident to investigate whether dose-effect relationships can be obtained, notably with respect to the induction of thyroid cancer resulting from internal irradiation by ^{131}I in young children and to the induction of leukaemia among workers resulting from external irradiation at low dose rates.

PHYSICAL CONSEQUENCES OF THE ACCIDENT

The Chernobyl reactor is a pressurized water reactor using light water as a coolant and graphite as a moderator. Detailed information about what is currently known about the accident and the accident sequence has been reported, notably in 1992 by the International Atomic Energy Agency (11), in 1994 in a report of the Massachusetts Institute of Technology (12), in 1995 by the Ukrainian Academy of Sciences (13), and in 1991-1996 by the Kurchatov Institute (15-19). A simplified description of the events leading to the accident and of the measures taken to control its consequences is provided in the following paragraphs. As is the case in an accident with unexpected and unknown events and outcomes, many questions remain to be satisfactorily resolved.

The events leading to the accident at the Chernobyl Unit 4 reactor at about 1.24 a.m. on 26 April 1986 resulted from efforts to conduct a test on an electric control system, which allows power to be provided in the event of a station blackout (20). Actions taken during this exercise resulted in a significant variation in the temperature and flow rate of the inlet water to the reactor core (beginning at about 1.03 a.m.). The unstable state of the reactor before the accident is due both to basic engineering deficiencies (large positive coefficient of reactivity under certain conditions) and to faulty actions of the operators (e.g., switching off the emergency safety systems of the reactor) (21). The relatively fast temperature changes resulting from the operators' actions weakened the lower transition joints that link the zirconium fuel channels in the core to the steel pipes that carry the inlet cooling water (13). Other actions resulted in a rapid increase in the power level of the reactor (11), which caused fuel fragmentation and the rapid transfer of heat from these fuel fragments to the coolant (between 1.23:43 and 1.23:49 a.m.). This generated a shock wave in the cooling water, which led to the failure of most of the lower transition joints. As a result of the failure of these transition joints, the pressurized cooling water in the primary system was released, and it immediately flashed into steam.

The steam explosion occurred at 1.23:49 and may have lifted the entire core assembly from the reactor cavity at least 14 m into the air over the reactor vessel floor (13). It is further surmised that during the time when the core assembly was moving up into the air, all water left the reactor core. This resulted in an extremely rapid increase in reactivity, which led to vaporization of part of the fuel at the centre of some fuel assemblies and which was terminated by a large explosion attributable to rapid expansion of the fuel vapour disassembling the core. This explosion, which occurred at about 1.24 a.m., blew the core apart and destroyed most of the building. Fuel, core components, and structural items were blown from the reactor hall onto the roof of adjacent buildings and the ground around the reactor building. A major release of radioactive materials into the environment also occurred as a result of this explosion.

The radionuclide releases from the damaged reactor occurred mainly over a 10-day period, but with varying release rates. An initial high release rate on the first day was caused by mechanical discharge as a result of the explosions in the reactor. There followed a five-day period of declining releases associated with the hot air and fumes from the burning graphite core material. In the next few days, the release rate of radionuclides increased until day 10, when the releases dropped abruptly, thus ending the period of intense release. Estimated core inventories, at the time of the accident, and atmospheric releases of some of the radionuclides are presented in Table 1. . From the radiological point of view, the releases of ^{131}I and ^{137}Cs, estimated to have been 1,760 and 85 PBq, respectively, are the most important to consider.

Table 1. Estimated inventories and releases of some of the radionuclides involved in the Chernobyl accident on 26 April 1986 (12, 22-28).

Radionuclide	Radioactive half-life	Core inventory (PBq)	Activity released (PBq)
Noble gases			
^{85}Kr	10.7 a	33	33
^{133}Xe	5.25 d	6 500	6 500
Volatile elements			
^{132}Te	3.26 d	4 200	1 040
^{131}I	8.04 d	3 200	1 760
^{133}I	20.8 h	4 800	910
^{134}Cs	2.06 a	170	54
^{137}Cs	30.0 a	260	85
Intermediate			
^{90}Sr	29.1 a	220	10
^{103}Ru	39.3 d	3 800	>168
^{106}Ru	368 d	850	>73
Refractory (including fuel particles)			
^{95}Zr	64.0 d	5 800	196
^{144}Ce	39.3 d	3 900	116
^{240}Pu	368 d	0.96	0.03

