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Executive Summary

The Chernobyl accident was the result of an inherently unsafe reactor design combined with a lack of "safety culture". The reactor was insufficiently safely constructed. Safety-related design principles such as a technology that forgives errors were not applied in the design of the RBMK. Additionally, the operators were not informed of the design weaknesses and were very probably not aware that the operating mode chosen for the test could have brought the reactor into explosive conditions. Deficiencies in safety culture were expressed in particular through the fact that the operators did not comply with established operational and safety-oriented procedures. The combination of these factors provoked the worst nuclear accident in which the reactor was totally destroyed within a few seconds. The consequences can be seen as the product of the superposition of two major accidents: the explosion of the reactor and the core melt down combined with the intense and long lasting fire of the graphite moderator.

The direct consequence of the Chernobyl accident was an enormous **release of radioactive materials** into the environment, producing a very heavy ground contamination mainly covering an area of ~ 4000 km^2. This central area is still an exclusion zone today. There is now a fairly accurate estimate of the total release of radioactive material. The duration of the release lasted more than a week. Immediately following the explosion, mostly gaseous, volatile (I, Cs), and solid materials – particularly fuel – with comparatively large particle sizes were released. The large particles were deposited in distances of less than 100 km, mainly in the 30 km radius area. The second phase with releases from the molten core with simultaneous fire of the graphite moderator achieved its peak after about 8 days. In this process, aerosols and solid materials with smaller particle sizes were released. As a result of the fire, these rose to great heights and were transported over large distances. Due to the nature of materials released, more remote regions (> about 100 km) were mostly affected by I, Cs, Te, while the immediate vicinity also received deposits of fuel (U, Pu) as well as refractory materials (Zr, Mo, Ce, Np) and intermediate products (Ru, Ba, Sr). The composition and characteristics of the radioactive material changed during the passage of the plume due to decay, chemical transformations, alterations in particle size and wet or dry deposition. The **pattern of deposition** was very irregular. Significant deposition of radionuclides occurred where the passage of the radioactive plume coincided with rainfall. Although the entire northern hemisphere was concerned, only territories of the former Soviet Union and small areas of remaining Europe experienced **significant contamination**.

In the first two weeks, inhalation, direct external irradiation, consumption of milk and fresh vegetables were the dominant **exposure pathways**. After several months, milk consumption as well as the consumption of meat and (freshwater) fish predominated. Even twenty years on, the values for milk, mushrooms and forest berries as well as for the meat of wild boar, elk and sheep are still high in heavily exposed areas, particularly in the contaminated zones of the former Soviet Union.

The Chernobyl accident took authorities by surprise as regards extent, duration and contamination at long distance. As no guidelines were available for such an accident, little help for decision-making was available. Additionally, great political and public pressure to take action prevailed and overly precautious decisions were often made inside and outside the Soviet Union. The psychological impact of some official decisions on the public was not predicted. Variable interpretations or even misinterpretations of ICRP recommendations, especially for **intervention levels** for food, led to inconsistent measures and advice. These added to public confusion and provoked mistrust and unnecessary economic losses. However, very soon international efforts were initiated **to harmonize** criteria and approaches to **emergency management**.

The amount of radionuclides deposited in the **environment** due to the accident is now well known. The intensity of ground contamination and the corresponding importance of radiation doses decreased with increasing distances and had no direct health consequences at distances larger than 200 km, although some hot spots – with significantly lower contamination levels than those found close to the reactor - were detected, e.g. in the Scandinavian countries, in Austria and in Bavaria. These hot spots were caused by washout through heavy rainfall. A total area of 11,000 km^2 was contaminated with $^{134/137}$Cs levels exceeding 555 kBq/m^2 [1]. In Ukraine, mainly the forests were affected. The countermeasures implemented in **agriculture** were effective, especially the agro-alimentary transformations, the reconditioning of the soil and the changes in farming methods. Today, the great majority of agricultural produce is at a level where average individual doses do not exceed 1 mSv per year. Environmental effects have been observed in plants and animals in the exclusion zone.

In the affected areas, twenty years after the accident, radionuclides are still present in the top layers of soils, and still **transfer to plants**, particularly mushrooms, berries and forest products. Contamination levels in soils decrease only slowly, e.g. by transfer to plants. Most of the decrease in the next years will be due to the physical half-life of ^{137}Cs (30 a) only. The recovery of affected flora and fauna in the exclusion zone has been positively influenced by the absence of human activities.

The **doses received** by the firemen and liquidators of the first phase ranged from a few hundred mSv to more than 10 Sv for few firemen. For the 200,000 to 600,000 liquidators involved in the later clean-up activities, the doses received remain uncertain, but largely range from 100 to 500 mSv. A large proportion of this group of persons received much lower doses. Their thyroid doses are badly evaluated. The evacuees received average doses estimated at approximately 20 mSv. This is comparable to the typical dose received by a patient undergoing a medical computer tomography examination of the torso. For residents of the strict control zones (270,000 people who continue to live in areas of ^{137}Cs deposition higher than 555 kBq/m^2), the average radiation dose is about 50 mSv. For populations living in contaminated territories (6,400,000 people living in regions of ^{137}Cs contamination higher than 37 kBq/m^2), annual estimated received doses were lower than 1 mSv for 2 thirds of the population and ranged between 1 to 10 mSv for the other third. This is comparable to natural background radiation which reaches a few mSv per year worldwide.

In western populations, the calculated total dose amounted to about 1 mSv for the north of Europe and 0.15 mSv for the western part. For self-sustaining families in hot spots outside the Soviet Union, living off their own produce, the radiation doses could have been 20 to 50 times higher than average. Precautionary measures such as avoidance of fresh milk for about 2 months were recommended for these groups.

Many studies have been performed in order to find relationships between the radiation dose and diverse **health impacts**. The possibly serious health problems related to this accident concern the populations who lived in or around the exclusion zone or were evacuated and relocated, as well as the many workers and soldiers (liquidators) deployed in the emergency response and in building the sarcophagus. Obvious acute effects were first observed among the fire fighters and certain heavily irradiated liquidators. 134 patients were treated, 28 of them died in 1986 and 11 later on. The second group of persons with health impacts attributable to radiation is the group of some 3,000 children and young adults developing **thyroid cancers**; nine of them have died. For **leukemia**, the most recent studies suggest an increase in the incidence between 1986 and 1996 in Russian emergency workers (11 cases) exposed to a radiation dose exceeding 150 mSv (external dose). For doses above 250 mSv, the Chernobyl accident may have had a

[1] In comparison: The contamination in the medium Nordic latitudes resulting from the atomic bomb fallout ranged between 1.5 and 5 kBq/m².

cataractogenic impact. Other potential health effects in the population such as leukemia or congenital malformations could not be statistically correlated with the radiation doses. A study of prenatally exposed children shows mental disorders and diseases of the nervous system which could be due to radiation or to the stress of the mothers who belonged to the group of evacuated and relocated persons.

Generally, the observed physical health effects which can be scientifically correlated with radiation are restricted to persons who received relatively high radiation doses (firemen, liquidators, evacuees and children living in contaminated areas).

The **number of fatalities** which have been and will be attributable to the Chernobyl accident has been of paramount interest to the general public, scientists, the mass media and politicians. This number has recently been estimated to lie around 4,000, including deaths from acute radiation syndrome, thyroid cancers in children and cancers in the population.

Twenty years have passed and the trauma of the Chernobyl accident is still very tangible among a population of 7 million living around the exclusion zone. The fear of potential late effects due to radiation has a paralysing and stress-inducing effect. Existing studies have shown that psychological problems associated with the accident did not decrease with time. Among a considerable part of the liquidators, a chronic fatigue syndrome has been observed which could be associated with radiation doses combined with **psychological stress**. Among the inhabitants of seriously contaminated areas, there is a significant increase of diverse psychiatric disorders. The post-accident stress considerably changed the attitude of the population to their health. Medical doctors are important multipliers; the perception of radiation risk by medical doctors is important because it affects their interactions with patients. An educational program for medical doctors would be very helpful. Also, the system of national compensation and privileges which is still in force conveys the message to many unaffected people that they are victims and produces a state of apathy. The overall result is a general mistrust. At present, Chernobyl is still a psychological, societal and economic catastrophe. However, certain positive actions have reduced the stress levels among some groups of the population. One of these was the ETHOS program for **sustainable rehabilitation** and also the exchange between pupils.

One of the **remaining risks** is the possibility of the collapse of the **sarcophagus**. The probability of this happening is not very high and its radiological consequences beyond the exclusion zone would remain low. An international project involves planning the construction of a new safe sarcophagus over the destroyed Chernobyl reactor. The second remaining risk could be the contamination of **natural waters** and aquatic ecosystems by runoff of ^{137}Cs and ^{90}Sr from contaminated soils and from the many improvised waste disposal sites in the exclusion zone.

The Chernobyl accident prompted a number of actions directed at preventing further accidents in RBMK reactors. Additionally, investigations were performed on other reactor types and mainly accident management measures were introduced. Important activities include also a strengthened **international cooperation** in safety matters. Good international cooperation is also vital for the improved response capability, including harmonized criteria based on accepted radiation protection principles and agreed upon cooperation procedures, as well as on effective national monitoring and response systems.

1 The accident sequence

The main focus of this statement rests on the consequences of the reactor accident. For this reason, passages on the reactor itself and on the accident sequence are only briefly mentioned.

1.1 The reactor

The Chernobyl Power Complex is situated about 130 km north of Kiev, Ukraine, and about 20 km south of the border with Belarus. At the time of the Chernobyl accident, on 26 April 1986, the Soviet Nuclear Power Program was based mainly on two types of reactors, the WWER, a pressurized light-water reactor, and the RBMK, a graphite moderated light-water reactor with an output of 1,000 (Chernobyl unit 4, corresponds to 3,200 MWth) or 1,500 MWel. The RBMK, a Soviet design, was restricted to republics within the Soviet Union. It uses slightly enriched (2 % uranium-235) uranium dioxide fuel. It is a pressure-tube boiling light water reactor, with direct steam feed to the turbines, without an intervening heat-exchanger. The water acts as a coolant and also provides the steam used to drive the turbines. The 1693 vertical pressure tubes contain the zirconium-alloy clad uranium-dioxide fuel around which the cooling water flows. Due to the reactor design and using a specially designed refueling machine, it is possible to exchange fuel bundles without shutting down the reactor.

The moderator consists of graphite. A mixture of nitrogen and helium is circulated between the graphite blocks to restrict temperature and thus to prevent oxidation of the graphite. The core itself is about 7 m high and about 12 m in diameter. Raising or lowering 211 control rods controls the power of the reactor. Various safety systems, such as an emergency core cooling system, a shut-off system and other technical precautions (cf. e.g. INSAG-7 Appendix II (IAEA 1992b)) are components of the safety system. These technical installations are supplemented by safety-oriented requirements. Among these is the requirement that at least 30 control rods must be inserted into the core during reactor operation.

In full power mode, the RBMK has a slightly negative overall power coefficient, which means that the reactor shows self-stabilizing behavior. Consequently, if reactivity is increased by withdrawing control rods, a new steady state power production is reached. Given an output of less than 20 % of the full-power performance and low steam content, however, the reactor displays a positive void coefficient, especially given equilibrium burn-up. That is to say, a higher steam content in the pressure tubes, caused by a higher output or reduced water circulation, does not lead to a stabilization, but instead to a further output increase. This fact represented an essential factor in the accident sequence.

A further essential technical factor that played a part was that the control rods could only be inserted at a slow rate (about 20 sec) and that this special construction (consisting of a water displacer made of graphite and an absorber part that are connected with each other via a rod linkage system) has the effect that the control rod or shutdown rod being inserted from the fully withdrawn position even leads to an increase in reactivity at the beginning of insertion.

