Chernobyl

Consequences of the Catastrophe for People and the Environment

Alexey V. **YABLOKOV**

Vassily B. **NESTERENKO**

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CONSULTING EDITOR Janette D. Sherman-Nevinger

ON THE COVER
Pine trees reveal changes in wood color, density, and growth rate following irradiation from the Chernobyl disaster.
T.A. Mousseau, University of South Carolina (2009)

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Consulting Editor
JANETTE D. SHERMAN-NEVINGER

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Foreword

More than 22 years have passed since the Chernobyl catastrophe burst upon and changed our world. In just a few days, the air, natural waters, flowers, trees, woods, rivers, and seas turned to potential sources of danger to people, as radioactive substances emitted by the destroyed reactor fell upon all life. Throughout the Northern Hemisphere radioactivity covered most living spaces and became a source of potential harm for all living things.

Naturally, just after the failure, public response was very strong and demonstrated mistrust of atomic engineering. A number of countries decided to stop the construction of new nuclear power stations. The enormous expenses required to mitigate the negative consequences of Chernobyl at once "raised the price" of nuclear-generated electric power. This response disturbed the governments of many countries, international organizations, and official bodies in charge of nuclear technology and led to a paradoxical polarization as to how to address the issues of those injured by the Chernobyl catastrophe and the effects of chronic irradiation on the health of people living in contaminated areas.

Owing to the polarization of the problem, instead of organizing an objective and comprehensive study of the radiological and radiobiological phenomena induced by small doses of radiation, anticipating possible negative consequences, and taking adequate measures, insofar as possible, to protect the population from possible negative effects, apologists of nuclear power began a blackout on data concerning the actual amounts of radioactive emissions, the doses of radiation, and the increasing morbidity among the people that were affected.

When it became impossible to hide the obvious increase in radiation-related diseases, attempts were made to explain it away as being a result of nationwide fear. At the same time some concepts of modern radiobiology were suddenly revised. For example, contrary to elementary observations about the nature of the primary interactions of ionizing radiation and the molecular structure of cells, a campaign began to deny non-threshold radiation effects. On the basis of the effects of small doses of radiation in some nonhuman systems where hormesis was noted, some scientists began to insist that such doses from Chernobyl would actually benefit humans and all other living things.

The apogee of this situation was reached in 2006 on the 20th anniversary of the Chernobyl meltdown. By that time the health and quality of life had decreased for millions of people. In April 2006 in Kiev, Ukraine, two international conferences were held in venues close to one another: one was convened by supporters of atomic energy and the other by a number of international organizations alarmed by the true state of health of those affected by the Chernobyl catastrophe. The decision of the first conference has not been accepted up to now because the Ukrainian party disagrees with its extremely optimistic positions. The second conference unanimously agreed that radioactive contamination of large areas is accompanied by distinctly negative health consequences for the populations and predicted increased risk of radiogenic diseases in European countries in the coming years.

For a long time I have thought that the time has come to put an end to the opposition between technocracy advocates and those who support objective scientific approaches to estimate the negative risks for people exposed to the Chernobyl fallout. The basis for believing that these risks are not minor is very convincing.

Declassified documents of that time issued by Soviet Union/Ukraine governmental commissions in regard to the first decade after 1986 contain data on a number of people who were hospitalized with acute radiation sickness. The number is greater by two orders of magnitude than was recently quoted in official documents. How can we understand this difference in calculating the numbers of individuals who are ill as a result of irradiation? It is groundless to think that the doctors' diagnoses were universally wrong. Many knew in the first 10-day period after the meltdown that diseases of the nasopharynx were widespread. We do not know the quantity or dose of hot particles that settled in the nasopharyngeal epithelium to cause this syndrome. They were probably higher than the accepted figures.

To estimate doses of the Chernobyl catastrophe over the course of a year, it is critical to consider the irradiation contributed by ground and foliage fallout, which contaminated various forms of food with short-half-life radionuclides. Even in 1987 activity of some of the radionuclides exceeded the contamination by Cs-137 and Sr-90. Thus decisions to calculate dose only on the scale of Cs-137 radiation led to obvious underestimation of the actual accumulated effective doses. Internal radiation doses were defined on the basis of the activity in milk and potatoes for different areas. Thus in the Ukrainian Poles'e region, where mushrooms and other forest products make up a sizable share of the food consumed, the radioactivity was not considered.

The biological efficiency of cytogenic effects varies depending on whether the radiation is external or internal: internal radiation causes greater damage, a fact also neglected. Thus, there is reason to believe that doses of irradiation have not been properly estimated, especially for the first year after the reactor's failure. Data on the growth of morbidity over two decades after the catastrophe confirm this conclusion. First of all, there are very concrete data about malignant thyroid disease in children, so even supporters of "radiophobia" as the principal cause of disease do not deny it. With the passage of time, oncological diseases with longer latency periods, in particular, breast and lung cancers', became more frequent.

From year to year there has been an increase in nonmalignant diseases, which has raised the incidence of overall morbidity in children in areas affected by the catastrophe, and the percent of *practically healthy* children has continued to decrease. For example, in Kiev, Ukraine, where before the meltdown, up to 90% of children were considered healthy, the figure is now 20%. In some Ukrainian Poles'e territories, there are no healthy children, and morbidity has essentially increased for all age groups. The frequency of disease has increased several times since the accident at Chernobyl. Increased cardiovascular disease with increased frequency of heart attacks and ischemic disease are evident. Average life expectancy is accordingly reduced. Diseases of the central nervous system in both children and adults are cause for concern. The incidence of eye problems, particularly cataracts, has increased sharply. Causes for alarm are complications of pregnancy and the state of health of children born to so-called "liquidators" (Chernobyl's cleanup workers) and evacuees from zones of high radionuclide contamination.

Against the background of such persuasive data, some defenders of atomic energy look specious as they deny the obvious negative effects of radiation upon populations. In fact, their reactions include almost complete refusal to fund medical and biological studies, even liquidating government bodies that were in charge of the "affairs of Chernobyl." Under pressure from the nuclear lobby, officials have also diverted scientific personnel away from studying the problems caused by Chernobyl.

Rapid progress in biology and medicine is a source of hope in finding ways to prevent many diseases caused by exposure to chronic nuclear radiation, and this research will advance much more quickly if it is carried out against the background of experience that Ukrainian, Belarussian, and Russian scientists and physicians gained after the Chernobyl catastrophe. It would be very wrong to neglect the opportunities that are open to us today. We must look toward the day that unbiased objectivity will win out and lead to unqualified support for efforts to determine the influence of the Chernobyl catastrophe on the health of people and biodiversity and shape our approach to future technological progress and general moral attitudes. We must hope and trust that this will happen.

The present volume probably provides the largest and most complete collection of data concerning the negative consequences of Chernobyl on the health of people and on the environment. Information in this volume shows that these consequences do not decrease, but, in fact, are increasing and will continue to do so into the future. The main conclusion of the book is that it is impossible and wrong "to forget Chernobyl." Over the next several future generations the health of people and of nature will continue to be adversely impacted.

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Chairman, Department of General Biology, Ukrainian National Academy of Sciences,
Chairman, Ukrainian National Commission on Radiation Protection

Preface

The principal idea behind this volume is to present, in a brief and systematic form, the results from researchers who observed and documented the consequences of the Chernobyl catastrophe. In our view, the need for such an analysis became especially important after September 2005 when the International Atomic Energy Agency (IAEA) and the World Health Organization (WHO) presented and widely advertised "The Chernobyl Forum" report [IAEA (2006), The Chernobyl Legacy: Health, Environment and Socio-Economic Impact and Recommendation to the Governments of Belarus, the Russian Federation and Ukraine 2nd Rev. Ed. (IAEA, Vienna): 50 pp.] because it lacked sufficiently detailed facts concerning the consequences of the disaster (http://www.iaea.org/Publications/Booklets/Chernobyl/chernobyl.pdf).