There were only a few measurements of the aerodynamic size of the radioactive particles released during the first days of the accident. A crude analysis of air samples, taken at 400-600 m above the ground in the vicinity of the Chernobyl power plant on 27 April 1986, indicated that large radioactive particles, varying in size from several to tens of micrometers, were found, together with an abundance of smaller particles (29). In a carefully designed experiment, aerosol samples taken on 14 and 16 May 1986 with a device installed on an aircraft that flew above the damaged reactor were analysed by spectrometry (30, 31). The activity distribution of the particle sizes was found to be well represented as the superposition of two log-normal functions: one with an activity median aerodynamic diameter (AMAD) ranging from 0.3 to 1.5 μm and a geometric standard deviation (GSD) of 1.6-1.8, and another with an AMAD of more than 10 μm. The larger particles contained about 80%-90% of the activity of non-volatile radionuclides such as ^{95}Zr, ^{95}Nb, ^{140}La, ^{141}Ce, ^{144}Ce, and transuranium radionuclides embedded in the uranium matrix of the fuel (32).

The radionuclides released in the accident deposited with greatest density in the regions surrounding the reactor in the European part of the former Soviet Union. Caesium-137 was chosen as reference radionuclide for the ground contamination because of its substantial contribution to the lifetime effective dose, its long radioactive half-life and its ease of measurement. As shown in Table 2, there was also appreciable ^{137}Cs contamination in other European coubtries.

Table 2. Contaminated areas in European countries following the Chernobyl accident (33)

Country	Area in deposition density ranges (km^2)			
	37-185 kBq m^{-2}	185-555 kBq m^{-2}	555-1 480 kBq m^{-2}	>1 480 kBq m^{-2}
Russian Federation	49 800	5 700	2 100	300
Belarus	29 900	10, 00	4 200	2 200
Ukraine	37 200	3 200	900	600
Sweden	12 000	-	-	-
Finland	11 500	-	-	-
Austria	8 600	-	-	-
Norway	5 200	-	-	-
Bulgaria	4 800	-	-	-
Switzerland	1 300	-	-	-
Greece	1 200	-	-	-
Slovenia	300	-	-	-
Italy	300	-	-	-
Moldova	60	-	-	-

RADIATION EXPOSURES

The highest doses were received by the approximately 600 emergency workers who were on the site of the Chernobyl power plant during the night of the accident. The most important exposures were due to external irradiation (relatively uniform whole-body gamma irradiation and beta irradiation of extensive body surfaces), as the intake of radionuclides through inhalation was relatively small (except in two cases). Acute radiation sickness was confirmed for 134 of those emergency workers. Forty-one of these patients received whole-body doses from external irradiation of less than 2.1 Gy. Ninety-three patients received higher doses and had more severe acute radiation sickness: 50 persons with doses between 2.2 and 4.1 Gy, 22 between 4.2 and 6.4 Gy, and 21 between 6.5 and 16 Gy . The skin doses from beta exposures evaluated for eight patients with acute radiation sickness ranged from 10 to 30 Gy

About 600,000 persons (civilian and military) have received special certificates confirming their status as liquidators (recovery operation workers), according to laws promulgated in Belarus, the Russian Federation, and Ukraine. Of those, about 240,000 were military servicemen. The principal tasks carried out by the recovery operation workers included decontamination of the reactor block, reactor site, and roads, as well as construction of the sarcophagus and of a town for reactor personnel. These tasks were completed by 1990. A registry of recovery operation workers was established in 1986. This registry includes estimates of doses from external irradiation, which was the predominant pathway of exposure for the recovery operation workers. The registry data show that the average recorded doses decreased from year to year, being about 0.17 Sv in 1986, 0.13 Sv in 1987, 0.03 Sv in 1988, and 0.015 Sv in 1989. It is, however, difficult to assess the validity of the results that have been reported for a variety of reasons, including (a) the fact that different dosimeters were used by different organizations without any intercalibration; (b) the high number of recorded doses very close to the dose limit; and (c) the high number of rounded values such as 0.1, 0.2, or 0.5 Sv. Nevertheless, it seems reasonable to assume that the average effective dose from external gamma irradiation to recovery operation workers in the years 1986-1987 was about 0.1 Sv. The distribution of the external doses received by emergency workers and various categories of liquidators is shown in Table 3.

Table 3. Distribution of the external doses received by emergency workers and liquidators (34).

