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Consequences of the chernobyl accident on health and the environment

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ABSTRACT

Because of the economic, health and ecological consequences, the Chernobyl accident is the most severe in the entire history of the nuclear energy industry. Here, we present a review of the accident and its aftermath.

KEYWORDS

Environment;
Health;
Chernobyl nuclear accident;
Radioisotopes.

THE ACCIDENT

The former Chernobyl nuclear power plant is located in Northern Ukraine. The site is only 18 km south of the border with Belarus. The town of Chernobyl (12,500 inhabitants at the time of the accident) is 16 km to the northwest. The town of Pripyat (49,000 inhabitants at the time of the accident) was built less than five kilometres away, also to the northwest of the power plant, to house personnel working at the facility and their families. The accident that occurred at the power plant during the night of 25 to 26 April 1986 at around one o'clock in the morning is, in terms of its scale and the environmental, economic and health consequences, the most severe accident to date in the history of the civil nuclear industry. At the time of the accident, the plant had four RBMK reactors each capable of producing 1000 Megawatts of electric power. Two more reactors were under construction but were never to be commissioned. These reactors, built to a design developed in the 1960s, are cooled using a system of ordinary water flowing through vertical pressure tubes in which is inserted zirconium alloy cladding containing the fuel: low-enriched uranium dioxide containing 2% uranium-235. The nuclear fission reaction that takes place in the core generates a massive output of heat. During the reaction, fission products, actinides and activation products are generated. The reactor coolant is water and four pumps are used to circulate it through the system (one of which is kept always as backup). The neutron moderator was graphite in the form of 211 moveable control rods that can be inserted between the pressure tubes containing the fuel cladding and coolant. The more rods that are inserted, the more neutrons are absorbed, thus reducing the fission rate. Three main causes combined to produce the disaster: the Soviet authorities had failed to take adequate account of safety issues in the design of the reactor; when the reactor was at reduced power, the test of a new emergency core cooling system was ineffectively managed; and, third, the operators' actions were inappropriate, thus aggravating the meltdown process.

The plant operators were performing a safety procedure test during a scheduled shutdown of the reactor in conditions that were not part of the plan. The purpose of this test was to see whether reactor core cooling would continue in the event of a loss of electric power. The accident occurred as a result of noncompliance with safety instructions and the intentional disabling of certain safety systems. (In violation of procedure) the operators had drastically slowed down the pumps used to circulate the coolant and the reactor core overheated. This caused the nuclear reaction to suddenly accelerate, leading, in the space of a few seconds, to a power surge of 100 times the nominal capacity for this reactor. In a final attempt to prevent disaster, the operators tried to lower all the graphite control rods at the same time (the safety instructions state that, during normal operating, at least 30 rods must be lowered to maintain reactor stability, at the time of the test, there were only 6 to 8 rods inserted) but in vain: this operation, which takes around thirty seconds, cannot take place before the reaction runaway and the graphite rods became blocked in their insertion columns that were deformed by the heat before they could be lowered into a position that would effectively moderate the reactor. During the ensuing power excursion, fuel elements fractured as did the boiling water outlet nozzles, with water turning to steam and leading to the destruction of the reactor core. The concrete slab (weighing 2,000 tons) that covered the reactor core was then lifted up. This type of nuclear power plant, unlike equivalent series designed in Western Europe and the United States, did not have containment surrounding each reactor, which would probably have contained most of the steam and radioactive products ejected as a result of leaks or breaches in the pressure tubes. During the accident at Three Mile Island (Pennsylvania, USA) in 1979, the prestressed concrete and steel containment did serve to limit the impact on health and the environment. At Chernobyl, the industrial building that housed the reactor, completely conventional when all is said and done, failed to fulfil this role.[1,2]