Stimulated by the IAEA/WHO "Chernobyl Forum" report, and before the 20th anniversary of the Chernobyl catastrophe, with the initiative of Greenpeace International, many experts, mostly from Belarus, Ukraine, and Russia (see the list below), presented their latest data/publications on the consequences of Chernobyl. Greenpeace International also collected hundreds of Chernobyl publications and doctoral theses. These materials were added to the Chernobyl literature collected over the years by Alexey Yablokov [A. V. Yablokov (2001): *Myth of the Insignificance of the Consequences of the Chernobyl Catastrophe* (Center for Russian Environmental Policy, Moscow): 112 pp. (//www.seu.ru/programs/atomsafe/books/mif_3.pdf) (in Russian)].

Just before the 20th anniversary of the Chernobyl catastrophe, on April 18, 2006, the report "The Chernobyl Catastrophe–Consequences on Human Health" was published by A. Yablokov, I. Labunska, and I. Blokov (Eds.) (Greenpeace, Amsterdam, 2006, 137 pp.; www.greenpeace.org/international/press/reports/chernobylhealthreport). For technical reasons, it was not possible to include all of the above-mentioned material in that book. Thus part of this original material was published as "The Health Effects of the Human Victims of the Chernobyl Catastrophe: Collection of Scientific Articles," I. Blokov, T. Sadownichik, I. Labunska, and I. Volkov (Eds.) (Greenpeace, Amsterdam, 2007, 235 pp.; http://www.greenpeace.to/publications.asp#2007). In 2006 multiple conferences were convened in Ukraine, Russia, Belarus, Germany, Switzerland, the United States, and other countries devoted to the 20th anniversary of the Chernobyl catastrophe, and many reports with new materials concerning the consequences of the meltdown were published. Among them:

- "The Other Report on Chernobyl (TORCH)" [I. Fairly and D. Sumner (2006), Berlin, 90 pp.].
- "Chernobyl Accident's Consequences: An Estimation and the Forecast of Additional General Mortality and Malignant Diseases" [Center of Independent Ecological Assessment, Russian Academy of Science, and Russian Greenpeace Council (2006), Moscow, 24 pp.].

- *Chernobyl: 20 Years On. Health Effects of the Chernobyl Accident* [C. C. Busby and A.V. Yablokov (Eds.) (2006), European Committee on Radiation Risk, Green Audit, Aberystwyth, 250 pp.].
- *Chernobyl. 20 Years After. Myth and Truth* [A. Yablokov, R. Braun, and U. Watermann (Eds.) (2006), Agenda Verlag, Münster, 217 pp.].
- "Health Effects of Chernobyl: 20 Years after the Reactor Catastrophe" [S. Pflugbeil *et al.* (2006), German IPPNW, Berlin, 76 pp.].
- Twenty Years after the Chernobyl Accident: Future Outlook [Contributed Papers to International Conference. April 24–26, 2006. Kiev, Ukraine, vol. 1–3, HOLTEH Kiev, www.tesec-int.org/T1.pdf].
- Twenty Years of Chernobyl Catastrophe: Ecological and Sociological Lessons. Materials of the International Scientific and Practical Conference. June 5, 2006, Moscow, 305 pp., www.ecopolicy.ru/upload/File/conferencebook_2006.pdf, (in Russian).
- National Belarussian Report (2006). Twenty Years after the Chernobyl Catastrophe: Consequences in Belarus and Overcoming the Obstacles. Shevchyuk, V. E, & Gurachevsky, V. L. (Eds.), Belarus Publishers, Minsk, 112 pp. (in Russian).
- National Ukrainian Report (2006). Twenty Years of Chernobyl Catastrophe: Future Outlook. Kiev, http://www.mns.gov.ua/news_show.php?news_id=614&p=1.
- National Russian Report (2006). Twenty Years of Chernobyl Catastrophe: Results and Perspective on Efforts to Overcome Its Consequences in Russia, 1986–2006. Shoigu, S. K. & Bol'shov, L. A. (Eds.), Ministry of Emergencies, Moscow, 92 pp. (in Russian).

The scientific literature on the consequences of the catastrophe now includes more than 30,000 publications, mainly in Slavic languages. Millions of documents/materials exist in various Internet information systems—descriptions, memoirs, maps, photos, etc. For example in GOOGLE there are 14.5 million; in YANDEX, 1.87 million; and in RAMBLER, 1.25 million citations. There are many special Chernobyl Internet portals, especially numerous for "Children of Chernobyl" and for the Chernobyl Cleanup Workers ("Liquidators so called") organizations. The *Chernobyl Digest*—scientific abstract collections—was published in Minsk with the participation of many Byelorussian and Russian scientific institutes and includes several thousand annotated publications dating to 1990. At the same time the IAEA/WHO "Chernobyl Forum" Report (2005), advertised by WHO and IAEA as "the fullest and objective review" of the consequences of the Chernobyl accident, mentions only 350 mainly English publications.

The list of the literature incorporated into the present volume includes about 1,000 titles and reflects more than 5,000 printed and Internet publications, primarily in Slavic languages. However, the authors apologize in advance to those colleagues whose papers addressing the consequences of the Chernobyl catastrophe are not mentioned in this review—to list all papers is physically impossible.

The authors of the separate parts of this volume are:

- Chapter I: Cherbobyl Contamination: An Overview—A. V. Yablokov and V. B. Nesterenko;
- Chapter II: Consequences of the Chernobyl Catastrophe for Public Health—A. V. Yablokov;
- Chapter III: Consequences of the Chernobyl Catastrophe for the Environment—A. V. Yablokov, V. B. Nesterenko, and A. V. Nesterenko;

- Chapter IV: Radiation Protection after the Chernobyl Catastrophe—A. V. Nesterenko, V. B. Nesterenko, and A. V. Yablokov.

The final text was coordinated by all authors and expresses their common viewpoint. Some important editorial remarks:

1. Specific facts are presented in the form that has long been accepted by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)—itemized by numbered paragraphs.
2. The words "Chernobyl contamination," "contamination," "contaminated territories," and "Chernobyl territories" mean the radioactive contamination caused by radionuclide fallout as a result of the Chernobyl catastrophe. Such expressions as "distribution of diseases in territory..." mean occurrence of diseases in the population of the specified territory.
3. The word "catastrophe" means the release of numerous radionuclides into the atmosphere and underground water as a result of the explosion of the fourth reactor at the Chernobyl nuclear power station (Ukraine), which started on April 26, 1986 and continued thereafter.
4. The expressions "weak," "low," and "high" ("heavy") radioactive contamination usually indicate a comparison among officially designated different levels of radioactive contamination in the territories: less than 1 Ci/km^2 (<37 kBq/m^2); 1–5 Ci/km^2 (37–185 kBq/m^2); 5–15 Ci/km^2 (185–555 kBq/m^2); and 15–40 Ci/km^2 (555–1480 kBq/m^2).
5. The term "clean territory" is a conventional one; however, during the first weeks and months of the catastrophe practically *all* territories of Belarus, Ukraine, and European Russia, and Europe and most of the Northern Hemisphere were to some extent contaminated by the Chernobyl radionuclide fallout.
6. Levels (amount) of contamination are expressed as in the original papers—either in Curies per square kilometer (Ci/km^2) or in Bequerels per square meter (Bq/m^2).

The structure of this volume is as follows: Chapter I provides an estimate of the level and character of radioactive contamination released from the Chernobyl accident, affecting primarily the Northern Hemisphere. Chapter II analyzes the public health consequences of the catastrophe. Chapter III documents the consequences for the environment. Chapter IV discusses measures for minimizing the Chernobyl consequences for Belarus, Ukraine, and Russia. The volume comes to an end with general conclusions and an index (available online only).

In spite of a vast amount of material, the current information is not comprehensive because new studies are continually being released. However, it is necessary for humankind to deal with the consequences of this, the largest technological catastrophe in history, and so these data are presented.

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ALEXEY V. YABLOKOV AND VASSILY B. NESTERENKO

This book had been nearly completed when Prof. Vassily Nesterenko passed away on August 23, 2008. He was a great person who, like Andrey Sakharov, stopped his own bright professional nuclear career as the general design engineer of the Soviet Union's mobile nuclear power plant "Pamir" and director of Belarussian Nuclear Center to devote his life's efforts to the protection of humankind from Chernobyl's radioactive dangers.

ALEXEY V. YABLOKOV

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The present book would have been impossible without the help of many experts and activists. Forty-nine researchers, primarily from Ukraine, Belarus, and Russia, provided original material or reviews of specific topics to Greenpeace International, which have been widely used (see below).

