Dosis und ihre Folgen, Strahlenunfälle

3.Teil

The Chernobyl Accident

Key facts [6]

The April 1986 disaster at the Chernobyl nuclear power plant is the product of a severely flawed reactor design. In addition, serious mistakes were made by the plant operators, who violated procedures intended to ensure safe operation of the plant (Figure 15).

Figure 15: Map of Chernobyl and surroundings [7]

The accident destroyed reactor Unit 4, killed 31 people (one immediately and 30 within three months) and contaminated large areas of Belarus, Ukraine and the Russian Federation. In addition, one person has subsequently died from acute radiation syndrome, and three children have died from thyroid cancer. The Chernobyl accident was a unique event, on a scale by itself. It was the only time in history of commercial nuclear electricity generation that radiation-related fatalities occurred [6].

Epidemiological studies have been hampered in the former Soviet Union by a lack of funds, an infrastructure with little or no experience in chronic disease epidemiology, poor communication facilities, and an immediate public health problem with many dimensions. Emphasis has been placed on screening rather than on well-designed epidemiological studies. International efforts to organize epidemiological studies have been slowed by some of the same factors, especially the lack of a suitable scientific infrastructure.

An increased incidence of thyroid cancer among children in areas of Belarus, Ukraine and Russia affected by the Chernobyl accident has been firmly established as a result of screening programs and, in the case of Belarus, an established cancer registry. The findings of most epidemiological studies must be considered interim, say experts, as analysis of the health effects of the accident is an ongoing process.

The activities undertaken by Belarus and Ukraine in response to the accident remediation of the environment, evacuation and resettlement, development of non-contaminated food sources and food distribution channels, and public health measures have overburdened the governments of those countries. International agencies and foreign governments have provided extensive logistic and humanitarian assistance. The work of the European Commission and World Health Organization in strengthening the epidemiological research infrastructure in Russia, Ukraine and Belarus is laying the basis for major advances in these countries` ability to carry out epidemiological studies of all kinds.

The accident: What happened

The accident, which occurred in the early morning of April 26, 1986, resulted from a safety experiment conducted in violation of the plant’s technical specifications. Plant operators were testing the ability of plant equipment to provide electrical power when the main source of on-site power was lost. The plant was being run at very low power, without adequate safety precautions. The plant operators took a number of actions that deviated from established safety procedures and led to a dangerous situation. The team in charge of the test had not coordinated the procedure with the personnel responsible for the safety of the nuclear reactor.

Another major cause of the accident are several significant flaws in the design of the plant, which made the reactor potentially unstable and easily susceptible to loss of control in case of operator error. The RBMK design used at Chernobyl has a "positive void coefficient." This means that nuclear chain reaction and power output increase when cooling water is lost. The large value of the "positive void coefficient" caused the uncontrollable power surge that led to Unit 4's destruction (Figure 16).

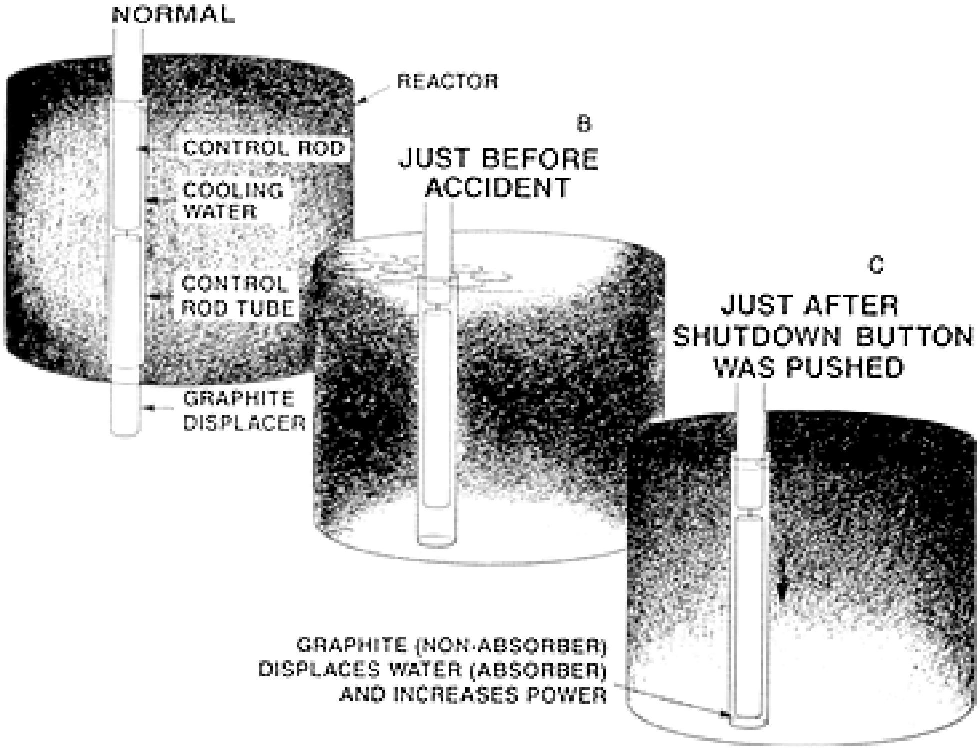


Figure 16: Effects of shutdown rods [8]

The power surge caused a sudden increase in heat, which ruptured some of the fuel-containing pressure tubes. The hot fuel particles reacted with water and caused a steam explosion, which lifted the 1000-metric ton cover off the top of the reactor, rupturing the rest of the 1660 pressure tubes, causing a second explosion and exposing the reactor core to the environment.

