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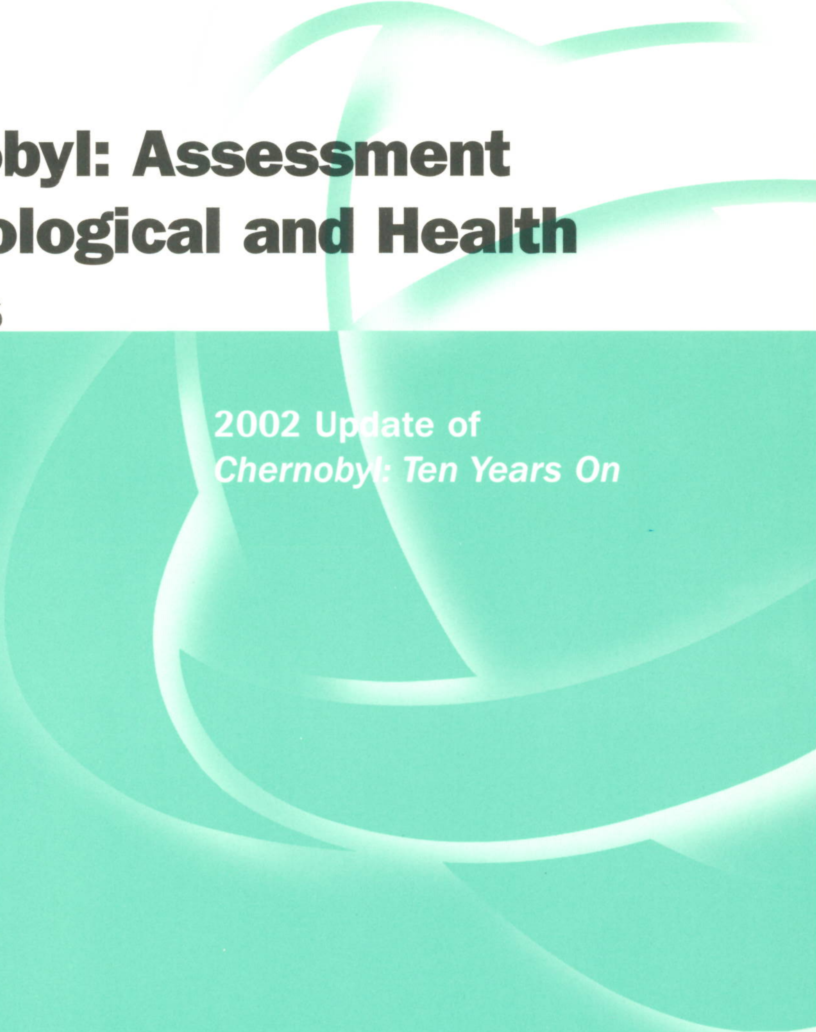

Chernobyl: Assessment of Radiological and Health Impacts

2002 Update of *Chernobyl: Ten Years On*

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Radiation Protection

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Assessment of Radiological and Health Impacts

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Chernobyl: Ten Years On

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of 28 OECD Member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its Member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

FOREWORD

Several years after the Three Mile Island accident in the United States, the Chernobyl accident in 1986 completely changed the public's perception of nuclear risk. While the first accident provided the impetus to develop new research programmes on nuclear safety, the second, with its human death toll and the dispersion of a large part of the reactor core into the environment, raised a large number of "management" problems, not only for the treatment of severely exposed persons, but also for the decisions that had to be taken in respect of the population. Clearly, not only the national authorities of the Soviet Union, but more broadly, authorities from many other affected countries were not ready to manage an accident whose consequences were not confined to their territory.

The way the accident was managed and the lack of information provoked a feeling of distrust in the minds of the public that was reinforced by the fact that radiation cannot be perceived by humans, although it can be easily identified with electronic detectors, even at a very low level. The prospect of contaminated food, aggravated by ambiguous, even contradictory recommendations by national authorities, gave rise to a variety of reactions, and sometimes overreactions, in the management of the accident consequences in several European countries. In the accident country itself, where political, social and economic conditions were worsening, the association of the Soviet regime with nuclear activities contributed to raise feelings of mistrust towards the public authorities.

More than sixteen years after the Chernobyl accident, public concern remains high in spite of the considerable amount of information disseminated by national authorities and large international organisations, the multitude of scientific papers in the specialised press, and the numerous symposia devoted to this accident. The same questions are still being asked and the general public, the media and sometimes the politicians concerned, still find it difficult to understand the information provided by the scientific community.

Public opinion in the former Soviet Union and in many other countries affected by the accident remains convinced that certain cancers, such as those of the thyroid, can only have resulted from the Chernobyl accident. This view is partly driven by statistics showing that in European countries the incidence of such cancers has increased. Although this cannot be attributed to the accident, because this increase has been ongoing and was recorded long before the accident occurred, it remains difficult for doctors to reassure patients in this regard. As the increase in childhood thyroid cancer, which occurred primarily in Belarus, emerged in the early 1990s, many experts were surprised by this "early" appearance of thyroid cancer and by its geographic distribution within the affected territories. This further aggravated public scepticism of the scientific community.

The media have at times published pictures of human and animal deformities without investigating their veritable connection with the accident, and the public, struck by such images, has been allowed, unchallenged, to lay the blame on Chernobyl. Here again, the accident has given rise to numerous studies showing that such deformities and diseases are not linked to radiation exposure. These conclusions, however, have not been effectively transmitted to decision makers or the public. On the other hand, many feared a catastrophic contamination of the River Dnieper, extending to the Mediterranean, which never materialised. Radionuclide retention in the soil has been high, and any remaining contamination is well below initial projections. So much the better.

In this context of public concern, the NEA has found that by far the most consulted document on its website is the one drafted in 1996 on the impact of the Chernobyl accident. That is why, with more recent information now available, in particular the new United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) report published in 2000, it was timely to update the *Chernobyl: Ten Years On* report. Several figures have changed as a result of the numerous and increasingly detailed studies carried out over the last years. The list of bibliographical references has also been updated, with one quarter more bibliographical references than in the previous edition. Furthermore, the NEA wished to address the questions raised by numerous other reports that have been issued, either on the tenth anniversary of the accident or immediately afterwards. Among these reports were those prepared by UNSCEAR, and by the International Atomic Energy Agency (IAEA) on the state of the environment, which had, to a large extent, served as a model for the present report.

This report presents the knowledge gained since the accident, which has evolved gradually. Environmental contamination, which seemed to be decreasing fairly quickly, has reached an ecological equilibrium and, in certain limited sectors, has even increased due to a reconcentration of ^{137}Cs, the only radionuclide remaining in the different soil compartments involved in food chain transfers. This process has gone as far as it can, and now, in places where contamination persists, only the radioactive decay of caesium will reduce the impact of the accident.

The huge effort by the international community to gain a better understanding of the real impact of Chernobyl continues, and should, in the next ten years, clarify the main consequences of the accident. The main trends described in 1996 continue to be valid in 2002: thyroid cancer in children remains the only striking manifestation of the accident as far as the public is concerned. The significant increase in cases of leukaemia, which had been so greatly feared, has not, on the other hand, materialised.

Many improvements in radiation protection and emergency preparedness have been made possible by the Chernobyl experience and we are also able to develop a more accurate assessment of the impact of this accident. Under the auspices of the NEA Committee on Radiation Protection and Public Health (CRPPH), supported by other international bodies, the most outstanding progress since the Chernobyl accident has been in learning about intergovernmental communications and co-operation in the case of nuclear emergencies. The International Nuclear Emergency Exercises (INEX) bear witness to this. Governments, initially reluctant to publicly discuss nuclear accident preparedness and management issues, now ask for such exercises to be carried out, operators are no longer reluctant to offer their sites for this purpose, and local authorities are pleased to invite the participants involved to appear before the media. This shows the progress achieved in terms of communication and involvement of all social partners. More impressive still is the progress made concerning the distribution of stable iodine near nuclear power plants, a subject that was more or less taboo before the accident. The NEA organised an international colloquium on this topic, and this issue is today openly debated.

Here again, the CRPPH played an experimental and innovative role, stressing how very important it is to involve all social partners. This idea, which originated in the context of accident management, has been taken up by many other disciplines, including the management of nuclear waste. This fundamental point is also one of the positive lessons learned from the accident.

The accident was followed by numerous assistance and research programmes supported by international organisations and bilateral agreements. All these organisations are or will be publishing their results. This report differs from the others in that it is a synthetic consensus view aimed at those persons who wish to know the salient points, without having to go into the technical details that can be found elsewhere.

We thank all those organisations (IAEA, UNSCEAR, FAO, WHO, EC and others) that have provided information so that this report could be as up to date as possible. The original report *Chernobyl: Ten Years On* was drafted by Dr. Peter Waight (Canada) under the direction of an editing committee chaired by Dr. Henri Métivier (France).

This edition was prepared by Dr. Henri Métivier on request of the CRPPH.

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EXECUTIVE SUMMARY

Introduction

On 26 April, 1986, the Chernobyl nuclear power station, located in Ukraine about 20 km south of the border of Belarus, suffered a major accident which was followed by a prolonged release to the atmosphere of large quantities of radioactive substances. The specific features of the release favoured a widespread distribution of radioactivity throughout the northern hemisphere, mainly across Europe. A contributing factor was the variation of meteorological conditions and wind regimes during the period of release. Activity transported by the multiple plumes from Chernobyl was measured not only in Northern and in Southern Europe, but also in Canada, Japan and the United States. Only the Southern hemisphere remained free of contamination.

This had serious radiological, health and socio-economic consequences for the populations of Belarus, Ukraine and Russia, which still suffer from these consequences. Although the radiological impact of the accident in other countries was generally very low, and even insignificant outside Europe, this event had, however, the effect of enhancing public apprehension all over the world on the risks associated with the use of nuclear energy.

This is one of the reasons explaining the renewed attention and effort devoted during the last sixteen years to the reactor safety studies and to emergency preparedness by public authorities and the nuclear industry. This also highlights the continuing public attention to the situation at Chernobyl, which was already significant 10 years after the accident and has not declined 6 years later. Parts of the population in some countries discuss aspects of the accident, such as the increase in thyroid cancer, even more than before.

It now appears, therefore, the right moment to review our knowledge of the serious aspects of the accident's impact, to take stock of the information accumulated and the scientific studies underway e.g. the UNSCEAR 2000 document, IAEA documents, etc; as well as to assess the degree to which national authorities and experts have implemented the numerous lessons that the Chernobyl accident taught us.

Moreover, since the last report, all units of the Chernobyl reactor have been shut down.

This new report, prepared for the Committee on Radiation Protection and Public Health (CRPPH) of the OECD Nuclear Energy Agency, does not differ from the former description of the accident, but brings new data on the health status of the population and a new view on environmental contamination.

The accident

The Unit 4 of the Chernobyl nuclear power plant was to be shutdown for routine maintenance on 25 April 1986. On that occasion, it was decided to carry out a test of the capability of the plant equipment to provide enough electrical power to operate the reactor core cooling system and emergency equipment during the transition period between a loss of main station electrical power supply and the start up of the emergency power supply provided by diesel engines.

Unfortunately, this test, which was considered to concern essentially the non-nuclear part of the power plant, was carried out without a proper exchange of information and co-ordination between the team in charge of the test and the personnel in charge of the operation and safety of the nuclear reactor. Therefore, inadequate safety precautions were included in the test programme and the operating personnel were not alerted to the nuclear safety implications and potential danger of the electrical test.

This lack of co-ordination and awareness, resulting from an insufficient level of “safety culture” within the plant staff, led the operators to take a number of actions which deviated from established safety procedures and led to a potentially dangerous situation. This course of actions was compounded by the existence of significant drawbacks in the reactor design which made the plant potentially unstable and easily susceptible to loss of control in case of operational errors.

The combination of these factors provoked a sudden and uncontrollable power surge which resulted in violent explosions and almost total destruction of the reactor. The consequences of this catastrophic event were further worsened by the graphite moderator and other material fires that broke out in the building and contributed to a widespread and prolonged release of radioactive materials to the environment.

Dispersion and deposition of radionuclides

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, over a 10-day period, with varying release rates. The duration and high altitude (about 1 km) reached by the release were largely due to the graphite fire which was difficult to extinguish until day 10, when the releases dropped abruptly, thus ending the period of intense release.

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.

Since the last report we have a better view of the behaviour of radionuclides in the contaminated areas, and we know now that the natural decontamination processes have reached an environmental equilibrium state. The decrease of contamination levels from now on will be mainly due to radioactive decay indicating that radioactive cesium will be present for approximately 300 years.

Reactions of national authorities

The scale and severity of the Chernobyl accident had not been foreseen and took most national authorities responsible for public health and emergency preparedness by surprise. The intervention criteria and procedures existing in most countries were not adequate for dealing with an accident of such scale and provided little help in decision making concerning the choice and adoption of protective measures. In addition, early in the course of the accident there was little information available and considerable political pressure, partially based on the public perception of the radiation danger, was being exerted on the decision makers.

In these circumstances, cautious immediate actions were felt necessary and in many cases measures were introduced that tended to err, sometimes excessively so, on the side of prudence rather than being driven by informed scientific and expert judgement.

Within the territory of the former Soviet Union, short-term countermeasures were massive and, in general, reasonably timely and effective. However, difficulties emerged when the authorities tried to establish criteria for the management of the contaminated areas on the long term and the associated relocation of large groups of population. Various approaches were proposed and criteria were applied over the years. Eventually, criteria for population resettlement or relocation from contaminated areas were adopted in which radiation protection requirements and economic compensation considerations were intermingled. This was and continues to be a source of confusion and possible abuse.

The progressive spread of contamination at large distances from the accident site caused considerable concern in many countries outside the former Soviet Union and the reactions of the national authorities to this situation were extremely varied, ranging from a simple intensification of the normal environmental monitoring programmes, without adoption of specific countermeasures, to compulsory restrictions concerning the marketing and consumption of foodstuffs.

Apart from the objective differences of contamination levels and regulatory and public health systems between countries, one of the principal reasons for the variety of situations observed in the different countries stems from the different criteria adopted for the choice and application of intervention levels for the implementation of protective actions. These discrepancies were in some cases due to misinterpretation and misuse of international radiation protection guidelines, especially in the case of food contamination, and were further enhanced by the overwhelming role played in many cases by non-radiological factors, such as socio-economic, political and psychological, in determining the countermeasures.

This situation caused concern and confusion among the public, perplexities among the experts and difficulties to national authorities, including problems of public credibility, as well as a waste of efforts and unnecessary economic losses. These problems were particularly felt in areas close to international borders due to different reactions of the authorities and media in bordering countries. However, all these issues were soon identified as an area where several lessons should be learned and international efforts were undertaken to harmonise criteria and approaches to emergency management.

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 in the population of children and infants at the time of the accident, due to external irradiation and inhalation and ingestion of radioactive iodine isotopes (^{131}I and short-lived radionuclides), and those to the whole body due to external irradiation from and ingestion of radioactive caesium isotopes (^{134}Cs and ^{137}Cs). According to the most wildly accepted 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 millisieverts to adults up to about 1 000 millisieverts (i.e., 1 sievert) to young children and an average individual dose of 15 millisieverts [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 600 000 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 people, 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 grays to well above 10 grays 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 no longer working in emergency conditions, and were subject to controls and dose limitations, they received significant doses ranging from tens to hundreds of millisieverts.

- ***People living in contaminated areas of the former Soviet Union*** – About 270 000 people continue to live in contaminated areas with radiocaesium deposition levels in excess of 555 kilobecquerels per square metre [kBq/m2], where protection measures still continue to be required. Thyroid doses, due mainly to the consumption of cow’s milk contaminated with radioiodine, 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 sieverts, and an average of about 1 sievert for children aged 0 to 7. Thanks to 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 radiocaesium 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 iodine and caesium) 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 microsieverts or tens of microsieverts outside Europe, to an upper extreme of 1 or 2 mSv in some specific areas of some European countries.

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 social/accident effects that may 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 people died as a consequence of the accident, and about 140 people suffered various degrees of radiation sickness and radiation-related acute 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, since the accident there has been a real and significant increase of carcinomas of the thyroid among the population of infants and children exposed at the time of the accident in the contaminated regions of the former Soviet Union. This 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 affected population has not to date revealed any significant increase in other cancers, 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 programmes, 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 predict 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, increases in cancer have not been observed to date, but a specific and detailed follow-up of this particular group might better reveal increasing trends should they exist.

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.

These accident related effects have resulted in a general degradation of the health of the population living in the contaminated territories. Illnesses that have been observed are not typically related to radiation exposure. Further study of those effects should continue.

Agricultural and environmental impacts

The impact of the accident on agricultural practices, food production and use and other aspects of the environment has been and continue to be much more widespread than the direct health impact on humans.

Several techniques of soil treatment and decontamination to reduce the accumulation of radioactivity in agricultural produce and cow's milk and meat have been tested with positive results in some cases. Nevertheless, within the former Soviet Union, large areas of agricultural land are still excluded from use and are expected to continue to be so for a long time. In a much larger area, although agricultural and dairy production activities are carried out, the food produced is subjected to strict controls and restrictions of distribution and use.

Although contamination levels showed a decreasing trend for some time following the accident, it increasingly appears that an ecological stability has been reached. This is particularly true in forest areas. The decrease now seems to be following the decay period for ^{137}Cs, which has a 30-year half-life. Should this trend continue, measurable contamination would be present in these areas for approximately 10 half-lives, or 300 years.

Similar problems of control and limitation of use, although of a much lower severity, were experienced in some countries of Europe outside the former Soviet Union, where agricultural and farm animal production were subjected to restrictions for variable durations after the accident. Most of these restrictions were lifted some time ago. However, there are still today some areas in Europe where restrictions on slaughter and distribution of animals are in force. This concerns, for example, several hundreds of thousands of sheep in the United Kingdom and large numbers of sheep and reindeer in some Nordic countries.

The forest is a special environment where problems persist. Because of the high filtering characteristics of trees, deposition was often higher in forests than in other areas. An extreme case was the so-called "red forest" near to the Chernobyl site where the irradiation was so high as to kill the trees which had to be destroyed as radioactive waste. In more general terms, forests, being a source of timber, wild game, berries and mushrooms as well as a place for work and recreation, continue to be of concern in some areas and are expected to constitute a radiological problem for a long time.

Water bodies, such as rivers, lakes and reservoirs can be, if contaminated, an important source of human radiation exposure because of their uses for recreation, drinking and fishing. In the case of the Chernobyl accident this segment of the environment has not contributed significantly to the total radiation exposure of the population. It was estimated that the component of the individual and collective doses that can be attributed to the water bodies and their products does not exceed 1 or 2% of the total exposure resulting from the accident. Since the accident, it has been noted that the contamination of the water system has not posed a public health problem during the last decade; nevertheless, in view of the large quantities of radioactivity deposited in the catchment area of the system of water bodies in the contaminated regions around Chernobyl, there will continue to be for a long time a need for careful monitoring to ensure that washout from the catchment area will not contaminate drinking-water supplies.

Outside the former Soviet Union, no concerns were ever warranted for the levels of radioactivity in drinking water. On the other hand, there are lakes, particularly in Switzerland and the Nordic countries, where restrictions were necessary for the consumption of fish. These restrictions still exist in Sweden, for example, where thousands of lakes contain fish with a radioactivity content which is still higher than the limits established by the authorities for sale on the market.

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.

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 kilometres. 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 ^{90}Sr 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.

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 have been achieved since the accident, 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) programme, 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 programmes. 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.

Another lesson of policy significance concerns the reclamation of contaminated land. As has been seen, contamination, particularly in forest environments, has tended to reach ecological stability. While it was previously thought that contamination levels would decline due to natural removal processes, this has not proven to be the case generally, such that policy makers will be forced to deal with such problems for longer periods than first thought.

Because of this persistence of contamination, the importance of stakeholder involvement in the development of approaches to living in the contaminated territories has been highlighted. The policy lesson has been that stakeholders, local, regional, national and international, must be involved, at the appropriate level, in decision making processes in order to arrive at accepted approaches to living with contamination. Such approaches need will to be long-lasting and to evolve with changing local conditions.

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 ionising radiation, had a significant impact on human society.

Not only did it produce 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 damage to the image of the nuclear energy, are expected to persist for sometime.

However, the international community has demonstrated a remarkable ability to apprehend and treasure the lessons drawn from this event, so that it will be better prepared to cope with future challenges of this or another nature in a more flexible fashion.

Chapter I

THE SITE AND ACCIDENT SEQUENCE

The site

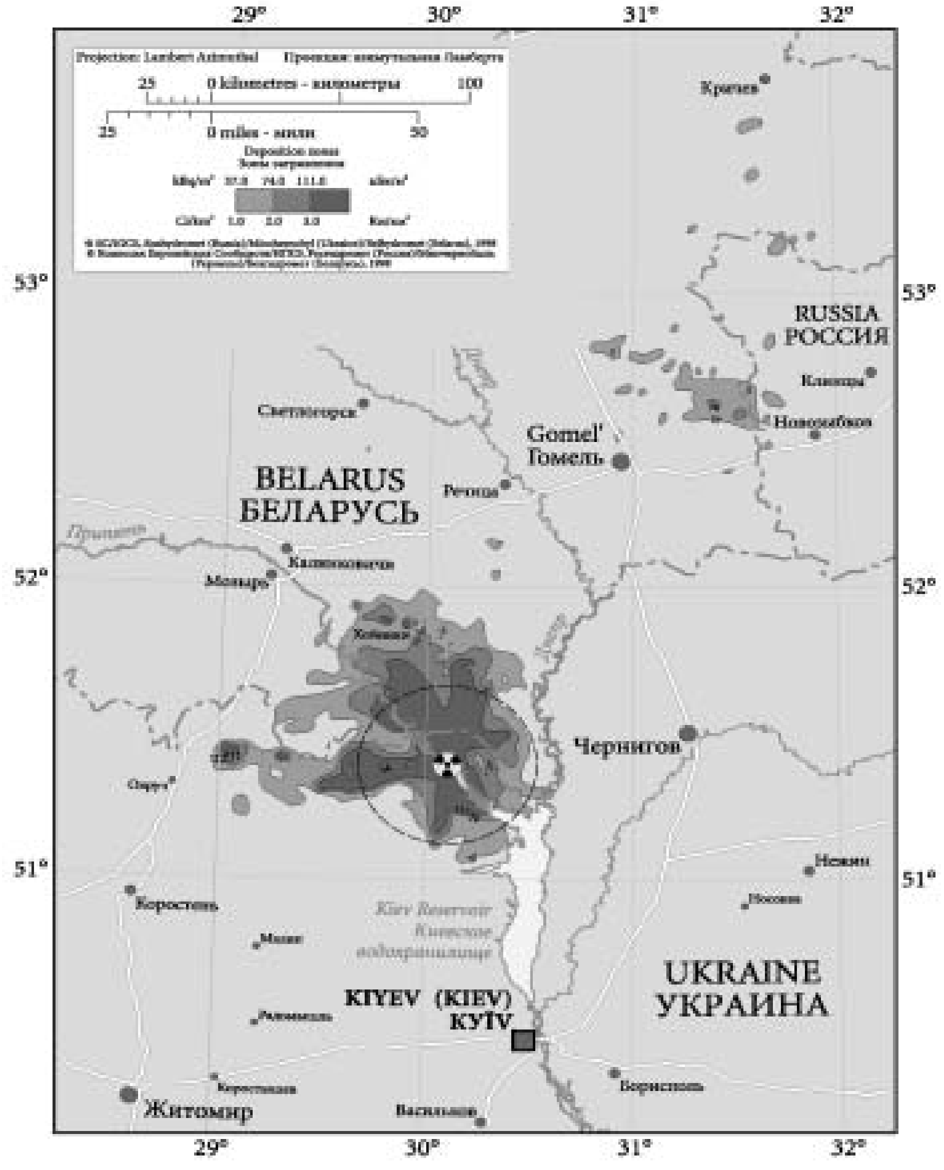
At the time of the Chernobyl accident, on 26 April 1986, the Soviet Nuclear Power Programme was based mainly upon two types of reactors, the WWER, a pressurised light-water reactor, and the RBMK, a graphite moderated light-water reactor. While the WWER type of reactor was exported to other countries, the RBMK design was restricted to republics within the Soviet Union.

The Chernobyl Power Complex, lying about 130 km north of Kiev, Ukraine, and about 20 km south of the border with Belarus (Figure 1), consisted of four nuclear reactors of the RBMK-1000 design, Units 1 and 2 being constructed between 1970 and 1977, while Units 3 and 4 of the same design were completed in 1983 (IA86). Two more RBMK reactors were under construction at the site at the time of the accident.

To the South-east of the plant, an artificial lake of some 22 km^2, situated beside the river Pripyat, a tributary of the Dniepr, was constructed to provide cooling water for the reactors.

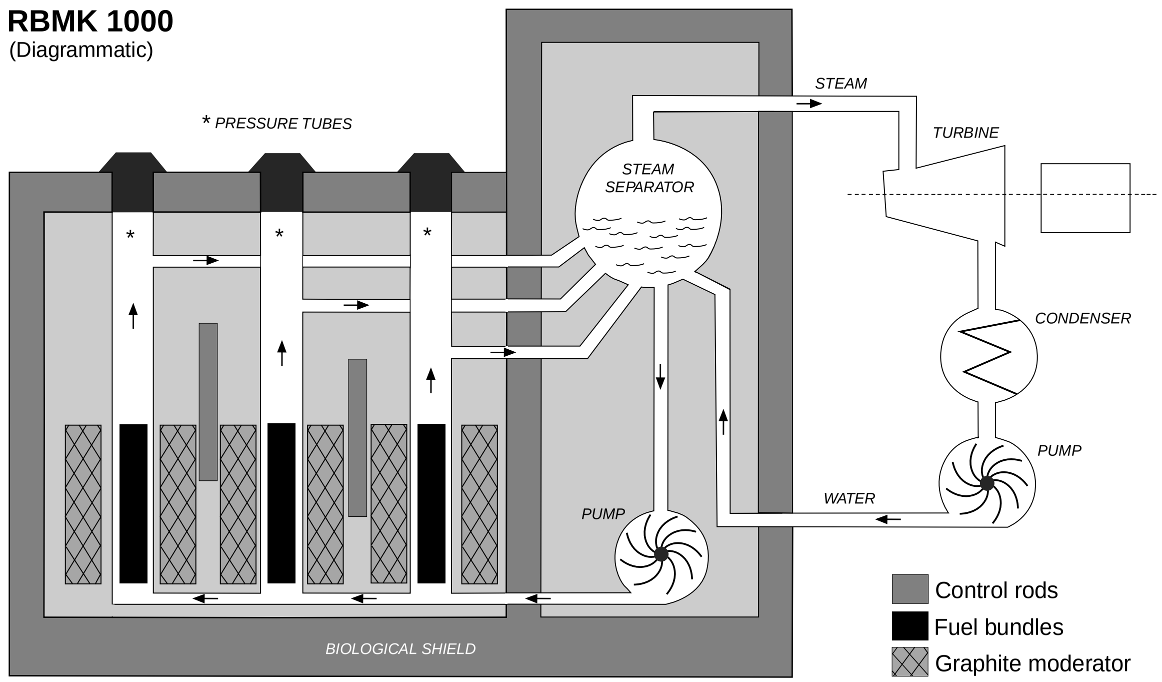
This area of Ukraine is described as Belarussian-type woodland with a low population density. About 3 km away from the reactor, in the new city, Pripyat, there were 49 000 inhabitants. The old town of Chernobyl, which had a population of 12 500, is about 15 km to the South-east of the complex. Within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

Figure 1. The site of the Chernobyl nuclear power complex (modif. from *IA91*)



Credit: Figure IV.1 *Distribution, in December 1989, of Deposited Strontium-90 Released in the Chernobyl Accident*. From: "Atlas of Caesium Deposition on Europe after the Chernobyl Accident". M. De Cort, G. Dubois, Sh.D. Fridman, M.G. Germenchuk, Yu.A. Izrael, A. Janssens, A.R. Jones, G.N. Kelly, E.V. Kvasnikova, I.I. Matveenko, I.M. Nazarov, Yu.M. Pokumeiko, V.A. Sitak, E.D. Stukin, L.Ya. Tabachny, Yu.S. Tsaturov and S.I. Avdyushin. EUR report nr. 16733, EC, Office for Official Publications of the European Communities, Luxembourg (1998).