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This English edition would have been impossible without Dr. Janette Sherman-Nevinger, who tirelessly scientifically edited our very rough translation.

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Introduction: The Difficult Truth about Chernobyl

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For millions of people on this planet, the explosion of the fourth reactor of the Chernobyl nuclear power plant on April 26, 1986 divided life into two parts: *before* and *after*. The Chernobyl catastrophe was the occasion for technological adventurism and heroism on the part of the "liquidators," the personnel who worked at the site attempting to contain the escaping radiation, and, in our view, for cowardice on the part of people in public life who were afraid to warn the population of the unimaginable threat to innocent victims. Chernobyl has become synonymous with human suffering and has brought new words into our lives—Chernobyl liquidators, children of Chernobyl, Chernobyl AIDs, Chernobyl contamination, Chernobyl heart, Chernobyl dust, and Chernobyl collar (thyroid disease), etc.

For the past 23 years it has been clear that there is a danger greater than nuclear weapons concealed within nuclear power. Emissions from this one reactor exceeded a hundredfold the radioactive contamination of the bombs dropped on Hiroshima and Nagasaki. No citizen of any country can be assured that he or she can be protected from radioactive contamination. One nuclear reactor can pollute half the globe. Chernobyl fallout covered the entire Northern Hemisphere.

The questions persist: How many radionuclides spread over the world? How much radiation is still stored inside the sarcophagus, the dome that covers the reactor? No one knows for certain, but the estimates vary from 50×10^6 Ci, or 4–5% of the total radionuclides released from the reactor, to the reactor being essentially empty and more than 10×10^9 Ci dispersed over the globe (Chapter I.1). It is not known how many liquidators ultimately took part in the mitigation; a directive from the USSR Ministry of Defense, dated June 9, 1989, mandated secrecy (Chapter II.3).

In April 2005, prior to the 20th anniversary of the catastrophe, the Third Chernobyl Forum Meeting was held in Vienna. Forum experts included representatives from the International Atomic Energy Agency (IAEA), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the World Health Organization (WHO), and other individuals from the United Nations, the World Bank, and governmental organizations from Belarus, Russia, and Ukraine. The result was a three-volume report presented in September 2005 (IAEA, 2005; UNDP, 2002; WHO, 2006; for the latest short version see IAEA, 2006).

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The basic conclusion of the report's medical volume is that 9,000 victims died or developed radiogenic cancers, but given the background of spontaneous cancers, "it will be difficult to determine the exact cause of the deaths." Some 4,000 children were operated on for thyroid cancer. In the contaminated areas, cataracts were increasingly seen in liquidators and children. Some believe that poverty, feelings of victimization, and fatalism, which are widespread among the population of the contaminated areas, are more dangerous than the radioactive contamination. Those experts, some of whom were associated with the nuclear industry, concluded that as a whole, the adverse consequences for the health of the people were not as significant as previously thought.

An opposing position was voiced by Secretary-General Kofi Annan:

> Chernobyl is a word we would all like to erase from our memory. But more than seven million of our fellow human beings do not have the luxury of forgetting. They are still suffering, everyday, as a result of what happened . . . The exact number of victims can never be known. But three million children demanding treatment until 2016 and earlier represents the number of those who can be seriously ill . . . their future life will be deformed by it, as well as their childhood. Many will die prematurely. (AP, 2000)

No fewer than three billion persons inhabit areas contaminated by Chernobyl's radionuclides. More than 50% of the surface of 13 European countries and 30% of eight other countries have been contaminated by Chernobyl fallout (Chapter I.1). Given biological and statistical laws the adverse effects in these areas will be apparent for many generations.

Soon after the catastrophe, concerned doctors observed a significant increase in diseases in the contaminated areas and demanded help. The experts involved with the nuclear industry and highly placed tribunals declared that there is no "statistically authentic" proof of Chernobyl radiation, but in the 10 years immediately following the catastrophe, official documents recognized that the number of thyroid cancers grew "unexpectedly." Prior to 1985 more than 80% of children in the Chernobyl territories of Belarus, Ukraine, and European Russia were healthy; today fewer than 20% are well. In the heavily contaminated areas it is difficult to find one healthy child (Chapter II.4).

We believe it is unreasonable to attribute the increased occurrence of disease in the contaminated territories to screening or socioeconomic factors because the only variable is radioactive loading. Among the terrible consequences of Chernobyl radiation are malignant neoplasms and brain damage, especially during intrauterine development (Chapter II.6).

Why are the assessments of experts so different?

There are several reasons, including that some experts believe that any conclusions about radiation-based disease requires a correlation between an illness and the received dose of radioactivity. We believe this is an impossibility because no measurements were taken in the first few days. Initial levels could have been a thousand times higher than the ones ultimately measured several weeks and months later. It is also impossible to calculate variable and "hot spot" deposition of nuclides or to measure the contribution of all of the isotopes, such as Cs, I, Sr, Pu, and others, or to measure the kinds and total amount of radionuclides that a particular individual ingested from food and water.

A second reason is that some experts believe the only way to make conclusions is to calculate the effect of radiation based upon the total radiation, as was done for those exposed at Hiroshima and Nagasaki. For the first 4 years after the atomic bombs were dropped on Japan, research was forbidden. During that time more than 100,000 of the weakest died. A similar pattern emerged after Chernobyl. However, the USSR authorities officially forbade doctors from connecting diseases with radiation and, like the Japanese experience, all data were classified for the first 3 years (Chapter II.3).

In independent investigations scientists have compared the health of individuals in various territories that are identical in terms of ethnic, social, and economic characteristics and differ only in the intensity of their exposure to radiation. It is scientifically valid to compare specific groups over time (a longitudinal study), and such comparisons have unequivocally attributed differences in health outcomes to Chernobyl fallout (Chapter II.3).

This volume is an attempt to determine and document the true scale of the consequences of the Chernobyl catastrophe.

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Chapter I. Chernobyl Contamination: An Overview

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Key words: **Chernobyl; radioactive contamination; lead contamination; Northern Hemisphere**

1. Chernobyl Contamination through Time and Space

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Radioactive contamination from the Chernobyl meltdown spread over 40% of Europe (including Austria, Finland, Sweden, Norway, Switzerland, Romania, Great Britain, Germany, Italy, France, Greece, Iceland, Slovenia) and wide territories in Asia (including Turkey, Georgia, Armenia, Emirates, China), northern Africa, and North America. Nearly 400 million people resided in territories that were contaminated with radioactivity at a level higher than 4 kBq/m^2 (0.11 Ci/km^2) from April to July 1986. Nearly 5 million people (including, more than 1 million children) still live with dangerous levels of radioactive contamination in Belarus, Ukraine, and European Russia. Claims that the Chernobyl radioactive fallout adds "only 2%" to the global radioactive background overshadows the fact that many affected territories had previously dangerously high levels of radiation. Even if the current level is low, there was high irradiation in the first days and weeks after the Chernobyl catastrophe. There is no reasonable explanation for the fact that the International Atomic Energy Agency and the World Health Organization (Chernobyl Forum, 2005) have completely neglected the consequences of radioactive contamination in other countries, which received more than 50% of the Chernobyl radionuclides, and addressed concerns only in Belarus, Ukraine, and European Russia.

To fully understand the consequences of Chernobyl it is necessary to appreciate the scale of the disaster. Clouds of radiation reached heights between 1,500 and 10,000 m and spread around the globe, leaving deposits of radionuclides and radioactive debris, primarily in the Northern Hemisphere (Figure 1.1).

There has been some dispute over the years as to the volume of radionuclides released when reactor number four of the Chernobyl Nuclear Power Plant (ChNPP) exploded, and it is critical to be aware of the fact that there continue to be emissions. That release, even without taking the gaseous radionuclides into account, was many hundreds of millions of curies, a quantity hundreds of times larger than the fallout from the atomic bombs dropped on Hiroshima and Nagasaki.

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1.1. Radioactive Contamination

Immediately after the explosion, and even now, many articles report levels of radioactivity calculated by the density of the contamination—Ci/km^2 (Bq/m^2). While these levels form a basis for further calculations of collective and individual doses, as shown below, such an approach is not completely valid as it does not take into account either the ecological or the physical aspects of radioactive contamination, nor does it provide exact calculations of received doses (see Chapter II.2).