1.2 The accident

The Unit 4 reactor was to be shut down for routine maintenance on 25 April 1986. It was decided to take advantage of this shutdown to test whether and for how long the cooling of the core could be maintained in the event of load dumping and loss of offsite power by the voltage produced by the turbo generator during rundown (GRS 1996). To this end, the turbine was shutdown and several cooling pumps were supplied by the running down generator. For this purpose, the emergency cooling system was intentionally switched to unavailability, the emergency power supply, however, remained activated.

Due to a delay in starting the tests, the initial conditions required substantial changes from the original plan. In particular, the power output of the reactor had fallen to about 200 MW and less than the required 30 control rods (6 – 8 control rods) were inserted in the core. Furthermore, the steam content was impermissibly low because the intended limiting system that would have shutdown the reactor in the event of insufficient steam ratio had been inactivated. Therefore, an extremely unstable condition already existed at the start of the test (strong positive void coefficient and overall positive power coefficient). According to the test program, the throughput of coolant decreased when the turbine was being shutdown. The coolant pumps that were switched on to the running down turbogenerator carried on for another 36 seconds following the start of the shutdown. As a result, the steam content increased, leading to a power increase due to the positive void coefficient.

Evidently, an attempt was made to counter this increase by performing a reactor scram. Due to the above-mentioned design flaw, the insertion of the control rods caused a positive insertion of reactivity, i.e. the power increased further during the insertion of the rods. This positive reactivity effect of the control- and shutdown rods, combined with an extremely positive void fraction effect and an overall positive power coefficient, led to a prompt critical condition where the doubling time of the reactor output lay in the millisecond area. In this way, heat generation in the core increased very rapidly.

The sudden increase in heat production ruptured part of the fuel and small hot fuel particles, reacting with water, caused a steam explosion, which destroyed the reactor core. Outside witnesses observed two explosions within three seconds.

The accident occurred at 01:23 a.m. on Saturday, 26 April 1986, when the explosions destroyed the core of Unit 4 and the roof of the reactor building. Fires started in what remained of the Unit 4 building, giving rise to clouds of steam and dust, and fires also broke out on the adjacent turbine hall roof and in various stores of diesel fuel and inflammable materials.

A first group of 14 firemen arrived on the scene of the accident at 1:28 a.m. Reinforcements were brought in until about 4 a.m., when 250 firemen were available and 69 firemen participated in fire control activities. By 2.10 a.m., the largest fires on the roof of the machine hall had been put out, while by 2.30 a.m., the largest fires on the roof of the reactor hall were under control. By 5:00 hr of the same day, the fire situation seemed to be under control but by then the graphite fire had started.

The Soviet scientists strongly emphasized the operators' responsibility for the accident, and not much attention was given to the design faults of the reactor (INSAG-1 and INSAG-7 Appendix II (IAEA 1992b)). Independent assessments (IAEA 1986b) show that the accident can be traced to a combination of these two factors.

1.3 The graphite fire

The graphite moderator fire was a special problem, and there was a very real fear that any attempt to put it out might well result in a greater release of radionuclides, perhaps by steam production, or it might even provoke a recriticality excursion in the nuclear fuel.

A decision was made in the end to layer the graphite fire with large amounts of different materials. The first measures taken to control fire and the radionuclide releases consisted of dumping neutron-absorbing compounds and fire-control material into the crater that resulted from the destruction of the reactor, in order to rule out recriticality of the fuel. The total amount of materials dumped on the reactor amounted to about 5,000 t including about 40 t of boron compounds, 2,400 t of lead, 1,800 t of sand and clay, and 600 t of dolomite, as well as sodium phosphate and polymer liquids. About 150 t of material were dumped on 27 April, followed by 300 t on 28 April, 750 t on 29 April, 1,500 t on 30 April, 1,900 t on 1 May and 400 t on 2 May. About 1,800 helicopter flights were carried out to dump materials onto the reactor. During the first flights, the helicopter remained stationary over the reactor while dumping materials. As the doses received by the helicopter pilots during this procedure were too high, it was decided that the materials should be dumped while the helicopters crossed the reactor without hovering. This procedure caused additional destruction of the standing structures and spread the contamination.

The further sequence of events is still speculative. The graphite top layer first had a filtering effect on the release of volatile compounds. But after some burning time, the filtering effect of an upper graphite layer disappeared and the release of volatile fission products from the fuel increased. On day 8 after the accident, the corium (damaged reactor core) melted through the lower thick shield and flowed onto the floor of the level beneath it. This redistribution of the corium may have enhanced the radionuclide releases. Contact of the corium with water produced steam, causing an increase of radionuclide releases at the last stage of the active period.

By May 9, the graphite fire had been extinguished, and work began on the construction of a massive reinforced concrete slab with a built-in cooling system beneath the reactor. This involved digging a tunnel from underneath Unit 3. About four hundred people worked on this tunnel, which was completed in 15 days. This core catcher project was never finalized.

Summary

The Chernobyl accident was the result of an inherently unsafe reactor design combined with a lack of “safety culture”. The reactor was insufficiently safely constructed. Safety-related design principles such as a technology that forgives some errors were not applied in the design of the RBMK. Additionally, the operators were not informed of the design weaknesses and were very probably not aware that the operating mode chosen for the test could have brought the reactor into explosive conditions. Deficiencies in safety culture were expressed in particular through the fact that the operators did not comply with established operational and safety-oriented procedures. The combination of these factors provoked the worst nuclear accident in which the reactor was totally destroyed within a few seconds. The consequences can be seen as the product of the superposition of two major accidents: the explosion of the reactor and the core melt down combined with the intense and long lasting fire of the graphite moderator.

2 Release, distribution and deposition of radioactive materials

The affected area of Ukraine around Chernobyl is described as Belarussian-type woodland with a low population density. About 3 km away from the reactor, the new city, Pripyat, had 49,000 inhabitants before the accident. The old town of Chernobyl, which had a population of 12,500, is about 15 km to the southeast of the complex. Within a 30-km radius of the power plant, the total population was between 115,000 and 135,000.

Releases of radionuclides to the atmosphere began during the initial reactor explosion and continued over an approximately 10-day period. The radionuclide composition of the release varied during this time. The initial explosions deposited fuel particles principally within a 30 km radius area around the reactor. Within this area, the majority of fallout was in the form of large "non-oxidized" fuel particles (10 µm). During the second phase, the subsequent graphite fire, particles were smaller and "oxidized". Volatile radionuclides were attached to these small dust particles (aerosols) and dispersed around Europe.

2.1 Release

The release of radioactive material to the atmosphere consisted of gases, aerosols and finely fragmented fuel. The two explosions also sent fuel, core components and structural items into the air and produced a shower of hot and highly radioactive debris, including fuel, core components, structural items and graphite and exposed the destroyed core to the atmosphere. The plume of smoke, radioactive fission products and debris from the core and the building rose 1 to 2 km into the air. The initial large release contained mainly the more volatile radionuclides such as noble gases, iodine and some cesium. The second large release between day 7 and day 10 was caused by the high temperatures of the core melt. The intense graphite fire was responsible for the dispersion of radionuclides and fission fragments high into the atmosphere. The emissions continued for about twenty days, but were much lower after the tenth day when the graphite fire had been extinguished.

The heavier debris in the plume was deposited close to the site, whereas smaller particles were more widely dispersed. Lighter components, including fission products and virtually the entire noble gas inventory were blown by the prevailing wind to the north-west of the plant. The particle size was found to be 0.3 to 1.5 µm for the small particles and 10 µm for the large particles. The larger particles contained non-volatile radionuclides such as ^{95}Zr, ^{95}Nb, ^{140}La, ^{144}Ce and transuranium elements embedded in the uranium matrix of the fuel. Other condensates from the vaporized fuel, such as radioactive ruthenium, formed metallic particles. These, as well as the small fuel particles, were often referred to as “hot particles”, and were found at large distances from the accident site (IAEA 1986a). However, in general, most fallout at large distances was not in the form of fuel particles.

In the initial assessment of releases made by the Soviet scientists and presented at the IAEA Post-Accident Assessment Meeting in Vienna (IAEA 1986a), it was estimated that 100 % of the core inventory of the noble gases (xenon and krypton) was released, and between 10 and 20 % of the more volatile elements of iodine, tellurium and cesium. The estimate for fuel material released to the environment was 3.5 ± 0.5 % (IAEA 1986a, Dreicer 1996). This corresponds to the emission of 6 t of fragmented fuel.

From the radiological point of view, ^{131}I and ^{137}Cs are the most important radionuclides to consider, because they are responsible for most of the radiation exposure received by the general population. For these two radionuclides, several estimations were made after the accident. The first was given by Soviet scientists. Later, the United Nations Scientific Committee on the Effects of Atomic Radiation gave, in 1988, release figures based not only on the Soviet data, but also on worldwide deposition. The total ^{137}Cs release was estimated to be 33 % of the core inventory i.e. 70 to 85 petabecquerels (PBq) (10^{15} Bq) of which 31 PBq were deposited in the Soviet Union. These figures were confirmed after an extensive review of the many reports (IAEA 1986a, Buzulukov 1993). For ^{131}I, the most accurate estimate was felt to be 50 to 60 % of the core inventory of 3,200 PBq.

The estimation made in 1986 is still valid but the results are assumed to be incomplete with respect to the release of the short-lived radionuclides (^{132}I and ^{135}I). In the UNSCEAR 2000 report (UNSCEAR 2000), the overall releases of short-lived radioiodines are presented on the basis of early and re-estimated information (Abagyan 1986, Izrael 1990); they are found to be substantially lower than those of ^{131}I (1,760 PBq), 1,040, 910, 25 and 250 PBq respectively for ^{132}I, ^{133}I, ^{134}I and ^{135}I. ^{132}I is assumed to be in radioactive equilibrium with ^{132}Te.

Radioactive contamination of the ground was found to some extent in practically every country of the northern hemisphere. The European Commission published an atlas of contamination in Europe (De Cort 1998, Izrael 1998) on the basis of local measurements.

2.2 Dispersion and deposition within the former-Soviet Union

During the first 10 days of the accident when important releases of radioactivity occurred, meteorological conditions changed frequently, causing significant variations in release direction and dispersion parameters. Deposition patterns of radioactive particles depended highly on the particle sizes and the occurrence of rainfall. The principal physico-chemical forms of the deposited radionuclides were: dispersed fuel particles, condensation-generated particles, and mixed-type particles. The distribution in the nearby contaminated zone (< 100km) reflected the radionuclide composition of the fuel and differed from that in the far zone (> 100km to 2,000 km). Large particles, deposited in the near zone, contained fuel (U, Pu), refractory elements (Zr, Mo, Ce and Np) and intermediate elements (Ru, Ba, Sr). The volatile elements (I, Te and Cs) in the form of condensation-generated particles, were more widely dispersed in the far zone. The largest particles, which were primarily fuel particles, were deposited essentially by sedimentation within 100 km of the reactor. Small particles were carried for large distances by the wind and were deposited primarily with rainfall. High contamination of ^{137}Cs occurred in various areas of the far zone, depending primarily on rainfall at the time the radioactive plume was passing. The regional pattern of contamination was mosaic-like. The radionuclide composition of the release and of the subsequent deposition on the ground also varied considerably during the accident due, for example, to variations in temperature during the release. ^{137}Cs was selected to characterize the magnitude of the ground deposition because (1) it is easily measurable, and (2) it was the main contributor to the radiation doses received by the population once the short-lived ^{131}I had decayed. All the iodine deposition maps established in the former Soviet Union were mainly based on the limited number of measurements of ^{131}I, and also they used ^{137}Cs measurements as a guide. These maps must be regarded with caution, as the ratio of ^{131}I to ^{137}Cs deposition densities (in Bq/m^2) was found to vary greatly over a large range in Belarus (by a factor of 5 to 10). This ratio has not been seriously studied in many countries.