The Chernobyl plant did not have the massive containment structure common to most nuclear power plants elsewhere in the world (Figure 17). Without this protection, radioactive material escaped into the environment.

However, because the estimated energy released by the explosions was greater than what most containment designs could withstand, it is highly unlikely that a containment structure could have prevented the release of radioactive material at Chernobyl. The crippled Chernobyl reactor is now enclosed in a hurriedly constructed concrete shelter, which is growing weaker over time. Ukraine and the

Group of Seven industrialized nations have agreed on a plan to stabilize the existing structure.

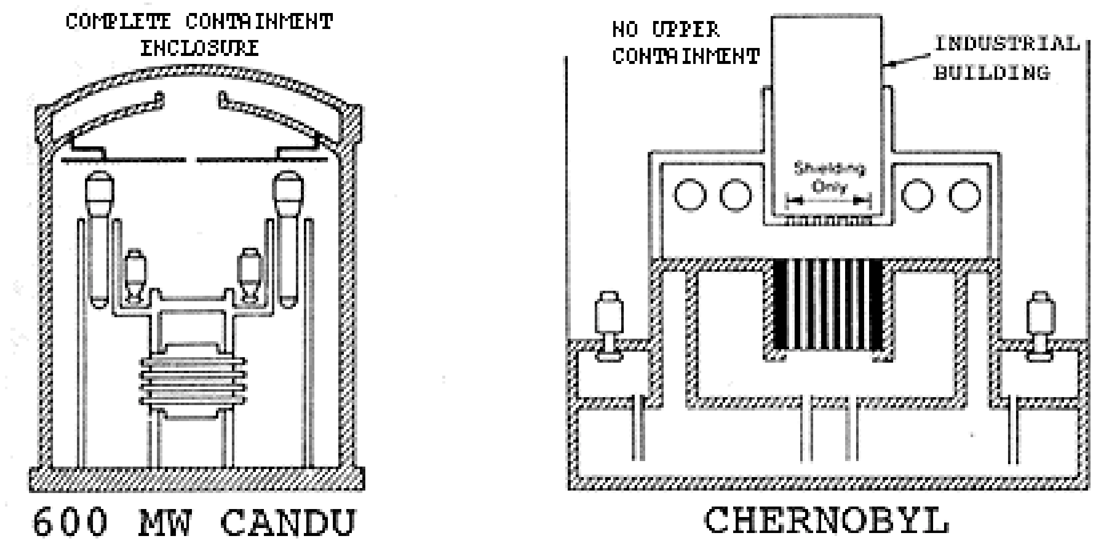


Figure 17: Comparison of containment of US and Soviet reactors [8]

Chernobyl timeline [9]

April 25, 1986 Day 1
1:00 am:
The reactor was running at full power with normal operation. Steam power was directed to both turbines of the power generators. Slowly the operators began to reduce power for the test. The purpose of the test was to observe the dynamics of the RMBK reactor with limited power flow.

1:05 pm:
Twelve hours after power reduction was initiated the reactor reached 50 % power. Now only one turbine was needed to take in the decreased amount of steam caused by the power decrease and turbine #2 was switched off.

2:00 pm:
Under the normal procedures of the test the reactor would have been reduced to 30 % power, but the Soviet electricity authorities refused to allow this because of an apparent need for electricity elsewhere, so the reactor remained at 50 % power for another 9 hours, with the safety protocols and computers switched off.

April 26, 1986 Day 2

12:28 am:

The Chernobyl staff received permission to resume the reactor power reduction. One of the operators made a mistake. Instead of keeping power at 30 %, he forgot to reset a controller which caused the power to plummet to 1 % because of water which was now filling the core, and xenon (a neutron absorber) which was building up in the reactor. This amount of power was too low for the test.

1:00-1:20 am:

The operator forced the reactor up to 7 % power by removing all but 6 of the control rods. This was a violation of procedure and the reactor was never built to operate at such low power. The RBMK reactor is unstable when its core is filled with water. The operator tried to take over the flow of the water which was returning from the turbine manually which is very difficult because small temperature changes can cause large power fluctuations. The operator was not succesful in getting the flow of water corrected and the reactor was getting increasingly unstable. The operator disabled emergency shutdown procedures because a shutdown would abort the test.

1:22 am:

By 01:22, when the operators thought they had the most stable conditions, they decided to start the test. The operator blocked automatic shutdown on low water level and the loss of both turbines because of a fear that a shutdown would abort the test and they would have to repeat tests.

1:23 am: The test begins:

The remaining turbine was shut down

1:23:40 am:

Power in the reactor began to gradually rise because of the reduction in water flow caused by the turbine shutdown which lead to an increase in boiling. The operator initiated manual shut down which lead to a quick power increase due to the control rod design.