Part of the molten nuclear fuel, radioactive fission products, activation products and actinides exploded out into the air in the form of a plume of gas and particles. At the time of the initial explosion, these products shot up to a height of over 1,200 metres. Once the emergency rescue teams had managed to control the fire, during the day of 26 April, the drop in air temperature and the reduction in the upward pressure brought the height of the radioactive releases down to less than 400 metres. Over the next five days, the releases diminished, mainly thanks to the sand, boron, clay and lead (around 5,000 tons of different materials) dropped by a fleet of helicopters that flew more than 1,800 times over what remained of the core to cover the burning graphite used as the neutron moderator inside the reactor. Nonetheless, the temperature of the fuel spiked again, reaching up to 2,000°C, due to the fact that it was insulated and smouldering beneath this covering, and large amounts of substances were again released between 2 and 5 May, before rapidly diminishing once again after this date. Nevertheless, small amounts of substances continued to be released throughout the month of May 1986. In all, the activity level of radionuclides released as a result of this accident in the space of 10 days is estimated to range between 12 and 14 billion billion becquerels (Bq, unit of radioactivity equal to one disintegration per second), i.e. 30,000 times higher than all the radioactivity released into the air every year by nuclear facilities worldwide[3]. Afterwards, fallout containing radionuclides released during the accident was observed across a vast area, including Western Europe. In France, radioactive deposits were mainly found along a strip in the East stretching from La Moselle down to Corsica (mostly between the 30 April and 6 May 1986, with air pollution peaking on 1 May 1986). Activity levels were much lower than those observed in the Ukraine, Belarus and Russia, but were still highly variable depending on rainfall[4]. In Eastern Europe, radioactive deposits at more than 37,000 Bq per m^2 were observed in three major regions (a figure that would later be used as the minimum level defining contaminated zones in the three republics): a circular area of 100 km radius around the nuclear power plant, the region of Gomel, Moguilev and Brest in Belarus, around 200 km north by northeast and, last, the region of Kaluga, Tula and Orel, 500 km to the northeast, in Russia. To compare, before the accident (from 1977 to 1984), caesium-137 deposits in the soil near to the power plant varied between 100 to 1,000 Bq per m^2 and strontium-90 deposits from 40 to 400 Bq per m^2. Prior to the accident, environmental radioactivity levels were measured here due to radioactive fallout from atmospheric nuclear weapons tests during the arms race between the major world powers following the Second World War, as well as from releases since the power plant came into operation.

Within a few months, to confine radioactive materials inside and around the ruins of the reactor, and also to protect personnel working at the other plant production units that remained in operation at the time, a “sarcophagus” was built, enclosing the damaged reactor and initially designed to last for 30 years. Over 190 tons of fuel (95% of all the fuel) are still inside the sarcophagus. However, the degraded foundations, the unsealed roof and structures prematurely aged by radiation are not safe. Building works on a new sarcophagus over 100 metres high to cover the old one have begun. This new structure is designed to last for a hundred years and should, in theory, soon be in place.

ENVIRONMENTAL CONSEQUENCES

What happened to the radionuclides in the air depended on their state when released.

Inert gases account for half the total released radioactivity and have not led to any deposits in the soil. They have gradually been diluted within air masses. The majority of low-volatile elements (especially strontium-90) were transported no more than a few kilometres from the site of the accident. After the release of aerosols, high- and intermediate-volatile elements (especially iodine-131 and caesium-134 and -137) formed fine particles which were carried by air currents and rain several hundred and even several thousand kilometres away from the site of the accident and have gradually been deposited in the soil[5,6].