An analysis of relevant meteorological conditions has allowed establishing that the radionuclide contamination on the territory of the Ukrainian and Belarus Polessye (the western trace) was mainly due to the release which took place on 26 and 27 April. Ground depositions of ^{137}Cs of over 40 kilobecquerels per square meter [kBq/m^2] covered large areas of the northern part of Ukraine and of the southern part of Belarus. The most highly contaminated area was the 30-km zone surrounding the reactor, where ^{137}Cs ground depositions generally exceeded 1,500 kBq/m^2 (= 40 Ci/km^2) (Balonov 1993).

The Gomel spot, situated 170 km away from Chernobyl, was due to rainfalls in the northeastern trace, which took place on 28/29 April. The ground depositions of ^{137}Cs in the most highly contaminated areas in this spot were comparable to the levels in the central spot and reached 5,000 kBq/m^2 in some villages (Balonov 1993).

The Bryansk-Kaluga-Tula-Orel spot in Russia, situated approximately 400 - 500 km northeast of the reactor, was produced by the same radioactive cloud. However, the levels of deposition of ^{137}Cs were lower.

Air mass transfer towards the south, which began on 30 April, was responsible for the contamination of the main part of Ukraine.

The radioactive fallout in the Russian Federation and Belarus contained a larger proportion of volatile nuclides such as $^{103/106}$Ru, ^{131}I, and ^{137}Cs. The contamination of the area of Ukraine south of Chernobyl also contained non-volatile elements.

In addition, outside the three areas of main deposition in the greater part of the European territory of the former Soviet Union, there were many spots of radioactive contamination with ^{137}Cs levels in the range of 40 to 200 kBq/m^2.

The total area affected by a serious deposition (above 555 kBq/m^2 = 15 Ci/km^2) covers 7,000 km^2 of Belarus, 2,700 km^2 of Russia and 1,300 km^2 of the Ukraine (de Cort 1998).

2.3 Dispersion and deposition outside the former Soviet Union

Radioactivity from Chernobyl was first detected in Western Europe by routine monitoring at a Swedish nuclear power station. Initially the wind was blowing in a northwesterly direction and this phase was responsible for much of the deposition in the north of Europe. Later the plume shifted to the south-west and much of Central Europe, as well as the northern Mediterranean and the Balkans, received some deposition, depending on the height of the plume, wind speed and direction, terrain features and the amount of rainfall that occurred during the passage of the plume. According to intense local showers, the contamination could be as high in some small areas of western countries (for example in Bavaria) as in the less contaminated areas of the successor states to the Soviet Union. The most radiologically important radionuclides detected outside the Soviet Union were ^{131}I, ^{132}Te/^{132}I, ^{137}Cs and ^{134}Cs.

In Austria, Eastern and Southern Switzerland, parts of Southern Germany and Scandinavia, where the passage of the plume coincided with heavy rainfall, the total deposition from the Chernobyl release was high locally (up to and even exceeding 37 kBq/m^2). On average, however, it remained 5 – 10 times weaker. Special mention should be given to a “hot spot” of 2-4 km^2 in the Swedish commune of Gävle (exceeding 185 kBq/m^2)) (Edvarson 1991). Further to the West, in Spain and Portugal, the depositions amounted to practically zero (0.02 kBq/m^2) (UNSCEAR 1988). In France, the depositions showed a strong gradient from east to west. In eastern France, the situation was comparable to the one found in Switzerland; western France was comparable to Spain. In Germany, the gradient ran from the South (“hot spots” in Southern Bavaria) to the North.

While the dispersion plume was detectable in the northern hemisphere as far away as Japan and North America, countries outside Europe received very little deposition of radionuclides from the accident, 0.13 kBq/m^2 in Japan and 0.08 kBq/m^2 in the USA. No deposition was detected in the southern hemisphere by the surveillance networks of environmental radiation, for example in Australia (UNSCEAR 1988).

Summary

The direct consequence of the Chernobyl accident was an enormous release of radioactive materials into the environment, producing a very heavy ground contamination mainly covering an area of approx. 4,000 km^2. This central area is still an exclusion zone today. There is now a fairly accurate estimate of the total release of radioactive material. The duration of the release lasted more than a week. Immediately following the explosion, mostly gaseous, volatile (I, Cs), and solid materials – particularly fuel – with comparatively large particle sizes were released. The large particles were deposited in distances of less than 100 km, mainly in the 30 km radius area. The second phase with releases from the molten core with simultaneous fire of the graphite moderator achieved its peak after about 8 days. In this process, aerosols and solid materials with smaller particle sizes were released. As a result of the fire, these rose to great heights and were transported over large distances. Due to the nature of materials released, more remote regions (> about 100 km) were mostly affected by I, Cs, Te, while the immediate vicinity also received deposits of fuel (U, Pu) as well as refractory materials (Zr, Mo, Ce, Np) and intermediate products (Ru, Ba, Sr). The composition and characteristics of the radioactive material changed during the passage of the plume due to decay, chemical transformations, alterations in particle size and wet or dry deposition. The pattern of deposition was very irregular. Significant deposition of radionuclides occurred where the passage of the radioactive plume coincided with rainfall. Although the entire northern hemisphere was concerned, only territories of the former Soviet Union and small areas of remaining Europe experienced significant contamination.

3 Exposure pathways

During the first post-accident year, two main sources were responsible for the external exposure of populations: the radioactive cloud in the first few days and radioactive fallout onto the ground, vegetation and buildings. The critical groups affected were people working in the forests and in agriculture. The direct radiation from the cloud (immersion) contributed to a small extent to the total dose, about 3 %. The internal dose was mainly caused by incorporation (inhalation and ingestion) of ^{131}I, ^{133}I, ^{134}Cs, ^{137}Cs and ^{90}Sr, and in the areas near the reactor also by inhaling ^{239}Pu and ^{241}Am with dust particles.

An analysis of effective doses (see chap. 6) received by the population shows that three periods can be defined:

- The first year, which corresponds to the period with the largest received doses amounting to approx. 30 % of the total accumulated doses.
- The second period corresponding to 1987-1991, during which the irradiation is only related to the ingestion of ^{134}Cs and ^{137}Cs. Due to regulation of consumption as well as activities and countermeasures implemented mainly at the level of agriculture, the radiation doses remained controlled and limited.
- The third period after 1991 is of comparable nature but with a lower level of protection because of increasing carelessness. The ^{137}Cs content in the human body today follows the natural rate of decrease in the environment.

Due to the implementation of protective measures for animal products, only a small quantity of milk was produced with ^{137}Cs content above the permissible levels. However, for self-sustaining families living off their own produced milk, the doses can be much higher than average.

Mushrooms and berries from forests are an important part of the diet of the residents of rural regions. The decrease in the concentration of the radionuclides they contain has been extremely slow. The contamination is now half the original level. This has to be compared with the radioactive decay of ^{137}Cs (half-life of 30 years), which clearly shows that the additional decrease due to, e.g., weathering is practically zero. Even today, high levels can be measured in mushrooms (1,000 Bq/kg) and in meat of wild forest animals (300 - 500 Bq/kg) in Belarus, Ukraine and Russia as well as in some areas of the Nordic countries.

The resuspension of radioactivity attached to soil particles in breathing air is dependent on local atmospheric conditions. It was only locally important, especially in the forests inside the exclusion zone, during the first months after the accident. With the exception of some areas of the exclusion zone, the air in the contaminated territories is no longer contaminated. Even when performing agricultural activities involving dust generation, the amount of released radioactive materials remains very low.

For the thyroid dose, ^{131}I was the major radionuclide contributing to the irradiation of the population. It is mainly related to ingestion of contaminated cow's milk, which accounts for 90% of the dose. Internal irradiation from thyroid uptake of short-lived ^{132}I and ^{133}I via inhalation during the passage of the radioactive cloud only represents a small proportion of the thyroid dose. The highest doses were found in children. The average dose to the thyroid in young children was 3 Gy in the most contaminated rural areas and 10 Gy, or more, in children evacuated from some settlements in Belarus.

In the rivers, lakes and ponds of the contaminated territories, radionuclides are concentrated in the sediments. In spite of great fears after the accident, the contribution of ^{90}Sr has been low because it has rapidly penetrated into deeper layers of soil more quickly than cesium.

Summary

In the first two weeks, inhalation, direct external irradiation, consumption of milk and fresh vegetables were the dominant exposure pathways. After several months, milk consumption as well as the consumption of meat and (freshwater) fish predominated. Even twenty years on, the values for milk, mushrooms and forest berries as well as for the meat of wild boar, elk and sheep are still high in heavily exposed areas, particularly in the contaminated zones of the former Soviet Union.

4 Protective measures taken

The scale and severity of an accident such as the Chernobyl one with its widespread radioactive contamination had not been foreseen. The national authorities responsible for emergency preparedness were taken by surprise by the impacts. Moreover, the information policy initially pursued by the authorities of the former Soviet Union mainly consisted in a "delay and denial" strategy. This attitude was taken towards the own population and also to the outside world. Criteria available for intervention in an accident were incomplete and provided little practical help in the given circumstances. In addition, considerable political pressure by the media was being exerted on the decision-makers, partially based on the public perception of the radiation danger. In these circumstances, cautious immediate actions was considered to be necessary, and in so doing measures were introduced on the basis of prudence rather than being driven by informed scientific findings and expert judgment.

The first stage is characterized by disaster management coordinated from Moscow. Many of the decisions that were taken centrally in Moscow have now been strongly criticized. These included late distribution of stable iodine to people in the contaminated territories and the delayed evacuation of villages in the 30 km zone around the reactor. From 1989 onwards, the public gradually became aware of the extent of the accident, and as of 1991, the successor states of the Soviet Union - Belarus, Russia and Ukraine – each pursued their own policies in this regard. The whole spectrum of the applied protective measures has been reviewed in a number of international reports (UNSCEAR 1988, IAEA 1990, IAC 1991, IAEA 1996a, UNSCEAR 2000, IAEA 2001).

4.1 Within the former Soviet Union

Late on 26 April, it was decided to evacuate the town of Pripyat. Arrangements for transport (1,200 buses) and accommodation of the evacuees were made. The announcement of evacuation was made at 11:00 a.m. the following day and Pripyat was evacuated within about two and a half hours. The remaining inhabitants in a 30 km zone around the reactor complex were gradually evacuated, bringing the total evacuees of the first phase to about 116,000. Other sources mention 135,000.

Other countermeasures taken especially in the exclusion zone to reduce dose loads were widely adopted (Komarov 1990), the washing of buildings, cleaning residential areas, removing contaminated soil, cleaning roads and decontaminating water supplies. Special attention was paid to schools, hospitals and other buildings used by large numbers of people. An attempt to reduce thyroid doses by the administration of stable iodine to block radioactive uptake by the thyroid was made (Mettler 1992), but its success was doubtful because it came too late.