1.2. Geographical Features of Contamination

Immediately after the NPP explosion, attempts began to reconstruct the radioactive fallout picture to determine radioactive fallout distribution levels using hydrometeorological data (wind direction, rainfall, etc.) for each

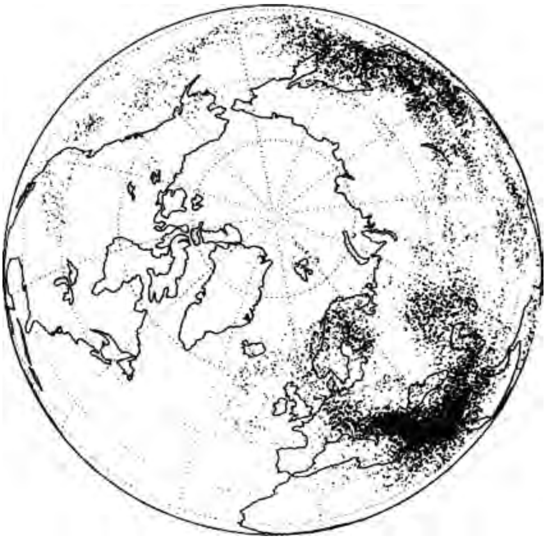

Figure 1.1. Spatial distribution of Chernobyl radionuclides in the Northern Hemisphere 10 days after the explosion. U.S. Livermore National Laboratory modeling (Lange *et al.*, 1992).

subsequent day and include emissions of fuel particles, aerosol particles, and radioactive gases from the destroyed reactor (see, e.g., Izrael, 1990; Borzylov, 1991; UNSCEAR, 2000; Fairlie and Sumner, 2006). Geographic distribution of Chernobyl radionuclides around the globe is shown in Figure 1.2. It is clear that most of the gaseous–aerosol radionuclides settled outside of Belarus, Ukraine, and European Russia (Figure 1.3, Table 1.1).

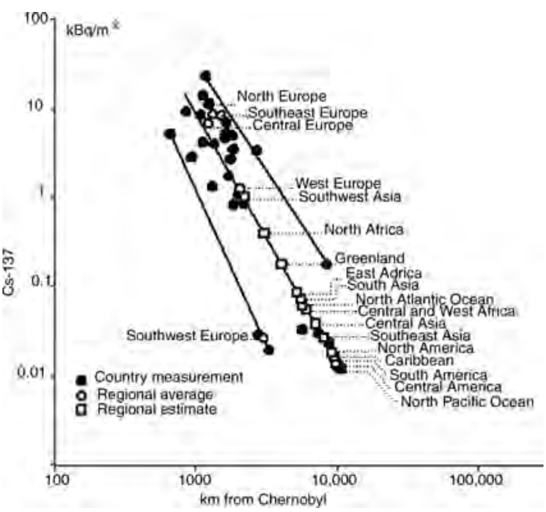

Figure 1.2. Geographic distribution of Chernobyl radionuclides (UNSCEAR, 1988).

1.2.1. Europe

According to other data (Fairlie and Sumner, 2006, table 3.6, cc. 48 & 49) Europe received from about 68 to 89% of the gaseous–aerosol radionuclides from the Chernobyl clouds in a distribution that was extremely nonuniform. From April 26 through May 5, 1986, the winds around Chernobyl varied by 360°, so the radioactive emissions from the mix of radionuclides varied from day to day and covered an enormous territory (Figures 1.4, 1.5, and 1.6).

Figure 1.7 is a reconstruction of only one of the Chernobyl clouds (corresponding to No. 2 on Figure 1.4). It is important to understand that radionuclide emissions from the burning reactor continued until the middle of May. The daily emissions formed several radioactive clouds, and each such cloud had its own radionuclide composition and geography. We do not have accurate instrumental data for Chernobyl radionuclide contamination for all of Europe. Calculated data (averaged for 1 km^2) were published only for Cs-137 and Pu, while Cs-137 contaminated all of the European countries, without exception (Table 1.2).

The data in Table 1.2 refer only to the distribution of Cs-137, but there were significant quantities of many other radionuclides in the form of gases, aerosols, and "hot particles" (see below) widely dispersed across Europe in the first weeks and months following the explosion: Cs-134, I-131, Sr-90, Te-132, and I-132. For example, in May 1986 in Wales and in the Cumbria area of England rainwater contained up to 345 Bq/liter of I-132 and 150 Bq/liter Cs-134 (Busby, 1995). The effective doses in May 1986 for Chernobyl radionuclides in England were: Cs-134 and Cs-137, 27 mSv; I-131, 6 mSv; Sr-90, 0.9 mSv (Smith *et al.* (2000).

If the distribution of radioactivity for Cs-134 and Cs-137 corresponds to their ratio in emissions (i.e., 48 and 85 PBq, or 36 and 64%, respectively), then the proportional distribution

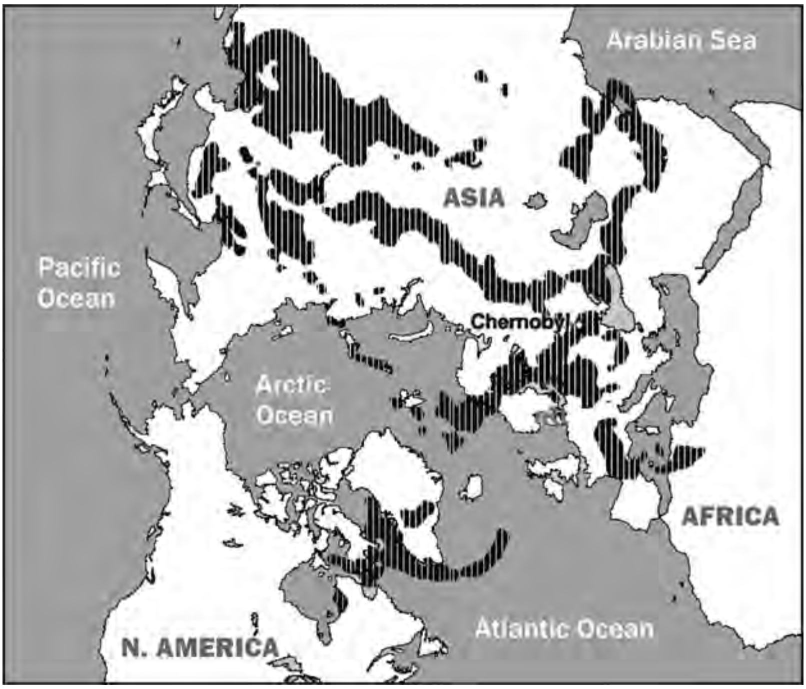

Figure 1.3. Chernobyl radioactive fallout in the Northern Hemisphere (Livermore National Laboratory data from Yablokov *et al.*, 2006).

of the main Chernobyl radionuclides in England should be as follows [Dreicer *et al.*, 1996; Fairlie and Sumner, 2006, Table 3.8(i)]:

	mSv	%
Cs-137	17.3	51.0
Cs-134	9.7	28.6
I-131	6.0	17.7
Sr-90	0.9	2.7
Total	33.9	100

If the proportional distribution of Chernobyl radionuclides in England is similar to that of other European countries (i.e., 70 PBq Cs-137 made up 51% of all the radionuclide fallout), one can assume that the total amount of radioactive fallout in Europe is nearly 137 PBq:

	%	PBq
Cs-137	51.0	70[a]
Cs-134	28.6	39
I-131	17.7	24
Sr-90	2.7	3.7
Total	100	136.7

[a]See Table 1.2.

Twenty years after the Chernobyl catastrophe, many areas in Europe remain contaminated. For example, in 2006, according to Great Britain's Ministry of Health 355 farms in Wales, 11 in Scotland, and 9 in England, pasturing more than 200,000 sheep, continue to be dangerously contaminated with Cs-137 (McSmith, 2006).

1.2.1.1. Belarus

Practically the entire country of Belarus was covered by the Chernobyl cloud. I-131, I-132, and Te-132 radioisotope fallout covered the entire country (Figures 1.8 through 1.12). A maximum level of I-131 contamination of 600 Ci/km^2 was measured in the Svetlovichi village in Gomel Province in May 1986.