The dispersion of different elements has mainly been dependent on the strength and direction of winds affecting the plume of smoke and debris. Due to air turbulence, the concentration of radionuclides was increasingly diluted as time passed and, therefore, as they were carried further away from Chernobyl. Belarus (the wind initially blew in a north-westerly direction), the Ukraine and Russia were the countries most affected right from the start of the accident. The extent to which radioactive elements were dispersed is related to variations in wind direction during the main period of release, between 26 April and 5 May. Throughout this phase of the accident, a proportion of the radionuclides was deposited on the ground. Two processes are involved in atmospheric fallout - dry and wet deposition. Dry deposition is related to the interaction between the air loaded with radioactive substances and horizontal or vertical surfaces: soil, water, vegetation and buildings. Among other things, this process depends on the type of surface; in a forest, for instance, deposition is three to five times higher that on grasslands, where, in turn, there is twice the amount of deposition as on bare soil. Wet deposition is related to atmospheric precipitations: rain transports radioactive particles and soluble gases (especially iodine) down into the soil, causing washout of the contaminated air from the height from which the rain droplets fall. This type of deposition is directly related to the intensity of the rainfall. Wet deposition (if it occurs) is always more intense than dry deposition, so, in the case of rainfall occurring during 10% of the time taken for the plume to pass over the area in question, wet deposition will account for up to 75% of total deposition. In mountainous regions where rainfall is heaviest, there is a greater level of deposition than in the plain areas. In addition, runoff water on the slopes concentrates radioactivity on the valley floor. The coexistence of these two forms of deposition can be explained by the extremely non-homogeneous nature of the fallout and the formation of “spots” of radioactivity on the ground depending on rainfall or dry conditions. One of the most important health and economic consequences was the direct contamination (of vegetables and cereals) or indirect contamination (via livestock feed of animals reared for meat or milk, for example) of the food chain, entailing bans on consumption and sales, most of which have now been lifted.

In 1986, vegetation was directly contaminated by deposition on foliage, given that the accident occurred in springtime, with grass, leafy vegetables (lettuce, leeks and spinach) being the most badly affected. Livestock was also affected through feed. This direct contamination peaked soon after deposition and considerably diminished in the course of the next few months. After three months, it was 100 times less significant that the initial peak.

Radioactive half-life is the amount of time it takes for half the atoms of a radioactive isotope to decay naturally. The decay of this proportion of atoms is the subject of a downward exponential function and varies from one radionuclide to another. The shorter the radioactive half-life, the sooner the radionuclide disappears.

At the time of the accident:

- 84% of the radioactivity released came from radionuclides with a radioactive half-life of less than 1 month,
- 16% of the radioactivity released came from radionuclides with a radioactive half-life of more than 1 month,
- 1% of the radioactivity released came from radionuclides with a radioactive half-life of more than 30 month,
- 0.001% of the radioactivity released came from radionuclides with a radioactive half-lives of more than 50 years (plutonium-238, -239 and -240 have half-lives of 86, 24,400 and 6,580 years respectively).

Iodine-131 and caesium-134 can no longer be detected due to the fact that they have short radioactive half-lives (8 days and approx. 2 years respectively), however, surface radioactivity which can mainly be attributed to caesium-137 (which has a radioactive half-life of approx. 30 years) can still be detected in many places. A durable stock of long-lived radionuclides has in fact formed in the subsoil.

The long-term behaviour of radionuclides in ecosystems mainly depends on how they are distributed in the various soil layers, how they migrate and their uptake by plants through the roots. Radionuclides migrate in different ways at deep levels below the ground. This affects the time taken for surface radioactivity to diminish. Caesium-137 with a long clearance time (the amount of time required for half the radioactivity to disappear from contaminated soils, depending on their nature: 10 to 25 years) has more stable surface radioactivity over time than other radionuclides. To compare, half-time for elimination varies between 7 to 12 years in the case of strontium-90, which, with a half-life of 28.78 years is quite similar to that of caesium-137. Root transfer, which is fortunately not as efficient as direct transfer via foliage, leads to chronic contamination of plants and the rest of the food chain. In the Gomel Region in Belarus, high levels of contamination were found in farm produce in 1986 and the following years up to the early 1990s. Most of the vegetables (potatoes) and cereals produced are now below the specific activity limit of 100 Bq per kilogram used to define contaminated products. There are, however, still some areas where the activity levels found in natural grass and forage are significant.

In the forests, the situation is different: via tree foliage and branches, the forests initially intercepted a larger proportion of radioactive aerosols than farmlands. Falling leaves contaminated the soil and trees over an area of around 40,000 km^2 close to the border between Ukraine and Belarus. Over twenty years after the accident, unlike in farmlands, contamination by caesium-137 persisted, with high activity levels in plant litter and the earth, via root transfer in forest plants – especially to young shoots, berries and mushrooms and, more generally, in natural products (including, via the food chain, game – wild boars and elks – and in wood, sales of which, in some highly-contaminated areas, have been subject to a ban) from the most highly-contaminated areas.