Category	Number of persons	Percentage in the dose interval (mSv)						
		0-10	10-50	50-100	100-200	200-250	250-500	>500
Emergency workers and accident	820	-	-	2	4	-	7	87
witnesses	2 358	13	45	24	14	2	2	-
Staff of nuclear power plant 1986	4 498	66	42	1	1	-	-	-
Staff of nuclear power plant 1987	21 500	23	24	11	18	11	13	-
Construction workers 1986	5 376	47	23	24	4	1	1	-
Construction workers 1987	61 762	13	22	16	23	19	19	-
Military servicemen 1986	63 751	15	15	49	15	6	6	-
Military servicemen 1987	3 458	78	21	1	-	-	-	-
Workers from other power plants 1987								

The doses received by the members of the general public resulted from the radionuclide releases from the damaged reactor, which led to the ground contamination of large areas. Iodine-131 was the main contributor to the thyroid doses, received mainly via internal irradiation within a few weeks after the accident, while ^{137}Cs was, and is, the main contributor to the doses to organs and tissues other than the thyroid, from either internal or external irradiation, which will continue to be received, at low dose rates, during several decades.

Within a few weeks after the accident, more than 100,000 persons were evacuated from the most contaminated areas of Ukraine and of Belarus. The thyroid doses received by the evacuees varied according to their age, place of residence, and date of evacuation. For example, for the residents of Pripyat, who were evacuated essentially within 48 h after the accident, the population-weighted average thyroid dose is estimated to be 0.17 Gy, and to range from 0.07 Gy for adults to 2 Gy for infants. For the entire population of evacuees, the population-weighted average thyroid dose is estimated to be 0.47 Gy. Doses to organs and tissues other than the thyroid were, on average, much smaller (Table 4).

Table 4. Summary of estimated thyroid and effective doses to populations of areas evacuated in 1986.

Country	Estimated arithmetic mean dose		
	Thyroid	External effective (excluding thyroid dose)	Internal effective (excluding thyroid dose)
Belarus	1.0	0.03	0.006
Ukraine	0.3	0.02	0.01

Thyroid doses also have been estimated for the approximately 6 million residents of the contaminated areas who were not evacuated. In each of the three Republics, thyroid doses exceeding 1 Gy have been estimated for the most exposed infants. For residents of a given locality, thyroid doses to adults were smaller than those to infants by a factor of about 10. The average thyroid dose was about 0.2 Gy; the variability of the thyroid dose was about two orders of magnitude, both above and below the average.

Following the first few weeks after the accident when ^{131}I was the main contributor to the radiation exposures, doses were delivered at much lower dose rates by radionuclides with much longer half-lives. Since 1987, the doses received by the populations from the contaminated areas have resulted essentially from external exposure from ^{134}Cs and ^{137}Cs deposited on the ground and internal exposure due to contamination of foodstuffs by ^{134}Cs and ^{137}Cs. Other, usually minor, contributions to the long-term radiation exposures include the consumption of foodstuffs contaminated with ^{90}Sr and the inhalation of aerosols containing ^{239}Pu. Both external irradiation and internal irradiation due to ^{134}Cs and ^{137}Cs result in relatively uniform doses in all organs and tissues of the body. The average effective doses from ^{134}Cs and ^{137}Cs that were received during the first ten years after the accident by the residents of contaminated areas are estimated to be about 0.01 Sv (Table 5).

Table 5. Summary of estimated average effective doses (excluding thyroid doses) to populations of areas contaminated by the Chernobyl accident (1986-1995).

Country	Estimated arithmetic mean effective dose (mSv)		
	External exposure	Internal exposure	Total
Belarus	5	3	8
Russian Federation	4	2.5	6.5
Ukraine	5	6	11

HEALTH EFFECTS

The papers available to date regarding the estimation of health effects resulting from the Chernobyl accident have in many instances suffered from methodological weaknesses that make them difficult to interpret. The weaknesses include inadequate diagnoses and classification of diseases, selection of inadequate control or reference groups (in particular, control groups with a different level of disease ascertainment than the exposed groups), inadequate estimation of radiation doses or lack of individual data, and failure to take screening and increased medical surveillance into consideration. The interpretation of the studies is complicated, and particular attention must be paid to the design and performance of epidemiological studies.

Apart from the substantial increase in thyroid cancer after childhood exposure, there is no evidence of a major public health impact related to the ionizing radiation 14 years after the Chernobyl accident. No increases in overall cancer incidence or mortality that could be associated with radiation exposure have been observed. The risk of leukaemia, one of the most sensitive indicators of radiation exposure, has not been found to be elevated even in the accident recovery operation workers or in children. There is no scientific proof of an increase in other non-malignant disorders, somatic or mental, that are related to ionizing radiation.