Figure 2. The RBMK reactor



The RBMK-1000 reactor

The RBMK-1000 (Figure 2) is a Soviet designed and built graphite moderated pressure tube type reactor, using slightly enriched (2% ^{235}U) uranium dioxide fuel. It is a boiling light water reactor, with direct steam feed to the turbines, without an intervening heat-exchanger. Water pumped to the bottom of the fuel channels boils as it progresses up the pressure tubes, producing steam which feeds two 500 MWe [megawatt electrical] turbines. The water acts as a coolant and also provides the steam used to drive the turbines. The vertical pressure tubes contain the zirconium-alloy clad uranium-dioxide fuel around which the cooling water flows. A specially designed refuelling machine allows fuel bundles to be changed without shutting down the reactor.

The moderator, whose function is to slow down neutrons to make them more efficient in producing fission in the fuel, is constructed of graphite. A mixture of nitrogen and helium is circulated between the graphite blocks largely to prevent oxidation of the graphite and to improve the transmission of the heat produced by neutron interactions in the graphite, from the moderator to the fuel channel. The core itself is about 7 m high and about 12 m in diameter. There are four main coolant circulating pumps, one of which is always on standby. The reactivity or power of the reactor is controlled by raising or lowering 211 control rods, which, when lowered, absorb neutrons and reduce the fission rate. The power output of this reactor is 3 200 MWt (megawatt thermal) or 1 000 MWe, although there is a larger version producing 1 500 MWe. Various safety systems, such as an emergency core cooling system and the requirement for an absolute minimal insertion of 30 control rods, were incorporated into the reactor design and operation.

The most important characteristic of the RBMK reactor is that it possesses a “positive void coefficient”. This means that if the power increases or the flow of water decreases, there is increased steam production in the fuel channels, so that the neutrons that would have been absorbed by the denser water will now produce increased fission in the fuel. However, as the power increases, so does the temperature of the fuel, and this has the effect of reducing the neutron flux (negative fuel coefficient). The net effect of these two opposing characteristics varies with the power level. At the high power level of normal operation, the temperature effect predominates, so that power excursions leading to excessive overheating of the fuel do not occur. However, at a lower power output of less than 20% the maximum, the positive void coefficient effect is dominant and the reactor becomes unstable and prone to sudden power surges. This was a major factor in the development of the accident.

Events leading to the accident (IA86, IA86a)

The Unit 4 reactor was to be shutdown for routine maintenance on 25 April 1986. It was decided to take advantage of this shutdown to determine whether, in the event of a loss of station power, the slowing turbine could provide enough electrical power to operate the emergency equipment and the core cooling water circulating pumps, until the diesel emergency power supply became operative. The aim of this test was to determine whether cooling of the core could continue to be ensured in the event of a loss of power.

This type of test had been run during a previous shut-down period, but the results had been inconclusive, so it was decided to repeat it. Unfortunately, this test, which was considered essentially to concern the non-nuclear part of the power plant, was carried out without a proper exchange of information and co-ordination between the team in charge of the test and the personnel in charge of the operation and safety of the nuclear reactor. Therefore, inadequate safety precautions were included in the test programme and the operating personnel were not alerted to the nuclear safety implications of the electrical test and its potential danger.

The planned programme called for shutting off the reactor's emergency core cooling system (ECCS), which provides water for cooling the core in an emergency. Although subsequent events were not greatly affected by this, the exclusion of this system for the whole duration of the test reflected a lax attitude towards the implementation of safety procedures.

As the shutdown proceeded, the reactor was operating at about half power when the electrical load dispatcher refused to allow further shutdown, as the power was needed for the grid. In accordance with the planned test programme, about an hour later the ECCS was switched off while the reactor continued to operate at half power. It was not until about 23:00 hr on 25 April that the grid controller agreed to a further reduction in power.

For this test, the reactor should have been stabilised at about 1 000 MWt prior to shut down, but due to operational error the power fell to about 30 MWt, where the positive void coefficient became dominant. The operators then tried to raise the power to 700-1 000 MWt by switching off the automatic regulators and freeing all the control rods manually. It was only at about 01:00 hr on 26 April that the reactor was stabilised at about 200 MWt.

Although there was a standard operating order that a minimum of 30 control rods was necessary to retain reactor control, in the test only 6-8 control rods were actually used. Many of the control rods were withdrawn to compensate for the build up of xenon which acted as an absorber of neutrons and reduced power. This meant that if there were a power surge, about 20 seconds would be required to lower the control rods and shut the reactor down. In spite of this, it was decided to continue the test programme.

There was an increase in coolant flow and a resulting drop in steam pressure. The automatic trip which would have shut down the reactor when the steam pressure was low, had been circumvented. In order to maintain power the operators had to withdraw nearly all the remaining control rods. The reactor became very unstable and the operators had to make adjustments every few seconds trying to maintain constant power.

At about this time, the operators reduced the flow of feedwater, presumably to maintain the steam pressure. Simultaneously, the pumps that were powered by the slowing turbine were providing less cooling water to the reactor. The loss of cooling water exaggerated the unstable condition of the reactor by increasing steam production in the cooling channels (positive void coefficient), and the operators could not prevent an overwhelming power surge, estimated to be 100 times the nominal power output.

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. A second explosion added to the destruction two to three seconds later. While it is not known for certain what caused the explosions, it is postulated that the first was a steam/hot fuel explosion, and that hydrogen may have played a role in the second.

Some medias had reported a sismic origin of the accident, however the scientific credibility of the paper at the origin of this rumour (St98) has been discarded.

The accident

The accident occurred at 01:23 hr on Saturday, 26 April 1986, when the two explosions destroyed the core of Unit 4 and the roof of the reactor building.

In the IAEA Post-Accident Assessment Meeting in August 1986 (IA86), much was made of the operators’ responsibility for the accident, and not much emphasis was placed on the design faults of the reactor. Later assessments (IA86a, UN00) suggest that the event was due to a combination of the two, with a little more emphasis on the design deficiencies and a little less on the operator actions.

The two explosions sent fuel, core components and structural items and produced a shower of hot and highly radioactive debris, including fuel, core components, structural items and graphite into the air and exposed the destroyed core to the atmosphere. The plume of smoke, radioactive fission products and debris from the core and the building rose up to about 1 km into the air. The heavier debris in the plume was deposited close to the site, but lighter components, including fission products and virtually all of the noble gas inventory were blown by the prevailing wind to the North-west of the plant.

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. Over 100 fire-fighters from the site and called in from Pripyat were needed, and it was this group that received the highest radiation exposures and suffered the greatest losses in personnel. 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. These fires were put out by 05:00 hr of the same day, but by then the graphite fire had started. Many firemen added to their considerable doses by staying on call on site. 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 was finally extinguished.

The graphite fire

While the conventional fires at the site posed no special firefighting problems, very high radiation doses were incurred by the firemen, resulting in 31 deaths. However, the graphite moderator fire was a special problem. Very little national or international expertise on fighting graphite fires existed, and there was a very real fear that any attempt to put it out might well result in further dispersion of radionuclides, perhaps by steam production, or it might even provoke a criticality excursion in the nuclear fuel.

A decision was made to layer the graphite fire with large amounts of different materials, each one designed to combat a different feature of the fire and the radioactive release. The first measures taken to control fire and the radionuclides releases consisted of dumping neutron-absorbing compounds and fire-control material into the crater that resulted from the destruction of the reactor. The total amount of materials dumped on the reactor was about 5 000 t including about 40 t of borons 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 (Bu93). 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 dose rates received by the helicopter pilots during this procedure were too high, it was decide that the materials should be dumped while the helicopters travelled over the reactor. This procedure caused additional destruction of the standing structures and spread the contamination. Boron carbide was dumped in large quantities from helicopters to act as a neutron absorber and prevent any renewed chain reaction. Dolomite was also added to act as heat sink and a source of carbon dioxide to smother the fire. Lead was included as a radiation absorber, as well as sand and clay which it was hoped would prevent the release of particulates. While it was later discovered that many of these compounds were not actually dropped on the target, they may have acted as thermal insulators and precipitated an increase in the temperature of the damaged core leading to a further release of radionuclides a week later.

The further sequence of events is still speculative, although elucidated with the observation of residual damage to the reactor (Si94, Si04a, Si94b). It is suggested that the melted core materials settled to the bottom of the core shaft, with the fuel forming a metallic layer below the graphite. The graphite layer had a filtering effect on the release of volatile compounds. But after burning without the filtering effect of an upper graphite layer, the release of volatile fissions products from the fuel may have increased, except for non-volatile fission products and actinides, because of reduced particulate emission. On day 8 after the accident, the corium melted through the lower biological shield and flowed onto the floor. This redistribution of corium would have enhanced the radionuclide releases, and on contact with water corium produced steam, causing an increase of radionuclieds at the last stage of the active period.

By May 9, the graphite fire had been extinguished, and work began on 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,allowing the installation of the concrete slab. This slab would not only be of use to cool the core if necessary, it would also act as a barrier to prevent penetration of melted radioactive material into the groundwater.

In summary

The Chernobyl accident was the product of a lack of “safety culture”. The reactor design was poor from the point of view of safety and unforgiving for the operators, both of which provoked a dangerous operating state. The operators were not informed of this and were not aware that the test performed could have brought the reactor into an explosive condition. In addition, they did not comply with established operational procedures. The combination of these factors provoked a nuclear accident of maximum severity in which the reactor was totally destroyed within a few seconds.

Chapter II

THE RELEASE, DISPERSION, DEPOSITION AND BEHAVIOUR OF RADIONUCLIDES

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 then Soviet Union. This was clear at the IAEA Post-Accident Review Meeting in August 1986 (IA86), 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 (Wa87, Ca87, Gu89). 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 (IA86), 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% (IA86). This estimate was later revised to 3.5 ± 0.5% (Be91). 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 (IA86a) 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 then available.

However, more deposition data (Be90) were available when, in their 1988 Report (UN88), 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 ^{137}Cs release was estimated to be 70 petabecquerels (PBq) of which 31 PBq were deposited in the Soviet Union.

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 ^{137}Cs 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 (Be91). After an extensive review of the many reports (IA86, Bu93), this was confirmed. For ^{131}I, the most accurate estimate was felt to be 50 to 60% of the core inventory of 3 200 PBq. The current estimate of the source term (De95) is summarised in Table 1.

From the radiological point of view, ^{131}I and ^{137}Cs are the most important radionuclides to consider, because they are responsible for most the radiation exposure received by the general population.

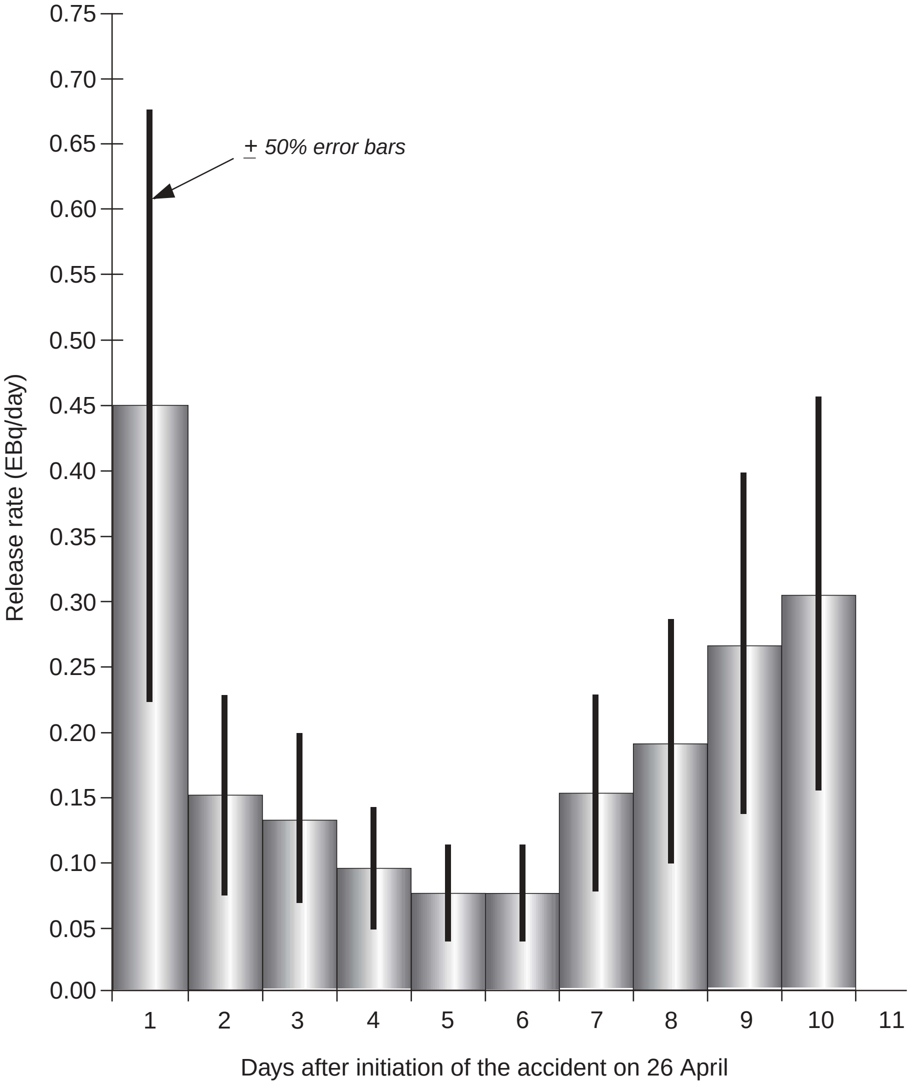
The release pattern over time is well illustrated in Figure 3 (Bu93). The initial large release was principally due to the mechanical fragmentation of the fuel during the explosion. It contained mainly the more volatile radionuclides such as noble gases, iodines and some caesium. The second large release 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.

Table 1. **Current estimate of radionuclide releases during the Chernobyl accident (modif. from ^{95}De)**

Core inventory on 26 April 1986			**Total release during the accident**	
Nuclide	Half-life	Activity (PBq)	Percent of inventory	Activity (PBq)
^{133}Xe	5.3 d	6 500	100	6500
^{131}I	8.0 d	3 200	50-60	~1760
^{134}Cs	2.0 y	180	20-40	~54
^{137}Cs	30.0 y	280	20-40	~85
^{132}Te	78.0 h	2 700	25-60	~1150
^{89}Sr	52.0 d	2 300	4-6	~115
^{90}Sr	28.0 y	200	4-6	~10
^{140}Ba	12.8 d	4 800	4-6	~240
^{95}Zr	65.0 d	5 600	3.5	196
^{99}Mo	67.0 h	4 800	>3.5	>168
^{103}Ru	39.6 d	4 800	>3.5	>168
^{106}Ru	1.0 y	2 100	>3.5	>73
^{141}Ce	33.0 d	5 600	3.5	196
^{144}Ce	285.0 d	3 300	3.5	~116
^{239}Np	2.4 d	27 000	3.5	~95
^{238}Pu	86.0 y	1	3.5	0.035
^{239}Pu	24 400.0 y	0.85	3.5	0.03
^{240}Pu	6 580.0 y	1.2	3.5	0.042
^{241}Pu	13.2 y	170	3.5	~6
^{242}Cm	163.0 d	26	3.5	~0.9

Fifteen years on, the estimation made in 1996 is still valid. However the results presented in Table 1 are incomplete with respect to the release of the short-lived radionuclides (^{132}I and ^{135}I). In the UNSCEAR 2000 report (UN00), the overall releases of short-lived radioiodines are presented on the basis of early and re-estimated informations (Ab86, Iz90); they are found to be substantially lower than those of ^{131}I (1760 PBq), 1040 PBq, 910, 25 and 250 respectively for ^{132}I, ^{133}I, ^{134}I and ^{135}I, ^{132}I is assumed to be in radioactive equilibrium with ^{132}Te.

Figure 3. **Daily release rate of radioactive substances into the atmosphere (modif. from IA86a)**



The estimated daily releases of ^{131}I during the accident is given in Table 2.

Table 2. **Daily releases of ^{131}I**

Day of release	**Daily releases (PBq)**
26 April	704
27 April	204
28 April	150
29 April	102
30 April	69
1 May	62
2 May	102
3 May	107
4 May	130
5 May	130
Total	1760

Although the releases were considerably reduced on 5 and 6 May (days 9 and 10) after the accident), continuing low-level releases occurred in the following week and for up to 40 days after the accident, particularly on 15 and 16 may, attributable to continuing outbreaks of fires or to hot areas in the reactor. These later releases can be correlated with increased concentrations of radionuclides in air measured at Kiev and Vilnius.

Chemical and physical forms

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. As mentioned above, 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. There were only a few measurements of the aero-dynamic size of the radioactive particle releases during the first days of the accident. The activity distribution of the particle size was found to be well represented as the superposition of two log-normal functions, one with an activity median aerodynamic diameter (AMAD) ranging from 0.3 to 1.5 μm and another with an AMAD of 10 μm. The larger particles contained about 80-90% of the activity of non-volatile radionuclides such as ^{95}Zr, ^{95}Nb, ^{140}La, ^{144}Ce and transuranium elements embedded in the uranium matrix of the fuel.

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, lanthanum 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 (De95). Typical activities per hot-particles are 0.1-1 kBq for fuel fragments and 0.5-10 kBq for ruthenium particles, the diameters being about 10 μm to be compared with sizes of 0.4-0.7 μm for the particles associated with the activities of ^{131}I and ^{137}Cs (De88, De91).

Dispersion and deposition

Radioactive contamination of the ground was found to some extend in practically every country of the northern hemisphere. European commission published on the basis of local measurements an atlas of contamination in Europe (De98).

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. 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. ^{137}Cs was selected to characterise 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. However, during the first weeks after the accident, most of the activity deposited on the ground consisted of short-lived radionuclides, of which ^{131}I was the most important radiologically. All the maps established in the former Soviet Union were mainly based on the limited number of measurement of ^{131}I, and they use ^{137}Cs measurements as a guide. These maps must be regarded with caution, as the ratio of ^{131}I to ^{137}Cs deposition densities was found to vary over a large range in Belarus, 5 to 10, this ratio has been not seriously studied in many countries.

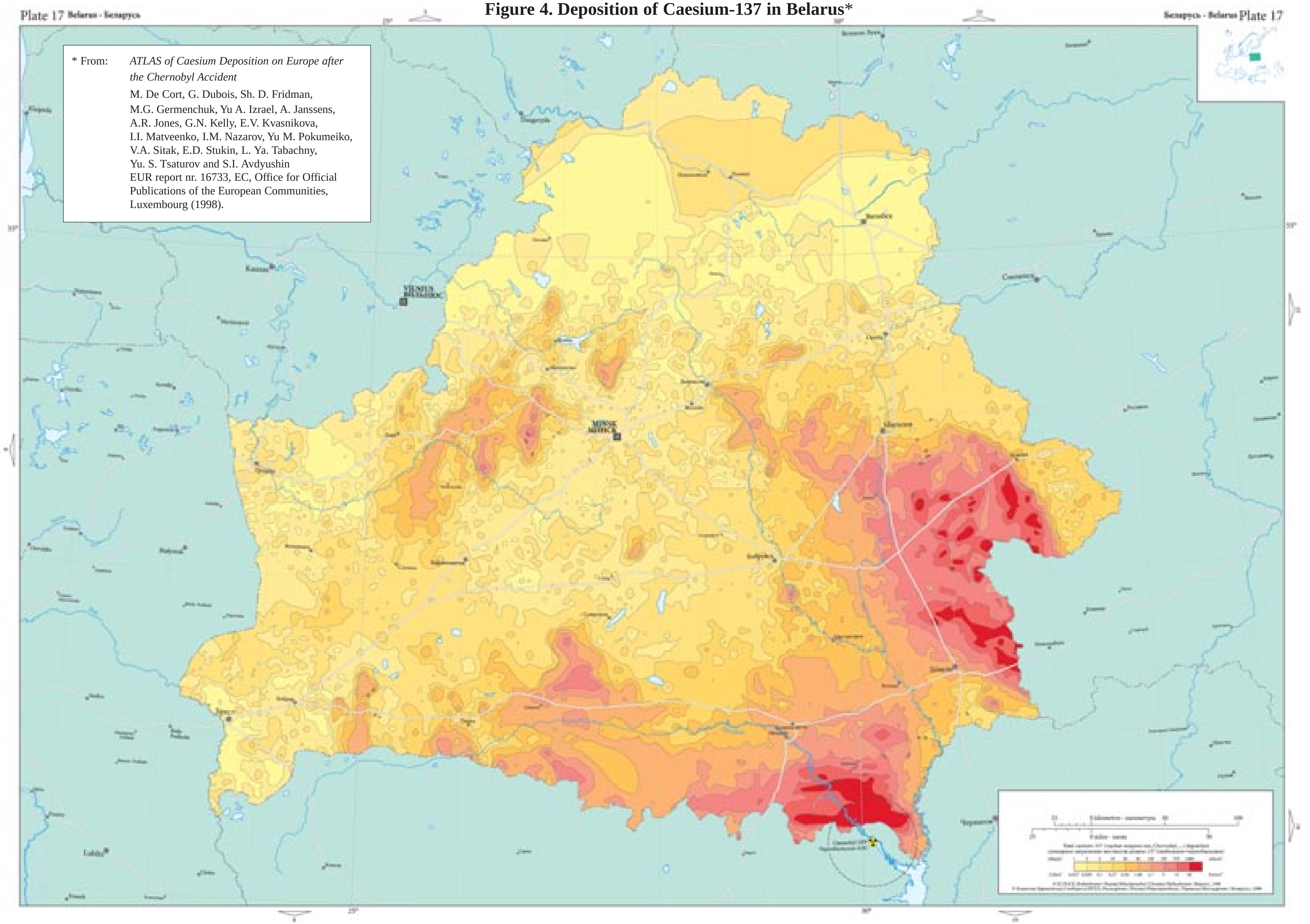
The three main spots of contamination resulting from the Chernobyl accident have been called the Central, Bryansk-Belarus, and Kaluga-Tula-Orel spots (Figure 4, pages 49-50). The Central spot was formed during the initial, active stage of the release predominantly to the West and North-west (Figure 5, pages 51-52). Ground depositions of ^{137}Cs of over 40 kilobecquerels per square metre [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 (Ba93).

Areas of high contamination of ^{137}Cs occurred thoughout the far zone, depending primarily on rainfall at the time the plume passed over. 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 ^{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 (Ba93).

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 ^{137}Cs were lower, usually less than 600 kBq/m^2 (Ba93).

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 ^{137}Cs levels in the range 40 to 200 kBq/m^2. Overall, the territory of the former Soviet Union initially contained approximately 3 100 km^2 contaminated by ^{137}Cs with deposition levels exceeding 1 500 kBq/m^2; 7 200 km^2 with levels of 600 to 1 500 kBq/m^2; and 103 000 km^2 with levels of 40 to 200 kBq/m^2 (US91).

Figure 4. Deposition of Caesium-137 in Belarus*



* From: *ATLAS of Caesium Deposition on Europe after the Chernobyl Accident*

M. De Cort, G. Dubois, Sh. D. Fridman,
M.G. Germenchuk, Yu A. Izrael, A. Janssens,
A.R. Jones, G.N. Kelly, E.V. Kvasnikova,
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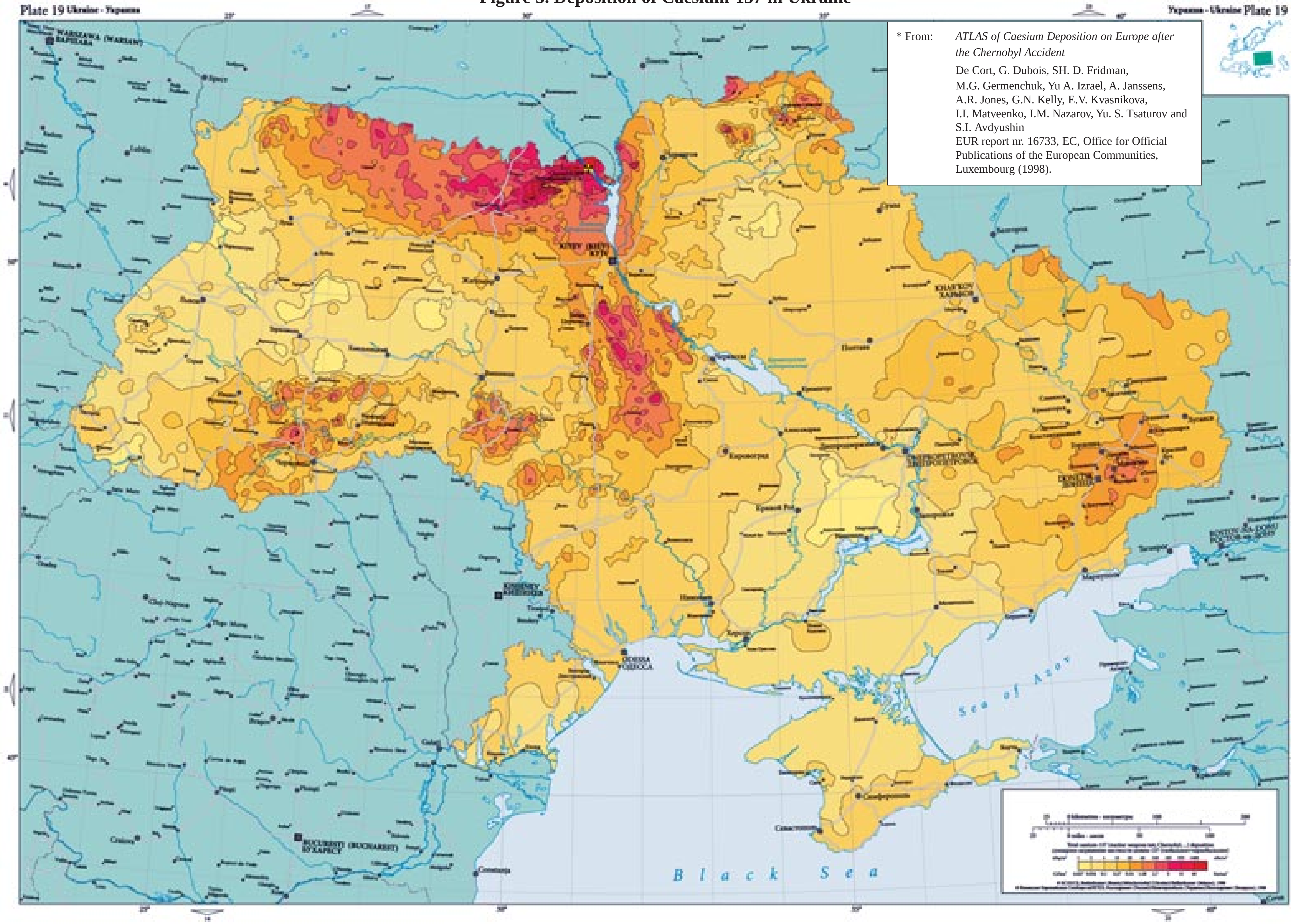
Yu. S. Tsaturov and S.I. Avdyushin
EUR report nr. 16733, EC, Office for Official
Publications of the European Communities,
Luxembourg (1998).