1:23:44 am: Disaster Point:

The reactor reached 120 times its full power. All the radioactive fuel disintegrated, and pressure from all of the excess steam which was supposed to go to the turbines broke every one of the pressure tubes and blew off the entire top shield of the reactor.

Dispersion and deposition of radionuclides [10]

The release of radioactive materials to the atmosphere consisted of gases, aerosols and finely fragmented nuclear fuel particles. This release was extremely high in quantity, involving a large fraction of the radioactive product inventory existing in the reactor, and its duration was unexpectedly long, lasting for more than a week. This duration and the high altitude (about 1 km) reached by the release were largely due to the graphite fire which was very difficult to extinguish.

For these reasons and the concomitant frequent changes of wind direction during the release period, the area affected by the radioactive plume and the consequent deposition of radioactive substances on the ground was extremely large, encompassing the whole Northern hemisphere, although significant contamination outside the former Soviet Union was only experienced in part of Europe.

The pattern of contamination on the ground and in foodchains was, however, very uneven in some areas due to the influence of rainfall during the passage of the plume. This irregularity in the pattern of deposition was particularly pronounced at larger distances from the reactor site.

The source term

The "source term" is a technical expression used to describe the accidental release of radioactive material from a nuclear facility to the environment. Not only are the levels of radioactivity released important, but also their distribution in time as well as their chemical and physical forms. The initial estimation of the Source Term was based on air sampling and the integration of the assessed ground deposition within the Soviet Union. This was clear at the IAEA Post-Accident Review Meeting in August 1986, when the Soviet scientists made their presentation, but during the discussions it was suggested that the total release estimate would be significantly higher if the deposition outside the Soviet Union territory were included. Subsequent assessments support this view, certainly for the caesium radionuclides (Cs-137 and Cs-134). The initial estimates were presented as a fraction of the core inventory for the important radionuclides and also as total activity released.

Atmospheric releases

In the initial assessment of releases made by the Soviet scientists and presented at the IAEA Post-Accident Assessment Meeting in Vienna, 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 caesium. The early estimate for fuel material released to the environment was 3 ± 1,5 %. This estimate was later revised to 3,5 ± 0,5 %. This corresponds to the emission of 6 t of fragmented fuel.

The IAEA International Nuclear Safety Advisory Group (INSAG) issued in 1986 its summary report based on the information presented by the Soviet scientists to the Post-Accident Review Meeting. At that time, it was estimated that 1 to 2 exabecquerels (EBq) were released. This did not include the noble gases, and had an estimated error of ±50 %. These estimates of the source term were based solely on the estimated deposition of radionuclides on the territory of the Soviet Union, and could not take into account deposition in Europe and elsewhere, as the data were not available at the time.

However, more deposition data were available when, in their 1988 Report, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) gave release figures based not only on the Soviet data, but also on worldwide deposition. The total Cs-137 release was estimated to be 70 petabecquerels (PBq) of which 31 PBq were deposited in the Soviet Union.

Isotope	**Half-life**	**Activity [TBq]**
Cs-137	30 y	85,000
Cs-134	2.1 y	54,000
I-131	8 d	176,0000
Xe-133	5.3 d	650,0000
Mo-99	66 h	168,000
Zr-95	64 d	196,000
Ru-103	39 d	168,000
Ru-106	368 d	73,000
Ba-140	12.7 d	240,000
Ce-141	32.5 d	196,000
Ce-144	284 d	116,000
Sr-89	59.5 d	115,000
Sr-90	29.2 y	10,000
Pu-239	24,000 y	72

Table 2: Radioactive Release from Chernobyl [11]

Later analyses carried out on the core debris and the deposited material within the reactor building have provided an independent assessment of the environmental release. These studies estimate that the release fraction of Cs-137 was 20 to 40 % (85 ± 26 PBq) based on an average release fraction from fuel of 47 % with subsequent retention of the remainder within the reactor building. After an extensive review of the many reports, this was confirmed. For I-131, the most accurate estimate was felt to be 50 to 60 % of the core inventory of 3200 PBq. The current estimate of the source term is summarized in Table 2 [11].

The initial large release was principally due to the mechanical fragmentation of the fuel during the explosion. It contained mainly the more volatile radionuclides such as noble gases, iodines and some caesium. The second large release between day 7 and day 10 was associated with the high temperatures reached in the core melt. The sharp drop in releases after ten days may have been due to a rapid cooling of the fuel as the core debris melted through the lower shield and interacted with other material in the reactor. Although further releases probably occurred after 6 May, these are not thought to have been large.

Chemical and physical forms [10]

The release of radioactive material to the atmosphere consisted of gases, aerosols and finely fragmented fuel. Gaseous elements such as krypton and xenon escaped more or less completely from the fuel material. In addition to its gaseous and particulate form, organically bound iodine was also detected. The ratios between the various iodine compounds varied with time.