Some 23% of the area of Belarus (47,000 km^2) was contaminated by Cs-137 at a level higher than 1 Ci/km^2 (Nesterenko, 1996; Tsalko, 2005). Until 2004, the density of Cs-137 contamination exceeded 37 kBq/m^2 in 41,100 km^2 (Figure 1.10).

TABLE 1.1. Estimations of a Geographic Distribution of Chernobyl's Cs-137, % (PBq) (Fairlie and Sumner, 2006, pp. 48–49)

	UNSCEAR, 1988; Fairlie and Sumner, 2006, p. 48	Goldman, 1987; Fairlie and Sumner, 2006: table 3.6.	UNSCEAR, 2000	
Belarus, Ukraine, European Russia	<50	41 (29)	34 (33)	47 (40)
Other European countries	;39	37 (26)	34 (33)	60 (45)
Asia	8	21 (15)	33 (32)	No
Africa	6	No	No	No
America	0.6	No	No	No
	100	100 (70)	100 (98)	100 (85)

Maximum levels of Cs-137 contamination were 475 Ci/km^2 in the village of Zales'ye, Braginsk District, and 500 Ci/km^2 in the village of Dovliady and the Narovlja District of Gomel Province. The maximum radioactive contamination in the soil found in 1993 in the village of Tchudyany, Mogilev District, was 5,402 kBq/m^2 or 145 Ci/km^2, exceeding the precatastrophe level by a factor of 3,500 (Il'yazov, 2002).

Contamination from Sr-90 has a more local character than that of Cs-137. Some 10% of the area of Belarus has levels of Sr-90 soil contamination above 5.5 kBq/m^2, covering an

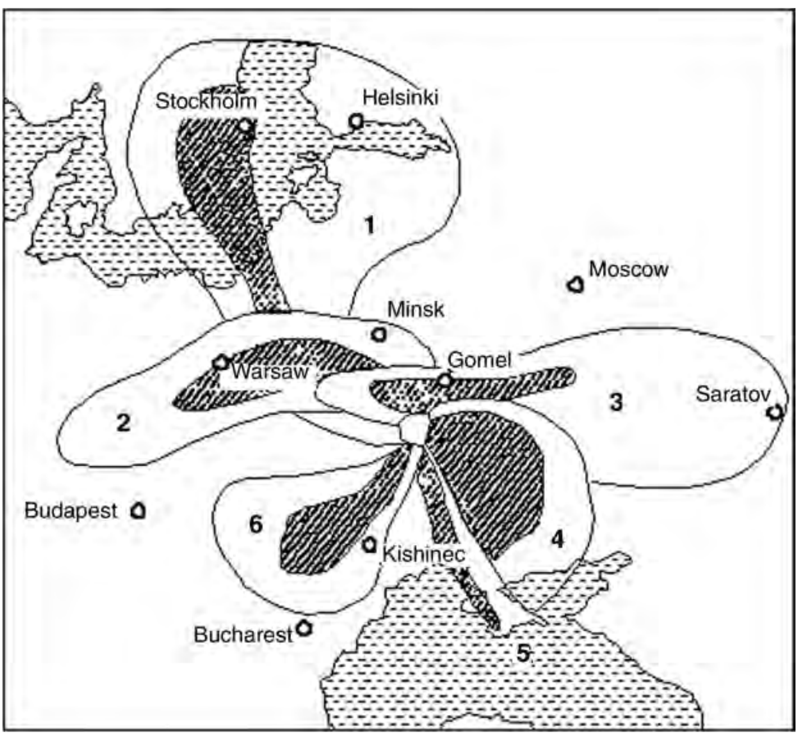

Figure 1.4. Six stages of formation of radioactive gaseous–aerosol emissions from Chernobyl from April 26 to May 4, 1986: (1) April 26, 0 hours (Greenwich time); (2) April 27, 0 hours; (3) April 27, 12.00 hours; (4) April 29, 0 hours; (5) May 2, 0 hours; (6) May 4, 12.00 hours (Borzylov, 1991). Shading indicates the main areas of the radionuclide fallout.

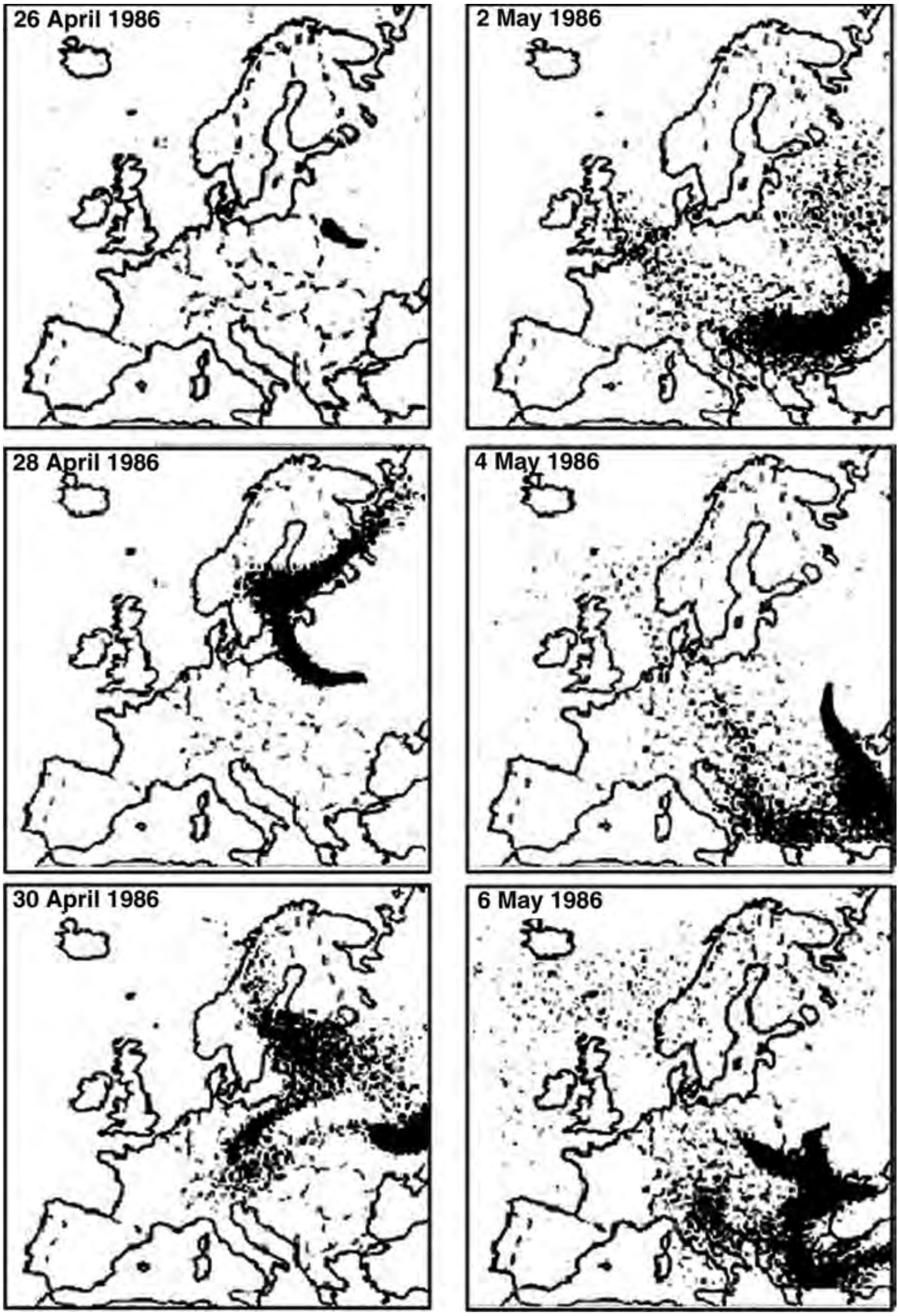

Figure 1.5. An alternative version of radioactive gaseous–aerosol distribution over Europe from April 26 to May 6, 1986 (National Belarussian Report, 2006).