Figure 5. Deposition of Caesium-137 in Ukraine*



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The principal physico-chemical form of the deposited radionuclides are: 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 differs 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 disperded in the far zone.

Deposition of ^{90}Sr was mostly in the near zone of the accident as for ^{239}Pu; the only area with plutonium exceeding 4 kBq m^{-2} was located within the 30-km zone, in the Gomel-Mogilev-Briansk area. (De98)

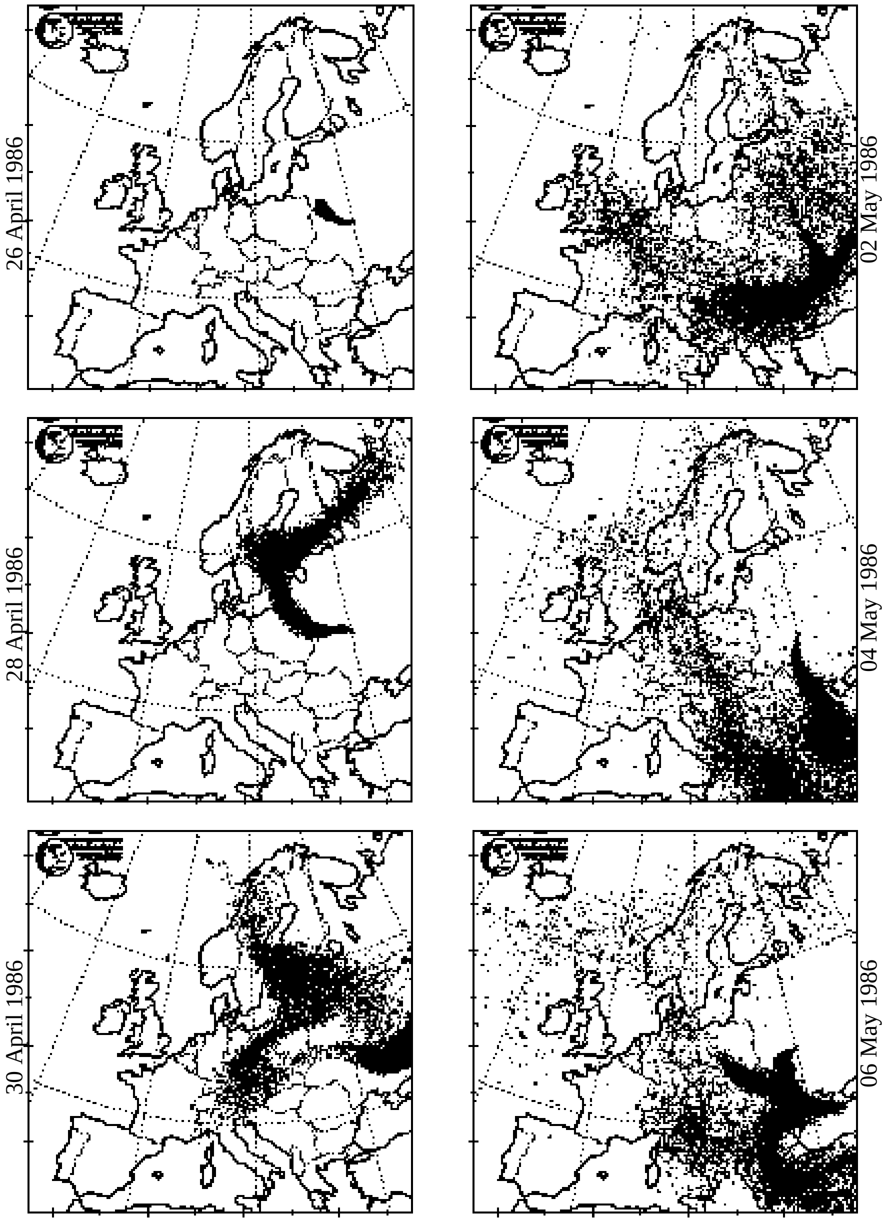
Outside the former Soviet Union

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 programmes.

The radioactive plume was tracked as it moved over the European part of the Soviet Union and Europe (Figure 6). 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.

Most countries in Europe experienced some deposition of radionuclides, mainly ^{137}Cs and ^{134}Cs, 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 (exceeding 37 kBq m^{-2}, with an extensive deposition in a 2-4 km^{2} area in Sweden within the commune of Gävle (exceeding 185 kBq m^{-2}) (Ed91) than that experienced by most other countries, whereas Spain, France and Portugal experienced the least deposition. For example, the estimated average depositions of ^{137}Cs in the provinces of Upper Austria, Salzburg and Carinthia in Austria were 59, 46 and 33 kBq/m^{2}

Figure 6. **Areas covered by the main body of the radioactive cloud on various days during the release**



Credit: ARAC

respectively, whereas the average ^{137}Cs deposition in Portugal was 0.02 kBq/m^2 (Un88). It was reported that considerable secondary contamination occurred due to resuspension of material from contaminated forest. This was not confirmed by later studies.

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 by the surveillance networks of environmental radiation (Un88).

Behaviour of deposited radionuclides

The environmental behaviour 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 particles generated by mechanical processes like explosion of fuel.

For short-lived radionuclides, such as iodine isotopes, the main pathway of exposure of humans is the transfer of the amount deposited on leafy vegetables that are consumed within a few days, or on pasture grass that is grazed on by cows or goats, giving rise to the contamination of milk. Long term behaviour is not relevant, because ^{131}I has a physical half-life of only 8 days.

Radionuclides deposited on soil migrate downwards and reach the part of soil containing roots, and the time of residence in this area would partly determinate migration to vegetation. Observations strongly suggest that the migration profiles are established very early after contamination under the influence of the early conditions prevailing immediately after contamination, such as soil moisture and first rain events, which may be the paramount in determining the extent to which radionuclides will penetrate in depth (Br00). The vertical migration of ^{137}Cs and ^{90}Sr in soil of different type of meadows has been rather slow, and the greater fraction of radionuclides is still contained in the upper soil layers (0-10 cm). The effective half-time of clearance from root layer has been estimated to range from 10 to 25 years for ^{137}Cs. Early after the accident the transfer coefficients of ^{137}Cs to plant decreased by 1.5 to 7 times but later from the observed persisting mobility of radiocaesium, and particularly the increase in effective ecological half lives tending towards the physical decay rate of ^{137}Cs, it now seems that the sorption-desorption process of radiocaesium in soils and sediments is tending towards a reversible steady-state and the practical consequences for plant contamination in the environment is that foodstuffs will remain contaminated for much longer than initially expected (Sm00).

The contribution of aquatic pathways to the dietary intake of ^{137}Cs and ^{90}Sr is usually quite small, However the relative importance, in comparison to terrestrial pathways, may be high in some lakes of Scandinavia and in Russia. In mountains we can observe by run-off some reconcentrations of the radioactivity in lower areas and for example in the South part of the French alps the ^{137}Cs contamination was in 1992 about 20 000 Bq.m^{-3}, corresponding to an activity of 1 760 Bq.kg^{-1} in soil samples. In some specific, small areas, (only a fraction of a square meter) hot spots have been measured at 55 800 Bq.kg^{-1} in 1992, 314 000 Bq.kg^{-1} in 1995, and500 000 Bq.m^{-2} in 2000. These hot spots are the consequences of the runoff of melting water coming from snow which fell after the 1986 contamination of the upper part of the mountain. These hot spots have been found in small basins lower in the forest or under larchs where snow accumulates. However these hot spots being of small surface (cm^2 to m^2) are offwalking tracks, pose little risk of irradiation for hikers. For example, it has been estimated that a hiker would receive about 0.001 mSv during a 4 hour rest in the vicinity of such a hot-spot. (Ma 97). These hot-spots will remain active for several decades, their decay following the physical half-life of ^{137}Cs.

Drinking water in the affected areas is weakly contaminated, less than 1Bq of ^{137}Cs or ^{90}Sr per litre. The mean annual activity of ^{137}Cs in the water of Pripiat river and in the Kiev reservoirs has now stabilised within a range of from 1 to 0.2 Bq.l^{-1} (Bq per litre), ten time higher than the values obtained before the 1986 accident. The ^{90}Sr activity of the Pripiat river is sometimes higher than authorised levels for drinking water (2 Bq.l^{-1}) due to meteorological conditions, rains and floods.

From 26 April to 6 March 1986, during the period of releases, the highest levels of radioactivity measured in water of the Pripiat river was of the order of 100 000 Bq/l, principally from ^{131}I. The activity in the Pripiat declined to around a few thousand Bq/l by mid-May 1986, and to 200 Bq/l in June 1986. From the end of November 1986 to the beginning of 1987, the activity in the Pripiat was rarely measured above 40 Bq/l. From 1987 on, ^{137}Cs and ^{90}Sr were the only radionuclides measured in significant quantities. Since 1988, ^{90}Sr is the radioelement of highest concentration in the waters of the Pripiat.

The chemical form of the ^{137}Cs that was deposited is fairly insoluable, and is not quickly extracted from soil by surface runoff water. Most of the ^{137}Cs transferred to the Pripiat river by runoff water came from the 30 km exclusion zone. As a result of this low solubility, only 1 to 5% of the initial ^{137}Cs activity reached the Black Sea, the rest accumulating in various reservoirs of the Dniepr, of which more than half stayed in the Kiev reservoir.

The activity of ^{90}Sr in Pripiat river water is a few times higher than the level authorised for human consumption, 2 Bq/l. During flooding in the fall of 1988, ^{90}Sr activity reached 9.6 Bq/l. As a result of significant blockage of water during particularly high flooding, ^{90}Sr concentrations reached 12.2 Bq/l in January 1991, and 5.9 Bq/l in February 1994.

In 1986, during the accident and the following months, the ^{137}Cs activity released into the Dniepr was estimated to be 66 TBq. Subsequently, leaching from soils by surface water and floods resulted in a measurable increase of radionuclide concentrations in the Pripiat river. The following Table 3 indicates the respective influxes of ^{137}Cs and ^{90}Sr in the Pripiat between 1986 and 1998, as well as the resulting water concentrations.

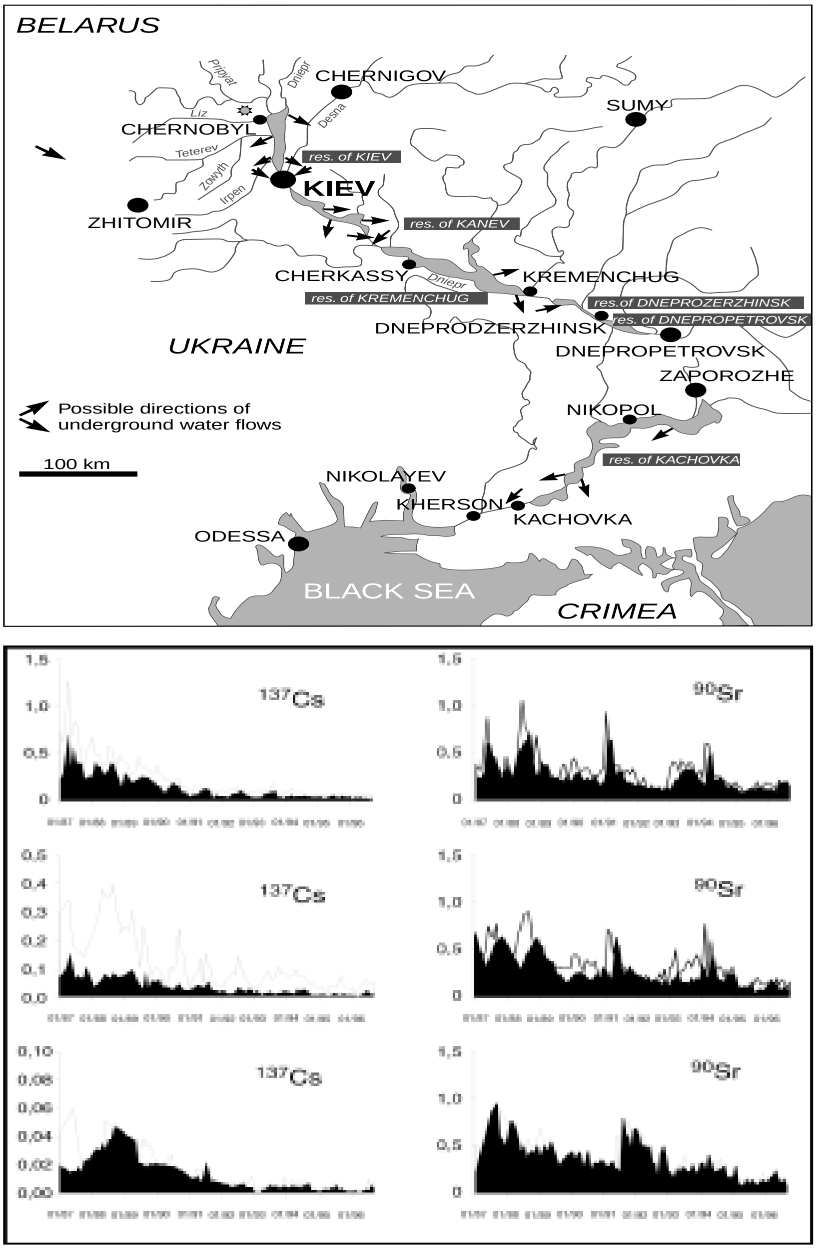
The cities of Kiev, Kremenchug et Kahovsk are partly fed by Dniepr reservoirs (see Figure 7). The table shows the annual average levels of ^{137}Cs and ^{90}Sr in the Pripiat river from 1986 to 1998 (Po01), but it could be observed peaks of activity ten time higher during floods.

Graphs in the Figure 7 show the evolution of ^{137}Cs and ^{90}Sr concentrations in these reservoirs from 1986 to 1998.

It has been shown that forests can deliver large radiation doses through the consumption of berries, mushrooms and game, but also through the industrial use of forest products. Radiological consequences result from energy production using radioactively contaminated biofuels from forests in the north of Europe and use of waste products or ashes and their recycling back to the forest as fertilizer.

On the forest podzolic soils, migration of ^{137}Cs is pronounced, with increased amounts in the mineral layers ten years after aerial distribution. More than a decade after Chernobyl accident, the total inventory is still rising in pine trees of boreal forests. There is almost no ^{137}Cs loss via runoff water from boreal forest ecosystems except from the wetter portions of bogs.

Figure 7. **Possible groundwater flow directions in the Dniepr basin**
^{137}Cs and ^{90}Sr concentrations in Bq/L-1, in the reservoirs of Kiev, Kremenchug and Kahkovka. Black area reresent activities entering in the reservoirs, white areas activities leaving reservoirs (From Po01)



Credit: “Catastrophes et accidents nucléaires dans l’ex-union soviétique”, D. Robeau.

Table 3. **Evolution of average radioactivity in the Pripiat river since the accident in 1986 (From Poïkarpov and Robeau, 2001)**

	Influx of ^{137}Cs (TBq/a)	Average spectrum activity of ^{137}Cs in the Pripiat river (Bq/l)	Influx of ^{90}Sr (TBq/a)	Average spectrum activity of ^{90}Sr in the Pripiat river (Bq/l)
1986	66,2	6,95	27,6	2,9
1987	12,8	1,65	10,4	1,34
1988	9,48	0,73	18,7	1,44
1989	6,44	0,521	8,97	0,725
1990	4,63	0,359	10,1	0.783
1991	2,9	0,208	14,4	1,033
1992	1,92	0,206	4,14	0,445
1993	3,48	0,208	14,2	0,838
1994	2,96	0,197	14,2	0,946
1995	1,15	0,11	3,4	0,326
1996	1,3	0,129	3,42	0,340
1997	1,7	0,158	2,68	0,25
1998	2,95	0,137	6,37	0,296

More than 16 years after the accident, only 2 to 3% of the deposited radioactivity still remains in the aerial part of the vegetation.

Since the accident, wood marketing has become regulated. Depending upon the intended use of harvested wood regulatory levels vary from 740 to 11 000 Bq $^{137}Cs\ kg^{-1}$, which result in 30% of the Pine trees in the exclusion zone not being harvestable.

At this stage in time, the transfer of material by resuspension from more to less contaminated areas is not significant. The classical farming practices, mechanical treatment such as ploughing and mulching and the use of fertilisers are efficient countermeasures.

However, one year after the accident a storm resuspended deposited radioactivity in the exclusion zone, and the radioactivity of air in the Pripiat city increased by a factor of 1 000 and reached 300 $Bq.m^{-3}$. Fires in forests have also led to increases of radioactivity. In 1992, in the vicinity of exclusion zone, radioactivity due to forest fires reached 20 $Bq.m^{-3}$ for beta emitters and 70 $mBq.m^{-3}$ from plutonium isotopes. Monitoring stations far from these zones registered some peaks of radioactivity.

In summary

It can be stated that there is now a fairly accurate estimate of the total radioactivity release, and the last years have strengthened previous evaluations. 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 changes in 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. The environmental behaviour of deposited radionuclides is increasingly well known. More than sixteen years after the accident, radionuclides are still in the first layers of soils, maintaining a transfer to plants, particularly mushrooms, berries and forest products. Moreover the change of speciation of ^{137}Cs in some soils has led to the fact that foodstuffs will remain contaminated for much longer than initially expected (Sm00). With the exception of some water tables, the contamination of environment is very well known. Contamination levels in soils decrease only slowly, mostly by transfer to plants. Most of the decrease in the coming years will be at only the rate of the physical half-life of ^{137}Cs.

Chapter III

REACTIONS OF NATIONAL AUTHORITIES

The scale and severity of the Chernobyl accident with its widespread radioactive contamination had not been foreseen and took by surprise most national authorities responsible for emergency preparedness. No provisions had been made for an accident of such scale and, though some radiation protection authorities had made criteria available for intervention in an accident, these were often incomplete and provided little practical help in the circumstances, so that very few workable national guidelines or principles were actually in place. Those responsible for making national decisions were suddenly faced with an accident for which there were no precedents upon which to base their decisions. In addition, early in the course of the accident there was little information available, and considerable political pressure, partially based on the public perception of the radiation danger, was being exerted on the decision makers. In these circumstances, cautious immediate action was felt necessary, and measures were introduced that tended to err, sometimes excessively so, on the side of prudence rather than being driven by informed scientific and expert judgement.

Within the former Soviet Union

The town of Pripyat was not severely contaminated by the initial release of radionuclides, but, once the graphite fire started, it soon became obvious that contamination would make the town uninhabitable. Late on 26 April it was decided to evacuate the town, and arrangements for transport and accommodation of the evacuees were made. The announcement of evacuation was made at 11:00 hr the following day. Evacuation began at 14:00 hr, and Pripyat was evacuated in about two and one half hours. As measurements disclosed the extensive pattern of deposition of radionuclides, and it was possible to make dose assessments, the remainder of the people in a 30-km zone around the reactor complex were gradually evacuated, bringing the total evacuees to about 135 000.

Other countermeasures to reduce dose were widely adopted (Ko90). Decontamination procedures performed by military personnel included 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. Streets were watered in towns to suppress dust. However, the effectiveness of these countermeasures outside the 30-km zone was small. An attempt to reduce thyroid doses by the administration of stable iodine to block radioactive uptake by the thyroid was made (Me92), but its success was doubtful.

The Soviet National Committee on Radiation Protection (NCRP) proposed a 350-mSv lifetime dose intervention level for the relocation of population groups (Il87). 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 strongly criticised as being a very high level. The situation was further complicated by the political and social tension in the Soviet Union at that time. As a result, the NCRP proposal was not adopted by the Supreme Soviet. Later, a special Commission was established which developed new recommendations for intervention levels. These recommendations were based on the levels of ground contamination by the radionuclides ^{137}Cs, ^{90}Sr and ^{239}Pu. As has been mentioned above, large areas were contaminated mainly by ^{137}Cs and a ground contamination level by this radionuclide of 1 480 kBq/m^2 was used as the intervention criterion for permanent resettlement of population, and of 555 to 1 480 kBq/m^2 for temporary relocation.

People who continued to live in the heavily contaminated areas were given compensation and offered annual medical examinations by the government. Residents of less contaminated areas are provided with medical monitoring. Current decisions on medical actions are based on annual doses. Compensation is provided for residents whose annual dose is greater than 1mSv. The use of locally produced milk and mushrooms is restricted in some of these areas. Relocation is considered in Russia for annual doses above 5 mSv.

As is mentioned in the section on health impacts effects, in Chapter V, the Soviet authorities did not foresee that their attempts to compensate those affected by the accident would be misinterpreted by the recipients and increase their stress, and that the label of “radiophobia” attributed to these phenomena was not only incorrect, but was one that alienated the public even more. Some of these initial approaches have been recognised as being inappropriate and the authorities are endeavouring to rectify their attitude to the exposed population.

Outside the former Soviet Union

The progressive spread of contamination at large distances from the accident site has caused considerable concern in Member countries, and the reactions of national authorities to this situation have been extremely varied, ranging from a simple intensification of the normal environmental monitoring programmes, without adoption of any specific countermeasures, to compulsory restrictions concerning the marketing and consumption of foodstuffs. This variety of responses has been accompanied by significant differences in the timing and duration of the countermeasures.

In general, the most widespread countermeasures were those which were not expected to impose, in the short time for which they were in effect, a significant burden on lifestyles or the economy. These included advice to wash fresh vegetables and fruit before consumption, advice not to use rainwater for drinking or cooking, and programmes of monitoring citizens returning from potentially contaminated areas. In reality, experience has shown that even these types of measures had, in some cases, a negative impact which was not insignificant.

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 the outdoor grazing of dairy cattle. In some areas, prohibitions were placed on travel to areas affected by the accident and on the import of foodstuffs from the Soviet Union and Eastern European countries. In most Member countries, restrictions were imposed on the import of foodstuffs from Member as well as non-member countries.

The range of these reactions can be explained primarily by the diversity of local situations both in terms of uneven levels of contamination and in terms of national differences in administrative, regulatory and public health systems. However, one of the principal reasons for the variety of situations observed in 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, in determining the countermeasures.

This situation caused concern and confusion among the public, perplexities among the experts and difficulties to national authorities, especially in maintaining their public credibility. This was, therefore, identified as an area where several lessons should be learned from the accident and efforts directed towards better international harmonisation of the scientific bases and co-ordination of concepts and measures for the protection of the public in case of emergency.

Nowhere was this problem better illustrated than by the way that contaminated food was handled. In some countries outside the Soviet Union the main source of exposure to the general population was the consumption of contaminated food. Mechanisms to handle locally produced as well as imported contaminated food had to be put in place within a few weeks of the accident. National authorities 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 added to the difficulties of the decision makers.

Some countries without nuclear power programmes and whose own food was not contaminated, argued that they did not need to import any “tainted” food and refused any food containing any radionuclides whatsoever. This extreme and impracticable measure might well have been regarded as an example of how well the authorities of those countries were protecting the health of their population. Sometimes this attitude appeared to promote a neighbourly rivalry between countries to see which could set the more stringent standards for food contamination, as though, by so doing, their own citizens were more protected. The result was that often slightly contaminated food was destroyed or refused importation to avoid only trivial doses.

In 1986, the EC imposed a ban on the importation of food containing more than 370 Bq/kg of radiocaesium for milk products and 600 Bq/kg for any other food, regardless of the quantity consumed in the average European diet. Thus, food items with a trivial consumption (and dose), such as spices, were treated the same as items of high consumption such as vegetables. However, these values were later relaxed for some food items in order to remove inconsistent treatment of food groups.

In some special circumstances, decisions had to be made based on the local situation. For example, in some Northern European communities, reindeer meat is a major component of the diet; due to the ecological circumstances, these animals tend to concentrate radiocaesium, which will then expose the populations which depend on them. Special countermeasures, such as pasturing reindeer in areas of lower contamination, were introduced in some countries to avoid this exposure.

The variety of solutions led to confusion and 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 any agreement was reached on guideline values for the radioactivity of food moving in international trade (Table 4).

Table 4. **Codex Alimentarius Guideline values for food moving in international trade (FA91)**

Foods for general consumption	
Radionuclide	Level (Bq/kg)
^{241}Am, ^{239}Pu	10
^{90}Sr	100
^{131}I, ^{134}Cs, ^{137}Cs	1 000
Infant foods and milk	
^{241}Am, ^{239}Pu	1
^{131}I, ^{90}Sr	100
^{134}Cs, ^{137}Cs	1 000

It should be remembered that these guideline values were developed to facilitate international trade in food, and should be regarded as levels "below which no restrictions to trade need be implemented for radiological reasons". Levels above these do not necessarily constitute a health hazard, and if found, the competent national authority should review what action should be taken.

Often the national authorities were not able accurately to predict the public response to some of their advice and pronouncements. For example, in some European countries, soon after the accident the public were advised to wash leafy vegetables. The national authority felt that this was innocuous advice as most people washed their vegetables anyway, and they were unprepared for the public response which was to stop buying these vegetables. This resulted in significant economic loss 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, and the national authority came under criticism from the media (Sj87). Outside the Soviet Union, the initial confusion led to inconsistent and precipitate actions which, although understandable, were sometimes ill-advised and unjustified.

However, it should be emphasised that great progress has been made since this early confusion. As a result of the actions of the international organisations to harmonise intervention criteria and the willingness of countries to cooperate in this endeavour, a firm groundwork for uniform criteria based on accepted radiation protection principles has been established, so that relative consistency can hopefully be expected in their implementation in the event of a possible future nuclear accident.