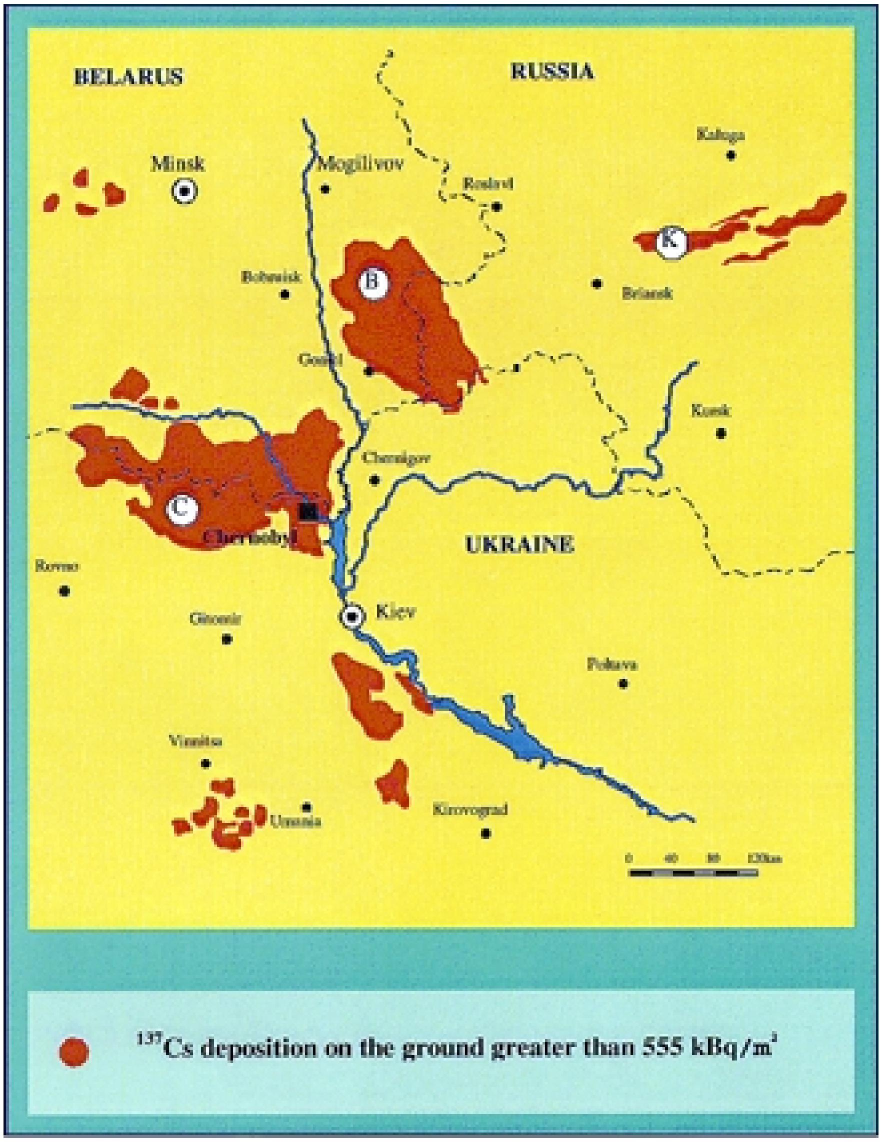
50 to 60 % of the core inventory of iodine was thought to have been released in one form or another. Other volatile elements and compounds, such as those of caesium and tellurium, attached to aerosols, were transported in the air separate from fuel particles. Air sampling revealed particle sizes for these elements to be 0.5 to 1 mm.

Unexpected features of the source term, due largely to the graphite fire, were the extensive releases of fuel material and the long duration of the release. Elements of low volatility, such as cerium, zirconium, the actinides and to a large extent barium, lanthanium and strontium also, were embedded in fuel particles. Larger fuel particles were deposited close to the accident site, whereas smaller particles were more widely dispersed. Other condensates from the vaporised 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.

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 dispersion parameters, the particle sizes, and the occurrence of rainfall. The largest particles, which were primarily fuel particles, were deposited essentially by sedimentation within 100 km of the reactor. Small particles were carried by the wind to large distances and were deposited primarily with rainfall.