area of 21,100 km^2 (Figure 1.11). Soil contaminated by Pu-238, Pu-239, and Pu-240 at levels higher than 0.37 kBq/m^2 was found in 4,000 km^2, or nearly 2% of the country (Konoplya *et al.*, 2006; Figure 1.12). As a whole, more than 18,000 km^2 of agricultural land or 22% of Belarus farmland is heavily contaminated. Of that, an area of 2,640 km^2 cannot be used

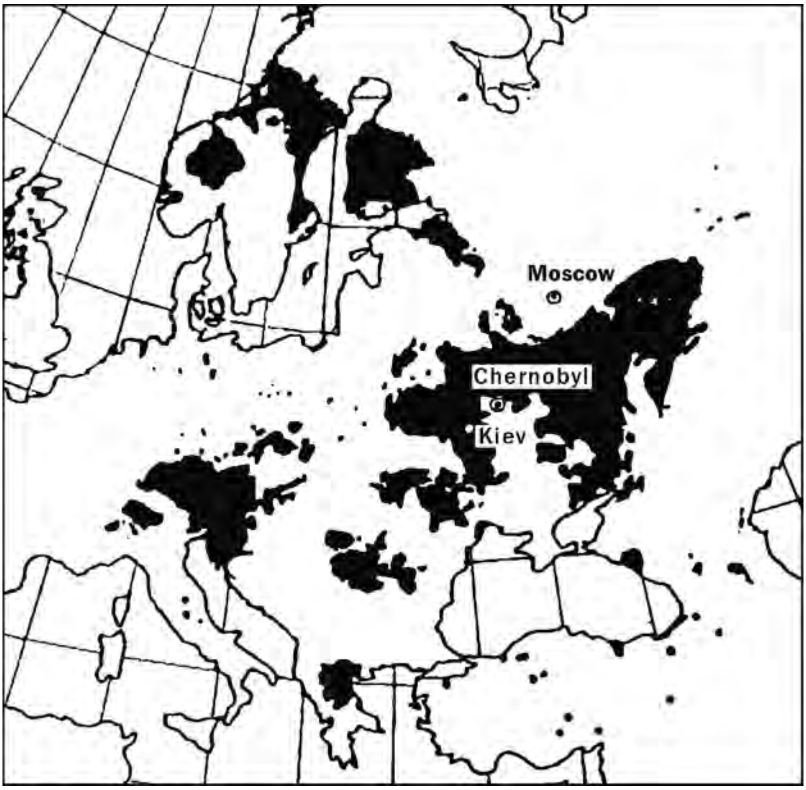

Figure 1.6. Some of the main areas of Europe contaminated at a level higher than 1 Ci/km^2 by Cs-137 as a result of the Chernobyl catastrophe. Turkey was surveyed only in part and Bulgaria, Yugoslavia, Portugal, Iceland, and Sicily were not surveyed at all (Cort and Tsaturov, 1998).

for agriculture and the 1,300-km^2 Polessk state radioactive reserve near the Chernobyl NPP is forever excluded from any economic activity owing to contamination by long half-life isotopes.

1.2.1.2. Ukraine

Chernobyl radionuclides have contaminated more than a quarter of Ukraine, with Cs-137 levels higher than 1 Ci/km^2 in 4.8% of the country (Figure 1.13).

1.2.1.3. European Russia

Until 1992 contamination in European Russia was found in parts of 19 Russian provinces (Table 1.3), so consideration must be given to serious contamination in the Asian part of Russia as well.

1.2.1.4. Other European Countries

The level of Chernobyl's Cs-137 contamination in each European country is shown in Table 1.2; some additional comments follow.

1. Bulgaria. The primary Chernobyl radionuclides reached Bulgaria on May 1–10, 1986. There were two peaks of fallout: May 1 and 9 (Pourchet *et al.*, 1998).

2. Finland. Chernobyl fallout clouds over southern Finland reached peak concentrations between 15:10 and 22:10 hours on April 28, 1986.

3. France. Official Service Central de Protection Contre les Radiations Ionisantes initially denied that the radioactive cloud had passed over France. This is contrary to the finding that a significant part of the country, especially the alpine regions, were

TABLE 1.2. Cs-137 Contamination of European Countries from Chernobyl (Cort and Tsaturov, 1998: table III.1; Fairlie and Sumner, 2006: tables 3.4 and 3.5)

			Portion (%)	
Country	PBq (kCi) Cort and Tsaturov, 1998[c]	Fairlie and Sumner, 2006[d]	Cort and Tsaturov, 1998[c]	Fairlie and Sumner, 2006[d]
Russia[a]	19 (520)	29	29.7	31.96
Belarus	15 (400)	15	23.0	16.53
Ukraine	12 (310)	13	18.0	14.33
Finland	3.1 (8.3)	3.8	4.80	4.19
Yugoslavia	?	5.4	–	5.95
Sweden	2.9 (79)	3.5	4.60	3.86
Norway	2.0 (53)	2.5	3.10	2.75
Bulgaria	?	2.7	–	2.98
Austria	1.6 (42)	1.8	2.40	1.98
Romania	1.5 (41)	2.1	2.40	2.31
Germany	1.2 (32)	1.9	1.80	2.10
Greece	0.69 (19)	0.95	1.10	1.05
Italy	0.57 (15)[b]	0.93	0.90	1.02
Great Britain	0.53 (14)	0.88	0.83	0.97
Poland	0.40 (11)	1.2	0.63	1.32
Czech Republic	0.34 (93)	0.6	0.54	0.66
France	0.35 (9.4)	0.93	0.55	1.02
Moldova	0.34 (9.2)	0.40	0.53	0.44
Slovenia	0.33 (8.9)	0.39	0.52	0.43
Albania	?	0.4	–	0.44
Switzerland	0.27 (7.3)	0.36	0.43	0.40
Lithuania	0.24 (6.5)	0.44	0.38	0.48
Ireland	0.21 (5.6)	0.35	0.33	0.39
Croatia	0.21 (5.8)	0.37	0.33	0.40
Slovakia	0.18 (47)	0.32	0.28	0.35
Hungary	0.15 (4.1)	0.35	0.24	0.39
Turkey[a]	0.10 (2.8)	0.16	0.16	0.18
Latvia	0.055 (1.5)	0.25	0.09	0.28
Estonia	0.051 (1.4)	0.18	0.08	0.2
Spain	0.031 (0.83)	0.38	0.05	0.42
Denmark	0.016 (0.43)	0.09	0.02	0.10
Belgium	0.01 (0.26)	0.05	0.02	0.06
The Netherlands	0.01 (0.26)	0.06	0.02	0.07
Luxembourg	0.003 (0.08)	0.01	<0.01	0.01
Europe as a whole	64 (1700)[c]	90.8[e]	100.0	100.0

[a]European Russia.
[b]Without Sicily.
[c]Without Yugoslavia, Bulgaria, Albania, Portugal, and Iceland.
[d]Without Portugal and Iceland.
[e]Includes nearly 20 PBq Cs-137, remaining from nuclear weapons tests before the 1970s.

contaminated on April 29 and 30, 1986 (see Figure 1.5).

4. GERMANY. The scale of Chernobyl's contamination in Germany is reflected in the fact that several shipments of powdered milk to Africa were returned to West Germany because they were dangerously contaminated with radiation (Brooke, 1988).