More recent decisions

Today, territories where populations receive a dose lower than 1 mSv per year are declared as zones permitting normal life. For areas higher than 1 mSv/year authorities continue to give social compensations, depending on the dose. Areas where annual dose is higher than 20 mSv per year are exclusion zones. With the new estimation of doses, some settlements in Russia have lost their status as contaminated area by a decree (N° 5924, 18 December 1997) which came into operation the 1 February 1998. This decision was badly received by local populations and local authorities.

The opposite is also true, as of the 1st of January 1999, 8 397 people were still living in areas where evacuation is an obligation (contamination higher than 30 Ci.km^{-2}).

The relocation of evacuees has not been completely resolved, as of 2000, more than 11 000 evacuees are still living in temporary provisory settlements.

Limits on trade exchange of agricultural productions were the same for the three republics up to 1997. They were lowered a first time in 1987, a second time in 1991 in the three republics, but in Ukraine these limits were lowered a fourth time on 25 June 1997 and now apply to four main products: 100 Bq per litre for milk (instead of 370 Bq/l in 1991); 200 Bq/kg for meat (instead 740 in 1991); 20 Bq/kg for bread and potatoes (instead of, respectively, 370 and 600 since 1991). In Russia, with the exception of Briansk, and Kalouga areas (jizdra, Khvastovitchi and Oulianovskii), a new regulation was adopted the first of

March 1998 (SanPiN 2.3.2.560-96) for agricultural products and for milk the limit is now 50 Bq.kg^{-1} of ^{137}Cs (Bo99) (Table 5).

Table 5. **Evolution of limits for trade exchange since 1986 in Russia, Bielorussia and Ukraine, the italics values for 1997 are only for Ukraine**

	06 May 86	**30 may 86**	**87**	**88**	**91**	**93**	**97 (Ukraine)**	**98 (Russia)**
Milk	3700	370	370	370	370	370	100	50
Meat		3 700	1 850	1 850	740	740	200	
Bread		370	370	370	370	370	20	
Potatoes		3 700	740	740	600	600	20	

In Russia, more than ten years after the accident, several programmes have been agreed upon to compensate for the delays in the implemantation of previous plans. A national centre of ecological medicine has been created in St.-Petersburg for health assistance to the liquidators. It can provide up to 1 500 sick people per year with high quality medical treatment. This centres was expanded to other national hospitals in the Russian federation. Ten expert councils have been created to establish a potential links between diseases and the Chernobyl accident. Four socio-psychological readaptation centres have been created in the Bryansk, Orel and Toula areas in Russia. These centers have been charged with delivering justice, social and psychological assistance to all those affected by the accident. Lastly a dosimetry register has been created, in 1999, in which more than 500 000 people have been registered (including 170 000 liquidators).

Several significant programmes were launched during 1998-2000, to take in account the huge delay of all national programmes, Including a National programme for the protection of the public, a Programme for Chernobyl children, and a Programme for settlements for liquidators (Bo99).

Lastly the Russian authorities are aware that some aspects of current federal law must be changed to eliminate significant obstacles to ending certain programmes that no longer contribute to the elimination of the consequences of the accident.

In summary

The Chernobyl accident took authorities by surprise as regards to its extent, duration and far reaching contamination. As there were no guidelines for such an accident, little information was available and great political and public pressure to do something were experienced, overprecautious decisions were often taken in and outside the Soviet Union. The social and psychological impact of some official decisions on the public were not expacted, and variable interpretations or even misinterpretations of ICRP recommendations, especially for intervention levels for food, led to inconsistent decisions and advice. These added to public confusion and provoked mistrust and unnecessary economic losses. However, there were exceptions, and very soon international efforts began to harmonise criteria and approaches to emergency management.

More than 16 years later the confusion still exist in spite of significant international efforts of harmonization. For example, in 1997 the Ukrain unilaterally lowered its radiological restrictions on trade, below the levels previously harmonised for Russia, Belarus and the Ukraine, reinforces this confusion. Lastly, the Russian federation has realised the need to change some apects of its former law, which has become an obstacle to appropriately addressing accident consequences.

Chapter IV

DOSE ESTIMATES*

The exposure of the population as a result of the accident resulted in two main pathways of exposure. The first is the radiation dose to the thyroid as a result of the concentration of radioiodine and similar radionuclides in the gland. The second is the whole-body dose caused largely by external irradiation mainly from radiocesium.

The absorbed dose to the whole body is thought to be about 20 times more deleterious, in terms of late health effects incidence, than the same dose to the thyroid (IC90).

The population exposed to radiation following the Chernobyl accident can be divided into four categories: (1) the staff of the nuclear power plant and workers who participated in clean-up operations (referred to as "liquidators"); (2) the nearby residents who were evacuated from the 30-km zone during the first two weeks after the accident; (3) the population of the former Soviet Union, including especially the residents of contaminated areas; and (4) the population in countries outside the former Soviet Union.

A number of liquidators, estimated at up to 600 000 (civilian and military according to laws promulgated in Belarus, the Russian Federation and Ukraine) took part in mitigation activities at the reactor and within the 30-km zone surrounding the reactor. The most exposed workers were the firemen and the power plant personnel during the first days of the accident. Most of the dose received by the workers resulted from external irradiation from the fuel fragments and radioactive particles deposited on various surfaces. Of particular interest are the 226 000 recovery operation workers who were employed in the 30-km zone in 1986-1987, as it is in this period that the highest doses were

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* Special thanks to Dr. André Bouville, of the US National Cancer Institute, for his verification of the facts in this Chapter.

received. The remainder of the recovery operation workers, who generally received lower doses, amounted to about 400 000 (UN00).

About 116 000 people were evacuated during the first days following the accident, mainly from the 30-km zone surrounding the reactor. Prior to evacuation, those individuals were exposed to external irradiation from radioactive materials transported by the cloud and deposited on the ground, as well as to internal irradiation essentially due to the inhalation of radioactive materials in the cloud.

The relative contributions to the external whole-body dose from the main radionuclides of concern for that pathway of exposure and during the first few months after the accident are shown in Figure 8. It is clear that ^{132}Te played a major role in the first week after the accident, and that, after one month, the radiocaesiums (^{134}Cs and ^{137}Cs) became predominant. Subsequently, however, ^{134}Cs decayed to levels much lower than those of ^{137}Cs, which became after a few years the only radionuclide of importance for practical purposes. It is usual to refer to ^{137}Cs only, even when the mix of ^{134}Cs and ^{137}Cs is meant, because the values for the constituents can be easily derived from those for ^{137}Cs.

With regard to internal doses from inhalation and ingestion of radionuclides, the situation is similar: radioiodine (^{131}I) was important during the first few weeks after the accident and gave rise to thyroid doses via inhalation of contaminated air, and, more importantly, via consumption of contaminated foodstuffs, mainly cow’s milk. After about one month, the radiocaesiums (^{134}Cs and ^{137}Cs) again became predominant, and, after a few years, ^{137}Cs became the only radionuclide of importance for practical purposes, even though ^{90}Sr may in the future play a significant role at short distances from the reactor.

Among the population of the former Soviet Union, it is usual to single out the residents of the contaminated areas, defined as those with ^{137}Cs deposition levels greater than 37 kBq/m^2. About 5 million people live in such areas. Of special interest are the inhabitants of the spots with ^{137}Cs deposition levels greater than 555 kBq/m^2. In those areas, called “strict control zones”, protection measures are applied, especially as far as control of consumption of contaminated food is concerned. In 1998, 42 554 measurements were performed in the Federal Republic of Russia, and the national authorities are planning to maintain such controls beyond 2000 (Bo99). In 1986, shortly after the accident, the All-Union Dose Registry (AUDR) was set up by the Soviet Government to record medical and dosimetric data on the population groups expected to be the most exposed: (1) the liquidators, (2) the evacuees from the 30-km zone, (3) the inhabitants of the contaminated areas, and (4) the children of those people. In

1991, the AUDR contained data on 659 292 persons. Starting from 1992, national registries in Belarus, Russian Federation, and Ukraine replaced the AUDR.

Outside the former Soviet Union, the radionuclides of importance are, again, the radioiodines and radiocaesiums, which, once deposited on the ground, give rise to doses from ingestion through the consumption of foodstuffs. Deposited radiocaesium is also a source of long-term exposure from external irradiation from the contaminated ground and other surfaces. Most of the population of the Northern hemisphere was exposed, in varying degrees, to radiation from the Chernobyl accident. The ^{137}Cs deposition outside the former Soviet Union ranged from negligible levels to about 50 kBq/m^2.

The liquidators

Most of the liquidators can be divided into two groups: (1) the people who were working at the Chernobyl power station at the time of the accident viz. the staff of the station and the firemen and people who went to the aid of the victims. They number a few hundred persons; and (2) the workers, estimated to amount up to 600 000, who were active in 1986-1990 at the power station or in the zone surrounding it for the decontamination, sarcophagus construction and other recovery operations.

On the night of 26 April 1986, about 400 workers were on the site of the Chernobyl power plant. As a consequence of the accident, they were subjected to the combined effect of radiation from several sources: (1) external gamma/beta radiation from the radioactive cloud, the fragments of the damaged reactor core scattered over the site and the radioactive particles deposited on the skin, and (2) inhalation of radioactive particles (UN88).

All of the dosimeters worn by the workers were over-exposed and did not allow an estimate of the doses received. However, information is available on the doses received by the 237 persons who were placed in hospitals and diagnosed as suffering from acute radiation syndrome. Using biological dosimetry, it was estimated that 41 of these patients received whole-body doses from external irradiation in the range 1-2 Sv, that 50 received doses between 2 and 4 Sv, that 22 received between 4 and 6 Sv, and that the remaining 21 received doses between 6 and 16 Sv. In addition, it was estimated from thyroid measurements that the thyroid dose from inhalation would range up to about 20 Gy, with 173 individuals in the 0-1.2 Gy range and seven workers with thyroid doses greater than 11 Gy (UN88). Internal exposure of those workers was mainly due to ^{131}I and shorter-lived radioiodines, the median value of the ratio of the internal thyroid dose to the external effective dose was estimated to be 0.3 Gy per Sv. The doses resulting from intakes of other radionuclides was estimated to about 30 mSv for the early months following the accident and 85 mSv for committed dose (UN00).

The second category of liquidators consists of the large number of adults who were recruited to assist in the clean-up operations. They worked at the site, in towns, forests and agricultural areas to make them fit to work and live in. About 600 000 of individuals participated in this work. Initially, about 240 000 of those workers came from the Soviet armed forces, the other half including personnel of civil organisations, the security service, the Ministry of Internal Affairs, and other organisations. The total number of liquidators has yet to be determined accurately, since only some of the data from some of those organisations have been collected so far in the national registries of Belarus, Russia, Ukraine and other republics of the former Soviet Union (So95). Also, it has been suggested that, because of the social and economic advantages associated with being designated a liquidator, many persons have contrived latterly to have their names added to the list. To day the total number of recovery operation workers recorded in the registries appears to be about 400 000 well below the figure of 600 000, which corresponds to the number of people who have received special certificates confirming their status as liquidators. The workers were all adults, mostly males aged 20-45 years.

There are only fragmented data on the doses received by these liquidators. Attempts to establish a dosimetric service were inadequate until the middle of June of 1986, until then, doses were estimated from area radiation measurements. The doses to the recovery operation workers who participated in mitigation activities within two months after the accident are not known with much certainty. The liquidators were initially subjected to a radiation dose limit for one year of 250 mSv. In 1987 this limit was reduced to 100 mSv and in 1988 to 50 mSv (Ba93). The registry data show that the average recorded doses in the three national registries decreased from year to year, being about 170 mSv in 1986, 130 mSv in 1987, 30 mSv in 1988 and 15 mSv in 1989 (Se95a). It is, however, difficult to assess the validity of the results as they have been reported since these statistics indicates that the dose is known for only 52% of workers for the period 1986-1989, with a lower percentage, 45% for the first year. Moreover uncertainties associated with dose estimations are assessed to be up to 50% for individual dosimetry, (if the dosimeter was correctly used), up to a factor 3 to 5 for group and time-and-motion dosimetry However, the doses do not seem to have been systematically overestimated, because biological dosimetry performed on limited number of workers produced results compatible with physical dose estimates.

It is interesting to note that a small special group of 672 scientists from the Kurchatov Institute who have worked periodically inside the sarcophagus for a number of years have initially estimated accumulated whole-body doses in the range 0.5 to 13 Gy (Se95a). These dose estimates had been reestimated. Recorded and calculated doses available for 501 workers show that more than 20% of them received doses between 0.05 and 0.25 Sv and about 5% of them received doses between 0.25 and 1.5 Sv (Sh97) Additional analysis by mean of FISH technique for three of them resulted in doses 0.9, 2.0 and 2.7 Sv (Sh00) While no deterministic effects have been noted to date, this group may well show radiation health effects in the future.

More than sixteen years after the accident, comparisons between the different techniques of dosimetry confirm the effectiveness of the chromosome aberration technique, but indicate that some new methods recommended by some scientists, such as fluorescent *in situ* hybridisation (FISH), do not appear to be a sufficiently sensitive or specific to allow the estimation of doses for the majority of recovery operation workers (Li98).

The evacuees from the 30-km zone

Immediately after the accident monitoring of the environment was started by gamma dose rate measurements. About 20 hours after the accident the wind turned in the direction of Pripyat, gamma dose rates increased significantly in the town, and it was decided to evacuate the inhabitants. About 20 hours later the 49 000 inhabitants of Pripyat had left the town in nearly 1 200 buses. About a further 67 000 people were evacuated in the following days and weeks (in fact, until September) from the contaminated areas (a number of 86 000 people given in the NEA’s 1996 report (NE95b) was not substantiated).

Information relevant for the assessment of the doses received by these people have been obtained by 30 000 responses of the evacuees to questionnaires about the location where they stayed, the types of houses in which they lived, the consumption of stable iodine, and other activities (Li94). The average effective dose from external irradiation was estimated to be 17 mSv, with individual values varying from 0.1 to 380 mSv (Li94). This value is concordant with the absorbed dose of 20 mGy estimated by Electron Spin resonance (ESR) measurements of sugar and exposure rate calculations (Na94).

The main source of uncertainty in the estimation of the average effective doses from external irradiation is the assessment of the activity ratios of ^{132}Te and ^{131}I to ^{137}Cs in the deposition.

Doses to the thyroid gland

The iodine activity in thyroid glands of evacuees was measured. More than about 5 000 measurements of former inhabitants of Pripyat had sufficient quality to be useful for dose reconstruction (Go95a). A comparative analysis with the questionnaire responses of 10 000 evacuees showed that thyroid doses were mainly due to inhalation of ^{131}I. Average individual doses and collective doses to the thyroid are shown in Table 6 for three age groups. Individual doses in the age classes were distributed over two orders of magnitude. The main factor influencing the individual doses was found to be the distance of the residence from the reactor.

Table 6. **Average doses to the thyroid gland and collective thyroid doses to the evacuees from Pripyat (Go95a)**

Year of birth	Number of people	Average individual dose (Gy)	Collective dose (person-Gy)
1983-1986	2 400	1.4	3 300
1971-1982	8 100	0.3	2 400
≤1970	38 900	0.07	2 600

Assessments of the doses to the thyroid gland of the evacuees from the 30-km zone (Li93a) showed similar doses for young children as those for the Pripyat evacuees. Exposures to adults were higher. These high doses were due to a greater consumption of food contaminated with ^{131}I among those evacuated later from the 30-km zone.

Whole-body doses

The whole-body doses to the evacuees were mainly due to external exposure from deposited ^{132}Te/^{132}I, ^{134}Cs and ^{137}Cs and short lived radionuclides in the air. Measurements of the gamma dose rate in air were performed every hour at about thirty sites in Pripyat and daily at about eighty sites in the 30-km zone. Based on these measurements and using the responses to the questionnaires, whole-body doses were reconstructed for the 90 000 persons evacuated from the Ukrainian part of the 30-km zone (Li94). There was a wide range of estimated doses with an average value of 15 mSv. The collective dose was assessed to be 1 300 person-Sv. The 24 000 persons evacuated in Belarus might have received slightly higher doses, since the prevailing wind was initially towards the north.

The estimates of collective doses for the populations that were evacuated in 1986 from the contaminated areas of Belarus, Russia and Ukraine was about 3 800 man Sv for effective dose and 25 000 man Gy for thyroid doses (UN00). Most of the collective doses were received by the populations of Belarus and Ukraine.

Because the distributions of iodine tablets was done with a one-week delay and because only part of the population was covered, the averted collective thyroid dose from ingestion of contaminated milk was about 30% of the expected collective thyroid dose from that pathway while the thyroid doses from inhalation remained unchanged.

People living in the contaminated areas

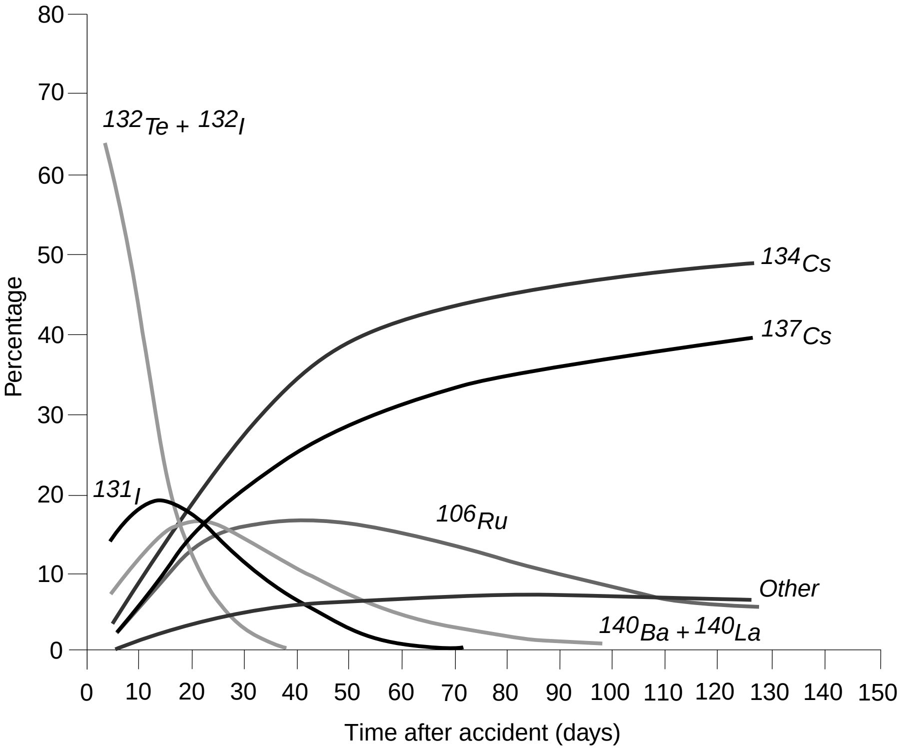
Areas contaminated by the Chernobyl accident have been defined with reference to the background level of ^{137}Cs deposition caused by the atmospheric weapons tests, which when corrected for radioactive decay to 1986, is about 2-4 kBq m^{-2}. considering variations about this level, it is usual to specify the level of 37 kBq m^{-2} as the area affected by the Chernobyl accident.

Approximately 3% of the European part of the former USSR was contaminated with ^{137}Cs deposition density greater than 37 kBq.m^{-2}. Many people continue to live in these contaminated territories, although efforts have been made to limit their doses, 4 400 000 inhabitants were living in areas with a ^{137}Cs contamination ranging from 37 to 185 kBq.m^{-2}, 580 000 in areas 185-555 kBq.m^{-2}. Areas of ^{137}Cs deposition density greater than 555 kBq km^{-2} were designated as areas of strict control. In these areas, preventive measures have been successfully maintained annual effective dose below 5 mSv. Because of extensive migration, the number of people living in these areas under strict control was about 193 000 people in 1995, down from 273 000 in 1986-1987.

In the first few months, because of the significant release of the short-term ^{131}I, the thyroid was the most exposed organ, the main route of exposure was cow-milk pathway. During the first year after the accident, doses from external irradiation arose from ground deposition of radionuclides with half-lives of one year or less only in areas close to the reactor, but the radiocesiums deposition was the greater contributors in more distant areas only one month after the accident. Over the following years, the doses received by the populations living in contaminated areas have come essentially from external exposure due to ^{134}Cs and ^{137}Cs deposited on the soil and internal exposure due to contamination of foodstuffs by these two isotopes.

A very large number of measurements have been done in the three republics. The publications prepared for regulatory purposes, tend to over estimate the average doses that were received during the years 1986-1990.

Figure 8. **Contributions of radionuclides to the absorbed dose rate in air in a contaminated area of the Russian Federation during the first several months after the Chernobyl accident**



Credit: Sources and Effects of Ionising Radiation – United Nations Scientific Committee on the Effects of Atomic Radiation – UNSCEAR 2000 report to the General Assembly with Scientific Annexes – Volume II: Effects, United Nations.

Doses to the thyroid gland

The main information source for the dose reconstruction is the vast number of iodine activity measurements of thyroid glands. In Ukraine 150 000 measurements, in Belarus several hundreds of thousands of measurements and in the Russian Federation more than 60 000 measurements were performed in May/June 1986. Some of the measurements were performed with inadequate instrumentation and measurement conditions and are not useful for dose assessment purposes. Using these measurements, the thyroid dose for people who lived in areas where direct thyroid measurements were done within a few weeks after the accident are being reconstructed using available data on ^{131}I and ^{137}Cs deposition.

The influence of having taken stable iodine for prophylactic purposes has usually not been taken into account in the determination of thyroid doses (except for the evacuees from Pripyat, iodine prophylaxis was not effective in reducing the doses substantially as it was done too late).

The large variability of individual doses makes estimates of dose distributions difficult and current dose estimates are still subject to considerable uncertainties, especially in areas where only a few activity measurements in the thyroid were performed. Children in the Gomel oblast (region) in Belarus received the highest doses. The distribution of estimated individual doses in the thyroid of 0-7 years children is shown in Table 7.

Table 7. **Distribution of estimated individual doses in the thyroid of 0-7 years old children in Gomel and Mogilev contaminated districts**

	Gomel	**Mogilev**	**Total**
<0.05	784	256	1040
0.05-0.1	527	339	866
0.1-0.3	1762	586	2348
0.3-1	3573	476	4049
1-2	1983	119	2102
>2	5727	44	5771

For the total population of Belarus, the average dose to the thyroid is 0.9 to 1 Gy for 0-7-year-old children and 0.3 Gy for the total population giving collective doses of 34 000 and 134 000 man Gy respectively. (Il91) For the populations of the three republics, the collective thyroid doses are roughly estimated to 550 000, 200-300 000, 390 000 man Gy for Belarus, Russian Federation and Ukraine respectively (UN00). The average thyroid dose received by the populations of the three republics is estimated to be 7 mGy and exceeding 1 Gy for the most exposed children (UN00). In the eight most contaminated districts of Ukraine where thyroid measurements were performed, the collective dose to this age group was about 60 000 person-Sv and for the whole population about 200 000 person-Sv (Li93). In the Russian Federation the collective dose to the whole population was about 100 000 person-Sv (Zv93).

The thyroid doses are about two times greater in rural areas than in urban aeras.

An estimate of the dose distribution among children from Gomel oblast is shown in Table 8. For the whole Belarus the collective thyroid dose to children (0 to 14 years) at the time of the accident was assessed to be about 170 000 person-Gy (Ri94). To day the UNSCEAR report give an estimation of 34 000 man Gy to 0-7 year old children (UN00).

Table 8. **Distribution of thyroid doses to children (0-15 years) in the Gomel oblast of Belarus (from UN00)**

	<1 year	**1-7 years**	**8-15 years**
<0.05	134	650	1 058
0.05-0.1	58	469	884
0.1-0.3	224	1 538	2 998
0.3-1	587	2 986	4 729
1-2	318	1 665	1 563
>2	3 667	2 060	1 107

In some Russian villages average doses exceeded 1 Gy, and individual doses exceeded 10 Gy.

Limited information is available on *in utero* thyroid doses. In a study in 250 children, born between may 1986 and February 1987 in Belarus, thyroid doses were estimated to range up to 4.3 Gy, with 135 children exposed to less than 0.3 Gy, 95 children between 0.3 and 1 Gy, and 20 children with doses greater than 1.Gy (Ig99).

Evaluations of questionnaires on food consumption rates in the period May/June 1986 and measurements of food contamination showed ^{131}I in milk as the major source for the thyroid exposure of the population living in the contaminated areas. However, in individual cases the consumption of fresh vegetables contributed significantly to the exposure.

Whole-body doses

Two major pathways contributed to the whole-body doses of the population in contaminated areas, the exposure to external irradiation from deposited radionuclides (Iv95) and the incorporation into the body of radio-caesium in food.

The external exposure is directly related to the radionuclide activity per unit area and it is influenced by the gamma dose rates in air at the locations of occupancy. Forestry workers and other workers living in woodframe houses received the highest doses.

Most of the higher contaminated areas are rural and a large part of the diet is locally produced. Therefore, the uptake of caesium by the plants from the soil is a deciding factor in the internal exposure. These are regions with extraordinarily high transfer factors, as the Rovno region in Ukraine, where even moderate soil contamination led to high doses. In order of decreasing magnitude of transfer factors these regions are followed by regions with peaty soil, sandy podzol (acidic infertile forest soil), loamy podzol, and chernozem which is rich black soil.

In the first years after the accident the caesium uptake was dominated practically everywhere by the consumption of locally produced milk (Ho94). However, later mushrooms began to contribute significantly in many settlements to the caesium incorporation for two reasons. First, the milk contamination decreased with time, whereas the mushroom contamination remained relatively constant. Second, due to changes in the economic conditions in the three republics, people are collecting more mushrooms than they were in the first years after the accident.

The normalised lifetime doses for urban and rural populations of the three republics is now estimated to range from 42 to 88 μSv per kBqm^{-2} of ^{137}Cs, 60% being received during the first 10 years. These values are lower than the first estimates, because they are more realistic and take account of, for example, the vertical migration of cesium in soils. During the first 10 years after the accident, average effective doses in theses areas ranged from 5mSv in Russian urban areas to 11 mSv in the rural areas of Ukraine. The variability of dose distribution could be represented by a log-normal distribution with a geometric standard deviation of 1.54. The decontamination measures had a limited impact on members of population. It was expected that less than 15% of the dose could be averted for the general population, and only 35% for school children. The total averted collective dose attributable to decontamination procedures was estimated to 1 500 mSv for the first four years.

The distribution of the collective dose from external irradiation by region and dose interval are presented in Table 9 and 10.