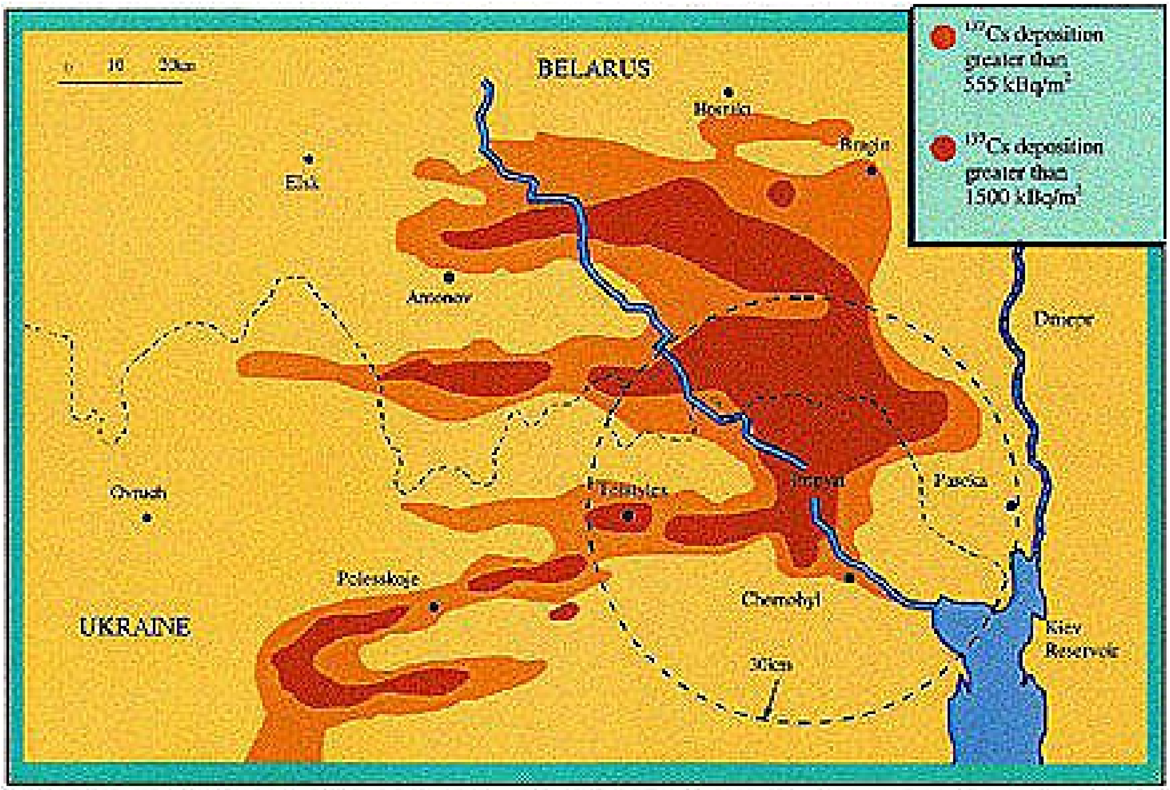


Credit: IPSN

Figure 18: Main spots of Cs-137 contamination

The radionuclide composition of the release and of the subsequent deposition on the ground also varied considerably during the accident due to variations in temperature and other parameters during the release. Cs-137 was selected to characterize the magnitude of the ground deposition because first, it is easily measurable, and second, it was the main contributor to the radiation doses received by the population once the short-lived I-131 had decayed.

The three main spots of contamination resulting from the Chernobyl accident have been called the Central, Bryansk-Belarus, and Kaluga-Tula-Orel spots (Figure 18). The Central spot was formed during the initial, active stage of the release predominantly to the west and north-west (Figure 19). Ground depositions of Cs-137 of over 40 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 Cs-137 ground depositions generally exceeded 1500 kBq/m^2.



Credit: IPSN

Figure 19: Central spot of Cs-137 contamination

The Bryansk-Belarus spot, centered 200 km to the north-northeast of the reactor, was formed on 28-29 April as a result of rainfall on the interface of the Bryansk region of Russia and the Gomel and Mogilev regions of Belarus. The ground depositions of Cs-137 in the most highly contaminated areas in this spot were comparable to the levels in the Central spot and reached 5000 kBq/m^2 in some villages.

The Kaluga-Tula-Orel spot in Russia, centered approximately 500 km north-east of the reactor, was formed from the same radioactive cloud that produced the Bryansk-Belarus spot, as a result of rainfall on 28-29 April. However, the levels of deposition of Cs-137 were lower, usually less than 600 kBq/m^2.

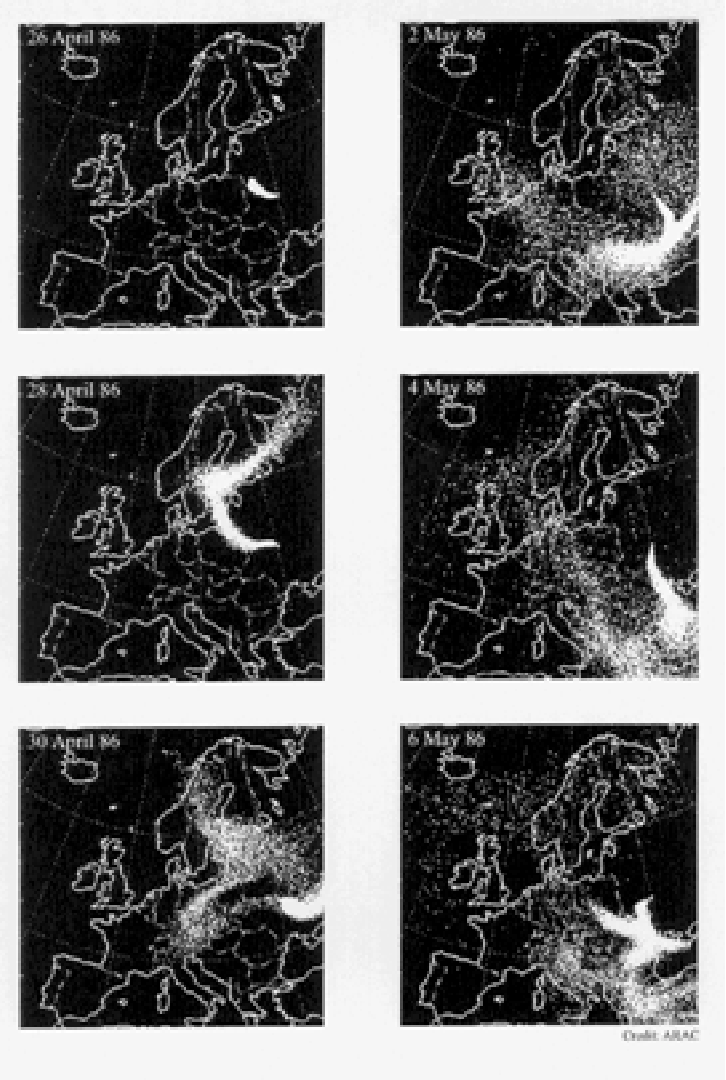
In addition, outside the three main hot spots in the greater part of the European territory of the former Soviet Union, there were many areas of radioactive contamination with Cs-137 levels in the range 40 to 200 kBq/m^2. Overall, the territory of the former Soviet Union initially contained approximately 3100 km^2 contaminated by Cs-137 with deposition levels exceeding 1500 kBq/m^2; 7200 km^2 with levels of 600 to 1500 kBq/m^2; and 103,000 km^2 with levels of 40 to 200 kBq/m^2.