5. GREECE. Greece reported significant fallout of several Chernobyl radionuclides

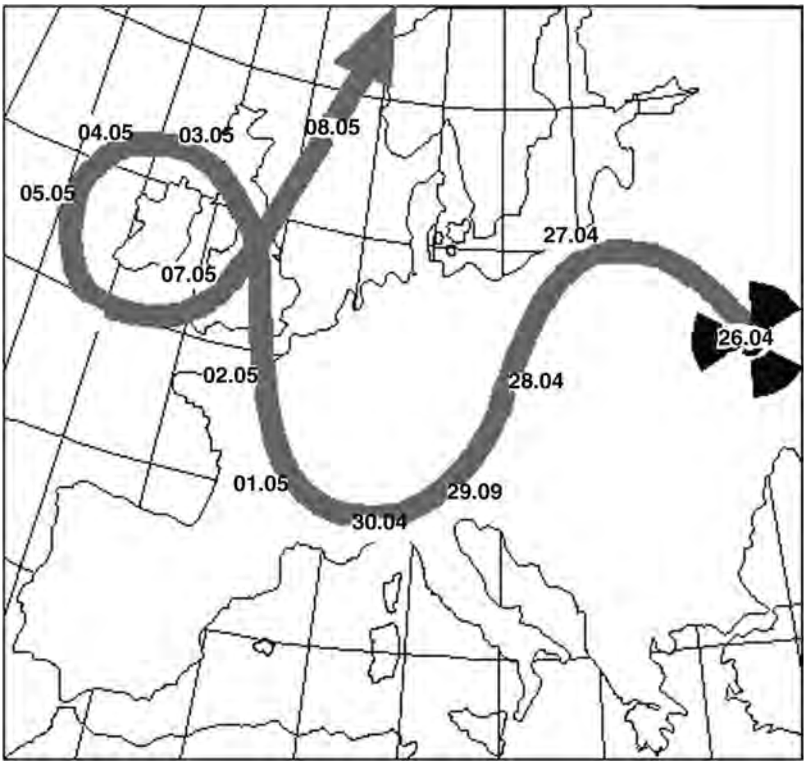

Figure 1.7. The path of one Chernobyl radioactive cloud across Europe from April 27 to early May 1986 (Pakumeika and Matveenka, 1996).

including: Ag-110 m, Cs-137, and Sb-125 (Papastefanou *et al.*, 1988a,b; see Figure 1.16).

Noting unusual contamination (see Section 1.4.1 below) is important, but it is also evidence of the inadequacy of the available data relevant to Chernobyl contamination: where are comparable data about radioactive Ag-110 m contamination in other countries? Do data not exist because no one has compiled it or because this radioactive Ag contaminated only Greece, Italy, and Scotland (Boccolini *et al.*, 1988; Martin *et al.*, 1988)?

6. ITALY. There were several radioactive plumes, but the main Chernobyl fallout cloud passed over northern Italy on May 5, 1986. Some 97% of the total deposition in Italy occurred between April 30 and May 7 (Spezzano and Giacomelli, 1990).

7. POLAND. The main plume passed over Poland around April 30, 1986, with Te-122 as the primary radionuclide. Numerous "hot particles" were detected with a prevalence of Ru-103 and Ru-106 (Broda, 1987). In June 1987, a 1,600-ton shipment of powdered milk from Poland to Bangladesh showed unacceptably high levels of radioactivity (Mydans, 1987).

8. SCOTLAND. The main radioactive plume passed Scotland between 21:00 and 23:00 hours on May 3, 1986, with the largest concentrations of Te-132, I-132, and I-131 (Martin *et al.*, 1988).

9. SWEDEN. The peak concentration of Cs-137 in air occurred on April 28, 1986, but 99% of Chernobyl-derived radionuclides were deposited in Sweden during a single period of rain on May 8, 1986. Patterns of fallout related to local weather conditions: Cs-137 dominated on the coast of southern Norrland, I-131 in the north and south, and Te-132 in the

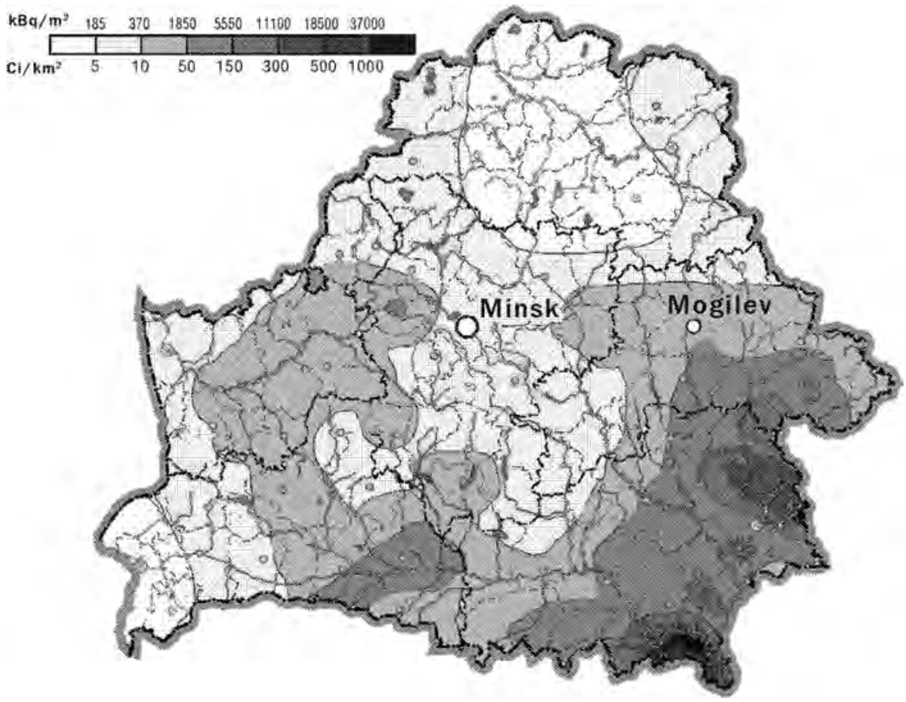

Figure 1.8. Reconstruction of I-131 contamination of Belarus for May 10, 1986 (National Belarussian Report, 2006).

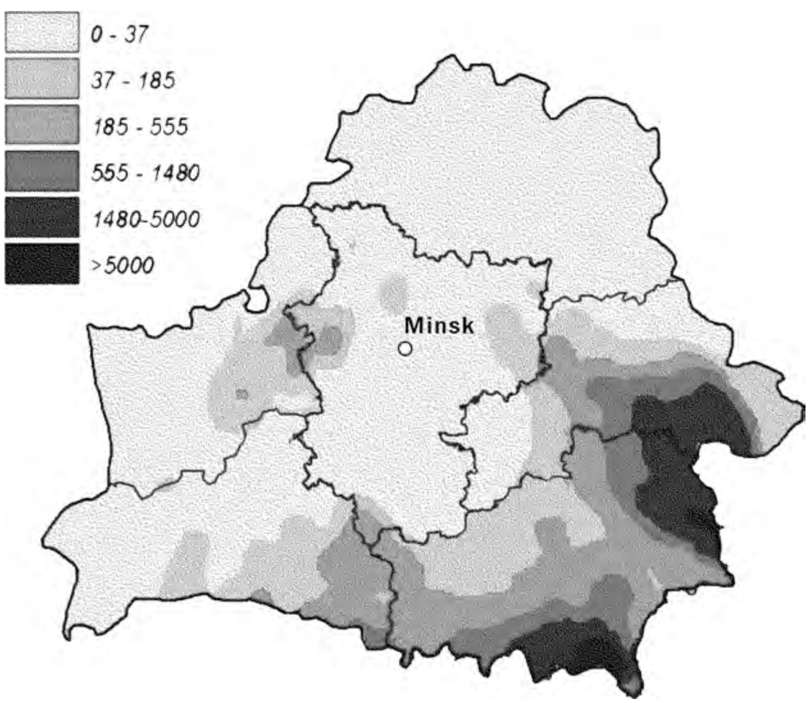

Figure 1.9. Reconstruction of Te-132 and I-132 contamination of Belarus from April to May 1986 (Zhuravkov and Myronov, 2005).