The Soviet National Committee on Radiation Protection (NCRP) in 1987 proposed a 350 mSv lifetime dose intervention level for the relocation of population groups (Ilyn 1987). This value was lower by a factor of 2 to 3 than that recommended by the International Commission on Radiological Protection (ICRP) for the same countermeasure. Nevertheless, this value proposed by the NCRP was criticized by international experts as being very high. Today, one is convinced that too many people were resettled and that this drastic measure brought more disadvantages than advantages. The situation was further complicated by the political and social tension in the Soviet Union at that time. As late as 1991, the resettling criteria were still being discussed and applied (e.g. 555 or 1,480kBq/m^2 or 5 mSv per year[1]). This led to renewed resettlements and also to returns to the earlier settlements. Mention is made of a total of 350,000 people that were temporarily or permanently resettled. Over time, relatively many people returned voluntarily to their earlier homes even if they were located in an exclusion zone. This was tolerated by the authorities. Life in a more strongly contaminated zone to this day still entitles people to higher compensations.

Today, territories where populations receive an accident-related dose under 1 mSv per year are declared as a zone permitting normal life. For areas with doses above 1 mSv/year, authorities continue to give social compensations depending on the dose or contamination level[2]. People who continue to live in the heavily contaminated areas also receive compensation and are offered annual medical examinations by the government. The consumption of locally produced milk and mushrooms is still restricted in some of these areas.

As is mentioned in the section on psychological effects in Chapter 8, the Soviet authorities did not foresee that their attempts to compensate those people affected by the accident would be misinterpreted by the recipients and increase their stress. The label of “radiophobia” attributed to these phenomena by the authorities was not only incorrect, but was one that even reinforced the alienation between them and the public.

[1] These strange values originate from the conversion of the former unit Curie (Ci) into the new unit Becquerel (Bq). 555 kBq/m^2 =15 Ci/km^2, 37 kBq/m^2 = 1 Ci/km^2

[2] In comparison: The natural background radiation in Europe amounts to about 2.4 mSv per year. Add to this another 1 mSv per year on average from medical applications.

Some of these initial approaches have been recognized as being inappropriate or even counterproductive and the authorities are now endeavoring to rectify their attitude toward the exposed population.

4.2 Outside the former Soviet Union

The progressive spread of contamination over large distances from the accident site has caused considerable concern in European countries. The reactions of national authorities to this situation have been extremely varied. They were in an unenviable position. They had to act quickly and cautiously to introduce measures to protect the "purity" of the public food supply and, what is more, they had to be seen to be effective in so doing. This inevitably led to some decisions, which even at the time appeared to be over-reactions, and not scientifically justified. In addition, dissenting opinions among experts obstructed the ability of decision-makers to find timely and clear protective measures.

In general, the most widespread countermeasures were not compulsory. These included advice to wash fresh vegetables and fruit before consumption, advice not to use rainwater for drinking or cooking. In reality, experience has shown that even these types of measures sometimes had a significant negative psychological impact.

Protective actions having a more significant impact on dietary habits and imposing a relatively important economic and regulatory burden included restrictions or prohibitions on the marketing and consumption of milk, dairy products, fresh leafy vegetables and some types of meat, as well as the control of outdoor grazing of dairy cattle. In some countries, prohibitions were declared on travel to areas affected by the accident and on the import of foodstuffs from the Soviet Union and Eastern European countries.

The variety of these reactions can be explained primarily by the diversity of local situations both in terms of different levels of contamination and in terms of national differences in administrative and public health systems. However, one of the principal reasons for the variety of situations observed in EU-Member countries stems from the criteria adopted for the choice and application of intervention levels for the implementation of protective actions. In this respect, while the general radiation protection principles underlying the actions taken in most Member countries following the accident have been very similar, discrepancies arose in the assessment of the situation and the adoption and application of operational protection criteria. These discrepancies were further enhanced by the overwhelming role played in many cases by non-radiological factors, such as socio-economic, political and psychological factors, in deciding the countermeasures.

This situation reinforced the existing concern and confusion among the public, and led to perplexities among the experts and difficulties for national authorities, especially in maintaining their public credibility. This was, therefore, identified as an area where international harmonization was needed.

In 1986, the EC imposed a ban on the import of food containing more than 370 Bq/kg of radiocesium for milk products and 600 Bq/kg for any other food, regardless of the quantity consumed in the average European diet (EC 1986). Thus, food items with a trivial consumption, such as spices, were treated the same way as items with high consumption such as vegetables. However, this situation was corrected. In some special circumstances, decisions had to be made based on the local situation. For example, in some Northern European communities, special countermeasures were ordered, such as pasturing reindeer in areas of lower deposition to reduce the contamination of meat.

The variety of solutions made any international consensus on Derived Intervention Levels for food extremely difficult to achieve, and it was only with the WHO/FAO *Codex Alimentarius* Meeting in Geneva in 1989 that an agreement was reached on guideline values for the radioactivity of food shipped in international trade (CODEX 1989). It should be remembered that these guideline values were developed to facilitate international trade in food, and should be regarded as levels “below regulatory concern”. Higher levels do not necessarily constitute a health hazard.

Often the national authorities were not able to predict the public response to some of their advice and regulation. For example, in some western European countries, soon after the accident the public was advised to wash leafy vegetables carefully. The national authority felt that this was innocuous advice as most people washed their vegetables anyway. They were unprepared for the public response, which was to stop buying these vegetables altogether. This resulted in significant economic losses to local producers, which far outweighed any potential benefit in terms of radiological health. In some countries, the public was told that the risks were very small but, at the same time, were given advice on how to reduce these low risks. It was very difficult to explain this apparently contradictory advice. The national authorities in question harvested criticism from the media as a result.

In 1987, NEA published an extensive report describing protective measures taken by member states (NEA 1987). All member states had enhanced monitoring of the environment, informed the public, and had developed different approaches for outside activities, drinking water, milk and milk-products, vegetables and meat.

Summary

The Chernobyl accident took authorities by surprise as regards extent, duration and contamination at long distance. As no guidelines were available for such an accident, little help for decision-making was available. Additionally, great political and public pressure to take action was experienced and overly precautious decisions were often made in and outside the Soviet Union. The psychological impact of some official decisions on the public was not predicted. Variable interpretations or even misinterpretations of ICRP recommendations, especially for intervention levels for food, led to inconsistent measures and advice. These added to public confusion and provoked mistrust and unnecessary economic losses. However, very soon international efforts were initiated to harmonize criteria and approaches to emergency management.

5 Impact on the environment and agriculture

5.1 Agricultural impact

The ingestion of radionuclides in food is one of the pathways leading to internal contamination and contributes to human exposure. Excessive contamination of agricultural land after the Chernobyl accident could have led to unacceptable levels of radionuclides in food. Protective measures had to be imposed immediately, ideally even before the levels of contamination were measured and known.

5.1.1 Within the former Soviet Union

The prohibited area (4,300 km^2) stretches between parts of Belarus, Ukraine and Russia and includes a circular area with a radius of 30 km. This zone is officially uninhabited, is not cultivated and is considered as lost. Critical nuclides include ^{137}Cs, ^{90}Sr and also ^{239}Pu. However, uptake of plutonium from soil to plant constitutes a small health hazard for the population, because transfer rates from soil to plant and plant to man are very low.

Beyond this zone, the critical radionuclides are only ^{137}Cs and ^{90}Sr. An area of approximately 7,000 km^2 was contaminated with $^{134/137}Cs$ levels exceeding 555 kBq/m^2 and about 30 km^2 with ^{90}Sr levels exceeding 10 kBq/m^2.

The food chains accounted for approximately 50% of the total dose received by the populations of the affected zones, and even up to 70% in the zones where poor soils prevail. This confirms the importance of a well adapted agriculture. Before the products from the contaminated territories arrive on the market, they are subject to radiological monitoring. The produce remains difficult to sell, even if their level of contamination lies below the official limit. This problem affects many farmers, who often subsist on their own produce.

Within the framework of a Franco-German agreement and with the collaboration of Belarussians, Ukrainians and Russian experts, an evaluation of countermeasures was carried out (Deville-Cavelin 2004). The change of farming culture and the application of fertilizers were very effective agricultural countermeasures. In the early phase, restriction of consumption was the most effective countermeasure, later mapping of contamination and guidance for cattle pasture, preparation of silage from maize instead of hay, milk processing, etc. became more efficient. Contamination of agricultural products was reduced by a factor of between 3 and 9 according to the composition of the ground and the choice of the plants. Concerning meadows, the soil rehabilitation led to a reduction factor of 4 for ^{137}Cs in grass. Before slaughtering, a supply of clean fodder was provided to animals. A more rational use of pastures was carried out. The net result of these measures was a reduction of the contamination of food by a factor of 2 to 15.

The agro-alimentary transformations, such as the transformation of milk into cheese, can reduce the activity of ^{137}Cs and ^{90}Sr by a factor of 50. The majority of activity remains in the whey.

Later soil treatments reduced uptake of radiocaesium. The procedures applied can involve deep ploughing (dilution in soil), application of nitrogen, potassium fertilisers and lime (dilution of Cs in the plant).

There is a continuous, if slow, reduction in the level of ^{137}Cs activity in agricultural soil. However, twenty years after the accident, exposures of populations are mainly due to the consumption of agricultural food contaminated by ^{137}Cs. Since July 1986, the dose rate from external irradiation in some areas has decreased by a factor of forty, and in some places, it is less than 1 per cent of its original value. Nevertheless, soil contamination with ^{137}Cs and ^{90}Sr is still high. Restrictions on the use of land are still necessary in the more contaminated regions in Belarus, Ukraine and Russia. In these areas, no lifting of restrictions is likely in the foreseeable future. It is not clear whether a return to the 30 km exclusion zone will ever be possible nor whether it would be feasible to utilize this land in other ways such as grazing for stud animals or hydroponic farming. There are, however, a small number of generally elderly residents who have returned to that area with unofficial tolerance of the authorities.

Today, the contamination of foodstuff should be at a level where average individual doses are not expected to exceed 1 mSv per year. Production of these foodstuffs is not expected to be more expensive in either economical or social terms. The amount of agricultural products exceeding trade limits fixed by Ukraine, Russia and Belarus are now very low. This means that, 20 years after the accident, food production can be performed without heavy restrictions and for the territories where the annual dose is lower than 1 mSv, life is considered as “normal”.

When the annual dose is higher than 1 mSv per year, as mentioned before, people still receive social compensations. In early 2001, 2,217 towns or villages were still under radiological control in the Ukraine. In fact, only 1,316 need permanent controls but the population of the 901 remaining towns or villages refuse liberation of their areas because this could be associated with the end of financial and social compensations (UNDP 2002).

In Ukraine, 84,000 km^2 of agricultural soil is still considered to be contaminated with ^{137}Cs (above 37 kBq/m^2) and is subject to countermeasures, mostly the use of adapted fertilizers. For most of the contaminated territories, agriculture produces foodstuffs that does not exceed the limits in effect since 1997 for milk products, meat, potatoes and bread. However, there is a large disparity and some private farms continue to produce milk exceeding the set contamination limit (Mays 1998).

5.1.2 Other European countries

In Western Europe, Sweden imposed action levels on ^{131}I and ^{137}Cs concentrations in imported and domestic food. Cattle were not put onto pasture in some areas and advice was given not to consume fresh leafy vegetables. In Norway, crops in fields were monitored after harvesting. In Germany, some milk in parts of Bavaria was converted into milk powder. In the UK, advice was issued to regulate the consumption of red grouse, and restrictions were imposed on the movement and slaughter of upland sheep from a number of the more contaminated areas of the UK. Austria issued advice not to feed fresh grass to cows for a short period in May 1986. In some areas of the United Kingdom, in spite of improvement, there are still problems with sheep. Restrictions on slaughter and consumption of sheep and reindeer are also still in force in some Nordic countries.

The regional average levels of ^{137}Cs in the diet of European Union citizens, which was a source of exposure after the early phase of the accident, have been falling so that, by the end of 1990, they approached pre-accident levels (EC 1994).