Outside the former Soviet Union

Radioactivity was first detected outside the Soviet Union at a Nuclear Power station in Sweden, where monitored workers were noted to be contaminated. It was at first believed that the contamination was from a Swedish reactor. When it became apparent that the Chernobyl reactor was the source, monitoring stations all over the world began intensive sampling programs.

The radioactive plume was tracked as it moved over the European part of the Soviet Union and Europe (Figure 20). Initially the wind was blowing in a northwesterly direction and was responsible for much of the deposition in Scandinavia, the Netherlands and Belgium and Great Britain. Later the plume shifted to the south and much of Central Europe, as well as the northern Mediterranean and the Balkans, received some deposition, the actual severity of which depended 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.

The radioactive cloud initially contained a large number of different fission products and actinides, but only trace quantities of actinides were detected in most European countries, and a very small number were found in quantities that were considered radiologically significant. This was largely due to the fact that these radionuclides were contained in the larger and heavier particulates, which tended to be deposited close to the accident site. The most radiologically important radionuclides detected outside the Soviet Union were I-131, I-132, Cs-137 and Cs-134. Most countries in Europe experienced some deposition of radionuclides, mainly Cs-137 and Cs-134, as the plume passed over the country. In Austria, eastern and southern Switzerland, parts of southern Germany and Scandinavia, where the passage of the plume coincided with rainfall, the total deposition from the Chernobyl release was greater than that experienced by most other countries, whereas Spain, France and Portugal experienced the least deposition. For example, the estimated average depositions of Cs-137 in the provinces of Upper Austria, Salzburg and Carinthia in Austria were 59, 46 and 33 kBq/m^2 respectively, whereas the average Cs-137 deposition in Portugal was 0.02 kBq/m^2. It was reported that considerable secondary contamination occurred due to resuspension of material from contaminated forest. This was not confirmed by later studies.



Credit: ARAC

Figure 20: Areas covered by the main body of the radioactive cloud on various days during the release

While the 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. No deposition was detected in the southern hemisphere.

In summary it can be stated that there is now a fairly accurate estimate of the total release. The duration of the release was unexpectedly long, lasting more than a week with two periods of intense release. Another peculiar feature was the significant emission (about 4 %) of fuel material which also contained embedded radionuclides of low volatility such as cerium, zirconium and the actinides. The composition and characteristics of the radioactive material in the plume changed during its passage due to wet and dry deposition, decay, chemical transformations, and alterations in particle size. The area affected was particularly large due to the high altitude and long duration of the release as well as the change of wind direction. However, the pattern of deposition was very irregular, and significant deposition of radionuclides occurred where the passage of the plume coincided with rainfall. Although all the northern hemisphere was affected, only territories of the former Soviet Union and part of Europe experienced contamination to a significant degree.

Radiation dose estimates

Most of the population of the northern hemisphere was exposed, to various degrees, to radiation from the Chernobyl accident. After several years of accumulation of dosimetric data from all available sources, and dose reconstruction calculations based on environmental contamination data and mathematical models, it is now possible to arrive at a reasonable, although not highly accurate, assessment of the ranges of doses received by the various groups of population affected by the accident.

The main doses of concern are those to the thyroid due to external irradiation and inhalation and ingestion of radioactive iodine isotopes, and those to the whole body due to external irradiation from and ingestion of radioactive caesium isotopes. According to current estimates, the situation for the different exposed groups is the following:

Evacuees:

More than 100,000 persons were evacuated, mostly from the 30-km radius area around the accident site, during the first few weeks following the accident. These people received significant doses both to the whole body and the thyroid, although the distribution of those doses was very variable among them depending on their positions around the accident site and the delays of their evacuation.