In 1986 and in subsequent years, the Dniepr and Pripyat Rivers that serve as a water reserve for the major cities in the Ukraine were contaminated by radioactive fallout and rainwater runoff. Dykes were built and water supplies from uncontaminated areas have been organised. There is washout of a proportion of the deposits in the soil thanks to rainfall, melting snow and high water. Except in the area surrounding the nuclear power plant, where debris was buried at the time of the disaster and during site cleanup operations, groundwater was hardly affected at all[7,8].

MEDICAL AND HEALTH CONSEQUENCES

During the accident or as a result of operations performed at the time, 31 rescue workers died within the first few weeks following the accident (from burns, trauma or non-stochastic effects of irradiation) out of the 600 emergency workers that were involved at this initial stage (firemen, helicopter pilots, etc.)[9]. From 1987 to 2004, a further 17 emergency workers died of various causes.

In 1986 and 1987, three hundred and fifty thousand liquidators, forming a relatively homogeneous population group of adults (mainly soldiers, fire-fighters, police and nuclear industry personnel), were exposed while decontaminating and cleaning up the site within a 30 km radius of the reactor. Of these, two hundred and forty thousand took part in major repair works, particularly in building the "Cascade" wall on the North side of the reactor (50 m high and 20 m wide at the base, this wall was to enclose nearly 20 tons of fuel that had been ejected from the reactor during the accident), the reinforced concrete slab (intended to cool the core and prevent contamination of underground water) placed underneath the damaged reactor by digging a tunnel leading from the basemat of the adjacent Reactor Unit 3, and the sarcophagus capping the remains of Reactor 4. During this stage, the workers' exposure to ionising radiation was meant to be brief, to remain below the dose limits authorised for workers, but in practice, dosimetric data for the liquidators is rarely available (partly because of the political collapse of the Soviet Union and the end to its federal and centralising structure) and cross-referencing the pathologies observed is a matter of pure chance. If we look at the years that followed, a total of six hundred and forty-five thousand liquidators worked at the site and were mainly exposed to relatively low doses of radiation, as the conditions were less severe and less urgent than during the initial period. Nonetheless, a great deal of uncertainty surrounds the received doses, which have often been overestimated in view of the social benefits and compensation related to liquidator status. Excessive rates of leukaemia were declared for Russian liquidators in 1997, but, between 1986 and 1996, mortality among liquidators was no higher than among a comparable control group, both in terms of frequency and the breakdown according to cause of deaths. The results of oncological epidemiology studies and of studies on other non-tumour pathologies, the onset incidence of which is supposedly higher among the liquidators compared with control groups, need to be confirmed[10,11].

At the time of the accident, around 6 million people lived in the areas most badly affected by radioactive fallout. Around 800,000 lived in zones where caesium-137 contamination exceeded 185,000 Bq per m². The people that lived in the regions in question at the time were first exposed to the plume which was heavily loaded with fine radioactive dust. They were then exposed to radiation emitted from radioactive deposits in the soil. Lastly, the inhabitants were exposed by consuming foodstuffs contaminated as a result of deposition on foliage (a key factor during the months that followed the accident) or by root transfer of residual soil contamination. Although the last two sources of exposure have considerably decreased over the years, they persist to this day in the most highly contaminated areas in Russia, Belarus and the Ukraine due to the long radioactive half-life of some radionuclides, mainly caesium-137. The doses received by the people subject to these different exposure pathways depend on their respective scale and on individual lifestyles. Regulations set out with regard to soil contamination are more or less the same in the three countries. They are based on measuring activity levels at the soil surface in the case of strontium-90 (which has a half-life of 28 years), caesium-137, and plutonium, but in practice, this mainly refers to surface activity levels of caesium-137 which are relatively consistent.