A comparison with the ^{137}Cs deposits from the atomic bomb fallout is interesting: The medium Nordic latitudes, i.e. 40° to 50°, were among the most heavily affected (1.5 to 5 kBq/m^2). Here, the distribution was more homogeneous than after Chernobyl: In Germany, Switzerland, Austria and the north of Italy, Chernobyl depositions ranged between less than 1 to over 40 kBq/m^2 with local maxima up to 70 kBq/m^2.

5.2 Impact on Forests

Forests are highly diverse ecosystems. Not only are they a site of recreational activity, but also a place of work and a source of food. Wild game, berries and mushrooms are a supplementary source of food for many inhabitants of the contaminated regions in the former Soviet Union. Timber and timber products are a viable economic resource. Since the accident, many families have lost this source of income.

The transfer of radionuclides to wild game could lead to an unacceptable exposure for some individuals heavily dependent on game as a food source. This became evident in Scandinavia where moose meat had to be controlled. In other areas, mushrooms were and are still severely contaminated with radiocesium (≥ 1,000 Bq/kg).

In 1990, forest workers in Russia were estimated to have received a dose up to three times higher than others living in the same area (IAEA 1994). In addition, some forest-based industries, such as pulp production, which often recycle products of the process, have been shown to be a potential radiation protection problem due to enhancement of radionuclides concentration in liquors, sludge and ashes. However, harvesting trees for pulp production may be a viable strategy for decontaminating forests (Holm 1995).

Since the accident, it has become apparent that natural decontamination of forests is proceeding extremely slowly. Without artificial intervention, it is the physical decay rate of ^{137}Cs that will largely determine how long forests continue to be affected by the accident in Chernobyl.

The most effective protective measure regarding forests of the highly contaminated areas was access control in relation to forest work, but also the restriction of use of forest products (wood, mushrooms, berries, game, etc). Countermeasures involving restrictions on public activities inevitably lead to a disturbance of normal societal behavior patterns.

5.3 Radiation-induced effects on environment

An environmental response to the Chernobyl accident has been observed in plants and animals in the exclusion zone: increased mortality of coniferous plants, soil invertebrates and mammals, chronic radiation syndrome in mammals and birds. Beyond the exclusion zone, no acute radiation-induced effects on animals and plants exposed to a cumulative dose of less than 0.3 Gy during the first month after the accident have been reported.

Both in the exclusion zone and beyond, different cytogenetic anomalies attributable to radiation continue to be reported, but their biological significance is not known.

The recovery of affected flora and fauna in the exclusion zone has been confounded by the overriding response to the removal of human activities. The populations of many plants and animals have expanded, so that the present environmental conditions have a positive impact on the flora and fauna of the exclusion zone.

Summary

The amount of radionuclides deposited in the environment due to the accident is now well known. The intensity of ground contamination and the corresponding importance of radiation doses decreased with increasing distances and had no direct health consequences at distances larger than 200 km, although some hot spots – with significantly lower contamination levels than those found close to the reactor - were detected, e.g. in the Scandinavian countries, in Austria and in Bavaria. These hotspots were caused by washout through heavy rainfall. A total area of 11,000 km^2 was contaminated with $^{134/137}Cs$ levels exceeding 555 kBq/m^2 [1]. In Ukraine, mainly the forests were affected. The countermeasures implemented in agriculture were effective, especially the agro-alimentary transformations, the reconditioning of the soil and the changes in farming methods. Today, the great majority of agricultural produce is at a level where average individual doses do not exceed 1 mSv per year. Environmental effects have been observed in plants and animals in the exclusion zone.

In the affected areas, twenty years after the accident radionuclides are still present in the top layers of soils, and still transfer to plants, particularly mushrooms, berries and forest products. Contamination levels in soils decrease only slowly, e.g. by transfer to plants. Most of the decrease in the next years will be due to the physical half-life of ^{137}Cs (30 a) only. The recovery of affected flora and fauna in the exclusion zone has been positively influenced by the absence of human activities.

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1 In comparison: The contamination in the medium Nordic latitudes resulting from the atomic bomb fallout ranged between 1.5 and 5 kBq/m^2.

6 Estimating radiation doses

Definition of effective dose on the basis of organ dose and typical dose values

Exposure to ionizing radiation is measured in terms of absorbed energy per unit mass, absorbed dose. The unit of **absorbed dose** is the ***Gray*** (Gy), which is a joule per kilogram (J/Kg). The absorbed dose in a human body of a few grays may cause acute radiation syndrome (ARS).

When many organs and tissues are exposed, it is very common to use an additional concept, that of **effective dose**, which characterizes the overall health risk due to any combination of radiation exposures. The effective dose accounts for absorbed energy, type of radiation and for susceptibility of various organs and tissues to develop a radiation-induced cancer or a genetic effect. Moreover, it applies equally to external and internal exposure and to uniform and non-uniform irradiation. The unit of effective dose is the ***Sievert*** (Sv). Normal exposures are commonly given in millisievert (mSv). In cases where the whole body is uniformly irradiated with gamma rays, 1 Sv is 1 Gy.

UNSCEAR has estimated annual natural background radiation doses to humans worldwide to average 2.4 mSv, with a typical range of 1-10 mSv. Lifetime doses due to natural irradiation would thus be about 100 - 700 mSv. The dose limit for professionally exposed workers under controlled conditions is normally 20 mSv per year. Radiation doses to humans may be characterized as low-level if they are comparable to natural background radiation or to occupational doses.

To place these figures into context, here are some typical dose values for comparison:

Average natural radiation exposure	≈ 2.4 mSv/a
Computer tomogram of the torso	≈ 20 mSv
X-ray of the lower back	≈ 2 mSv
Szintigram of the thyroid	≈ 1 mSv
Transatlantic flight Frankfurt – New York – Frankfurt	≈ 0.1 mSv

6.1 Firemen and Liquidators

Over 100 on-site fire fighters and those called in from Pripyat constituted the group that received the highest radiation exposures and suffered the most fatalities. While the conventional fires at the site posed no special fire fighting problems, the firemen incurred very high radiation doses. Initial diagnosis of acute radiation syndrome was made for 237 persons. Later on, the diagnosis of an acute radiation syndrome of varying severity was confirmed for 134 of these patients. All people diagnosed with ARS are under long-term medical monitoring being carried out by specialized hospitals. 28 of them died in 1986 of ARS and 11 later on of various causes (Smith and Beresford 2005).

The exposure was external and relatively uniform for the gamma radiations and more localized for the beta radiation. The doses were estimated *a posteriori*, they ranged between a few hundred mSv and more than 10 Sv. The uncertainty of dose estimation of liquidators is high because partly not enough dosimeters were available or because the measurement range of the dosimeter was exceeded.

“Liquidators” is the name given to a group of approximately 200,000 to 600,000 people who intervened on the site in the first years following the accident. Different figures exist on the number of liquidators. These differences have never been fully clarified so far. This confusion comes partly from the bureaucracy in the different republics of the former Soviet Union. Many liquidators were possibly counted twice, and many persons succeeded to achieve the status of liquidator because of compensation payments.

Despite the existence of numerous publications, the dosimetric results concerning clean-up activities remain unclear. The system of recording individual doses among the troops was well established and cumulative doses were registered daily. Unfortunately, a significant number of registration logbooks were destroyed with the explanation "due to high radioactive contamination of the documents". For civilian personnel, individual dosimetry monitoring was performed. Upon receiving cumulative doses of 50, 100, 150 and 200 mSv, personal dosimeters were replaced by new ones. Upon receiving a dose of 200 mSv, a worker was withdrawn from the zone. Since the accident, Ukraine has performed the collection of biological samples for dosimetry, more especially teeth, for purposes of electron spin resonance dosimetry of tooth enamel. 167 regional medical institutions including 314 dentists take part in this effort. This concerns 3,875 liquidators (Chumak 2004).

According to UNSCEAR, the average dose received in the years 1986-1987 was about 0.1 Sv, whereby numerous liquidators received approximately 0.5 Sv. The skin dose due to external contamination could reach up to several hundreds of mGy. The thyroid internal doses received by these liquidators are badly evaluated, but are lower than those for external exposure.

6.2 Evacuees

About 116,000 people were evacuated from the 30 km zone during the first days following the accident. Prior to their evacuation, these people were exposed to external and internal irradiation.

The evacuated populations received average total doses estimated at approximately 20 mSv, with peaks of up to 380 mSv for certain individuals according to UNSCEAR. Uncertainties are large, because the influence of isotopes with short half-lives was difficult to establish (UNSCEAR 2000).

The internal exposure of these populations was estimated at approximately 10 mSv, with the thyroid being the most affected organ. The iodine activity in the thyroid of evacuees was measured in more than 5,000 Pripyat inhabitants, a population size that is large enough for dose reconstruction. Average individual thyroid dose varies from 0.07 to 1.4 Gy according to age. The younger the age, the higher the dose. Maximum dose in the thyroid could reach 50 Gy among children and teenagers. The distribution of stable iodine as a prophylactic measure was performed one week after the accident; this countermeasure was late, but still effective against the consecutive uptake of iodine. The averted collective dose from ingestion of milk was about 30% (Balonov 2003, Liktharev 2003).

6.3 Population of the former Soviet Union living in the contaminated areas

In the rural population of the contaminated areas of the Ukraine, the annual effective doses due to the ingestion of products contaminated by ^{134}Cs and ^{137}Cs are now lower than 1 mSv for 2/3 of the population and range between 1 and 10 mSv for the other third. It is estimated that less than 1 ‰ of the population received cumulated effective doses up to 100 mSv. In the same area, another study allots an average dose of about 0.2 mSv due to ^{90}Sr, with a maximum value of 1.5 mSv. The main part of the received doses is related to the consumption of contaminated milk. (UNSCEAR 2000)

In Russia, in the area of Briansk, the average annual internal dose received in recent years by children of the contaminated zones amounts to about 0.2 mSv. It exceeds 1 mSv per year for 2% of the 26,000 children studied. In the area of Gomel, in Belarus, the internal effective doses received by the population cumulated for the first 10 years varied from 20 to 70 mSv, the external dose from 5 to 25 mSv.

In summary, the fact of living in the most contaminated zones of these three countries resulted on average in a radiation burden two to five times higher than natural background radiation, but individual peak values could be one or two orders of magnitude higher, e.g. for self-sustaining families living in a hot spot and off their own produce. Beside the fact that these average effective doses are astonishingly low, the thyroid exposures were nevertheless much larger. The reason for this is that the thyroid dose contributes to only 5 % of the effective dose.

6.4 Western European and Overseas population

After the accident, the released radioactive materials were further dispersed throughout the atmosphere and the volatile radionuclides of primary importance (^{131}I and ^{137}Cs) were detected in most countries of the northern hemisphere. Frequently, however, the doses received by the population were much lower than in the contaminated areas of the former Soviet Union; they reflected the deposition levels of ^{137}Cs and were higher in areas where the passage of the radioactive cloud coincided with rainfall.

During the first weeks, ^{131}I was the main contributor to the dose, via ingestion of milk. Infant thyroid doses generally ranged from 1 to 20 mGy in Europe, from 0.1 to 5 mGy in Asia, and were about 0.1 mGy in North America. Adult thyroid doses were lower by a factor of about 5 (UNSCEAR 1988).

Later on, ^{134}Cs and ^{137}Cs were responsible for most of the dose through external and internal irradiation. In south-eastern Europe, the calculated total effective dose is slightly less than 1.2 mSv, for northern and central Europe it is slightly less than 1 mSv, and for Western Europe it lies around 0.15 mSv.