Doses to the thyroid ranging from 70 mSv to adults up to about 1 Sv to young children and an average individual dose of 15 mSv to the whole body were estimated to have been absorbed by this population prior to their evacuation. Many of these people continued to be exposed, although to a lesser extent depending on the sites of their relocation, after their evacuation from the 30-km zone.

"Liquidators":

Hundreds of thousands of workers, estimated to amount up to 800,000 and including a large number of military personnel, were involved in the emergency actions on the site during the accident and the subsequent clean-up operations which lasted for a few years. These workers were called "liquidators".

A restricted number, of the order of 400, including plant staff, firemen and medical aid personnel, were on the site during the accident and its immediate aftermath and received very high doses from a variety of sources and exposure pathways. Among them were all those who developed acute radiation syndrome and required emergency medical treatment. The doses to these people ranged from a few Gy to well above 10 Gy to the whole body from external irradiation and comparable or even higher internal doses, in particular to the thyroid, from incorporation of radionuclides. A number of scientists, who periodically performed technical actions inside the destroyed reactor area during several years, accumulated over time doses of similar magnitude. The largest group of liquidators participated in clean-up operations for variable durations over a number of years after the accident. Although they were not operating anymore in emergency conditions and were submitted to controls and dose limitations, they received significant doses ranging from tens to hundreds of mSv.

People living in contaminated areas of the former Soviet Union:

About 270,000 people continue to live in contaminated areas with Cs-134 and Cs-137 deposition levels in excess of 555 kBq/m^2, where protection measures still continue to be required. Thyroid doses, due mainly to the consumption of cow's milk contaminated with I-131, were delivered during the first few weeks after the accident; children in the Gomel region of Belarus appear to have received the highest thyroid doses with a range from negligible levels up to 40 Sv and an average of about 1 Sv for children aged 0 to 7. Because of the control of foodstuffs in those areas, most of the radiation exposure since the summer of 1986 is due to external irradiation from the Cs-137 activity deposited on the ground; the whole-body doses for the 1986-89 time period are estimated to range from 5 to 250 mSv with an average of 40 mSv.

Populations outside the former Soviet Union:

The radioactive materials of a volatile nature (such as I-131 and Cs-137) that were released during the accident spread throughout the entire northern hemisphere. The doses received by populations outside the former Soviet Union are relatively low, and show large differences from one country to another depending mainly upon whether rainfall occurred during the passage of the radioactive cloud. These doses range from a lower extreme of a few µSv or tens of µSv outside Europe, to an upper extreme of 1 or 2 mSv in some European countries. The latter value is of the same order as the annual individual exposure from natural background radiation.

Health impact

The health impact of the Chernobyl accident can be described in terms of acute health effects (death, severe health impairment), late health effects (cancers) and psychological effects liable to affect health.

The acute health effects occurred among the plant personnel and the persons who intervened in the emergency phase to fight fires, provide medical aid and immediate clean-up operations. A total of 31 persons died as a consequence of the accident, and about 140 persons suffered various degrees of radiation sickness and health impairment. No members of the general public suffered these kinds of effects.

As far as the late health effects are concerned, namely the possible increase of cancer incidence, in the decade following the accident there has been a real and significant increase of carcinomas of the thyroid among the children living in the contaminated regions of the former Soviet Union, which should be attributed to the accident until proved otherwise. There might also be some increase of thyroid cancers among the adults living in those regions. From the observed trend of this increase of thyroid cancers it is expected that the peak has not yet been reached and that this kind of cancer will still continue for some time to show an excess above its natural rate in the area.

On the other hand, the scientific and medical observation of the population has not revealed any increase in other cancers, as well as in leukaemia, congenital abnormalities, adverse pregnancy outcomes or any other radiation induced disease that could be attributed to the Chernobyl accident. This observation applies to the whole general population, both within and outside the former Soviet Union. Large scientific and epidemiological research programs, some of them sponsored by international organisations such as the WHO and the EC, are being conducted to provide further insight into possible future health effects. However, the population dose estimates generally accepted tend to indicate that, with the exception of thyroid disease, it is unlikely that the exposure would lead to discernible radiation effects in the general population above the background of natural incidence of the same diseases. In the case of the liquidators this forecast should be taken with some caution.

An important effect of the accident, which has a bearing on health, is the appearance of a widespread status of psychological stress in the populations affected. The severity of this phenomenon, which is mostly observed in the contaminated regions of the former Soviet Union, appears to reflect the public fears about the unknowns of radiation and its effects, as well as its mistrust towards public authorities and official experts, and is certainly made worse by the disruption of the social networks and traditional ways of life provoked by the accident and its long-term consequences.

Potential residual risks

Within seven months of the accident, the destroyed reactor was encased in a massive concrete structure, known as the "sarcophagus", to provide some form of confinement of the damaged nuclear fuel and destroyed equipment and reduce the likelihood of further releases of radioactivity to the environment. This structure was, however, not conceived as a permanent containment but rather as a provisional barrier pending the definition of a more radical solution for the elimination of the destroyed reactor and the safe disposal of the highly radioactive materials.