Table 9. **Estimated collective effective dose to the populations of contaminated areas (1986-1995) excluding thyroid dose**

Region	**Population**	**Collective effective dose (man Gy)**		
		External	Internal	Total
Belarus	1 880 612	9 636	5 504	15 140
Russian Federation	1 983 000	8 450	4 990	13 440
Ukraine	1 296 000	6 100	7 860	13 960
Total	5 159 600	24 186	18 354	42 540

Table 10. **Distribution of estimated total effective doses received by the populations of contaminated areas (1986-1995) excluding thyroid dose**

	Number of persons		
Dose interval (mGy)	**Belarus**	**Russian Federation**	**Ukraine**
<1	133 053	155 301	–
1-5	1163 490	1 253 130	330 900
5-20	439 620	474 176	807 900
20-50	113 789	82 876	148 700
50-100	25 065	14 580	7 700
100-200	5 105	2 979	400
>200	790	333	–

Table 11 summarises an estimate of whole-body doses to people living in the higher contaminated areas. On average, external irradiation was by far the highest contributor to the total population exposure (Er94). However, the highest doses to individuals were produced by the consumption of food from areas with high transfers of radionuclides.

Table 11. **Distribution of external and total whole-body doses during 1986-89, to inhabitants of contaminated areas (^{137}Cs activity per unit area >555 kBq/m^2) (Ba94)**

Whole-body dose (mSv)	**External exposure**		**Total exposure**	
	No. of persons	**Collective dose (man.Sv)**	**No. of persons**	**Collective dose (man.Sv)**
5-20	132 000	1 700	88 000	1 200
20-50	111 000	3 500	132 000	4 200
50-100	24 000	1 600	44 000	3 000
100-150	2 800	330	6 900	820
150-200	530	88	1 500	250
>200	120	26	670	160
Total	**270 000**	**7 300**	**273 000**	**9 700**

The total collective effective dose received during the first 10 years after the accident by the approximately 5.2 million people living in the contaminated areas of Belarus, the Russian federation and Ukraine is estimated to be 24 200 man.Sv. This means, as ten years represents 60%, that the lifetime collective dose from external irradiation would be 40 300 man.Sv (UN00).

Internal doses were 5 500 man Sv for Belarus, 5 000 man.Sv for the Russian Federation an 7 900 man.Sv for Ukraine. As 10 years represents 90%, the lifetime total for the three republics would be 20 400 man.Sv, corresponding to an average individual lifetime effective dose of 3.9 mSv [UN00].

Total collective thyroid doses in Belarus, the Russian Federation, and the Ukrain, respectivly, were estimated to be 550 000 250 000 and 740 000 man Gy.

The total of about 60 700 man Sv for external and internal doses corresponds to an average individual lifetime effective dose of 12 mSv, excluding thyroid collective dose delivered during the first year. This is estimated to be 1 500 000 man Gy in total for the three countries.

Populations outside the former Soviet Union

Even though the releases of radioactive materials during the Chernobyl accident mainly affected the populations of Belarus, Russia and Ukraine, the released materials became 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. However, population doses were, in most places, 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. Generally speaking, however, and with a few notable exceptions, the doses decreased as a function of distance from the reactor (Ne87).

During the first few weeks after the accident, ^{131}I was the main contributor to the dose, via ingestion of milk (Ma91). 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 (UN88).

Later on, ^{134}Cs and ^{137}Cs were responsible for most of the dose, through external and internal irradiation (Ma89). The whole-body doses received during the first year following the accident generally ranged from 0.05 to 0.5 mGy in Europe, from 0.005 to 0.1 mGy in Asia, and of the order of 0.001 mGy in North America. The total whole-body doses expected to be accumulated during the lifetimes of the individuals are estimated to be a factor of 3 greater than the doses received during the first year (UN88).

In summary

A large number of people received substantial doses as a result of the Chernobyl accident:

- **Liquidators** – Hundreds of thousands of workers, estimated to amount up to 600 000, were involved in clean-up operations. The most exposed, with doses of several grays, were the workers involved immediately after the beginning of the accident and the scientists who have performed special tasks in the sarcophagus. The average doses to liquidators are reported to have ranged between 170 mSv in 1986 and 15 mSv in 1989.

- **Evacuees** – More than 100 000 persons were evacuated during the first few weeks following the accident. The evacuees were exposed to internal irradiation arising from inhalation of radioiodines, especially ^{131}I, and to external irradiation from radioactivity present in the cloud and deposited on the ground. Thyroid doses are estimated to have been, on average, about 1 Gy for small children under 3 years of age at the time of the accident, and about 70 mGy for adults. Whole-body doses received from external irradiation prior to evacuation from the Ukrainian part of the 30-km zone showed a large range of variation with an average value of 15 mGy.

- **People living in contaminated areas of the former Soviet Union** – About 270 000 people live in contaminated areas with ^{137}Cs deposition levels in excess of 555 kBq/m2. Thyroid doses, due mainly to the consumption of cow's milk contaminated with ^{131}I, 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 Gy and an average close to 1 Gy for children aged 0 to 7. Thanks to the control of foodstuffs in those areas, most of the radiation exposure has been due to external irradiation from the ^{137}Cs activity deposited on the ground; the whole-body doses for the 1986-1989 time period are estimated to range from 5 to 250 mGy with an average of 40 mGy. In areas without food control, there are places, such as the Rovno region of Ukraine, where the transfer of ^{137}Cs from soil to plant is very high, resulting in doses from internal exposure being greater than those from external exposure.

- **Populations outside the former Soviet Union** – The radioactive materials of a volatile nature (such as iodine and caesium) that were released during the accident spread throughout the entire northern hemisphere. The doses received by populations outside the former Soviet Union were relatively low, and showed large differences from one country to another depending mainly upon whether rainfall occurred during the passage of the radioactive cloud.

Chapter V

HEALTH IMPACT

As ionising radiation passes through the body, it interacts with the tissues transferring energy to cells and other constituents by ionisation of their atoms. This phenomenon has been extensively studied in the critical genetic material, DNA, which controls the functions of the cells. If the damage to DNA is slight and the rate of damage production is not rapid, i.e. at low dose rate, the cell may be able to repair most of the damage. If the damage is irreparable and severe enough to interfere with cellular function, the cell may die either immediately or after several divisions.

At low doses, cell death can be accommodated by the normal mechanisms that regulate cellular regeneration. However, at high doses and dose rates, repair and regeneration may be inadequate, so that a large number of cells may be destroyed leading to impaired organ function. This rapid, cell death at high doses leads to early deleterious radiation effects which become evident within days or weeks of exposure, and are known as "deterministic effects". These deterministic effects can be life-threatening in the short term if the dose is high enough, and were responsible for most of the early deaths in the Chernobyl accident.

Lower doses and dose rates do not produce these acute early effects, because the available cellular repair mechanisms are able to compensate for the damage. However, this repair may be incomplete or defective, in which case the cell may be altered so that it may develop into a cancerous cell, perhaps many years into the future, or its transformation may lead to inheritable defects in the long term. These late effects, cancer induction and hereditary defects, are known as "stochastic effects" and are those effects whose frequency, not severity, is dose dependent. Moreover, they are not radiation-specific and, therefore, cannot be directly attributed to a given radiation exposure.

For this reason, low dose health effects in humans cannot be measured and, therefore, risk projections of the future health impact of low-dose ionising radiation exposure have to be extrapolated from measured high-dose effects.

The assumption is made that no dose of ionising radiation is without potential harm, and that the frequency of stochastic effects at low doses is proportional to that occurring at high doses. This prudent assumption has been adopted to assist in the planning of radiation protection provisions when considering the introduction of practices involving ionising radiations. The ICRP has estimated the risk of fatal cancer to the general population from whole-body exposure to be 5% per sievert (IC90).

The health impact of the Chernobyl accident can be classified in terms of acute health effects ("deterministic effects") and of late health effects ("stochastic effects"). Moreover, there are also social and psychological effects which can influence health.

Radiation induced health effects

Acute health effects

All the acute deterministic health effects occurred among the personnel of the plant, or in those persons brought in for fire fighting and immediate clean-up operations.

Two deaths were immediately associated with the accident: one person killed by the explosion and another who suffered a coronary thrombosis. A third person died early the morning of the accident from thermal burns. Twenty-eight other persons died later in the treatment centres, bringing the total to 31 deaths in the first weeks after the accident (UN88).

All symptomatic exposed persons from the site were placed in hospitals. Of the total of 499 people were admitted for observation, 237 of these were initially diagnosed as suffering from acute radiation syndrome. The severity and rapidity of onset of their symptoms depended on their dose. The initial early signs and symptoms of radiation sickness from high doses included diarrhoea, vomiting, fever and erythema. Over 200 patients were placed in regional hospitals and specialised centres in the first 24 hours. Patients were allocated to four categories of radiation sickness severity according to their symptoms, signs and dose estimates. The differential white blood cell count showed reduced circulating lymphocytes (lymphocytopenia) which was the initial indicator of the severity of the exposure and became evident in the first 24-36 hours for those most severely irradiated.

No members of the general public received such high whole-body doses as to induce Acute Radiation Syndrome (IA86). This was confirmed in Belarus, where, between May and June 1986, 11 600 people were investigated without the discovery of any cases of acute radiation sickness.

In the highest exposure group of those who were acutely exposed (6-16 Gy), the first reaction was usually vomiting, occurring within 15-30 minutes of exposure. These patients were desperately ill; fever and intoxication as well as diarrhoea and vomiting, were prominent features. Mucous membranes were severely affected, becoming swollen, dry and ulcerated, making breathing and swallowing extremely painful and difficult. Extensive burns both thermal and due to beta radiation often complicated the illness. Within the first two weeks white blood cells and platelets fell dramatically, indicating a very high dose which had compromised the production of blood cells in the bone marrow, making it virtually impossible for the patients to fight infection or to retain the natural clotting activity of the blood. Almost all the patients with such high doses died (20 of 21), in spite of the intensive specialised medical treatment provided.

At lower exposures, the symptoms, signs and laboratory findings improved. Vomiting began later, platelet and white cell counts did not drop so precipitously and the fever and toxaemia were less pronounced. Beta radiation burns to the skin were a major complicating factor and mucous membrane damage was difficult to treat, but survival improved markedly at lower doses, so that no early deaths were noted in the less than 1-2 Gy exposure group (Table 12).

Table 12. **Outcome of radiation exposure among persons hospitalised for acute radiation syndrome**

Number of patients	Estimated dose (Gy)	Deaths
21	6-16	20
21	4-6	7
55	2-4	1
140	less than 2	0
Total 237		**28**

There is a large range of medical treatments that can be attempted to mitigate acute radiation syndrome. All these procedures were applied to the persons hospitalised with varying degrees of success. The hospital treatment following the accident included replacement therapy with blood constituents, fluids and electrolytes, antibiotics, antifungal agents, barrier nursing and bone marrow transplantation.

The treatment of the depression of bone-marrow function encountered after the accident was largely supportive. Special hygienic measures were taken; patients' clothes were changed at least twice a day and aseptic techniques used. Those patients who received doses above 2 Gy were given anti-fungal agents after the second week. Antibiotics and gamma globulin were also administered.

Bone-marrow transplantation was undertaken in 13 patients who were judged to have irreversible bone marrow damage after doses greater than 4 Gy. All but two of these patients died, some before the transfused marrow had had a chance to "take", but others had short-term takes. It was concluded that, even after very high radiation doses, the bone marrow may well not be completely destroyed and may recover at least some function at a later stage. It is this recovery which may lead to later rejection of the transplanted marrow through a "Host versus Graft" reaction. The physicians responsible for treating the victims of the accident concluded that bone marrow transplantation should play a very limited role in treatment.

Burns, both thermal and from beta radiation, were treated with surgical excision of tissue that was not viable, and any fluid and electrolyte loss was compensated for by the parenteral feeding set up to treat the gastro-intestinal syndrome which is a prominent feature of acute radiation sickness. The oro-pharyngeal syndrome of mucosal destruction, oedema and the absence of lubrication caused by radiation damage to the mucosa of the mouth and pharynx was extremely difficult to treat, and severely impaired swallowing and breathing.

The organisational aspects of treating large numbers of very ill patients also presented significant problems. Intensive nursing care and monitoring had to be provided 24 hours a day in small units. Personnel had to be taught new techniques of care and patient handling, and a large number of diagnostic samples had to be examined. The logistic requirements of medical handling needed to be well-established before any therapeutic programme could be run efficiently.

There were eleven deaths between 1987 and 1998 among confirmed acute radiation sickness survivors who received doses of 1.3-5.2 Gy. There were three cases of coronary heart disease, two cases of myelodysplasic syndrome, two cases of liver cirrhosis, and one death each of lung gangrene, lung tuberculosis and fat embolism. One patient, classified with Grade II, died in 1988 from acute myeloid leukaemia.

Radiation skin burns were observed in 56 patients. Cataracts scarring and ulceration are the most important causes of persistent disability in acute radiation sickness survivors.

Sexual function and fertility was investigated until 1996 in acute radiation sickness survivors. Functional sexual disturbances predominated, while fourteen normal children were born to acute radiation sickness survivor families, within the first five years.

Patients with acute radiation sickness, Grades III and IV, were severely immuno-suppressed. These abnormalities, however, are not necessarily associated with clinically manifest immuno-deficiency.

Late health effects

There have been many reports of an increase in the incidence of some diseases as a result of the Chernobyl accident. In fact, the accident has, according to present knowledge, given rise to an increase in the incidence of thyroid cancers. Also, it has had negative social and psychological consequences. As far as other diseases are concerned, as yet the scientific community has not been able to relate those to the effects of ionising radiation. However, large research projects have been conducted and are under way to further study the matter. For example, the WHO (WH95) established the International Programme on the Health Effects of the Chernobyl Accident (IPHECA). This programme initially concentrated on pilot projects involving leukaemia, thyroid diseases, oral health in Belarus, mental health in children irradiated before birth and the development of epidemiological registries. The pilot phase came to an end in 1994 and, as a result of the findings, efforts are underway to develop long-term permanent programmes involving thyroid diseases, the accident recovery workers, dose reconstruction and guidance to the public in the event of an accident. It is expected that these new projects will provide further insight into any future health effects.

An estimate (An88) of the total lifetime cancers which could be expected in Europe as a result of the accident suggested an increase of about 0.01% above their natural incidence. Another assessment placed the increase in cancer incidence at 0.004% in the Northern hemisphere, a lower percentage increase due probably to including the large population of the whole hemisphere (Pa89). These predictions are remarkably similar and support the view that the average doses to the general population of the Northern hemisphere were so low that only fractions of a percent increases in cancer incidence could be expected in this population (Pe88, Re87). Large parts of the Northern hemisphere, such as

North America (Hu88, Br88), Asia and Siberia, were not significantly contaminated and doses were inconsequential. Therefore, the following sections focus on the late health effects in the population of the contaminated regions of the former Soviet Union.

In the International Chernobyl Project organised by the IAEA (IA91), field studies were undertaken in the latter half of 1990 on the permanent residents of the rural settlements with a surface caesium contamination of greater than 555 kBq/m^2, and on control settlements of 2 000 to 50 000 persons, using an age matched study design. Seven contaminated and six control settlements were chosen by the medical team of the Chernobyl Project. Since all persons could not be examined, representative samples were taken from various age groups. In all, 1 356 people were examined, and the aim was to examine about 250 from each of the larger settlements. Three medical teams each spent two weeks conducting medical examinations to provide the data for these assessments.

The medical examinations were quite comprehensive, and the general conclusions reached were that there were no health abnormalities which could be attributed to radiation exposure, but that there were significant non-radiation related health disorders which were similar in both contaminated and control settlements. The accident had had substantial negative social and psychological consequences which were compounded by the socio-economic and political changes occurring in the former Soviet Union. The official data provided to the medical teams was incomplete and difficult to evaluate, and were not detailed enough to exclude or confirm the possibility of an increase in the incidence of some tumour types. On this subject, it was suggested in 1991 that the incidence of cancer in Ukraine showed no large increase even in the most contaminated areas (Pr91).

The International Chernobyl Project Report (IA91) suggested that the reported high thyroid doses in some children were such that there could be a statistically detectable increase in the incidence of future thyroid tumours. The Chernobyl Project team finally concluded that, on the basis of the doses estimated by the team and the currently accepted radiation risk estimates, future increases over the natural incidence of cancer or hereditary defects would be difficult if not impossible to discern, even with very large and well-designed long-term epidemiological studies. However, it should be remembered that this health survey took place four years after the accident, before any increase in cancer incidence might be expected and reflects the status of the people examined in a few months of 1990. The sample size was also criticised as being too small.

Nevertheless, the dose estimates generally accepted indicate that, with the exception of thyroid disease, it is unlikely that the exposure would lead to discernible radiation effects in the general population. Many predictions of the future impact of the accident on the health of populations have been made, all of which, apart from thyroid disease, indicate that the overall effect will be small when compared with the natural incidence and therefore not expected to be discernible (An88, Be87, Hu87, Mo87, De87, Be87).

Thyroid cancer

Early in the development of the Chernobyl accident, it became obvious that the radioiodines were contributing significant thyroid doses (Il90), especially to children, and the then Soviet authorities made every effort not only to minimise doses, but also to record the thyroid doses as accurately as possible. The results of these measurements and dose reconstruction assessments indicated that some groups in the population received high doses to their thyroids, and that an increase in thyroid abnormalities, including cancer, was a very real possibility in the future. This was particularly true for children in the contaminated regions in Belarus, northern Ukraine and the Bryansk and Kaluga regions of the Russian Federation. These were not inconsequential thyroid doses and, as early as 1986, it was predicted by experts from the Soviet Union that the thyroid would be the target organ most likely to show evidence of radiation effects, especially an increased incidence of benign and malignant tumours.

It was known from previous studies of largely external irradiation of the thyroid that an increase in thyroid tumours tended to appear six to eight years following irradiation, and continue for more than twenty years after exposure, particularly in children. What was not expected was that thyroid abnormalities would already become detectable about four years after the accident. At that time, the conventional wisdom was that internal radioiodine exposure was less carcinogenic than external irradiation of the thyroid. Two recent studies found an elevated risk of thyroid cancer mortality following adult ^{131}I treatment for hyperthyroidim, which is in contrast to prevuious studies (Ro98, Fr99). It was estimated that the incidence of thyroid cancers in children, defined as those diagnosed between the ages of 0 and 14, might increase by about 5%, and in adults by about 0.9% over the next 30 years. As will be seen, a substantial increase has been detected in the more contaminated regions. The large number of cases appearing within five year of the accident was surprising, since it had been believed that thyroid cancer had a latency period of at least 10 years. A determined effort was made to estimate doses, record the data, initiate medical examinations and follow the cohorts already identified as being most at risk.

In Ukraine, more than 150 000 examinations were conducted by special dosimetric teams, and a realistic estimate of the collective thyroid dose of 64 000 person-Sv has been made, leading to a projection of 300 additional thyroid cancers (Li93a). In the contaminated regions of Russia, namely Bryansk, Tula and Orel, it was predicted that an excess thyroid cancer total of 349 would appear in a population of 4.3 million (Zv93). This represents an increase of 3 to 6% above the spontaneous rate.

A programme to monitor the thyroid status of exposed children in Belarus was set up in Minsk in May/June 1986. The highest doses were received by the evacuated inhabitants of the Hoiniki rayon (district) in the Gomel oblast. In the course of this study, it was noted that the numbers of thyroid cancers in children were increasing in some areas. For Belarus as a whole (WH90, Ka92, Wi94), there has been a significantly increasing trend in childhood thyroid cancer incidence since 1990 (Pa94). It was also noted that this increase is confined to regions in the Gomel and Brest oblasts, and no significant increase has been noted in the Mogilev, Minsk or Vitebsk areas where the radioactive iodine contamination is assessed to have been lower. Over 50% of all the cases are from the Gomel oblast.

For the eight years prior to 1986, only five cases of childhood (less than 15 years old on the day of accident) thyroid cancer were seen in Minsk, which is the main Belarussian centre for thyroid cancer diagnosis and treatment for children (De94). From 1986 to 1989, 3 to 6 cases of thyroid cancer in children were seen annually in Belarus. In 1990, the number jumped to 31, to 62 in 1991, then to 87 in 1993. By the end of 1998 the total had reached over 600 in Belarus. Nearly 50% of the early (1992) thyroid cancers appeared in children who were aged between one and four years at the time of the accident. Atthe same time 382 were diagnosed in the Ukraine.

The histology of the cancers has shown that nearly all were papillary carcinomata (Ni94) and that they were particularly aggressive, often with prominent local invasion and distant metastases, usually to the lungs. This has made the treatment of these children less successful than expected, whether undertaken in Minsk or in specialised centres in Europe. In all, about 150 000 children in Belarus had thyroid uptake measurements following the accident. Other data from Ukraine and Russia show a similar, but not as pronounced, increase in the incidence of childhood thyroid cancer since 1987.

The increase in Belarus was confirmed by the final report of an EC Expert Panel (EC93) convened in 1992 to investigate the reported increase. In 1992 the incidence of childhood thyroid cancer in Belarus as a whole was estimated to be 2.77 per 100 000, more recent information (Un00) raises the incidence in 1992 to 3.9 per 100 000, whereas in the Gomel and Brest oblasts it was 11.2 and 3.7 respectively. In Belarus, it was observed that children 0-4 years old at the time of accident still had an increase in absolute numbers of thyroid cancers in 1997, while the number of cancers among those who were 5-9 years old seem to decrease after 1995, in those of 10-14 years of age at exposure, the number of cancers seems to be stable for the period 91-97 (Ko99).

There is some difficulty in comparing the numbers quoted by the health authorities of the former Soviet Union with previous incidence statistics, as previous data collection was not sufficiently rigorous. Moreover, the absolute numbers can differ from one report to another, and the age scale taken into consideration can differ between 0-14, 0-17 or 0-18 years of age. However, in Belarus all cases of childhood thyroid cancer have been confirmed since 1986 by international review of the histology and, because of more rigid criteria for data collection, reliance can be placed on accuracy and completeness. An attempt to review incidence estimates was made in the above-mentioned EC Report (EC93). These experts confirmed that the incidence of childhood thyroid cancer (0-14 y) prior to the accident in Belarus (between 0 and 0.14/100 000/y) was similar to that reported by other cancer registries. This indicates that the data collection in Belarus was adequate. They noted that it jumped to 3.9/100 000/y in 1991, and 5.6/100 000 in 1995 and 1997, about a forty-fold increase.

The most recent published rates of childhood thyroid cancer (St95) show unequivocal increases as seen in Table 13. At the time of this writing, three of the 1036 children cited in Table 13 below have died of their disease.

Table 13. **Number of cases of thyroid cancers in children under 15 years old at diagnosis and cancer incidence rates number of cases per 100 000 children**

	86	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**
Belarus	3	4	6	5	31	62	62	87	77	82	67	73	48
	0.2	0.3	0.4	0.3	1.9	3.9	3.9	5.5	5.1	5.6	4.8	5.6	3.9
Russian Federation	–	1	–	–	1	1	3	1	6	7	2	5	–
		0.3			0.3	0.3	0.9	0.3	2.8	2.5	0.6	2.2	
Ukraine	8	7	8	11	26	22	49	44	44	47	56	36	44
	0.2	0.1	0.1	0.1	0.2	0.2	0.5	0.4	0.4	0.5	0.6	0.4	0.5
Total	**11**	**12**	**14**	**16**	**58**	**85**	**114**	**132**	**127**	**136**	**125**	**114**	**92**

When this increase was first reported, it was very quickly pointed out (Be92) that any medical surveillance programme introduced would apparently increase the incidence by revealing occult disease and rectifying misdiagnoses. While this may account for some of the increase (Ro92), it cannot possibly be the sole cause, as the increase is so large and many of the children presented not with occult disease, but with clinical evidence of thyroid and/or metastatic disease. In fact, only 12% of the childhood thyroid cancers were discovered by ultrasound screening alone in Belarus (WH95). In addition, subsequent examination by serial section of the thyroids of persons coming to autopsy in Belarus have confirmed that the number of occult thyroid cancers is similar to that found in other studies (Fu93) and showed none of the aggressive characteristics found in the childhood cancers presenting in life (Fu92).

It can be concluded that there is a real, and large, increase in the incidence of childhood thyroid cancer in Belarus and Ukraine which is likely to be related to the Chernobyl accident. This is suggested by features of the disease, which differ somewhat from the so-called natural occurrence, as well as by its temporal and geographic distribution.

As far as other thyroid disorders are concerned, no difference in Russia was detected by ultrasound examination, in the percentage incidence of cysts, nodules or autoimmune thyroiditis in the contaminated versus the un-contaminated areas (Ts94). Following the accident, children in the Ukrainian contaminated regions exhibited a transient dose-dependent increase in serum thyroxine level, without overt clinical thyrotoxicosis, which returned to normal within 12 to 18 months (Ni94). This was most marked in the youngest children. This finding cannot be regarded as an adverse health effect, as no abnormality was permanent. However, it may be a pointer to future thyroid disease, especially when it may be associated with mild regional dietary iodine deficiency, and indicates the need for continued monitoring.

This increased incidence was not confined to children, as a larger number of adult cases was registered in Belarus and in Ukraine (WH94). In a more recent report (Iv99) 3 082 thyroid cancer cases in persons less than 60 years of age at diagnosis were recorded in Russian Federation between 1982 and 1996 in the four most contaminated regions. Among those 0-17 years of age at time of the accident, 178 cases were found. In the same report we can observe that before the accident, the incidence of cancer in women in these contaminated areas was lower than the national incidence in the Russian federation for the period 1982-1986, but increased.

For the period of 12 years after the Chernobyl accident, thyroid carcinoma increased by 4 057 cases in Belarus, as compared to the same period of time before. Since 1974 to 1985 thyroid carcinomas developed in 1 392 patients, but from 1986 up to July 1998, 5 449 new cases were diagnosed (De99). The standard index reached 7.9 per 100 000 in population above 18 years old and 3-4 per 100 000 in children. Thyroid carcinomas were mainly diagnosed in children born before the accident. Once all ^{131}I had disintegrated, spontaneous carcinomas were diagnosed only in six children born in 1987 and 1988. Since 1996, the number of child patients has gradually decreased, while the incidence rates in adults continue to increase. We can expect during the second decade after the accident a peek of incidence for young people at age from 15 to 34 at the time of the accident. Among children and teenagers (age 0-18 at the time of the Chernobyl accident) we observe among thyroid cancers a mortality of 0.7% (observed time – 1986-2001) (Ke01).

An analysis of thyroid cancers in children and adolescents of the Ukraine (0-18 years of age at the time of surgery) showed that for period 1986 to 1997, 577 cases were registered (Tr99). Among 358 cases in children (0-14 years of age at time of surgery), the incidence per 100 000 children for the whole of the Ukraine has increased from 0.05 before the accident to 0.11 in 1986-1990, 0.39 in 1991-1995, and 0.44 in 1996-1997. The increase of incidence takes place mainly in children who were 5-years old or less in 1986.