The total whole-body doses expected to be accumulated during the lifetimes of the individuals are estimated to be a factor of 3 larger than the doses received during the first year (UNSCEAR 1988).

Summary

The doses received by the firemen and liquidators of the first phase ranged from a few hundred mSv to more than 10 Sv for few firemen. For the 200,000 to 600,000 liquidators involved in the later clean-up activities, the doses received remain uncertain, but largely range from 100 to 500 mSv. A large proportion of this group of persons received much lower doses. Their thyroid doses are badly evaluated. The evacuees received average doses estimated at approximately 20 mSv. This is comparable to the typical dose received by a patient undergoing a medical computer tomography examination of the torso. For residents of the strict control zones (270,000 people who continue to live in areas of ^{137}Cs deposition higher than 555 kBq/m^2), the average radiation dose is about 50 mSv. For populations living in contaminated territories (6,400,000 people living in regions of ^{137}Cs contamination higher than 37 kBq/m^2), annual estimated received doses were lower than 1 mSv for 2 thirds of the population and ranged between 1 to 10 mSv for the other third. This is comparable to natural background radiation which reaches a few mSv per year worldwide.

In western populations, the calculated total dose amounted to about 1 mSv for the north of Europe and 0.15 mSv for the western part. For self-sustaining families in hot spots outside the Soviet Union, living off their own produce, the radiation doses could have been 20 to 50 times higher than average. Precautionary measures such as avoidance of fresh milk for about 2 months were recommended for these groups.

7 Impact on health

Twenty years have passed after the Chernobyl accident, but it remains difficult to arrive at a full picture of its health impacts. In the affected regions in Belarus, Ukraine and Russia, the sanitary conditions are precarious and the general state of health is poor. Life expectancy amounts to a little over 60 years. The main causes are the catastrophic economic conditions, alcoholism and smoking.

Many epidemiological studies have been performed in order to find the relationships between the radiation dose and diverse health impacts. These studies often do not allow reaching any significant conclusions due to incomplete or bad data or due to missing comparative data (IAEA 2005c).

7.1 Thyroid diseases

Cancers

There is no doubt as to the existence of a causal relationship between exposure to radioactive iodines and increased risk of thyroid cancer in children or young people. However, differences exist between Ukraine and Belarus in the relationship between thyroid cancer incidence and age. The reasons are not yet fully understood (UNDP 2002, WHO 2005)

Experimental studies indicate that regional iodine deficiency may be an important modifier of the risk of radiation-induced thyroid cancer, because it affects not only the level of dose but also thyroid function. In Belarus, Ukraine and Russia, a total of approximately 3,000 cases of thyroid cancers were registered and treated to date; nine of these died.

No data are currently available from Chernobyl regarding risk of thyroid cancer from *in utero* exposure.

There is still considerable uncertainty for adults. Although an increase of thyroid cancers has been reported, this has not been related to dose and might be accounted for by the increased intensity of screening. Screening programs increase the apparent incidence of thyroid cancer by advancing the time of diagnosis of tumors, and possibly by identifying tumors that would never have become clinically manifest.

Outside the former Soviet Union, thyroid cancer incidence cannot be linked to the Chernobyl accident.

Non-cancer thyroid diseases.

Radiation-induced thyroid disorders other than cancers, including benign nodules and hypothyroidism, have been reported after exposure to radioactive iodine. However, the available information is rather inconsistent (WHO 2005).

7.2 Leukemia

Children

Several epidemiological studies have examined the association between radiation exposure of children under age of 15 and the occurrence of leukemia. Although the number of leukemia cases increased two years after the accident, there is no evidence showing that this increase was more pronounced in areas that were most affected by the accident. In Ukraine, Belarus, Russia, Finland, Sweden and Greece there is a slight tendency for an increase in rates of childhood leukemia. However, there was no association between the extent of contamination and the increase in occurrence. (WHO 2005)

Adults

Studies of leukemia in adults have largely focused on the liquidators. In liquidators, initial studies revealed a light increase in the incidence of leukemia; however, a two-fold increase in incidence was shown for those Russian workers exposed to more than 150 mSv. Approximately half of the 21 cases that were found in 70,000 liquidators can be statistically attributed to radiation.

There is no convincing evidence that the incidence of leukemia has increased in adult residents of the exposed populations in Russia and Ukraine (WHO 2005).

7.3 Solid cancers

Recent publications concluded that the occurrence of radiation-related solid-tumors other than thyroid cancers in workers or in residents of contaminated areas have so far not been observed. However, the possibility of a later increase cannot be ruled out in liquidators, especially among those who had received the highest doses (WHO 2005).

7.4 Prediction of cancer mortality

The question concerning the number of cancer-deaths that are, or ultimately may be, attributable to the Chernobyl accident has been of great interest to scientists, politicians, the population and the mass media.

The evaluation of the number of radiation–induced cancer deaths is complicated by the fact that radiation causes the same types of cancer which also develop spontaneously. A direct epidemiological observation is therefore only possible if the radiation–induced cases are sufficiently frequent to be discriminated against the statistically varying background of the spontaneous ones. This is the case for spontaneously rare types of cancers like thyroid cancer and maybe leukemia, but not for the more frequent types and therefore not for the total number of deaths from all types of cancers.

In the absence of direct observation, estimations can be made on the basis of the absorbed dose and dose–risk relations derived mainly from the observation of Hiroshima and Nagasaki survivors. In this way, the number of deaths in Russian emergency workers attributable to radiation was estimated to be about 120 for solid cancers and about 30 for leukemia. So far the estimates have been performed only up to 1998. Estimates exist for the general population based on the current radiation risk models and the highly unrealistic assumption of a life expectancy of 95 years (Cardis 1996). According to these estimates, the radiation-related increase of total cancer morbidity (incidence) and mortality (death) rates above the spontaneous level could be 1 – 1.5 % for low and 4 – 6 % for highly contaminated areas. This would result in about 2,000 predicted radiation-induced deaths among liquidators, about 1,500 among evacuees of highly contaminated areas and 4,600 in other contaminated areas. This evaluation does not take into account any uncertainty ranges in dose and risk factors. Such an increase would be very difficult to detect epidemiologically.

The assumed life expectancy plays an important role. We know that spontaneous cancers appear mainly after 60 years of age. We also know from the findings of long term epidemiologic studies that radiation induced cancers follow a multiplicative model, i.e., the number of radiation-induced cancers is proportional to the spontaneous ones and thus follows the same disease progression. From these two considerations, it could be expected that the majority of the cancers predicted in the estimate would occur in the coming decades and affect older people. Since the life expectancy for males in the three republics is estimated to lie between 58.4 and 66.7 years, following the above calculations, many of the estimated cases are unlikely to actually come about.

For estimates of accident-related deaths, WHO experts arrive at a number close to 4,000. This is about 3% of the total number of cancer deaths predicted in the same population and about one-third of the number expected to die from smoking-related diseases. It is very far from the earlier claims of tens or even hundreds of thousands of deaths (WHO 2005).

7.5 Non-cancer diseases

Epidemiological studies of the atomic bomb survivors in Japan have suggested dose-related increases in mortality from diseases other than cancer. Cardiovascular disease is one such non-cancer disease. The recognition in the atomic-bomb survivors in Japan of non-cancer effects for doses in the order of 0.5 Sv should direct attention to the deterministic effects and non-cancer morbidity and mortality among certain groups of liquidators.

Over the last 20 years, there have been a vast number of other health effects attributed to the Chernobyl accident: cataracts, immunological system effects, hereditary effects, stillbirths and diverse effects on children's health, mental, psychological and central nervous system effects.

For most of the mentioned diseases, the results are less scientifically rigorous than for the leukemia and thyroid studies. With the exception of cataracts, the diagnoses of many of these health effects were often the result of a clinical impression. Many of the studies do not have sufficient control groups. The original data are often not available. Moreover, it is not possible to exclude confounding factors such as smoking and alcohol consumption. Additionally, one cannot exclude that radiation stress can increase smoking habits and alcohol consumption, in turn provoking more cancer and cardiovascular diseases (WHO 2005). Furthermore, in addition to iodine deficiency, the situation in terms of nutrition (quality of foodstuffs, vitamins, etc.), health, medical services, etc. (particularly for children) was generally poor in the former Soviet Union. This could be another confounding factor.

<u>The eyes</u>

For children and liquidators, the studies clearly show an association between cataracts and exposure to radiation from the Chernobyl accident above a threshold of 250 mGy. However, uncertainty remains concerning this threshold, especially since the results observed here are compared to recent studies on astronauts and on patients having had CT scans.

<u>Cardiovascular diseases</u>

Cardiovascular diseases are observed for high radiation doses such as those used in radiation therapy of Hodgkin's disease or breast cancer.

Consequently, liquidators are likely to be at increased risk for cardiovascular diseases. In Russia, a large study on liquidators has shown a significant increase of death from cardiovascular diseases. However, the correlation with radiation dose is unclear. Data on the effect of "chronic" exposure of long duration at low dose rates are insufficient for assessment of this type of radiation damage. No reports (Mettler 2005) were made about the commonly associated heart pathology such as coronary insufficiency and myocardial infarction. One cannot exclude a small effect that may be obscured by statistical fluctuation. In the Ukraine and Belarus, no large epidemiological studies concerning the cardiovascular diseases exist.

Effects on cells

While effects on cells have been reported in a number of studies, the possible role of confounding factors, such as heavy metals, complicates the evaluation. The results of these studies are difficult to interpret since it is as yet unknown if the observed changes correspond to any specific disease (WHO 2005).

Chronic fatigue syndrome

Among a considerable part of the liquidators, especially those who worked in the 1990s, the diagnosed pathology meets the criteria for Chronic Fatigue Syndrome (CFS). This led to a suggested unconfirmed hypothesis on the development of CFS under the impact of ionizing irradiation doses combined with psychological stress.

7.6 Children's health

Infant mortality

Infant mortality was studied by a project entitled the "Franco-German initiative for Chernobyl". The objective was to compare the changes in infant mortality in Ukrainian contaminated areas (doses ranging from 6 to 30 mSv) with the data of non-contaminated areas. Results show that prior to the accident, infant mortality was higher than after the accident in Ukraine as a whole, both for contaminated and non-contaminated areas. After the accident, a statistically non-significant increase is only observed in the most contaminated area. However, there is no obvious temporal trend indicating radiation as the direct cause of infant mortality (Dzikovich 2004, WHO 2005).

Effect of prenatal irradiation on the brain

Recently, a study was published describing a group ("cohort") of 154 children born between April 26th, 1986 and February 26th, 1987 to mothers who had been evacuated from Pripyat to Kiev, and compared them with 143 classmates from Kiev as a control group. The prenatally exposed children show significantly more mental disorders and diseases of the nervous system. Emotional and behavioral disorders occur more frequently in the exposed children for emotional withdrawal, somatic complaints, anxiousness/depression, social problems, and attention problems. However, there is no general correlation of the IQ deterioration and mental health disorders of the *in utero* exposed children with radiation dose (Nyagu 2004, WHO 2005).

Congenital malformations

The possibility that preconceptional or *in utero* exposure to ionizing radiation may affect pregnancy outcome remains a matter of public concern and scientific debate. Most epidemiological studies performed in Europe failed to show clear effects of radiation exposure due to the Chernobyl accident on the incidence of congenital malformations (CM).