The large number of thyroid cancers in individuals exposed in childhood, particularly in the severely contaminated areas of the three affected countries, and the short induction period are considerably different from previous experience in other accidents or exposure situations. Other factors, e.g. iodine deficiency and screening, are most certainly influencing the risk. Few studies have addressed these problems, but those that have still find a significant influence of radiation after taking confounding influences into consideration. The most recent findings indicate that the thyroid cancer risk for those older than 10 years at the time of the accident is levelling off, while the increase continues for those younger than 4-5 years in 1986.

There is a tendency to attribute increases in cancer rates (other than thyroid) over time to the Chernobyl accident, but it should be noted that increases were also observed before the accident in the affected areas, even for chronic lymphatic leukaemia, which is a malignancy not associated with radiation (35). Moreover, a general increase in mortality has been reported in recent years in most areas of the former USSR, and this must also be taken into account in interpreting the results of the present Chernobyl-related studies. Because of these and other uncertainties, there is a need for well-designed, sound analytical studies, especially of recovery operation workers from Belarus, the Russian Federation, Ukraine, and the Baltic countries, in which particular attention is given to individual dose reconstruction and the effect of screening and other possible confounding factors.

Increases of a number of non-specific detrimental health effects other than cancer in accident recovery workers have been reported, e.g. increased suicide rates and deaths due to violent causes. It is difficult to interpret these findings without reference to a known baseline or background incidence. The exposed populations undergo much more intensive and active health follow-up than the general population. As a result, using the general population as a comparison group, as has been done so far in most studies, is thus inadequate.

Adding iodine to the diet of populations living in iodine-deficient areas and screening the high-risk groups could limit the radiological consequences. Most data suggest that the youngest age group, i.e. those who were less than five years old at the time of the accident, continues to have an increased risk of developing thyroid cancer and should be closely monitored. In spite of the fact that many childhood thyroid cancers are presented at an more advanced stage in terms of local aggressiveness and distant metastases, than in adulthood,, they have a good prognosis. Continued follow-up is necessary to allow planning public health actions, to gain a better understanding of influencing factors, to predict the outcomes of any future accidents, and to ensure adequate radiation protection measures.

Present knowledge of the late effects of protracted exposure to ionizing radiation is limited, since the dose-response assessments rely heavily on high-dose exposure studies and animal experiments; extrapolations are needed, which involves uncertainty. The Chernobyl accident could, however, shed light on the late effects of protracted exposure, but given the low doses received by the majority of exposed individuals, any increase in cancer incidence or mortality will most certainly be difficult to detect in epidemiological studies. The main goal is to differentiate the effects of the ionizing radiation and effects that arise from many other causes in exposed populations.

Apart from the radiation-associated thyroid cancers among those exposed in childhood, the only group that received doses high enough to possibly incur statistically detectable increased risks are the recovery operation workers. Among the recovery operation workers there is a particular group of approximately 100 individuals who survived relatively high doses of radiation in the immediate, acute phase of the accident and are presently experiencing health impairments as sequelae of their original injuries. Studies of these populations will probably contribute to the scientific knowledge on the late effects of ionizing radiation. Many of these individuals receive annual medical examinations, providing a sound basis for future studies of this cohort. It is, however, notable that no increased risk of leukaemia, an entity known to appear within 2-3 years after exposure, has been identified more than 10 years after the accident.

The future challenge is to provide reliable individual dose estimates for the subjects enrolled in epidemiological studies and to predict the effects of doses accumulated over protracted time (days to weeks for thyroid exposures of children, minutes to months for bone-marrow exposures of emergency and recovery operation workers, and months to years for whole-body exposures of those living in contaminated areas). In doing this, many difficulties must be taken into consideration, such as (a) the role played by different radionuclides, and especially the short-lived radioiodines; (b) the accuracy of direct thyroid measurements; (c) the relationship between ground contamination and thyroid doses; and (d) the reliability of the recorded or reconstructed doses for the emergency and recovery operation workers.

Finally, it should be emphasized that although those exposed as children and the emergency and recovery operation workers are at increased risk of radiation-induced effects, the vast majority of the population need not live in fear of dire health consequences from the Chernobyl accident. For the most part, they were exposed to radiation levels comparable to or a few times higher than the natural background levels, and future exposures are diminishing as the deposited radionuclides decay. Lives have been disrupted by the Chernobyl accident, but from the radiological point of view and based on the assessments of this document, generally positive prospects for the future health of most individuals should prevail.

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