In Belarus, a ministry was specially set up in 1991 to deal with the consequences of the accident. The first Act adopted in February 1991 defined the status of the people involved: liquidators, workers and residents of the contaminated areas. Another Act, passed in November 1991, defined the status of contaminated zones, living conditions and the economic and scientific activities that could be carried out there in light of the zoning criteria.

In "compulsory resettlement" zones, surface activity levels for caesium-137 are above 555,000 Bq per m². Any housing or industrial and agricultural production development is prohibited and entering and leaving the zone is subject to authorisation. Approximately 4,000 people live in these zones. Zones where surface activity of caesium-137 is between 555,000 and 1,480,000 Bq per m² must be evacuated but this is not compulsory. Above 1,480,000 Bq per m² and evacuation is compulsory. The "exclusion zone" in Belarus, known as Polesia – where 400 people still lived in 2006 - covers 2,100 km² (out of a total of approximately 4,000 km² across all three countries) is basically an area that was evacuated as soon as the accident occurred or in the following months in 1986. In "voluntary resettlement zones", with 185,000 to 555,000 Bq per m², setting up and developing any industrial or agricultural business is regulated (subject mainly to production conditions that comply with consumer standards). The population –

around 192,000 people in all – can apply to be rehoused in uncontaminated zones, but this is not compulsory. Last, in the case of "controlled radiological" zones, between 37,000 and 185,000 Bq per m², restrictions are similar to those applicable to voluntary resettlement zones but only apply to certain polluting firms. In theory, healthcare institutions cannot be set up there. Over one million one hundred and thirty six thousand people live in these zones. Sixteen years after the event, these laws, which have changed very little in that time, are still applicable and cover 20% of Belarus (around 40,000 km², while the rest is deemed uncontaminated). The contaminated zones are scattered far apart and contamination levels vary a great deal. Nearly 93% of the contaminated areas and their populations (97%) are in the oblasts (administrative districts) of Gomel, Moguilev and Brest. The Grodno and Minsk oblasts were less severely affected, while the Vitebsk oblast now seems to be little affected. In all, around one million three hundred and thirty-two thousand people live in zones contaminated to levels of over 37,000 Bq per m² (15% of the population of Belarus). Since 1991, in application of the two Acts cited, one hundred and thirty-five thousand people, who were ultimately resettled, were displaced. After the accident in 1986, the significantly contaminated zones were estimated to cover a total area of 200,000 km². In 1995, due to radionuclide decay, the total was down to 145,000 km² for the three Republics, it is now around 125,000 km². Around 5 million people now live in these areas.

Forecast calculations taking the radioactive half-life of caesium-137 into account suggest (depending on climate scenarios and plausible long-term meteorological forecasts) that, for 2016 and 2046 respectively, 15% of Belarus territory 30 years after the accident and 10% 60 years after the accident will still be contaminated at levels above 37,000 Bq per m², the legal minimum surface activity level as defined for contaminated zones.

The incidence of cancer and other pathologies among the civilian populations (which are heterogeneous in terms of age groups) who were exposed to radioactive fallout from the accident and who lived in the contaminated areas and were subject to the stochastic effects of radiation, have increased.

Insofar as regards stochastic effects, the rise in the number of cases of thyroid cancer in Russia, Belarus and the Ukraine is due to exposure to and contamination by radioactive elements, especially iodine-131. In particular, a distinct increase in the incidence of thyroid cancer in children who were under 18 at the time of the accident has been observed compared to control groups. The rate of rare cancers in children has risen by a factor of 10 to 100 has also been observed. The increase observed in adults aged over 50 and affecting more women more men, does not seem to differ from that seen in countries less exposed to severe fallout. The number of cases of thyroid cancer diagnosed in the regions affected by the accident is around 5,000 cases. The risk of thyroid cancer in people who were exposed during childhood or adolescence continues to be manifest more than twenty years after Chernobyl. Monitoring these forms of cancer must continue. The majority of cases diagnosed was observed in Belarus (approx. 4,000 cases). However, similar results in terms of frequency have been found in adolescents and young adults in Ukraine and in some highly-contaminated areas in Russia[12-14].