Within the framework of a Franco-German agreement, an evaluation of congenital malformations was carried out in Belarus. The Belarus National Registry (BNR) of CM, a population-based monitoring system set up by the Belarus Institute for Hereditary Diseases since 1979, is the only CM register that existed in the three republics before the reactor accident. 9 types of congenital malformations including Down's syndrome are compared pre- and post-accident. In the period 1983-1999, 12,167 congenital malformations were registered among newborns and miscarriages (about 30 per 10,000 newborns, i.e. 3 ‰). The results of the project do not exclude an increase of CM, at least during the first period after the accident. The increase is observed both in low and high contamination areas. Statistically, there were less congenital abnormalities in the high contamination area compared with low contamination areas (Lazjuk 2004).

An increase in Down's syndrome in children conceived during the period of high radiation exposure in Belarus is reported. A peak in January 1987 is clearly visible. However, the same observation was made in May 1990 following a (statistical) trough a few months earlier. Globally, no trend was observed pointing to an increase before or after the accident when taking all entries in the Belarus registry since 1981 into account. These two observed peaks are probably statistical clusters.

For congenital malformations and miscarriages, especially from outside of the former Soviet Union, there are many reports of doubtful credibility, whose confirmation is only possible if the original data can be checked. As things stand, many of these claims are non-verifiable.

7.7 Radiation-induced health impairments in Germany

The radiation doses in Germany caused by the Chernobyl reactor accident were comparatively low even in the most heavily affected areas (especially in Bavaria) and were still in the fluctuation range of natural background radiation. Nevertheless, in the years since Chernobyl, there have been a number of publications that claim or at least suspect a relationship between conspicuous investigation findings in Germany and the ionizing radiation brought about by Chernobyl. Primarily, mention was made of the Down's syndrome (trisomy 21), infant mortality, leukemias, neuroblastomas and cleft lip and palate (CLP).

A number of findings speak against a causal connection between the ionizing radiation induced by Chernobyl and the observed medical findings. Foremost among them are the negative diagnostic findings from other European regions with in part clearly higher radiation doses. Furthermore, no biological mechanisms have been found thus far which could explain such a causal relationship to the extent described in the publications. Additionally, it needs to be considered that the scientific quality of some reports leaves much to be desired. Also, the fact that there are no indications that the radiation effect having the highest probability of occurrence, thyroid gland tumour cases in children, has an increased level of incidence in Germany following Chernobyl, speaks against the suspected causal connection.

Summary

Many studies have been performed in order to find relationships between the radiation dose and diverse health impacts. The possibly serious health problems related to this accident concern the populations who lived in or around the exclusion zone or were evacuated and relocated, as well as the many workers and soldiers (liquidators) deployed in the emergency response and in building the sarcophagus. Obvious acute effects were first observed among the fire fighters and certain heavily irradiated liquidators. 134 patients were treated, 28 of them died in 1986 and 11 later on. The second group of persons with health impacts attributable to radiation is the group of some 3,000 children and young adults developing thyroid cancers; nine of them have died. For leukemia, the most recent studies suggest an increase in the incidence between 1986 and 1996 in Russian emergency workers (11 cases) exposed to a radiation dose exceeding 150 mSv (external dose). For doses above 250 mSv, the Chernobyl accident may have had a cataractogenic impact. Other potential health effects in the population such as leukemia or congenital malformations could not be statistically correlated with the radiation doses. A study of prenatally exposed children shows mental disorders and diseases of the nervous system which could be due to radiation or to the stress of the mothers who belonged to the group of evacuated and relocated persons.

Generally, the observed physical health effects which can be scientifically correlated with radiation are restricted to persons who received relatively high radiation doses (firemen, liquidators, evacuees and children living in contaminated areas).

The number of fatalities which have been and will be attributable to the Chernobyl accident has been of paramount interest to the general public, scientists, the mass media and politicians. This number has recently been estimated to lie around 4,000, including deaths from acute radiation syndrome, thyroid cancers in children and cancers in the population.

8 Psychological and societal impact

People living in the areas affected by the accident suffer from a number of medical, psychological and societal problems. While this can be stated without doubt, it is difficult to distinguish what contributions to these problems come from different causes such as radiation, circumstances surrounding the accident (evacuation, etc), the collapse of the Soviet Union, the generally poor living conditions in this region, etc. The most important problems are mental health disorders.

8.1 Firemen and Liquidators

Neuropsychiatric and neuropsychophysiological follow-up studies confirm that Acute Radiation Sickness (ARS) patients who survived the Chernobyl accident show progressive structural-functional brain damage. At present, this is observed in 62% of patients who had confirmed ARS. The apathetic type of organic personality disorder is a characteristic for ARS and its severity correlates with the dose. The observed long-term organic brain damage of these patients has been verified by diverse clinical methods.

Although liquidators were especially burdened by the Chernobyl accident, epidemiological data on psychological disorders among them are still scarce. A study has been conducted in the framework of the Franco-German Initiative in order to validate data already collected on psychological and psychiatric disorders in Ukrainian liquidators and to upgrade a database on this subject. The preliminary results testify two-fold increases of the prevalence of any mental disorders (36%) in liquidators in comparison with the Ukrainian general population (20.5%), and a dramatic increase of the prevalence of depression (24.5%) in liquidators in comparison with Ukrainian general population (9.1%). Anxiety (panic disorder) is also more commonly found among liquidators (12.6% vs. 7.1%). At that time, there was no dramatic increase of alcohol dependence in liquidators (8.6% vs. 6.4%) (Romanenko 2004). However, a study in Belarus concerning 103 liquidators shows no higher levels of psychological distress or psychiatric morbidity.

Working and everyday living in the Chernobyl exclusion zone in the last 20 years shows signs of deterioration in the mental health among the workers living there. This deterioration is in the order of 3.4—6.2 times larger in comparison with the general population and 2—3.9 times larger than among survivors of military conflicts or natural disasters. Since 1990, the increase in schizophrenia among the workers in comparison with the general population testifies to a risk of developing schizophrenia that is 2.4 – 3.4 times higher. This enhanced incidence feeds the hypothesis that ionizing radiation may activate a predisposition to schizophrenia or indeed cause schizophrenia-like disorders.

8.2 Inhabitants of contaminated areas

An epidemiological study in the Gomel region (Belarus) shows that 64.8% of the population sample has psychological distress above average levels. A psychiatric disorder was observed among 35.8% of them, with especially high rates of affective and anxiety disorders. A higher prevalence of mental health problems was also observed among people who had been evacuated from the Chernobyl exclusion zone and in mothers with children under 18 years of age.

Two groups of mothers, those exposed to radiation and those who were not exposed (control group) did not show differences in verbal abilities. However, exposed mothers have been shown to have higher level of stress and a higher occurrence of depression, somatic disorders, anxiety/insomnia, and social dysfunctions, than the control group from Kiev. Statistically significant relationships exist between the mental health of the mothers and the neuropsychiatric disorders in their children.

The post-accidental stress considerably changed the relation of the populations with their health. They consult a doctor for the slightest ailment. The doctors are important multipliers: the greater weight they attribute to the accident and the radiation risk, the more anxious their patients will be (Havenaar 1996). An educational program for medical doctors on radiation risk and psychology would be very helpful.

Studies have shown that psychological problems associated with the Chernobyl accident are not decreasing with time (Rumyantseva 1996, UNDP 2002, Romanenko 2004, Havenaar 2003).

8.3 Effects of the response of the authorities in the former Soviet Union

One of the contributing factors to the psychological problems was inappropriate action of the authorities. The lack of information in the first years severely undermined the confidence of the affected people and fed their anxieties.

The subjective perception was the feeling of being surrounded by an invisible danger. People were unsure which consequences the accident would have on their health and that of their children. A contributing factor here was that the population did not receive any information, often over long time periods, that was specifically related to the local situation, and that the explanations given by the scientists were sometimes contradictory. People developed their own risk perception and a lack of trust in public announcements. The arrival of foreign experts did not improve the situation, because the population too often associated them with the existing public authorities, since the foreign experts were accompanied by the experts of the authorities.

Another inappropriate measure of the authorities was to grant compensations or “privileges” to the radiation victims to try to attenuate the social impact of the accident. In Belarus, a law in 1991 allotted social compensation to 2.1 million inhabitants of the contaminated territories similar to those for liquidators. In Ukraine, there are 3.1 million people who are entitled to similar rights and today, there are “cards” in the Ukraine for liquidators giving the holder rights to special treatment in the hospitals and state organizations. These well-intentioned measures unfortunately distorted the perception of the risk and induced secondary reactions on the psychological level.

These subsidies and privileges (7 millions people are entitled) support the feeling “I am a victim” and obstruct the development of individual initiative. A dependency culture has developed. According to experts of UNDP, many of these people have become apathetic and fatalist, which hampers their ability to take control of their own future. Such a situation is a social and economic catastrophe; it still persists (UNDP 2002). However, it seems obvious that it is not possible to attribute the observed stress situations leading to psychological impact to only one cause.

The identification of the total number of liquidators has proven to be extremely difficult. Many of them were called from different republics of the former Soviet Union and returned there. Later on, some people falsely declared themselves as liquidators in order to get compensation payments. However, others did not want to be identified as liquidators because of the impact on their immediate social environment.

8.4 Improvements

Among positive actions for decreasing stress levels, one experiment performed under the aegis of the European Community (project ETHOS) should be mentioned (Lochard 1999). It concerns the sustainable rehabilitation of living conditions for inhabitants of contaminated areas. French experts sustained a continuous dialogue with the village populations and local authorities on contaminated food management and how to reduce the contamination of food by simple actions. They did not participate actively in the actions led by the villagers. They only had an advisory role, offering advice where necessary. This experiment showed that improving knowledge on radiation risk and its management by the affected people without by-passing the national authorities decreased the stress levels and increased confidence. Similarly, the extent to which people believed that they were able to control the dose they received also reduced stress levels. This experience clearly shows that the perception of low confidence in their own ability to improve their situation can be reversed if the proper actions are performed. The project thus also helps to restore confidence in experts and authorities.

Among the actions which appreciably contributed to improving everyday life, mention must be made of school exchanges between Belarussian and West-European children that were encouraged by western countries. Not enough of these educational programs have been performed; they should be multiplied. The paradox of such programs is that they not only improve life in the affected countries, but also increase the western parents' understanding of the true risks related to the aftermath of this accident (Ayrault 2005).

Summary

Twenty years have passed and the trauma of the Chernobyl accident is still very tangible among a population of 7 million living around the exclusion zone. The fear of potential late effects due to radiation has a paralysing and stress-inducing effect. Existing studies have shown that psychological problems associated with the accident did not decrease with time. Among a considerable part of the liquidators, a chronic fatigue syndrome has been observed which could be associated with radiation doses combined with psychological stress. Among the inhabitants of seriously contaminated areas, there is a significant increase of diverse psychiatric disorders. The post-accident stress considerably changed the attitude of the population to their health. Medical doctors are important multipliers; the perception of radiation risk by medical doctors is important because it affects their interactions with patients. An educational program for medical doctors would be very helpful. Also, the system of national compensation and privileges which is still in force conveys the message to many unaffected people that they are victims and produces a state of apathy. The overall result is a general mistrust. At present, Chernobyl is still a psychological, societal and economic catastrophe. However, certain positive actions have reduced the stress levels among some groups of the population. One of these was the ETHOS program for sustainable rehabilitation and also the exchange between pupils.

9 Potentially remaining risks

9.1 Sarcophagus

In 1986, the Russian authorities ordered to build, in a few months, a sarcophagus to reduce the dispersion of radioactive materials, to avoid penetration of rainwater and to exploit unit 3, which has now been permanently shut down. The sarcophagus was built on not completely destroyed parts of unit 4; the walls have a thickness of up to 20 meters on the lowest point of the northern side. The roof is composed of pipes and sheet plates. It has uncovered spaces, its structural integrity is dubious.