Nine years after its erection, the sarcophagus structure, although still generally sound, raises concerns for its long-term resistance and represents a standing potential risk. In particular, the roof of the structure presented for a long time numerous cracks with consequent impairment of leaktightness and penetration of large quantities of rain water which is now highly radioactive. This also creates conditions of high humidity producing corrosion of metallic structures which contribute to the support of the sarcophagus. Moreover, some massive concrete structures, damaged or dislodged by the reactor explosion, are unstable and their failure, due to further degradation or to external events, could provoke a collapse of the roof and part of the building.

According to various analyses, a number of potential accidental scenarios could be envisaged. They include a criticality excursion due to change of configuration of the melted nuclear fuel masses in the presence of water leaked from the roof, a resuspension of radioactive dusts provoked by the collapse of the enclosure and the long-term migration of radionuclides from the enclosure into the groundwater. The first two accident scenarios would result in the release of radionuclides into the atmosphere which would produce a new contamination of the surrounding area within a radius of several tens of kilometers. It is not expected, however, that such accidents could have serious radiological consequences at longer distances.

As far as the leaching of radionuclides from the fuel masses by the water in the enclosure and their migration into the groundwater are concerned, this phenomenon is expected to be very slow and it has been estimated that, for example, it will take 45 to 90 years for certain radionuclides such as Sr-90 to migrate underground up to the Pripyat River catchment area. The expected radiological significance of this phenomenon is not known with certainty and a careful monitoring of the evolving situation of the groundwater will need to be carried out for a long time.

The accident recovery and clean-up operations have resulted in the production of very large quantities of radioactive wastes and contaminated equipment which are currently stored in about 800 sites within and outside the 30-km exclusion zone around the reactor. These wastes and equipment are partly buried in trenches and partly conserved in containers isolated from groundwater by clay or concrete screens. A large number of contaminated equipment, engines and vehicles are also stored in the open air. All these wastes are a potential source of contamination of the groundwater which will require close monitoring until a safe disposal into an appropriate repository is implemented.

In general, it can be concluded that the sarcophagus and the proliferation of waste storage sites in the area constitute a series of potential sources of release of radioactivity that threatens the surrounding area. However, any such releases are expected to be very small in comparison with those from the Chernobyl accident in 1986 and their consequences would be limited to a relatively small area around the site. On the other hand, concerns have been expressed by some experts that a much more important release might occur if the collapse of the sarcophagus should induce damage in the Unit 3 of the Chernobyl power plant, which was shut down finally in December 2000.

In any event, initiatives have been taken internationally, and are currently underway, to study a technical solution leading to the elimination of these sources of residual risk on the site.

Lessons learned

The Chernobyl accident was very specific in nature and it should not be seen as a reference accident for future emergency planning purposes. However, it was very clear from the reactions of the public authorities in the various countries that they were not prepared to deal with an accident of this magnitude and that technical and/or organisational deficiencies existed in emergency planning and preparedness in almost all countries.

The lessons that could be learned from the Chernobyl accident were, therefore, numerous and encompassed all areas, including reactor safety and severe accident management, intervention criteria, emergency procedures, communication, medical treatment of irradiated persons, monitoring methods, radioecological processes, land and agricultural management, public information, etc.

However, the most important lesson learned was probably the understanding that a major nuclear accident has inevitable transboundary implications and its consequences could affect, directly or indirectly, many countries even at large distances from the accident site. This led to an extraordinary effort to expand and reinforce international co-operation in areas such as communication, harmonisation of emergency management criteria and co-ordination of protective actions. Major improvements were achieved in this decade and important international mechanisms of co-operation and information were established, such as the international conventions on early notification and assistance in case of a radiological accident, by the IAEA and the EC, the international nuclear emergency exercises (INEX) program, by the NEA, the international accident severity scale (INES), by the IAEA and NEA and the international agreement on food contamination, by the FAO and WHO.

At the national level, the Chernobyl accident also stimulated authorities and experts to a radical review of their understanding of and attitude to radiation protection and nuclear emergency issues. This prompted many countries to establish nationwide emergency plans in addition to the existing structure of local emergency plans for individual nuclear facilities. In the scientific and technical area, besides providing new impetus to nuclear safety research, especially on the management of severe nuclear accidents, this new climate led to renewed efforts to expand knowledge on the harmful effects of radiation and their medical treatment and to revitalise radioecological research and environmental monitoring programs. Substantial improvements were also achieved in the definition of criteria and methods for the information of the public, an aspect whose importance was particularly evident during the accident and its aftermath.

Conclusion

The history of the modern industrial world has been affected on many occasions by catastrophes comparable or even more severe than the Chernobyl accident. Nevertheless, this accident, due not only to its severity but especially to the presence of ionizing radiation, had a significant impact on human society. Not only produced it severe health consequences and physical, industrial and economic damage in the short term, but, also, its long-term consequences in terms of socio-economic disruption, psychological stress and damaged image of nuclear energy, are expected to be long standing.

However, the international community has demonstrated a remarkable ability to apprehend and treasure the lessons to be drawn from this event, so that it will be better prepared to cope with a challenge of this kind, if ever a severe nuclear accident should happen again.

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