Since Year 2000, the rate of onset of thyroid cancer in children under 5 is dropping back to the rate observed prior to the accident, suggesting that residual radioactivity observed in some areas of Belarus is not causing excessive rates of thyroid cancer. No significant statistical increase has been observed for tumours other than thyroid tumours in exposed or non-exposed areas. The same seems to apply to leukaemia, in Belarus, the tendency to rise with the passage of time is similar in the control oblasts and the contaminated oblasts. Nonetheless, long-term monitoring of all forms of tumours remains a key subject of concern in the public health sector, given the amount of time it can take before cancerous pathologies become detectable, among other things. At the present time, it is not possible to predict how the incidence rates of certain types of tumour (particularly leukaemia and breast cancer in women before menopause, regarding which it has been suggested that rates are rising) will evolve, due to the fact that the studies are too incomplete. Over time, an increase in congenital malformations has been observed in Belarus, nonetheless, this increase appears to be quite similar in regions that were badly and not so badly contaminated, suggesting that there may be several causes for such an increase. There has been no rise in infant mortality since 1986 in Belarus in either contaminated or uncontaminated regions. An increase in the frequency of cataracts and cardiovascular disease has been demonstrated, but here too, the results must be confirmed by larger-scale studies. Nutritional problems related to population movements following the accident, and to restrictions concerning the consumption of certain locally-produced foodstuffs have resulted in deficiencies that may be conducive to the development of specific pathologies.

The lack of certainty regarding received doses and incomplete epidemiological monitoring of the rescue workers, liquidators and the population exposed to fallout means that it is impossible to form an overall view of the health consequences of the accident at Chernobyl, even more so since public health data from before the disaster are also extremely incomplete. Another factor that makes it difficult to define the radiological consequences of the accident accurately is the fact that the Soviet Union collapsed at more or less the same time as the post-Chernobyl accident period. The crude death rate in Russia rose from 488 per 100,000 people in 1990 to 741 per 100,000 in 1993 (a rise of 52%). Male life expectancy dropped by six years between 1987 and 1993. Similar results can be found in other former Eastern Bloc countries, independently of fallout from the accident. This health calamity (comparable in its intensity to that seen in war-torn countries) is related to the social and economic changes that have taken place, and cannot all be directly attributed to the disaster at Chernobyl[14,15]. The accident's potential impact on health does create a great deal of concern among the populations in question.

CONCLUSION

The disaster at Chernobyl has radically altered our perception of the risks and of how to manage severe accidents. Since 1986, considerable progress has been made insofar as regards the resources that can be deployed in the event of an emergency.

In economic terms, the real cost of the disaster at Chernobyl is difficult to ascertain in its entirety. Any economic analysis needs to take account not only of the damage caused but also the cost of cleanup, repair work and relative site rehabilitation (emergency rescue operations, evacuating victims, building the two sarcophagi, waste management, building the hydraulic dam and, between 1986 and 2000, 130,000 houses and apartments, 111,000 school places, 11,000 hospital beds, etc. – together with the cost of resettlement and development works – for example, a 9,000km gas pipeline – to bring resources from uncontaminated regions – as well as long-term radiological monitoring, etc.). The indirect consequences - compensation for the liquidators, securing contaminated zones, site surveillance and security, treating victims, the cost of research studies and, also losses in farm and industrial production - all need to be taken into account. The total cost of the disaster for the three most severely affected republics is over 500 billion dollars. The cost over a period of thirty years is an estimated 235 billion dollars for Belarus and around 175 to 200 billion dollars for the Ukraine. In spite of the fact that they have barely been reviewed over the passing years, compensation payments to the victims account for the heaviest expense for the three countries. Seven million people are currently in receipt of benefits related to the accident at Chernobyl.

A great deal more research on the accident and its consequences is needed if we are to learn all we can from this disaster[16]. On 15 December 2000, the last reactor still operating at the plant was finally shut down.

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