The bulk of the 190 tons of reactor fuel is still in the sarcophagus. The surface of the lava has meanwhile reached ambient temperature. The lower part containing collected rainwater is periodically pumped.

There are currently two principal risks: the first is the risk of criticality, which cannot be entirely excluded but is very improbable; the second pertains to the release to the atmosphere of radioactive dust due to the decomposition of the lava.

The Ukrainians estimate the total mass of radioactive dust in the sarcophagus to be about thirty tons. The radioactivity is now mainly due by 50% to ^{90}Sr, the other 50% being ^{137}Cs. Collapse of the sarcophagus would disperse a part of this dust. It is a plausible assumption. Indeed, the area is prone to strong rains and violent storms which can weaken the structure. Even if this risk is not very high, it is to be considered for the workers still present on the site. The studies, financed by the European Commission and the EBRD, estimate that from 5 to 10 tons of dust containing 1% of nuclear fuel (50 to 100 kg) would be suspended in the air in the case of a collapse. This would lead to a release of 50 to 100 TBq of ^{137}Cs and of 40 to 80 TBq of ^{90}Sr. This dispersion would also carry from 0.65 to 1.3 TBq of plutonium and 0.5 to 1 TBq of ^{241}Am (Nemchinov 2004, Borovoy 2004a, Borovoy 2004 b).

This study shows that the cloud of dust would rise to a hundred meters above the ground and would cause a new contamination. However, the radiological risk represents a threat only for the people present in a zone of 200 to 300 m around the sarcophagus and up to 2 km downwind. They could receive effective doses estimated at 20 - 50 mSv. Outside of the 30 km zone, the dose would not exceed 1 mSv.

In conclusion, the various studies performed by Germans, Russians, Ukrainians and Belarussians all conclude that the risk of collapse of the sarcophagus is not very high and that the additional radiological risk beyond the zone of exclusion would remain very low. However, they all suggest that actions to consolidate the sarcophagus should be continued and recommend maintaining the exclusion zone at 30 km.

In 1997 Ukraine agreed to the "Shelter Implementation Plan (SIP)", a program developed by Western and Ukrainian experts to transfer unit 4 and the sarcophagus into an environmentally stable state. The Chernobyl Shelter Fund, managed by the EBRD, was set up to finance the implementation of the SIP. The international community (the G7, EC, Ukraine and others) has so far contributed 650 million €, pledges and interest amount to another 200 million €. Major projects under the SIP, such as stabilization measures reducing the collapse risk of the sarcophagus, an integrated monitoring system controlling structural integrity, radiation levels, seismic activity, etc., as well as necessary infrastructure projects are well advanced or completed. The tender process for the main project, design and construction of a New Safe Confinement to enclose the existing sarcophagus is nearing completion. The New Safe Confinement, which will prevent water from entering, contain dust and provide the necessary equipment and a safe working environment for future deconstruction works, has a design life of 100 years. The program also provides project management support, which is ensured by a consortium of three Western companies (Bechtel, EdF, Batelle) and licensing support to the regulator

(Riskaudit, Scientech). The cost of the overall program is currently estimated at 1.1 billion $ and completion is expected by 2010.

9.2 Groundwater

Surface run-off after rain or snow from contaminated land is one of the major processes responsible for the contamination of water bodies. The large area of land contaminated after the Chernobyl accident is a continuing source of radionuclide contamination for natural waters and aquatic ecosystems (NEA 2002, IAEA 2005).

For the Ukraine, contamination via river water is still a major problem, particularly during flooding, since most of the rivers flow southwards. The cities of Kiev, Kremenchug and Kahovsk are partly fed by the Dniepr. A few weeks after the accident, the ^{137}Cs and ^{90}Sr remained the only radionuclides measured in water at a significant level. Since 1988, ^{90}Sr is the radioelement whose level of measurement is highest. The average annual activity of ^{137}Cs in the water of the Pripiat river and the lake serving as a water reservoir for the above-mentioned cities has stabilized at around 0.1 to 0.2 Bq/l and is only ten times higher than the measurement levels recorded before the accident. (IAEA 2005b)

The environmental behavior of deposited radionuclides depends on the physical and chemical characteristics of the radionuclides and on the type of fallout, dry or wet, the size and shape of particles and the environment. For example, particles produced by gas-to-particle conversion through chemical reactions, nucleation and condensation as well as coagulation have a large specific surface and are generally more soluble than explosion generated particles, such as large fuel particles generated by mechanical processes like explosion of fuel.

^{137}Cs which is not in a very soluble form is mainly not extracted from the ground by surface waters. The greatest part, 90 to 95 %, of the ^{137}Cs transferred to the Pripiat river by surface waters comes from the 30 kilometer zone. However, because of its capacity for absorption, only 1 to 5 % of the initial activity arrives in the Black Sea. The remainder accumulates in the sediments of the various reservoirs of the Dniepr, more than half remains in the Kiev reservoir.

The hydro-geologic studies of the contamination of subsoil waters in the zone of exclusion show that ^{90}Sr is the most critical radionuclide, which could contaminate drinking water in the next 100 years above the currently acceptable limits, because it has penetrated deeper layers of soil more quickly than cesium. A European study proposes to study in the next years the migrations of ^{90}Sr in water. For this purpose, one water body has been chosen in each of the three countries, the Dniepr Reservoir in Ukraine, the lake Svyatskoye in Belarus and the lake Khozanovskoye in Russia.

Lastly, in the 30 km zone, the experts also fear contamination of the groundwater by ^{241}Am, a decay product of plutonium. As this radionuclide migrates into deeper layers of earth more quickly than plutonium (Smith and Beresford, 2005), this problem is to be monitored over the very long term. In the course of remediation activities, large volumes of radioactive waste were generated and placed in temporary near-surface waste storage and improvised disposal facilities. Trenches and landfill facilities were created from 1986 to 1988 in the exclusion zone at distances of 0.5 to 15 km from the reactor. These facilities (some 800) were established without proper design or engineered barriers (IAEA 1997). As they were not documented, the memory of their location is getting lost. They also contribute to the contamination of groundwater.

Summary

One of the remaining risks is the possibility of the collapse of the sarcophagus. The probability of this happening is not very high and its radiological consequences beyond the exclusion zone would remain low. An international project involves planning the construction of a new safe sarcophagus over the destroyed Chernobyl reactor. The second remaining risk could be the contamination of natural waters and aquatic ecosystems by runoff of ^{137}Cs and ^{90}Sr from contaminated soils and from the many improvised waste disposal sites in the exclusion zone.

10 Lessons learnt from the accident

As mentioned above, few people were prepared to manage a situation of this scale. The first western experts who considered the situation have meanwhile recognized that, in spite of errors, the Soviet technical management of the crisis had not been too bad, probably because of the experience gained with a similar accident (in Kyshtym) which happened in 1957 and was kept secret.

In Western Europe, the reactions were very varied and uncoordinated, thereby leading to confusion among the public. A comparison of TV programs of Switzerland, France, Germany or Italy, for example, demonstrated the diversity of the official reactions. A need for quick coordination was essential. Very soon one of the more spectacular lessons learned after the accident became apparent: the change of government attitudes towards technological catastrophes. This included recommending common actions at the international level, assuming the possibility of a large accident, and starting to organize transboundary exercises. It is clear that it was necessary to develop a rapid transboundary communication system.

The transboundary nature of the contamination prompted the international organizations to promote international cooperation and communication and to harmonize actions (Boeri 1988, ICRP 1991, ICRP 1992, NEA 1993, NEA 1989, NEA 1990, WH0 1987, WHO 1988, IAA 1987, IAEA 1989, IAEA 1991, IAEA 1992, IAEA 1994, EC 1989a, EC 1989b). Moreover, international emergency exercises such as those organized by the OECD/NEA in its INEX Programme (NEA 1995) were developed.

A major accomplishment of the international community was establishing conventions on early notification in the event of a radiological accident and on assistance in radiological emergencies (EC 1987, IAEA 1986c, IAEA 1986d). Based on these two conventions, the International Atomic Energy Agency (IAEA) established a system for notification and information exchange in case of a nuclear or radiological emergency, as well as a network to provide assistance, on request, to affected countries. The Council Decision 87/600/EURATOM of 14 December 1987 stipulated the European Community arrangements for the early exchange of information in the event of a radiological emergency. Based on this council decision, the European Commission established the European Community Urgent Radiological Information System (ECURIE) through which the EU Member States are required to notify the Commission on radiological emergencies and to promptly provide available information relevant to minimizing the foreseen radiological consequences. The system focuses on communication and information and data exchange in case of a nuclear or radiological emergency.

Furthermore, in order to facilitate communication with the public on the severity of nuclear accidents, the International Nuclear Event Scale INES was developed by the IAEA and the NEA and is currently applied by a large number of countries.

Estimates of internal doses also posed problems. The ICRP in 1986 only used dose-coefficients (internal dose per unit of intake e.g. in mSv/kBq) for workers. Fortunately, certain radiation protection organizations had anticipated the problem by proposing age-related dose-coefficients. However, only specialists had access to the relevant information. Refinement and clarification of international advice was needed and in August 1986, the ICRP launched a series of calculations of age-related dose coefficients for populations. The recommendations for intervention in an accident stipulated in ICRP Publication 40 were not clearly understood when they came to be applied, and the Commission revised this advice in Publication 63.

Another lesson of the accident was the deep change of public opinion towards industrial risk management. This change had not occurred after the Bhopal accident. Only after the reactor accident in Chernobyl did it become clear that the public wants to be involved in the decisions (stakeholder involvement), and this evolution has since become firmly established.

To explore for the first time in an international context the transboundary aspects of nuclear accidents, the NEA initiated the preparation and conduct of the first international nuclear emergency exercise INEX 1, performed in 1993. With this table-top exercise, the international community could for the first time test procedures and mechanisms in place to manage a nuclear or radiological emergency, leading to a wealth of lessons learned and to an improvement in nuclear emergency management. Related workshops allowed the exchange of experience in the implementation of short-term countermeasures after a nuclear accident, in agricultural aspects of nuclear and/or radiological emergency situations including the distribution of iodine pills as a prophylactic measure, and in nuclear emergency data management. This first series of exercises was followed by two other series.

Lastly, nobody had considered that an industrial catastrophe of such a scale could destabilize the population in the vicinity. Beyond the direct impact of radiation and the countermeasures taken, the exaggerated fear of radiation impact is a major contributor to the social destabilization in the affected zones of the former Soviet Union. Although there was no factual danger in the rest of Europe, anxiety levels were very high here as well.

The accident had also important consequences for reactor safety. A number of improvements have been performed on the RBMK reactors. The extremely large impact of the Chernobyl accident is due to the design of the RBMK reactor at that time. Later on, other Soviet-design reactors were also upgraded. The importance of attitudes toward safety was underlined and, as a consequence, the concept of safety culture was developed. Additionally, the focus on measures to cope with “beyond design basis accidents” was strengthened. This resulted in the introduction of accident management measures in many countries, among them Germany. The international cooperation on safety issues was broadened and incorporated for the first time fully the countries of the former Soviet block. On the level of the governments the Safety Convention (IAEA 1994b) was signed, on the level of the operators the World Association of Nuclear Operators (WANO) was established.

Summary

The Chernobyl accident prompted a number of actions directed at preventing further accidents in RBMK reactors. Additionally, investigations were performed on other reactor types and mainly accident management measures were introduced. Important activities include also a strengthened international cooperation in safety matters. Good international cooperation is also vital for the improved response capability, including harmonized criteria based on accepted radiation protection principles and agreed upon cooperation procedures, as well as on effective national monitoring and response systems.

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