Jacob *et al* reported a correlation between collective dose and incidence of thyroid cancers in 5 821 settlements in the three republics in 1991-1995. Using the southern half of Ukraine as a reference, the excess thyroid cancers risk was found to be linear in the dose interval 0.07 Gy to 1.2 Gy. For the 0-18 years of age group, Jacob *et al* obtain an excess absolute risk of 2.1 per 104 person-year Gy (Je98). In this study the authors did not relate any age (at exposure)-dependence for excess absolute risk for the birth cohort 1968-1985 (Je99) in contradiction with the Trosko report (Tr99) and the Japanese observations within the framework of the Sasakawa project in Belarus (Sh98). In another study, Ivanov *et al* (Iv99) reported excess absolute risk for children and adolescents comparable to those described by Jacob et al, 2.21 per 104 person-year Gy for girls and 1.62 for boys, described also a dose-risk linear relationship, but observed a dependence of risk with age at exposure, 14 times higher than in adults than for 0-4 years, 2.3 for children and adolescents.

The radiogenic nature of these thyroid tumours is supported by their relationship with thyroid exposure dose, clinical and morphological changes, aggressiveness of cancers, geostatistical studies (Bl97). This is in spite of the increase of ultrasound screening, which can explain a part of the increase in observed cases. However certain uncertainties remain, such as iodine deficiency and genetic predisposition, as well as the role of ^{131}I. For example, it has been suggested that the geographical distribution of thyroid cancers cases correlates better to the distribution of short-lived radioisotopes (^{132}I, ^{133}I and ^{135}I) than to that of ^{131}I (Av95).

Table 14. **Thyroid cancers and risk for children 0-18 years old at the time of the Chernobyl accident for the years 1991-1995 in three cities and 2 729 settlements in Belarus and the Russian Federation**

Thyroid dose	**Person years at risk**	**Observed number of cases**	**Expected number of cases** [a]	**Exsess absolute risk** [b] **(10^4 PY Gy)$^{-1}$**
0-0.1 (0.05)	1 756 000	38	16	2.6 (0.5-6.7)
0.1-0.5 (0.21)	1 398 000	65	13	1.9 (0.8-4.1)
0.5-1.0 (0.68)	386 000	52	3.6	2.0 (0.9-4.2)
1.0-2.0 (1.4)	158 000	50	1.5	2.3 (1.1-4.9)
>2.0 (3.0)	56 000	38	0.5	2.4 (1.1-5.1)

a) Calculated by multiplying the age-specific incidence observed in Belarus in 1983-1987 by three.

b) 95% confidence intervals in parentheses.

Credit: Sources and Effects of Ionising Radiation – United Nations Scientific committee on the Effects of Atomic Radiation – UNSCEAR 2000 report to the General Assembly with Scientific Annexes – Volume II: Effects, United Nations.

In the six most contaminated regions of the Russian Federation, the thyroid cancer incidence increased over time in adults. The incidence was 11 per 100 000 for women compared to 4 for the Russian Federation as a whole and 1.7 and 1.1 respectively for men.

In a study of Lithuanian recovery operation workers, three thyroid cancers were detected. There was no significant difference compared with the Lithuanian male population and no association with level of radiation dose or duration of stay in the area of Chernobyl. In Europe, where several studies were carried out, no increase of thyroid cancer among children was observed.

The majority of the estimates indicate that the overall health impact from these thyroid disorders will be extremely small and not detectable when averaged over the population potentially at risk. This viewpoint is widely held by the competent risk assessors who have examined the potential effects of the accident.

Other late health effects

From data in the Russian National Medical Dosimetric Registry (RNMDR), the reported incidence of all types of disease has risen between 1989 and 1992 (Iv94). There has also been a reported increase in malignant disease which might be due to better surveillance and/or radiation exposure. The crude mortality rate of the liquidators from all causes in the Russian Federation has increased from 5 per 1 000 in 1991 to 7 per 1 000 in 1992. The crude death rate from respiratory cancer is reported to have increased significantly between 1990 and 1991, and for all malignant neoplasms between 1991 and 1992. It is not clear what influence smoking has had on these data, and the overall significance of these findings will need to be established by further surveillance, especially when there are distinct regional variations in the crude death rate and the mortality rates from lung, breast and intestinal cancer are rising in the general population of the Russian Federation.

From the dosimetric data in the RNMDR (Iv94), a predicted excess 670 cancer deaths may occur in the exposed groups covered by the Registry, peaking in about 25 years. This is about 3.4% of the expected cancer deaths from other causes. Data from the other national dose registries is not readily available in the published literature.

In view of the difficulties associated with these Registry data, such as the dose estimates, the influence of such confounding factors as smoking, the difficulty in follow-up, the possible increase in some diseases in the general population and also the short time since the accident, it is not possible to draw any firm conclusions from these data at this time. The only inference that can be made is that these groups are the most exposed and that, if any radiation effects are to be seen, they will occur in selected cohorts within these registries, which will require long-term future surveillance.

A predicted increase of genetic effects in the next two generations was 0.015% of the spontaneous rate, and the estimated lifetime excess percentage of all cancers as a result of living in the strict control zones was 0.5%, provided that a lifetime dose limit of 350 mSv was not exceeded (Il90).

Childhood leukemia incidence has not changed in the decade since the accident. There is no significant change in the level of leukemia and related diseases in the contaminated (more than 555 kBq/m^2) and noncontaminated territories of the three states (WH95). Other attempts through epidemiological studies have failed to establish a link between radiation exposure from the Chernobyl accident and the incidence of leukemia and other abnormalities. No epidemiological evidence of an increase in childhood leukemia around

Chernobyl (Iv93, Iv 97), in Sweden (Hj94, To96), Germany (Mi97) or the rest of Europe (Pa92, Wi94) has been established. However, if the last OECD/NEA report recommended to be prudent, to withold final judgement, 6years later, no increased risk of leukemia related to ionising radiation has as yet been found among recovery operation workers. The probability of observing a significant increase of leukemias decreases with time, and the next five years will be conclusive.

Other studies

Various reports (Pa93, Sc93, Se95, St93, Ve93) have been published on the incidence of chromosome aberrations among people exposed both in the contaminated regions and in Europe. Some of these have shown little or no increase, while others have. This may reflect the wide variation in dose. However, there is a trend for the incidence of chromosome aberrations to return to normal with the passage of time. Other studies have not shown evidence of lymphocytic chromosome damage (Br92).

In East Germany one study found no rise in foetal chromosome aberrations between May and December 1986. Chromosome aberrations are to be expected in any exposed population, and should be regarded as biological evidence of that exposure, rather than an adverse health effect.

Another study in Germany suggesting a link between Down's syndrome (Trisomy 21) and the Chernobyl accident has been severely criticised and cannot be accepted at face value because of the absence of control for confounding factors (Sp91), and it was not confirmed by more extensive studies (Li93). Another study in Finland (Ha92) showed no association of the incidence of Trisomy 21 with radiation exposure from Chernobyl.

In a group of Belarussian children born to exposed mothers with *in utero* doses ranging from 8 to 21 mSv, no relationship between birth defects and residency in contaminated areas was seen (La90). At this time, no clear trends in data for birth anomalies in Belarus or Ukraine be established (Li93, Bo94). Later study of Lazuk *et al.* has shown increase of birth defects and malformations in contaminated areas (1997), but no changes could be related to exposure to ionising radiation since the same increase was observed in the city of Minsk used as control.

Two epidemiological studies in Norway concluded that no serious gross changes as to pregnancy outcome were observed (Ir91), and that no birth defects known to be associated with radiation exposure were detected (Li92). In

Austria, no significant changes in the incidence of birth defects or spontaneous abortion rates which could be attributed to the Chernobyl accident were detected (Ha92a).

A review by the International Agency for Research on Cancer (IARC) showed no consistent evidence of a detrimental physical effect of the Chernobyl accident on congenital abnormalities or pregnancy outcomes (Li93, EG88). No reliable data have shown any significant association between adverse pregnancy outcome or birth anomalies even in the most contaminated regions and the doses indicate that none would be expected.

On the basis of many studies, UNSCEAR in its last report (UN00) conclude that “no increase in birth defects, congenital malformations, stillbirths, or premature births could be linked to radiation exposures caused by the accident”.

No association between thyroid abnormalities and ^{137}Cs activity in the body or soil contamination was seen in 115 000 children in the Sasakawa framework health and Medical cooperation project (Ya97).

There have been reports that have suggested that radiation exposure as a result of the accident resulted in altered immune reactions. While immune suppression at high whole-body doses is known to be inevitable and severe, at the low doses experienced by the general population it is expected that any detected alterations will be minor and corrected naturally without any medical consequences. These minor changes may be indicative of radiation exposure, but their mild transitory nature is unlikely to lead to permanent damage to the immune system. All immunological tests of radiation exposure are in their infancy, but tests such as stimulated immunoglobulin production by lymphocytes hold promise for the future as a means of assessing doses below one Gy (De90).

Psychological and social health effects

One of the most significant effects of the Chernobyl accident has been the degridation of the social fabric in the affected territories. This has, it is felt (UN02), contributed to a general decline in well being through an increase in health effects that are related to the accident, but which are not necessarily radiation related. That is, the non-cancer health effects that are currently being studied seem not to result directly from irradiation, but from the stresses (physical and psychological) that have persisted since the accident.

In addition, the severity of the psychological effects of the Chernobyl accident appears also to be related to the public’s growing mistrust of officialdom, politicians and government, especially in the field of nuclear power. Public scepticism towards authority is reinforced by its difficulty in understanding radiation and its effects, as well as the inability of the experts to present the issues in a way that is comprehensible. The impression that an unseen, unknowable, polluting hazard has been imposed upon them by the authorities against their will, fosters a feeling of outrage.

Public outrage is magnified by the concept that their existing or future descendants are also at risk from this radiation pollution. This widespread public attitude was not confined to one country, and largely determined the initial public response outside the Soviet Union. The public distrust was increased by the fact that the accident that they had been told could not happen, did happen, and it induced anxiety and stress in people not only in the contaminated areas but, to a lesser extent, all over the world.

While stress and anxiety cannot be regarded as direct physical adverse health effects of irradiation, their influence on the well-being of people who were exposed or thought that they might have been, may well have a significant impact on the exposed population. Several surveys have shown that the intensity of the anxiety and stress are directly related to the presence of contamination. It should also be remembered that the stress induced by the radiological contamination caused by the accident was in addition to that produced in the general population by the upheaval in local social structures due to massive evacuation and relocations, and the severe economic and social hardship caused by the break-up of the Soviet Union.

These non-radiological effects related to the Chernobyl accident have been studied extensively. Symptoms such as headaches, depression, sleep disturbance, inability to concentrate, and emotional imbalance have been reported and seen to be related to the difficult conditions ands stressful events that followed the accident (Le96, Le96a). The psychological development of 138 belarussian children who were exposed in utero was compared with 122 children from non contaminated areas. A correlation was found between anxiety among parents and emotional stress in children; No differences could be related to ionising radiation (Ko99).

It was concluded that the Chernobyl accident has had a significant long-term impact on psychological well-being, health-related quality of life, and illness in the affected populations. However, none of these findings could be directly associated with ionising radiation (Ha97, UN00).

Within the former Soviet Union

Within the Soviet Union additional factors came into play to influence the public reaction. It should be remembered that this accident occurred during the initial period of “glasnost” and “perestroika”. After nearly seventy years of repression, the ordinary people in the Soviet Union were beginning openly to express all the dissatisfaction and frustration that they had been harbouring. Distrust and hatred of the central government and the Communist system could be expressed for the first time without too much fear of reprisal. In addition, nationalism was not repressed. The Chernobyl accident appeared to epitomise everything that was wrong with the old system, such as secrecy, witholding information and a heavy-handed authoritarian approach. Opposition to Chernobyl came to symbolise not only anti-nuclear and anti-communist sentiment but also was associated with an upsurge in nationalism.

The distrust of officialdom was so great that even scientists from the central government were not believed, and more reliance was placed on local “experts” who often had very little expertise in radiation and its effects. The then Soviet Government recognised this problem quickly, and tried to counteract the trend by inviting foreign experts to visit the contaminated areas, assess the problems, meet with local specialists and publicise their views in open meetings and on television. These visits appeared to have a positive effect, at least initially, in allaying the fears of the public. In the contaminated Republics, anxiety and stress were much more prevalent and were not just confined to the more heavily contaminated regions (WH90a). Several surveys conducted by Soviet (Al89) and other researchers (Du94) have shown that the anxiety induced by the accident has spread far beyond the more heavily contaminated regions.

During this period there was severe economic hardship which added to the social unrest and reinforced opposition to the official system of government. Anti-nuclear demonstrations were commonplace in the larger cities in Belarus (Gomel and Minsk), and Ukraine (Kiev and Lvov) in the years following the accident (Co92). The dismissive attitude of some Soviet scientists and government officials in describing the public reaction as “radiophobic” tended to alienate the public even further by implying some sort of mental illness or reaction which was irrational and abnormal. It also served as a convenient catch-all diagnosis which suggested that the public was somehow at fault, and the authorities were unable to do anything about its manifestations.

The concern of people for their own health is only overshadowed by their concern for the health of their children and grandchildren. Major and minor health problems are attributed to radiation exposure no matter what their origin, and the impact that the accident has had on their daily lives has added to the stress. Whole communities are facing or have faced evacuation or relocation. There are still widespread restrictions on daily life affecting schooling, work, diet and recreation.

The accident has caused disruption of social networks and traditional ways of life. As most inhabitants of the contaminated settlements are native to the area and often have lived there all their lives, relocation has in many cases, destroyed the existing family and community social networks, transferring groups to new areas where they may well be resented or even ostracised. In spite of these drawbacks, about 70% of the people living in contaminated areas wished to be relocated (IA91). This may well be influenced by the economic incentives and improved living standards that result from relocation by the government.

There are two additional circumstances and events which have tended to increase the psychological impact of the accident, the first of which was an initiative specifically designed to alleviate these effects in Ukraine. This was the introduction of the compensation law in Ukraine in 1991. Some three million Ukrainians were affected in some way by the post-accident management introduced, upon which approximately one sixth of the total national budget was spent (Du94). Different surveys have shown a general feeling of anxiety in all sectors of the population, but it was particularly acute among those who had been relocated. People were fearful of what the future might bring for themselves and their offspring, and were concerned about their lack of control over their own destiny.

The problem is that the system of compensation may well have exaggerated these fears by placing the recipients into the category of victims. This tended to segregate them socially and increased the resentment of the native population into whose social system these “victims” had been injected without consultation. This had the effect on the evacuees of increasing stress, often leading to withdrawal, apathy and despair. Locally, this compensation was often referred as a “coffin subsidy”! It is interesting to note that the 800 or so mostly elderly people who have returned to their contaminated homes in the evacuated zones, and hence receive no compensation, appear to be less stressed and anxious, in spite of worse living conditions, than those who were relocated. It should be pointed out that compensation and assistance are not harmful in themselves, provided that care is taken not to induce an attitude of dependence and resignation in the recipients.

The second factor which served to augment the psychological impact of the accident was the acceptance by physicians and the public of the disease entity known as "vegetative dystonia". This diagnosis is characterised by vague symptoms and no definitive diagnostic tests. At any one time, up to 1 000 children were hospitalised in Kiev, often for weeks, for treatment of this "disease" (St92). The diagnosis of vegetative dystonia appears to be tailor-made for the post-accident situation, assigned by parents and doctors to account for childhood complaints and accepted by adults as an explanation for vague symptoms.

There is great pressure on the physicians to respond to their patients' needs in terms of arriving at an acceptable diagnosis, and "Vegetative Dystonia" is very convenient as it will fit any array of symptoms. Such a diagnosis not only justifies the patients' complaints by placing the blame for this "disease" on radiation exposure, it also exonerates the patient from any responsibility, which is placed squarely on the shoulders of those responsible for the exposure – the Government. When the need for extended hospitalisation is added, the justification to accept this as a real disease is enhanced. It can be understood why there is an epidemic of this diagnosis in the contaminated areas.

Outside the former Soviet Union

Social and psychological effects in other countries were minimal compared with those within the former Soviet Union, and were generally exhibited more as concerned social reactions rather than health symptoms. In the contaminated regions of the former Soviet Union, many people were convinced that they were suffering from radiation induced disease, whereas in the rest of the world, where contamination was much less, news of the accident appeared to reinforce anti-nuclear perceptions in the general population. This was evidenced, for example, by the demonstrations on 7 June 1986 demanding the decommissioning of all nuclear power plants in the Federal Republic of Germany (Ze86). While in France public support for nuclear power expansion dropped since the accident, 63% of the population felt that French nuclear power reactors operated efficiently (Ch90). The minimal impact of the Chernobyl accident on French public opinion was probably due to the fact that about 75% of their electrical power is derived from nuclear stations, and in addition, France was one of the least contaminated European countries.

The Swedish public response has been well-documented (Dr93, Sj87). In the survey, the question was asked: "With the experience that we now have, do you think it was good or bad for the country to invest in Nuclear Energy?" Those that responded "bad" jumped from 25% before, to 47% after Chernobyl. The accident probably doubled the number of people who admitted negative attitudes towards nuclear power (Sj87). This change was most marked among women, who, it was felt, regarded nuclear power as an environmental problem, whereas men regarded it as a technical problem which could be solved. Media criticism of the radiation protection authorities in that country became more common, with the charge that the official pronouncements on the one hand said that the risk in Sweden was negligible, and yet on the other, gave instructions on how it could be reduced. The concept that a dose, however small, should be avoided if it could be done easily and cheaply, was not understood.

This sort of reaction was common outside the former Soviet Union, and while it did not give rise to significant health effects, it tended to enhance public apprehension about the dangers of nuclear power and foster the public's growing mistrust of official bodies.

In addition, public opinion in Europe was very sceptical of the information released by the Soviet Union. This mistrust was reinforced further by the fact that the traditional sources of information to which the public tended to turn in a crisis, the physicians and teachers, were no better informed and often only repeated and reinforced the fears that had been expressed to them. Added to this were the media, who tended to respond to the need to print "newsworthy" items by publishing some of the more outlandish claims of so-called radiation effects.

The general public was confused and cynical and responded in predictable but extreme ways such as seeking induced abortions, postponing travel and not buying food that might conceivably be contaminated. Another global concern that was manifested, was the apprehension over travel to the Soviet Union. Potential travellers sought advice from national authorities on whether to travel, what precautions to take and how they could check on their exposure. Many people, in spite of being reassured that it was safe to travel, cancelled their trip, just to be on the safe side, exhibiting their lack of confidence in the advice they received.

As has been seen, governments themselves were not immune from the influence of these fears and some responded by introducing measures such as unnecessarily stringent intervention levels for the control of radionuclides in imported food. Thus, in the world as a whole, while the effects on individuals, due to anxiety and stress, were probably minimal, the collective perception and response had a significant economic and social impact. It became clear that there was a need to inform the public on radiation effects, to provide clear instructions on the precautions to be taken so that the public regains some level of personal control, and for the authorities to recognise the public's need to be involved in the decisions that affect them.

In summary

It can be stated that:

- Thirty-one people died in the course of the accident or soon after and another 134 were treated for the acute radiation syndrome. Forty-one of these patients received whole-body doses from external irradiation of less than 2.1 Gy, 2& between 6.5 and 16 Gy.
- Extensive accident-related health effects are apparent in the affected regions of the former Soviet Union, manifested as anxiety and stress, as well as diverse health effects not directly related to radiation exposure. Severe forms induce a feeling of apathy and despair often leading to withdrawal. In the rest of the world these individual effects were minimal.
- In the last decade, there has been a real and significant increase in childhood and, to a certain extent, adult carcinoma of the thyroid in contaminated regions of the former Soviet Union (Wi940) which should be attributed to the Chernobyl accident until proven otherwise.
- In children, the thyroid cancers are:

  - largely papillary and particularly aggressive in nature often self presenting with local invasion and/or distant metastases;
  - more prevalent in children aged 0 to 5 years at the time of the accident, and in areas assessed to be the more heavily contaminated with ^{131}I;
  - apparently characterised by a shorter latent period than expected; and
  - still increasing for children younger than 5 years in 1986.

Iodine deficiency and screening, have almost certainly had an influence on observed risk factors can be said that the increase of thyroid cancers in children is clearly established to be linked to exposure of radioactive iodine isotopes releases. The number of these cancers is still increasing in adults. Conversely, no increase in leukaemia has been observed to date.

No increase of congenital abnormalities, adverse pregnancy outcomes or any other radiation induced disease in the general population, either in the contaminated regions or in Western Europe, could be attributed to this exposure sixteen years after the accident. It is unlikely that surveillance of the general population will reveal any significant increase in the incidence of cancer but continued follow-up is necessary to allow planning of public health actions and to gain a better understanding of influencing factors.

The present knowledge of the effects of protracted exposure to ionising radiations is limited, since the dose-assessments rely heavily on high-dose exposure. An increase in cancer rates was already observed before the Chernobyl accident in the affected areas and, moreover, a general increase in mortality has been reported in recent years in most areas of the former USSR.

Among recovery operation workers, no increase of leukaemia has been identified more than sixteen years after the accident.

Among the health consequences resulting from the Chernobyl accident, are radiological consequences, and other, non-radiological health problems. The radiological aspects have been studied in great detail since the accident, and have been well characterised, within the limits of scientific uncertainty of radiological sciences. However, increasingly, medical specialists are studying other health effects that are not associated with radiation exposure, but more with the effects of significant and prolonged stress, physical and psychological. These effects, which have been classified as “Vegetative Dystonia”, are increasingly recognised as real, but are felt to result from the social, cultural and psychological stress caused by the accident and the general social degradation that followed the accident and the end of the Soviet Union. To obtain a more exact understanding of these “accident-related effects”, it is important to expand current studies to include specialists from studies of the health and social effects of other natural and technological disasters.

Chapter VI

AGRICULTURAL AND ENVIRONMENTAL IMPACTS

Agricultural impact

All soil used anywhere in the world for agriculture contains radionuclides to a greater or lesser extent. Typical soils (IA89a) contain approximately 300 kBq/m^3 of ^{40}K to a depth of 20 cm. This radionuclide and others are then taken up by crops and transferred to food, leading to a concentration in food and feed of between 50 and 150 Bq/kg. The ingestion of radionuclides in food is one of the pathways leading to internal retention and contributes to human exposure from natural and man-made sources. Excessive contamination of agricultural land, such as may occur in a severe accident, can lead to unacceptable levels of radionuclides in food.

The radionuclide contaminants of most significance in agriculture are those which are relatively highly taken up by crops, have high rates of transfer to animal products such as milk and meat, and have relatively long radiological half-lives. However, the ecological pathways leading to crop contamination and the radioecological behaviour of the radionuclides are complex and are affected not only by the physical and chemical properties of the radionuclides but also by factors which include soil type, cropping system (including tillage), climate, season and, where relevant, biological half-life within animals. The major radionuclides of concern in agriculture following a large reactor accident are ^{131}I, ^{137}Cs, ^{134}Cs and ^{90}Sr (IA89a). Direct deposition on plants is the major source of contamination of agricultural produce in temperate regions.

While the caesium isotopes and ^{90}Sr are relatively immobile in soil, uptake of roots is of less importance compared with plant deposition. However, soil type (particularly with regard to clay mineral composition and organic matter content), tillage practice and climate all affect propensity to move to groundwater. The same factors affect availability to plants insofar as they control concentrations in soil solution. In addition, because caesium and strontium are taken up by plants by the same mechanism as potassium and calcium respectively, the extent of their uptake depends on the availability of these elements. Thus, high levels of potassium fertilisation can reduce caesium uptake and liming can reduce strontium uptake.

Within the former Soviet Union

The releases during the Chernobyl accident contaminated about 125 000 km^2 of land in Belarus, Ukraine and Russia with radiocaesium levels greater than 37 kBq/m^2, and about 30 000 km^2 with radiostrontium greater than 10 kBq/m^2. About 52 000 km^2 of this total were in agricultural use; the remainder was forest, water bodies and urban centres (Ri95). While the migration downwards of caesium in the soil is generally slow (Bo93), especially in forests and peaty soil, it is extremely variable depending on many factors such as the soil type, pH, rainfall and agricultural tilling. The radionuclides are generally confined to particles with a matrix of uranium dioxide, graphite, iron-ceramic alloys, silicate-rare earth, and silicate combinations of these materials. The movement of these radionuclides in the soil not only depends on the soil characteristics but also on the chemical breakdown of these complexes by oxidation to release more mobile forms. The bulk of the fission products is distributed between organomineral and mineral parts of the soil largely in humic complexes. The 30-km exclusion zone has improved significantly partly due to natural processes and partly due to decontamination measures introduced.

There were also large variations in the deposition levels. During 1991 the ^{137}Cs activity concentrations in the 0-5 cm soil layer ranged from 25 to 1 000 kBq/m^3 and were higher in natural than ploughed pastures. For all soils, between 60 and 95% of all ^{137}Cs was found to be strongly bound to soil components (Sa94). Ordinary ploughing disperses the radionuclides more evenly through the soil profile, reducing the activity concentration in the 0-5 cm layer and crop root uptake. However, it does spread the contamination throughout the soil, and the removal and disposal of the uppermost topsoil may well be a viable decontamination strategy.

The problem in the early phase of an accident is that the countermeasures designed to avoid human exposure are of a restrictive nature and often have to be imposed immediately, even before the levels of contamination are actually measured and known. These measures include the cessation of field work, of the consumption of fresh vegetables, of the pasturing of animals and poultry, and also the introduction of uncontaminated forage. Unfortunately, these measures were not introduced immediately and enhanced the doses to humans in Ukraine (Pr95).

Furthermore, some initial extreme measures were introduced in the first few days of the accident when 15 000 cows were slaughtered in Ukraine irrespective of their level of contamination, when the introduction of clean fodder could have minimised the incorporation of radiocaesium. Other countermeasures, such as the use of potassium fertilisers, decreased the uptake of radiocaesium by a factor of 2 to 14, as well as increased crop yield.

In some podzolic soils, lime in combination with manure and mineral fertilisers can reduce the accumulation of radiocaesium in some cereals and legumes by a factor of thirty. In peaty soils, sand and clay application can reduce the transfer of radiocaesium to plants by fixing it more firmly in the soil. The radiocaesium content of cattle for human consumption can be minimised by a staged introduction of clean feed during about ten weeks prior to slaughter. A policy of allocating critical food production to the least contaminated areas may be an effective common sense measure.

In 1993, the concentration of ^{137}Cs in the meat of cows from the Kolkhoz in the Sarny region, where countermeasures could be implemented effectively, tended to be much lower than that in the meat from private farms in the Dubritsva region (Pr95). The meat of wild animals which could not be subjected to the same countermeasures had a generally high concentration of radiocaesium. Decontamination of animals by the use of Prussian Blue boli was found to be very effective where radiocaesium content of feed is high and where it may be difficult to introduce clean fodder (Al93). Depending on the local circumstances, many of the above mentioned agricultural countermeasures were introduced to reduce human exposure.

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% of its original value. Nevertheless, soil contamination with ^{137}Cs, ^{90}Sr and ^{239}Pu is still high and in Belarus, the most widely contaminated Republic, eight years after the accident 2 640 km^2 of agricultural land had been excluded from use (Be94). Within a 40-km radius of the power plant, 2 100 km^2 of land in the Poles'e state nature reserve have been excluded from use for an indefinite duration.

The uptake of plutonium from soil to plant parts lying above ground generally constitutes a small health hazard to the population from the ingestion of vegetables. It only becomes a problem in areas of high contamination where root vegetables are consumed, especially if they are not washed and peeled. The total content of the major radioactive contaminants in the 30-km zone has been estimated at 4.4 PBq for ^{137}Cs, 4 PBq for ^{90}Sr and 32 TBq for ^{239}Pu and ^{240}Pu.

However, it is not possible to predict the rate of reduction as this is dependent on so many variable factors, so that 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 return to the 30 km exclusion zone will ever be possible, nor whether it would be feasible to utilise this land in other ways such as grazing for stud animals or hydroponic farming (Al93). It is however, to be recognised that a small number of generally elderly residents have returned to that area with the unofficial tolerance of the authorities.

Within Europe

In Europe, a similar variation in the downward migration of ^{137}Cs has been seen, from tightly bound for years in the near-surface layer in meadows (Bo93), to a relatively rapid downward migration in sandy or marshy areas (EC94). For example, Caslano (TI) experienced the greatest deposition in Switzerland and the soil there has fallen to 42% of the initial ^{137}Cs content in the six years after the accident, demonstrating the slow downward movement of caesium in soil (OF93). There, the ^{137}Cs from the accident has not penetrated to a depth of more than 10 cm, whereas the contribution from atmospheric nuclear weapon tests has reached 30 cm of depth.

In the United Kingdom, restrictions were placed on the movement and slaughter of 4.25 million sheep in areas in southwest Scotland, northeast England, north Wales and northern Ireland. This was due largely to root uptake of relatively mobile caesium from peaty soil, but the area affected and the number of sheep rejected are reducing, so that, by January 1994, some 438 000 sheep were still restricted. In northeast Scotland (Ma89), where lambs grazed on contaminated pasture, their activity decreased to about 13% of the initial values after 115 days; where animals consumed uncontaminated feed, it fell to about 3.5%. Restrictions on slaughter and distribution of sheep and reindeer, also, are still in force in some Nordic countries.

The regional average levels of ^{137}Cs in the diet of European Union citizens, which was the main source of exposure after the early phase of the accident, have been falling so that, by the end of 1990, they were approaching pre-accident levels (EC94). In Belgium, the average body burden of ^{137}Cs measured in adult males increased after May 1986 and reached a peak in late 1987, more than a year after the accident. This reflected the ingestion of contaminated food. The measured ecological half-life was about 13 months. A similar trend was reported in Austria (Ha91).

In short, there is a continuous, if slow, reduction in the level of mainly ^{137}Cs activity in agricultural soil.

Environmental impact

Forests

Forests are highly diverse ecosystems whose flora and fauna depend on a complex relationship with each other as well as with climate, soil characteristics and topography. They may be not only 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. Timber and timber products are a viable economic resource.

Because of the high filtering characteristics of trees, deposition was often higher in forests than in agricultural areas. When contaminated, the specific ecological pathways in forests often result in enhanced retention of contaminating radionuclides. The high organic content and stability of the forest floor soil increases the soil-to-plant transfer of radionuclides with the result that lichens, mosses and mushrooms often exhibit high concentrations of radionuclides. The transfer of radionuclides to wild game in this environment could pose an unacceptable exposure for some individuals heavily dependent on game as a food source. This became evident in Scandinavia where reindeer meat had to be controlled. In other areas, mushrooms became severely contaminated with radiocaesium.

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 (IA94). In addition, some forest-based industries, such as pulp production which often recycle chemicals, have been shown to be a potential radiation protection problem due to enhancement of radionuclides in liquors, sludges and ashes. However, harvesting trees for pulp production may be a viable strategy for decontaminating forests (Ho95).

Different strategies have been developed for combating forest contamination. Some of the more effective include restriction of access and the prevention of forest fires.

One particularly affected site, known as the “Red Forest” (Dz95), lies to the South and West close to the site. This was a pine forest in which the trees received doses up to 100 Gy, killing them all. An area of about 375 ha was severely contaminated and in 1987 remedial measures were undertaken to reduce the land contamination and prevent the dispersion of radionuclides through forest fires. The top 10-15 cm of soil were removed and dead trees were cut down. This waste was placed in trenches and covered with a layer of sand. A total volume of about 100 000 m^3 was buried, reducing the soil contamination by at least a factor of ten.

These measures, combined with other fire prevention strategies, have significantly reduced the probability of dispersion of radionuclides by forest fires (Ko90). The chemical treatment of soil to minimise radionuclide uptake in plants may be a viable option and, as has been seen, the processing of contaminated timber into less contaminated products can be effective, provided that measures are taken to monitor the by-products.

Changes in forest management and use can also be effective in reducing dose. Prohibition or restriction of food collection and control of hunting can protect those who habitually consume large quantities. Dust suppression measures, such as re-forestation and the sowing of grasses, have also been undertaken on a wide scale to prevent the spread of existing soil contamination.

Water bodies

In an accident, radionuclides contaminate bodies of water not only directly from deposition from the air and discharge as effluent, but also indirectly by washout from the catchment basin. Radionuclides contaminating large bodies of water are quickly redistributed and tend to accumulate in bottom sediments, benthos, aquatic plants and fish. The main pathways of potential human exposure may be directly through contamination of drinking-water, or indirectly from the use of water for irrigation and the consumption of contaminated fish. As contaminating radionuclides tend to disappear from water quickly, it is only in the initial fallout phase and in the very late phase, when the contamination washed out from the catchment area reaches drinking-water supplies, that human exposure is likely. In the early phase of the Chernobyl accident, the aqueous component of the individual and collective doses from water bodies was estimated not to exceed 1-2% of the total exposure (Li89). The Chernobyl Cooling Pond was the most heavily contaminated water body in the exclusion zone.

Radioactive contamination of the river ecosystems (see Chapter 2) was noted soon after the accident when the total activity of water during April and early May 1986 was 10 kBq/L in the river Pripyat, 5 kBq/L in the Uzh river and 4 kBq/L in the Dniepr. At this time, shortlived radionuclides such as ^{131}I were the main contributors. As the river ecosystem drained into the Kiev, then the Kanev and Kremenchug reservoirs, the contamination of water,sediments, algae, molluscs and fish fell significantly.

In 1989, the content of ^{137}Cs in the water of the Kiev reservoir was estimated to be 0.4 Bq/L, in the Kanev reservoir 0.2 Bq/L, and in the Kremenchug reservoir 0.05 Bq/L. Similarly, the ^{137}Cs content of Bream fish fell by a factor of 10 between the Kiev and Kanev reservoirs, and by a factor of two between the Kanev and Kremenchug reservoirs to reach about 10 Bq/kg (Kr95). In the last decade, contamination of the water system has not posed a public health problem. However, monitoring will need to be continued to ensure that washout from the catchment area which contains a large quantity of stored radioactive waste will not contaminate drinking-water.

A hydrogeological study of groundwater contamination in the 30-km exclusion zone (Vo95) has estimated that 90Sr is the most critical radionuclide, which could contaminate drinking-water above acceptable limits in 10 to 100 years from now.

Outside the former Soviet Union, direct and indirect contamination of lakes has caused and is still causing many problems, because the fish in the lakes are contaminated above the levels accepted for sale in the open market. In Sweden, for instance, about 14 000 lakes (i.e., about 15% of the Swedish total) had fish with radiocaesium concentrations above 1 500 Bq/kg (the Swedish guideline for selling lake fish) during 1987. The ecological half-life, which depends on the kind of fish and types of lakes, ranges from a few years up to some tens of years (Ha91).

In the countries of the European Union, the content of ^{137}Cs in drinking-water has been regularly sampled and reveals levels at, or below, 0.1 Bq/L from 1987 to 1990 (EC94), which are of no health concern. The activity concentration in the water decreased substantially in the years following the accident due largely to the fixation of radiocaesium in the sediments.

Sixteen years later

Over sixteen years after the accident, exposures of populations are mainly due to the consumption of agricultural food contaminated with ^{137}Cs. Production is today based on the following criteria:

- The contamination of foodstuffs should be at a level not leading to an average individual doses higher than 1 mSv per year.

- Production of these foodstuffs should not be more expensive in either economical or social terms.
- Some large population groups may receive low doses from these contaminated foodstuffs, but collective dose and excess risk should be evaluated.

In the Ukraine, agriculture in most contaminated territories produces foodstuffs respecting the limits fixed the 25 June 1997: 100 Bq/l for milk products; 200 Bq/kg for meat; 20 Bq/kg for potatoes and bread. Currently, milk contamination levels are about 50 Bq/l.

However, there are large disparities in production in Ukraine, and some private farms continue to produce milk more contaminated than the level fixed by the new limits. This is due to animal grazing in contaminated meadows, and to the large differences of transfer coefficients for caesium (1 to 20) depending on the chemical composition of soils. Some experts predict that the fixation of caesium in soils will be enough in the next 4 to 8 years to prevent more contamination of foodstuffs, but some predictions seem more pessimistic. (Sm00).

In Ukraine, 8,4 million hectares of agricultural soil are contaminated with ^{137}Cs, and are subject to countermeasures, mostly the use of fertilisers:

- The 54 900 hectares in the exclusion zone and the 35 600 ha contaminated with more than 555 kBq/m2 are exclude from agricultural farming.
- 130 800 ha are contaminated between 185 and 555 KBq/m2, including 15 000 ha of peat bog where the transfer of caesium to plants is the highest.
- 1.1 million ha contaminated between 37 and 185 kBq/m2, including 99 500 ha of peat bog.
- 7 238 millions ha contaminated between 3.7 and 37 kBq/m2.

An exclusion zone of about 4 000 km^2 has been defined, including a circular area with a radius of 30 km around the reactor. The areas affected are 2 100 km^2 in Belarus, 2 040 km^2 in Ukraine and 170 km^2 in the Russian Federation. All agricultural activities are forbidden, as is transfer of products. However, studies are underway as to how the less contaminated portions of this excluded land can be used.

Outside this area, 1.4 million of people are living on 30 000 km2 of land contaminated higher than 185 kBq/m^2, and 130 000 people are living in areas where the contamination is higher than 555 kBq/m^2. For the territories where the annual dose is lower than 1mSv, life is considered as normal. When the annual dose is higher than 1 mSv per year, people receive social compensations.

In Russia, some districts were declassified in January 1998, and this decision was accepted badly by the affected populations.

The amount of agriculture products exceeding trade limits fixed by Ukraine, Russia and Bielorussia are now very low, in spite of new restrictive limits given by Ukraine in 1997 (100 Bq/kg for milk, 200 Bq/kg for meat, 20 Bq/kg for bread and potatoes). Today, the combination of soil transfers, physical half-life of ^{137}Cs and efficacy of the countermeasures could lead to an agricultural production that is lower than the fixed limits within the next 4 to 8 years. This means that, 20 to 25 years after the accident, food production could be operated without any restriction.

In early 2001, 2 217 cities are still under radiological control in the Ukraine. In fact, only 1 316 need permanent controls, but the population of the 901 remaining cities refuse the declassification of their areas because this could be associated with the end of financial and social compensation.

In the exclusion zone, the impact on fauna and flora is characterised by the extremely heterogenous deposition of radioactive particles, which produces a wide range of doses to which the biota were subjected. In some cases, even in very small geographic areas, the impacts differed by an order of magnitude (IA01).

Somes consequences of the accident for the natural plant and animal populations are determined by secondary ecological factors resulting from changes in human activities. For example, the forbidding of hunting alters the types and numbers of birds. In general, animal numbers have greatly increased compared to adjacent inhabited areas. These favourable conditions for large numbers of commercially hunted mammal species will be preserved (IA01).

The transfer of radionuclides by water and wind, and by extreme seasonal weather conditions has not led to long term contamination beyond the exclusion zone. In the exclusion zone, the future radioactive contamination will be reduced slowly through radioactive decay.

The area in the exclusion zone covered by coniferous and deciduous forests will increase to 65-70% of the whole zone. The areas of meadowland and swap land will be correspondingly significantly reduced and gradually replaced by forests. These changes create a stable and fire-resistant vegetation layer. Associated with destruction of drainage systems, the level of groundwater will rise (IA01).

Since the accident, trade of wood is regulated. Depending upon its use, commercialisation levels range from 740 to 11 000 Bq of ^{137}Cs.kg^{-1}. With this new regulation, 30% of pines trees in the excluding zone are not usable.

In summary

- Many countermeasures to control the contamination of agricultural products were applied with varying levels of efficiency. Nevertheless, within the former Soviet Union large areas of agricultural land are still excluded from use, and are expected to continue to be so for a long time. In a much larger area, although agricultural and farm animal activities are carried out, the food produced is subject to strict controls and restrictions on distribution and use.
- Similar problems, although of a much lower severity, were experienced in some countries of Europe outside the former Soviet Union, where agricultural and farm animal production were subjected to controls and limitations for variable durations after the accident. Most of these restrictions were lifted several years ago. However, there are still some areas in Europe where restrictions on slaughter and distribution of animals are applied. This concerns, for example, several hundreds of thousands of sheep in the United Kingdom and large numbers of sheep and reindeer in some Nordic countries.
- Produce from forests, such as mushrooms, berries and game meat, may continue to be a radiological protection problem for a long time. The decrease of radioactivity will be now slow through radioactivity decay.
- At present drinking water is not a problem. Contamination of groundwater, especially with ^{90}Sr, could be a problem for the future in the catchment basins downstream of the Chernobyl area.
- Contaminated fish from lakes may be a long-term problem in some countries.
- However, the rehabilitation programmes must create conditions attractive enough for a younger workforce, especially engineers and qualified workers, to return. It is necessary and quite possible to create conditions where the environmental contamination will not result in the exclusion of important dietary components from consumption.

Chapter VII

POTENTIAL RESIDUAL RISKS

The Sarcophagus

In the aftermath of the accident several designs to encase the damaged reactor were examined (Ku95). The option which was chosen provided for the construction of a massive structure in concrete and steel that used as a support what remained of the walls of the reactor building (Ku95).

By August 1986 special sensors monitoring gamma radiation and other parameters were installed in various points by using cranes and helicopters. These sensors had primarily the function of assessing the radiation exposure in the areas where the work for the construction was to be carried out.

An outer protective wall was then erected around the perimeter and other walls in the turbine building, connected to the reactor Unit 3 building through an intermediate building, the so-called “V” building, and a steel roof completed the structure. The destroyed reactor was thus entombed in a 300 000 tonne concrete and steel structure known as the “Envelope” or “Sarcophagus”. This mammoth task was completed in only seven months, in November 1986.

Multiple sensors were placed to monitor such parameters as gamma radiation and neutron flux, temperature, heat flux, as well as the concentrations of hydrogen, carbon monoxide and water vapour in air. Other sensors monitor the mechanical stability of the structure and the fuel mass so that any vibration or shifts of major components can be detected. All these sensors are under computer control. Systems designed to mitigate any changing adverse conditions have also been put into place. These include the injection of chemicals to prevent nuclear criticality excursions in the fuel and pumping to remove excess water leaking into the Sarcophagus (To95).

An enormous effort was required to mount the clean-up operation; decontaminating ground and buildings, enclosing the damaged reactor and building the Sarcophagus was a formidable task, and it is impressive that so much was achieved so quickly. At that time the emphasis was placed on confinement as rapidly as possible. Consequently, a structure which would effectively be permanent was not built and the Sarcophagus should rather be seen as a provisional barrier pending the definition of a more radical solution for the elimination of the destroyed reactor and the safe disposal of highly radioactive materials. In these conditions, to maintain the existing structure for the next several decades poses very significant engineering problems. Consultations and studies by an international consortium are currently taking place to provide a permanent solution to this problem.

The fuel in the damaged reactor exists in three forms, (a) as pellets of 2% enriched uranium dioxide plus some fission products essentially unchanged from the original forms in the fuel rods, (b) as hot particles of uranium dioxide a few tens of microns in diameter or smaller particles of a few microns, made of fuel fused with the metal cladding of the fuel rods, and (c) as three extensive lava-like flows of fuel mixed with sand or concrete. The amount of dispersed fuel in the form of dust is estimated to amount to several tons (Gl95).

The molten fuel mixture has solidified into a glass-like material containing former fuel. The estimates of the quantity of this fuel are very uncertain. It is this vitrified material that is largely responsible for the very high dose rates in some areas (Se95a). Inside the reactor envelope, external exposure is largely from ^{137}Cs, but the inhalation of fuel dust is also a hazard. As was noted earlier, a small special group of scientists who have worked periodically inside the Sarcophagus for a number of years have accumulated doses in the estimated range of 0.5 to 13 Gy (Se95a). Due to the fact that these doses were fractionated over a long time period, no deterministic effects have been noted in these scientists. Since the beginning of 1987 the intensity of the gamma radiation inside the structure fell by a factor 10. The temperature also fell significantly. Outside the Sarcophagus, the radiation levels are not high, except for the roof where dose rates up to 0.5 Gy/h have been measured after the construction of the Sarcophagus. These radiation levels on the roof have now decreased to less than 0.05 Gy/h.

Nine years after its erection, the Sarcophagus structure, although still generally sound, raises concerns for its stability and long-term resistance and represents a standing potential risk. Some supports for the enclosure are the original Unit 4 building structures which may be in poor condition following the explosions and fire, and their failure could cause the roof to collapse. This situation is aggravated by the corrosion of internal metallic structures due to the high humidity of the Sarcophagus atmosphere provoked by the penetration of large quantities of rain water through the numerous cracks which were present on the roof and were only recently repaired (La95*)*. The existing structure is not designed to withstand earthquakes or tornados. The upper concrete biological shield of the reactor is lodged between walls, and may fall. There is considerable uncertainty on the condition of the lower floor slab, which was damaged by the penetration of molten material during the accident. It this slab failed, it could result in the destruction of most of the building.

A number of potential situations have been considered which could lead to breaches in the Sarcophagus and the release of radionuclides into the environment. These include the collapse of the roof and internal structures, a possible criticality event, and the long-term migration of radionuclides into groundwater.

Currently, the envelope is not leaktight even if its degree of confinement has been recently improved. Although the current emissions into the environment are small, not exceeding 10 Gbq/y for ^{137}Cs and 0.1 GBq/y for plutonium and other transuranic elements, disturbance of the current conditions within the Sarcophagus, such as the dislodgement of the biological shield could result in more significant dispersion of radionuclides (To95). The dispersion in this case would not be severe and would be confined to the site provided that the roof did not collapse. However, collapse of the roof, perhaps precipitated by an earthquake, a tornado or a plane crash, combined with collapse of internal unstable structures could lead to the release of the order of 0.1 PBq of fuel dust, contaminating part of the 30-km exclusion zone (Be95).

More improbable worst case scenarios would result in higher contamination of the exclusion zone, but no significant contamination is expected beyond that area. Currently, criticality excursions are not thought to be likely (IP95). Nevertheless, it is possible to theorise (Go95, Bv95) on hypothetical accident scenarios, however remote, which could lead to a criticality event. One such scenario would involve a plane crash or earthquake with collapse of the Sarcophagus, combined with flooding. An accident of this type could release about 0.4 PBq of old fuel dust and new fission products to the atmosphere to contaminate the ground mainly in the 30-km zone.

Leakage from the Sarcophagus can also be a mechanism by which radionuclides are released into the environment. There are currently over 3 000 m^3 of water in various rooms in the Sarcophagus (To95). Most of this has entered through defects in the roof. Its activity, mainly ^{137}Cs, ranges from 0.4 to 40 MBq/L. Studies on the fuel containing masses indicate that they are not inert and are changing in various ways. These changes include the pulverisation of fuel particles, the surface breakdown of the lava-like material, the formation of new uranium compounds, some of which are soluble on the surface, and the leaching of radionuclides from the fuel containing masses. Studies to date indicate that this migration may become more significant as time passes.

Another possible mechanism of dispersion of radioactivity into the environment may be the transport of contamination by animals, particularly birds and insects, which penetrate and dwell in the Sarcophagus (Pu92). Finally, the possibility of leaching of radionuclides from the fuel masses by the water in the enclosure and their migration into the groundwater has been considered. This phenomenon, however, 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 ^{90}Sr, to migrate undergound 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.

Radioactive waste storage sites

The accident recovery and clean-up operations have resulted in the production of very large quantities of radioactive wastes and contaminated equipment. Some of these radioactive wastes are buried in trenches or in containers isolated from the groundwater by clay or concrete screens within the 30-km zone (Vo95). A review of these engineered sites concluded that, provided the clay layer remained intact, their contribution to groundwater contamination would be negligible. On the other hand, 600 to 800 waste trenches were hastily dug in the immediate vicinity of the Unit 4 in the aftermath of the accident. These unlined trenches contain the radioactive fallout that had accumulated on trees, grass, and in the ground to a depth of 10-15 cm and which was bulldozed from over an area of roughly 8 km^2. The estimated activity amount is now of the order of 1 PBq, which is comparable to the total inventory stored in specially constructed facilities next to Unit 4. Moreover, a large number of contaminated equipment, engines and vehicles are also stored in the open air.

The original clean-up activities are poorly documented, and much of the information on the present status of the unlined trenches near Unit 4 and the spread of radioelements has been obtained in a one-time survey. Some of the findings of the study (Dz95) are that:

- The water table in the vicinity of Unit 4 has risen by 1 to 1.5 m in a few years to about 4 m from the ground level and may still be rising (apparently this is due mostly to the construction, in 1986, of a wall 3.5 km long and 35 m deep around the reactor to protect the Kiev reservoir from possible spread of contamination through the underground water, as well as to the ceasing of drainage activities formerly connected with the construction of new units on the site).

- In the most targeted study area 32 of 43 explored trenches are periodically or continually flooded.

- In that area the upper unconfined aquifer is contaminated everywhere with ^{90}Sr to levels exceeding 4 Bq/L. Caesium and plutonium are less mobile and contamination from these elements is confined to the immediate vicinity of the disposal trenches.

- The relative mobility of the ^{90}Sr is especially important in that, from the closest trenches, it might reach the Pripyat River in 10 to 20 years.

It is clear that large uncertainties remain which require a correspondingly large characterisation effort. For instance, at present, most disposal sites are unexplored, and a few are uncharted; monitoring for groundwater movement is insufficient and the interpretation of the hydrologic regime is complicated by artificial factors (pumping, mitigative measures, etc.); the mechanisms of radionuclide leaching from the variety of small buried particles are not well understood, but are being studied.

Although it was previously felt that, radioelements could spread to the Pripyat river and down stream to the Black see, this has not occurred. Radionuclides have been effectively held up in soils and river sediments near the accident site (see Chapter 2).

In summary

The sarcophagus was never intended to be a permanent solution to entomb the stricken reactor. The result is that this temporary solution may well be unstable in the long term. This means that there is the potential for collapse which needs to be corrected by a permanent technical solution.

The accident recovery and clean-up operations have also 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 are partly conserved in containers and partly buried in trenches or stored in the open air.

In general, it has been assessed 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 accidental releases from the sarcophagus are expected to be very small in comparison with those from the Chernobyl accident in 1986 and their radiological consequences would be limited to a relatively small area around the site. As far as the radioactive wastes stored in the area around the site are concerned, they are a potential source of contamination of the groundwater which will require close monitoring until a safe disposal into an appropriate repository is implemented. Radionuclides have not, however, migrated as far from the site as was once expected.

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. This will be developed in the following Chapter.

Chapter VIII

SHUTDOWN OF THE CHERNOBYL PLANT[1]

The agreement to build the Chernobyl power plants dates from 1966, when the former Soviet Union decided to develop nuclear production of electricity. The RBMK reactor design also dates from this period. Six 1 000 MWe reactors were planned at that time.

Unit 1, which begin production in 1977, stopped in November 1996. In December 1997, it was decided to decommission.

Unit 2, which was first connected to the grid in December 1978, was stopped in 1991 after damage due to fire. The Ukrainian national authorities decided to definitely close this plant in March 1999.

Unit 3, which started in 1981 has had many shut downs for maintenance, inspections and repairs since 1997. In June 2000, the Ukrainian authorities decided to close it definitely on 15 December 2000.

Units 5 and 6 were under constructions at the site at the time of accident, but were never finished.

After the accident in reactor 4 and the fire in reactor 2, western countries attempted to persuade the Ukrainian authorities to definitively close reactor number 3. This was a priority for many countries in the bilateral exchanges and agreements with Ukraine. This western pressure crystallised when the Ukrainian parliament decided, in October 1993, to cancel a 1990s decision which recommended to immediate stop of all RBMK reactor construction, and the closure of the Chernobyl site. Later the European Union and the Ukraine concluded, on 20 December 1995, a memorandum of understanding for the closure of Chernobyl plant. In exchange for the definitive closure of all

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[1] This Chapter was prepared with the assistance of E. Gailliez and J.B. Chérié (IPSN), (IP00, IP01).

Chernobyl plants, the European Union (in the framework of TACIS programme) and western countries agreed to provide financial assistance to the Ukraine for the provision of electricity, and to solve social problems resulting from the closure of the site. Financial projects were estimated, in 1995, to be 2.3 billion dollars. A part of these funds has been committed to modifications of reactor number 3, creation of building for used fuel, and workshops for liquid and solid waste treatments.

Later, many other projects relating to the modernisation of VVER reactors have been discussed with the European Bank for Reconstruction and Development (EBRD).

Concerning the stabilisation of reactor 4, the safety analyses for all installations described in the next paragraphs will be jointly performed. From the European side, the Riskaudit consortium, a common subsidiary of the French IPSN (now the IRSN) and the German GRS in collaboration with ANPA (Italy) and AVN (Belgium) under contract of the European Union will perform this work. From the Ukrainian side, the Ukrainian State Scientific Technical Center for nuclear and radiation safety (SSTC) will perform the work. The two groups will combine their analyses for the benefit of the Ukrainian Safety Authority (Nuclear Regulatory Department, NRD).

Preparation of the definitive dismantling of the Chernobyl power plant

It is planned to build different installations on the Chernobyl site to accomplish the dismantling of the reactors. These facilities will be for the:

- storage of used fuel;
- treatment of liquids and solids wastes produced by dismantling operations;
- storage of resulting waste packages.

Storage of used fuel

Used fuel coming from the three reactors is today stored inside reactor cores, in pools close to the reactors, and in a former storage building. A new dry storage installation is under construction, using the Nuhoms process, certified by the US Nuclear Regulatory Commission. Two other building are under construction. The first new building will be used for the cutting of fuel rods, and the storage of control rods. The second building will consist to modular cells in which containers including fuel will be inserted. Each cell will receive one container. Cooling will be passive. It is planed to build 256 cells in 10 years. Funding for this operation is provided through the EBRD, Westinghouse (USA), Bouygues and Campenon Bernard (France), the operating western companies for the Chernobyl Nuclear Power Plant operator.

This project began in June 1999, and buildings are under construction and forecast receiving operating licenses in the beginning of 2003. Transfer of all fuel assemblies is planned for the following ten years.

Treatment of liquids effluents

Liquid effluents, containing mainly ^{60}Co, ^{137}Cs, ^{134}Cs, are stored on the site in two groups of tanks. The first group contains 5 outside tanks of 5 000 m^3 each, the second contains 9 tanks of 1 000 m^3 in individual cells. Today 26 000 m^3 are stored, the total capacity of the installation being 34 000 m^3.

The treatment of these liquid wastes is a delicate operation, requiring the construction of ventilated boxes for pumping operations. For the 5 000 m^3 tanks, it will be necessary to construct coverage.

Another building has been under construction since 2000, and will be used for the transformation of these liquid wastes into solid wastes. Licensing of this facility is planned for completion by the end of 2002. Transformation operations will consist of mixing liquid wastes with concrete. The resulting solid packages will be stored in a surface storage center close to Chernobyl. All effluents produced by dismantling operations would be treated in these installations. Liquid effluent processing operations are planned to last for ten years.

These buildings are funded by the EBRD, Westinghouse (USA), Belgatom (Belgium), SGN (France) and Ansaldo (Italy).

Treatment of solid wastes

A new installation for solid waste treatment is needed. Low and intermediate-level wastes were generated by reactor operations, and consist of metal, concrete, plastic, wood and paper. Today, these solid wastes are stored in a decrepit building consisting in three compartments, the two first of which (1 000 m^3 each) are quite full. The third compartment (1 800 m^3), containing the most highly contaminated wastes, is 20% filled, bring the total volume of waste in this facility to approximately 2 350 m^3. Currently, these wastes are covered with concrete which must be removed and itself conditioned for disposal. This existing storage installation can be used for waste conditioning, but only at a rate of 3 m^3 per day.

The solid wastes produced during dismantling of the reactors will also need to be treated. Wastes will be sorted, and low and intermediate-level wastes will be stored in the surface storage site, outside the exclusion area of Chernobyl site.

The most highly contaminated wastes will be inserted into waterproof containers for temporary storage before future treatment. The workshop to perform this waste conditioning will be built for a daily production of 20 m^3.

These operations will be funded by European Union under the framework of the TACIS programme. A call for proposals is in progress. The choice of the western contractors will be decided for starting of operations at the end of 2003, beginning of 2004. These operations are planned to last for at least 5 years.

The Sarcophagus

In the aftermath of the accident several designs to encase the damaged reactor were examined. The Sarcophagus, build in only few weeks after the accident, is largely described in Chapter VII, along with the potential residual risks that the sarcophagus currently poses. Today, work is needed to reinforce the existing sarcophagus to prevent or to limit radioactive dust releases, and to reduce the risk of collapse either spontaneously of due to natural catastrophe. A list of about 15 tasks has been established on the basis of estimated risks. Today, only priority tasks have been performed, including the reinforcement of a common ventilation chimney for reactors 3 and 4, and the reinforcement of the roof concrete girders.

A new project, SIP (Shelter Implementation Plan) was launched in 1998, to last for 8 years, by a working group of nuclear safety experts coming from the G7[2] countries and the Ukraine. This project is funded by the EBRD, and its cost is estimated to be 760 million dollars, 50 million of which will be paid by the Ukrainian government.

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2. The G7 group consists of the 7 more industrialized countries of the world; Canada, France, Germany, Italy, Japan, United Kingdom and United States.

The SIP project has two main objectives; reinforcement of the sarcophagus and enhancement of protection of workers and environment. Five subsidiary objectives have been defined:

- reduction of the probability of sarcophagus collapse;
- reduction of consequence of an eventual collapse;
- increase of safety of the installation (criticality, management of contaminated water, characterisation of materials containing remaining fuel);
- increase of security of workers and environment;
- definition of a long tem strategy for safety.

This project is performed by a group independent from the Chernobyl plant operator, and is assisted by a project management team unit including Betchel and Battelle from USA, and EDF from France. This organization has to main tasks: to define the elementary tasks for reaching SIP objectives, and to request approval from competent Nuclear Regulatory Department of Ukraine. Once more, the Ukrainian NRD will be assisted by the SSTC and western companies (Scientech and Riskaudit).

Reinforcement of roof girders had involved about 300 workers. The collective dose estimated from Ukrainian information is 3.5 man Sv, 10% for preparation and 90% for the actual work. Preparative works had involved about 100 people, the highest doses were lower than 15 mSv, and approximately ten people have received doses ranging from 10 to 15 mSv. The reinforcement work has involved about 200 people, about 20 of whom have received doses ranging from 30 to 40 mSv.

Ukrainian authorities claim that no workers have exceeded fixed the limit for these operations, i.e. 40 mSv. The collective dose objective for the fifteen tasks planed in the SIP project is 25 man Sv. Particular attention is being paid to the monitoring of worker internal contamination.

Sarcophagus database

In the framework of “German-French initiative”, the IRSN (France) and the GRS (Germany) have collaborated with the operator (CHNPP), the International Scientific and Technical Center (ISTC) of the Ukrainian Academy of Sciences, the Ukrainian National Engineering and Sciences Institute (NIISK), and the Kurchatov Institute (Moscow) to produce a database on the “health status” of the sarcophagus.

This database will facilitate and improve estimation of radiological risks inside and outside the damaged building, and validate the today’s radiological protection guidelines. This database will be used by SIP projects operators. When finished this database will allow workers and planners to take a virtual visit of the sarcophagus and its immediate surroundings. This database is based on:

- construction and equipment of the sarcophagus, and new infrastructure annexes;
- the radiological situation inside the sarcophagus (Kurchatov Institute);
- the radiological situation in the vicinity of the sarcophagus (ISTC);
- gathering of data concerning amounts, quality, and characteristics of radioactive materials inside the sarcophagus (Kurtchatov Institute).

The first version of this database was transmitted to the Chernobyl Center in June 1999.

The social consequences

A large part of the 7 000 Chernobyl workers are living in Slavoutich city, 50 km east of Chernobyl. Ending the operation of the Chernobyl power plants will reduce manpower needs on the site by about 2 000 people.

The closure of the Chernobyl site will be an additional stress on this region, which has already suffered extensively as a result of the accident. The social, economic and personal effects that the loss of employment at the site will have on these individuals, these cities and this region should be studied and taken into account in any final resolution of this situation.

Chapter IX

LESSONS LEARNED*

The accident did not affect each country in the same way and a different emphasis was placed on various aspects of the accident with particular reference to the circumstances of that country. Thus, countries remote from the accident, with no domestic nuclear power programmes or neighbouring reactors, tended to emphasise food control and information exchange as their major thrust for improvement. Whereas those countries which were contaminated by the accident, and had their own nuclear power programmes and/or reactors in neighbouring countries, drew extensive lessons from the way the accident developed and was treated. For these reasons, not all the lessons learned were applied universally with the same emphasis.

Operational aspects

The Chernobyl accident was one of a kind, and, although it highlighted deficiencies in emergency preparedness and radiation protection, it should not be seen as the reference accident for future emergency planning purposes (Bu91).

It was very clear from the initial reactions of the competent national authorities that they were unprepared for an accident of such magnitude and they had to make decisions, as the accident evolved, on criteria that could have been established beforehand. This also meant that too many organisations were involved in the decision making, as no clear-cut demarcations had been agreed and established. Areas of overlapping responsibility and jurisdiction needed to be clearly established prior to any accident. A permanent infrastructure needed also to be in place and maintained for any efficient implementation of protective measures. Such an infrastructure had to include rapid communications systems, intervention teams and monitoring networks. Mobile ground monitoring teams

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* With the contribution of Stefan Mundigl (OECD/NEA).

were required, as was aerial monitoring and tracking of the plume. Many countries responded to this need by establishing such monitoring networks and reorganising their emergency response.

Logistic problems associated with intervention plans, such as stable iodine distribution (Sc94, NE95a) and evacuation obviously needed to be in place and rehearsed long before the accident, as they are too complex and time-consuming to be implemented during the short time available during the evolution of the accident. Intervention actions and the levels at which they should be introduced needed to be agreed, preferably internationally, and incorporated into the emergency plans so that they could be immediately and efficiently implemented.

The accident also demonstrated the need to include the possibility of transboundary implications in the emergency plans, as it had been shown that the radionuclide release would be elevated and the dispersion of contamination more widespread. The concern, raised by the experience of Chernobyl, that any country could be affected not only by nuclear accidents occurring on its territory but also by the consequences of accidents happening abroad, stimulated the establishment of national emergency plans in several countries.

The transboundary nature of the contamination prompted the international organisations to promote international cooperation and communication, to harmonise actions (NE88, IA94, IC90, IC92, NE93, NE89, NE90, NE89b, WH88, WH87, IA89b, IA92, IA91a, IA89c, IA87a, IA94a, EC89a, EC89b) and to develop international emergency exercises such as those organised by the OECD/NEA in its INEX Programme (NE95). A major accomplishment of the international community were the agreements reached on early notification in the event of a radiological accident and on assistance in radiological emergencies through international Conventions in the frame of the IAEA and the EC (EC87, IA86b, IA86c). In 1987, two Conventions came into effect, namely the Convention on Early Notification of a Nuclear Accident ("Early Notification Convention") and the Convention on Assistance in the Case of a Nuclear or Radiological Emergency ("Assistance Convention"). At present, 83 States are Party to the Early Notification Convention, and 79 States Parties to the Assistance Convention. In addition, the Food and Agriculture Organisation of the United Nations (FAO), the World Meteorological Organisation (WMO) and the World Health Organisation (WHO) are parties to both conventions.

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 minimising the foreseen radiological information. 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 adopted by a large umber of countries.

The accident provided the stimulus for international agreement on food contamination moving in trade, promoted by the WHO/FAO, as there is a need to import at least some food in most countries, and governments recognised the need to assure their citizens that the food that they eat is safe. Monitoring imported food was one of the first control measures instituted and continues to be performed (FA91, EC89c, EC93a).

This event also clearly showed that all national governments, even those without nuclear power programmes, needed to develop emergency plans to address the problem of transboundary dispersion of radionuclides. Of necessity these plans had to be international in nature, involving the free and rapid exchange of information between countries.

It is essential that emergency plans are flexible. It would be foolish to plan for another accident similar to Chernobyl without any flexibility, as the only fact that one can be sure of is that the next severe accident will be different. Emergency planners need to distil the general principles applicable to various accidents and incorporate these into a generic plan.

The accident emphasised the need for public information and public pressure at the time clearly demonstrated this need. A large number of persons who are knowledgeable about techniques in providing information are needed to establish a credible source of information to the public before an accident, so that clear and simple reports can be disseminated continuously in a timely and accurate form (EC89).

Emergency plans also need to include a process by which large numbers of people could have their exposure assessed, and those with high exposures differentiated. The accident also highlighted the need for the prior identification of central specialised medical facilities with adequate transportation to treat the more highly exposed individuals.

Refinement and clarification of international advice was needed (Pa88). The recommendations for intervention in an accident contained in ICRP Publication 40 were not clearly understood when they came to be applied, and the Commission reviewed this advice in Publication 63 (IC92). This guide placed emphasis on the averted dose as the parameter against which an intervention measure should be assessed. It was also made clear that an intervention had to be "justified" in as far as it produced more good than harm, and that where a choice existed between different protection options, "optimisation" was the mechanism to determine the choice. Emphasis was also placed on the need to integrate all protective actions in an emergency plan, and not to assess each one in isolation, as one may well influence the efficacy of another.

Scientific and technical aspects

Prior to the accident, it was felt that the flora and fauna of the environment were relatively radio-resistant and this was supported by the fact that no lethal radioecological injuries were noted after the accident except in pine forests (600 ha) and small areas of birch close to the reactor. A cumulative dose of less than 5 Gy has no gross effect even in the most sensitive flora of ecological systems, but there are still ecological lessons to be learned especially on the siting of nuclear power reactors (Al93).

Plant foliar and root uptake is being studied, as are resuspension and weathering. The transfer coefficients at all stages of the pathways to human exposure are being refined. Following the accident, an assessment of the models used at thirteen sites to predict the movement of ^{131}I and ^{137}Cs from the atmosphere to food chains (Ho91) indicated that models commonly used tended to overpredict by anything up to a factor of ten. The extensive whole-body monitoring of radioactivity in persons undertaken in conjunction with the measurement of ground and food contamination allowed refinement of the accuracy of the models for human dose assessment from the exposure through different pathways. The methods and techniques to handle contamination of food, equipment and soil have been improved.

Meteorological aspects, such as the relationship between deposition and precipitation and greater deposition over high ground and mountains, have been shown to be important especially in the development of more realistic models (NE96a). The importance of synoptic scale weather patterns used in predictions was established, and different models have been developed to predict deposition patterns under a wide variety of weather conditions. The chemico-physical changes in the radioactive gases and aerosols transported through the atmosphere are being studied to improve the accuracy of transport models.

Other impacts of the accident on model refinement include the improvement in understanding the movement of radionuclides in soil and biota, pathways and transfer factors; the effect of rainstorms and the influence of mountains and the alignment of valleys on deposition patterns; particulate re-suspension; long range pollution transport mechanisms; and the factors which influence deposition velocities (NE89a, NE96).

Uniform methods and standards were developed for the measurement of contaminating radionuclides in environmental samples.

In the case of high exposures, the importance of symptomatic and prophylactic medical and nursing procedures, such as antibiotics, anti-fungal and anti-viral agents, parenteral feeding, air sterilisation and barrier nursing was demonstrated, as were the disappointing results of bone-marrow transplantation.

In addition, the accident led to an expansion of research in nuclear safety and the management of severe nuclear accidents.

On the other hand, there is a need to set up sound epidemiological studies to investigate potential health effects, both acute and chronic. In the Chernobyl case, the lack of routinely collected data, such as reliable and complete cancer registry data, led to difficulty in organising appropriate epidemiological investigations in timely manner. There appears to be a need for developing and maintaining a routine health surveillance system within and around nuclear facilities.

In Russia, the government has decided to create a national system for the handling of information on all aspects of crisis management. This system will be operational at national level, but also at regional level. The database will be managed by the IBRAE Russian Institute.

The INEX Programme (Nuclear Emergency Preparedness and Management)

The OECD Nuclear Energy Agency (NEA), as a result of interest by its member countries, has been actively involved in emergency planning, preparedness and management for nuclear accidents, and created, in 1990, the Expert Group on Emergency Exercises, which became later the standing NEA Working Party on Nuclear Emergency Matters. This Working Party focuses on innovative ideas and new approaches to improve existing procedures in place for response to nuclear emergencies. In order to most efficiently achieve an improvements, the group creates, as needed, temporary sub-groups with well defined tasks, time lines and products, employing the most appropriate experts from NEA Member countries, but also from non-NEA members. In addition, the Working Party initiates the organisation of workshops and discussion groups, the launching of questionnaires on specific topics, or the organisation of international exercise series.

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. Three INEX 1 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, and in nuclear emergency data management.

The INEX 2 exercise series, also initiated by the NEA and performed between 1996 and 1999, was more ambitious than the INEX 1 exercise, seeking to improve actual emergency response procedures and existing “hardware” through a truly international command post exercise. This experience established for the first time an international nuclear emergency “exercise culture” leading to a clear improvement of the international aspects of nuclear emergency preparedness and management. The INEX 2 series offered a wealth of lessons learned with respect to emergency planning and management, particularly in the areas of communication and information exchange, public and media information, and decision making based on limited and uncertain information. The identified deficiencies in the area of communication and information exchange led to the most prominent outcome of INEX 2 and a major step forward in nuclear emergency management: the development of a new communication and information exchange strategy *Monitoring and Data*

Management Strategies for Nuclear Emergencies, which is currently implemented by various NEA member countries as well as by the international community.

Regarding the role of international organisations, the INEX 2 series contributed to better understanding who are the relevant international organisations, what obligations and responsibilities each has, and how to co-ordinate and harmonise their response in case of a nuclear emergency. The relevant international organisations used the experience to establish a mechanism for co-operation and collaboration through an Inter-Agency Committee on the Response to Nuclear Accidents (IACRNA), for which the IAEA serves as Secretariat.

On a national level, many countries participating in INEX 1 and INEX 2 exercises used the experiences and lessons learned to modify and improve national procedures for nuclear emergency preparedness and management. Countries also used the outcome of the exercises to update bilateral agreements.

In 2001, the INEX 2000 exercise was organised, similar to the four INEX 2 exercises, as a command-post real-time notification and communication exercise, dealing with the first hours of a nuclear emergency. In addition, the INEX 2000 exercise included for the first time a second major objective, to test compensation and third party liability issues after a nuclear accident, performed as a NEA workshop in November 2001 focusing on decision-making mechanisms in later phases of a nuclear emergency. This exercise, therefore, served as a bridging exercise between the INEX 2 series and the next generation of international nuclear emergency exercise programmes. On one hand, early notification and communication exercises will be institutionalised by the IAEA in collaboration and co-operation with other international organisations, and repeated periodically. On the other hand, a new innovative INEX 3 programme was initiated by the NEA to investigate post-accident management of contaminated sites and regions.

In summary, the Chernobyl accident triggered the start of many national and international programmes, which led to a considerable improvement of national and international procedures for nuclear emergency management and preparedness, especially in the areas of international communication and information exchange, and in harmonisation of response. However, there still remains room for improvement, for example in the field of co-ordinating and harmonising the response to nuclear accidents, as well as in the area of decision making in later phases after an accident. The work programmes of various international organisations are focusing on these aspects.

Psycho-sociological programmes

ETHOS project

ETHOS is a European project that is looking at new methodologies for sustainable rehabilitation of living conditions for inhabitants of contaminated areas. It is a new approach to strategic co-expertise, and includes experts from different fields of activities. The project also vigorously involves the local population in the evaluation and the management of risk, in collaboration with the local authorities and experts, (Lo99, He99) thus helping to restore their confidence in experts and authorities.

The ETHOS methodology and practical approach were used in the first stage (1996-1999), in the village of Olmany, which is located in the Stolyn district of Belarus. This village, in the south east portion of Belarus, is located 200 km from Chernobyl. Great improvement in living conditions, especially in the area of radiological protection and private farm production, was achieved thanks to the strong involvement of the village people. A group of mothers became involved in activities to improve the radiological protection of their children. New pedagogic modules from this radiological protection culture were later introduced in the village school.

While it is too early to draw final conclusions about the long term impact of the actions implemented, it is interesting to note that during the project's three years, a profound change with regard to radiological protection took place and several lessons have been learned. The first concerns the negative role played by regulatory limits when they are interpreted as a boundary between safe and unsafe. This was seen as a strong blocking factor, discouraging those confronted by higher levels, and destroying any potential initiative an ALARA attitude. The process followed by the mothers illustrates how it is possible to develop a framework for setting protection targets, where limits lose their previous status and are considered merely as a point of reference to guide action.

On a village scale, the ETHOS project also has been successful at improving the radiological quality of the food produced by the villagers. This has improved the local economic and radiological situations in a “hand-in-hand” fashion. The Bielorussian authorities, in agreement with European Union, launched in 1999 a similar project at a district scale, the Stolyn district (90 500 inhabitants). The aim of this second stage is to demonstrate that the ETHOS process could be implemented in everyday activity by locals such as physicians, nurses, head of collective farms, teachers and a radioactivity measurement specialist to improve radiological and economic conditions. All these activities are based on voluntary service.

Other studies

Murphy and Allen (Mu99) have studied the factors that determine personal parameters guiding individuals to respect, or not, regulations regarding forest used and forest product consumption. The gathering of mushrooms and berries is, for these populations, a tradition and also a social and leisure activity. Behavioural compliance, with forest and forest food restrictions, was largely predicted by factors relating to behaviour itself: lifestyle factors. Factors concerning radiation had little or no impact. This suggests that people's decisions about whether or not to go to the forest and consume forest produce are largely based on whether they want or need to, and whether other people they know are engaging in the behaviour. Concerns over radiation appear to play little part in these behaviours.

However, more than sixteen years after the accident, these populations that did not respect the measures of protection are not ignoring the radiation situation, they are still aware of and concerned about the threat of radiation to their health. This concern may manifest itself in the increased risk of stress-related health problems.

In another study, Mays *et al*. (Ma99) have shown through the consumption of contaminated milk in rural settlements that it is necessary for the radiation protection experts to widen consideration of risk and impacts, beyond radioactive dose, to social and psychological costs of both the nuclear accident and countermeasures programmes.

In conclusion these studies clearly show the necessity to take in account the socio-psychological factors for acceptance by the public of the radiological protection measures taken by the national authorities.

In summary

Besides providing new impetus to nuclear safety research, especially on the management of severe nuclear accidents, the Chernobyl accident stimulated national authorities and experts to a radical review of their understanding of, and attitude to radiation protection and nuclear emergency issues.

This led to an expansion of knowledge of radiation effects and their treatment, and to a revitalisation of radioecological research and monitoring programmes, emergency procedures, and criteria and methods for the information of the public.

Moreover, a substantial role in these improvements was played by multiple international co-operation initiatives, including revision and rationalisation of radiation protection criteria for the management of accident consequences, as well as reinforcement or creation of international communication and assistance mechanisms to cope with the transboundary implications of potential nuclear accidents.

More than sixteen years after the accident, we can observe that its consequences have not been completely addressed. Some pathologies have appeared, the amplitude of these being not directly correlated with the real impact of the accident.

But, one of the more spectacular lesson learned after the Chernobyl accident is probably the change of government attitudes with regard to technological catastrophes. The change includes the recognition of the need for some common action at the international level, the admittance that a large accident is possible, and the necessity to organize national and transboundary exercises. In this field we can note the major role played by the NEA/CRPPH in the INEX exercises, and the significant maturing of mentalities. This can be measured by the fact that it was necessary to create artificial countries (Acciland and Neighbourland) in the INEX 1 exercise, whereas subsequent exercises have used real plants in real countries. These exercises are well appreciated by national and local authorities, who do not hesitate to invite local media for celebration of these exercises.

This important effort is now materialized in the form of an international document, the Joint radiation emergency management plan of the international organizations, jointly sponsored by Food and Agriculture Organization of the United Nations, International Atomic Energy Agency, Nuclear Energy Agency of the Organisation for Economic Co-operation and Development, United Nations Office for the Co-ordination of Humanitarian affairs, World Health Organization and the World Meteorological Organization (IA00).

EXPLANATION OF TERMS

Activity

Quantity of a radionuclide. It describes the rate at which spontaneous nuclear transformations (i.e., radioactive decay) occur in it. It is measured in becquerels (Bq), where 1 Bq equals one nuclear transformation per second.

Several multiples of the becquerel (Bq) are used throughout the text. They are the following:

exabecquerel (EBq) = 10^{18} Bq
petabecquerel (PBq) = 10^{15} Bq
terabecquerel (TBq) = 10^{12} Bq
gigabecquerel (GBq) = 10^{9} Bq
megabecquerel (MBq) = 10^{6} Bq
kilobecquerel (kBq) = 103 Bq

Collective dose

Total dose over a population group exposed to a given source. It is represented by the product of the average dose to the individuals in the group by the number of persons comprising the group. It is measured in person-sieverts (person-Sv).

Dose

A general term denoting a quantity of radiation. Depending on its application it can be qualified as “absorbed dose”, “equivalent dose” and “effective dose”.

Absorbed dose

Quantity of energy imparted by radiation to a unit mass of matter such as tissue. Absorbed dose is measured in grays (Gy), where 1 Gy equals 1 joule of energy absorbed per kilogramme of matter. One gray produces a different intensity of biological effects on tissue depending on the type of radiation (alpha, beta, gamma, neutrons). One common submultiple of the gray, the milligray, is often used. One milligray (mGy) is equal to 10-3 Gy.

Effective dose

Weighted sum of the "equivalent doses" to the various organs and tissues multiplied by weighting factors reflecting the differing sensitivities of organs and tissues to radiation. The weighting factor for each organ or tissue expresses the fractional contribution of the risk of death or serious genetic defect from irradiation of that organ or tissue to the total risk from uniform irradiation of the whole body. Effective dose is measured in sieverts (Sv). Some submultiples of the sievert are used throughout the text. They are the following:

millisievert (mSv) = 10-3 Sv
microsievert (μSv) = 10-6 Sv

Equivalent dose

Quantity obtained by multiplying the "absorbed dose" in an organ (e.g., thyroid) or tissue by a factor representing the different effectiveness of the various types of radiation in causing harm to the organ or tissue. This factor, whose value varies between 1 and 20 depending on the type of radiation, has been introduced in order to allow grouping or comparing biological effects due to different radiations. Equivalent dose is measured in sieverts (Sv). One sievert produces the same biological effect, irrespective of the type of radiation.

Health effects

Acute radiation syndrome

A clinical scenario characterized by a complex of acute deterministic effects affecting various organs and body functions in the irradiated person.

Deterministic effects *(also called* ***acute health effects****)*

Early deleterious radiation effects on living tissues (e.g., body, organ or tissue death, cataracts), which generally occur only above a threshold of dose and whose severity depends on the level of dose absorbed. They become generally evident within a short time from the irradiation (hours, days or weeks, depending on the dose received). Throughout the text the doses producing Deterministic effects are expressed in grays (Gy).

Genetic effects *(also called* ***hereditary effects****)*

Stochastic effect which occur in the progeny of the exposed person.

Stochastic effects *(also called* ***late health effects****)*

Late deleterious radiation effects (e.g., leukaemia, tumours) whose severity is independent of dose and whose probability of occuring is assumed to be proportional to the dose received. It is also assumed that there is no threshold dose below which stochastic effects will not occur. The stochastic effects occur, therefore, at doses lower than those producing deterministic effects and may manifest themselves after a long time (years, decades) from the irradiation. Throughout the text the doses producing stochastic effects are expressed in sieverts (Sv).

Intervention level

The value of a quantity (dose, activity concentration) which, if exceeded or predicted to be exceeded in case of an accident, may require the application of a given protective action.

LIST OF ACRONYMS

AUDR	Soviet All-Union Dose Registry
CRPPH	NEA Committee on Radiation Protection and Public Health
DNA	Desoxyribonucleic Acid
EC	European Commission
ECCS	Emergency Core Cooling System
FAO	Food and Agriculture Organization
GSF	Forschungszentrum für Umwelt und Gesundheit
IAEA	International Atomic Energy Agency
IARC	International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
INES	International Nuclear Event Scale
INEX	NEA Nuclear Emergency Exercises Programme
INSAG	International Nuclear Safety Advisory Group
IPHECA	International Programme on the Health Effects of the Chernobyl Accident
IPSN	Institut de Protection et de Sûreté Nucléaire
JAERI	Japan Atomic Energy Research Institute
NAZ	Nationale Alarmzentrale
NCRP	Soviet National Committee on Radiation Protection
NEA	OECD Nuclear Energy Agency
OECD	Organisation for Economic Cooperation and Development
RNMDR	Russian National Medical Dosimetry Registry
SKI	Swedish Nuclear Power Inspectorate
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organization

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