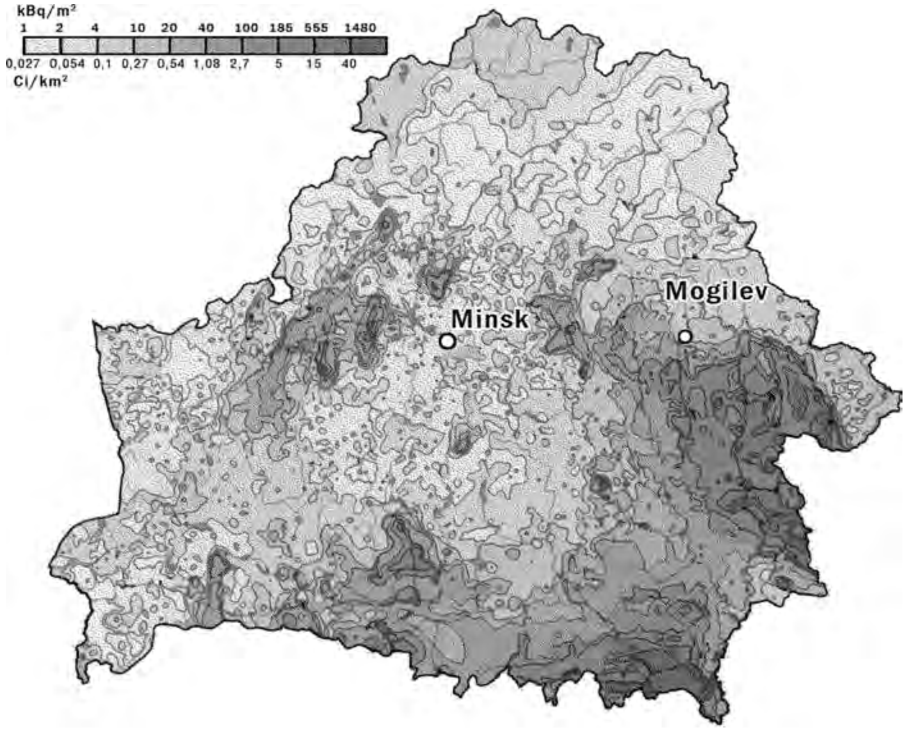

Figure 1.10. Reconstruction of contamination of territory of Belarus by Cs-137 for May 10, 1986 (National Belarussian Report, 2006).

central Upland area (Kresten and Chyssler, 1989; Mattson and Vesanen, 1988; Mellander, 1987).

10. United Kingdom. Official reports grossly underestimated the Chernobyl-derived fallout and its radiological impact on the United Kingdom. Cs-137 deposition in Cumbria was up to 40 times higher than originally reported by the Ministry of Agriculture, Fisheries and Food (RADNET, 2008; Sanderson and Scott, 1989).

11. Yugoslavia. The main radioactive fallout occurred on May 3–5, 1986 (Juznic and Fedina, 1987).

1.2.2. Asia

Up to 10% of all the Chernobyl radionuclides fell on Asia, including, basically, some tens of PBq of the first, most powerful emissions on the first days of the catastrophe. Huge areas of Asian Russia (Siberia, Far East), East and Central China (Figure 1.14), and the Asian part of Turkey were highly contaminated. Chernobyl fallout was noted in central Asia (Imamniyazova, 2001) and in Japan (Imanaka, 1999; Figure 1.14).

1. Trans-Caucasus. Western Georgia was especially heavily contaminated. The average soil radioactivity due to Cs-137 from 1995 to 2005 was 530 Bq/kg, and that figure was twice as high in East Georgia. The combined activity of Cs-137 and Sr-90 reached 1,500 Bq/kg (Chankseliany, 2006; Chankseliany *et al.*, 2006).

2. Japan. Twenty Chernobyl radionuclides were detected in two plumes in early and late May 1986, with the highest level in northwestern Japan and a maximum concentration on May 5. Chernobyl-derived stratospheric fallout continued until the end of 1988 (Higuchi *et al.*, 1988; Imanaka and Koide, 1986).

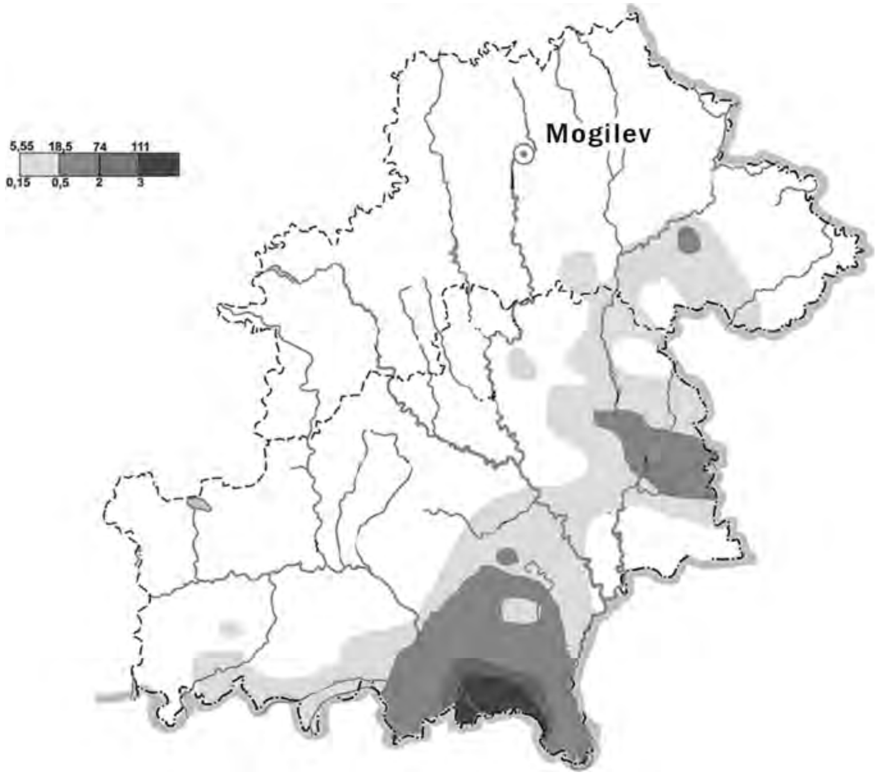

Figure 1.11. Sr-90 contamination of Belarus at the beginning of 2005 (National Belarussian Report, 2006).

There is still a high probability of small but dangerously radioactive areas in the Caucasus; Trans-Caucasia; lower, central, and middle Asia (including Turkey, Iran, Iraq, and Afghanistan); China; and the Persian Gulf area, continuing until the present time.

1.2.3. North America

Areas in North America were contaminated from the first, most powerful explosion, which lifted a cloud of radionuclides to a height of more than 10 km. Some 1% of all Chernobyl radionuclides—nearly several PBq—fell on North America.

1. Canada. There were three waves of Chernobyl airborne radioactivity over eastern Canada composed of: Be-7, Fe-59, Nb-95, Zr-95, Ru-103, Ru-106, I-131, La-140, Ce-141, Ce-144, Mn-54, Co-60, Zn-65, Ba-140, and Cs-137. The fallout of May 6 and 14 arrived via the Arctic, and that of May 25 and 26 via the Pacific (Roy *et al.*, 1988). By the official "Environmental Radioactivity in Canada" report for 1986 (RADNET, 2008) Chernobyl Ru-103, Ru-106, Cs-134, and Cs-137 were consistently measurable until about mid-June.

2. United States. The Chernobyl plumes crossed the Arctic within the lower troposphere and the Pacific Ocean within the mid-troposphere, respectively. Chernobyl isotopes of Ru-103, Ru-106, Ba-140, La-140, Zr-95, Mo-95, Ce-141, Ce-144, Cs-134, Cs-136, Cs-137, I-132, and Zr-95 were detected in Alaska, Oregon, Idaho, New Jersey, New York, Florida, Hawaii, and other states (Table 1.4).

An Associated Press release on May 15, 1986, noted "Officials in Oregon have warned that those who use rainwater for drinking should use other sources of water for some time."

Figure 1.12. Transuranic radionuclide contamination of Belarus in 2005 (National Belarussian Report, 2006).

1.2.4. Arctic Regions

A high level of Chernobyl contamination is found in Arctic regions. The moss *Racomitrium* on Franz Josef Land contained up to 630 Bq/kg (dry weight) of Cs-137 of which 548 Bq/kg (87%) came from the Chernobyl fallout (Rissanen *et al.*, 1999).

1.2.5. Northern Africa

Radionuclide fallout in northern Africa came from the most powerful emissions on the first day of the catastrophe and that area has been subject to more than 5% of all Chernobyl releases—up to 20 PBq.

1. Egypt. The Cs-137 to Pu-239/Pu-240 ratio in accumulated Nile River sediment is evidence of significant Chernobyl contamination (Benninger *et al.*, 1998).

1.2.6. Southern Hemisphere

In the Southern Hemisphere Cs-137 and Cs-134 from Chernobyl have been found on Reunion Island in the Indian Ocean and on Tahiti in the Pacific. The greatest concentration of Cs-137 in the Antarctic was found near the South Pole in snow that fell from 1987 to 1988 (UNSCEAR, 2000).

1.3. Estimates of Primary Chernobyl Radionuclide Emissions

The official view was that the total radionuclide emissions calculated for May 6, 1986, the

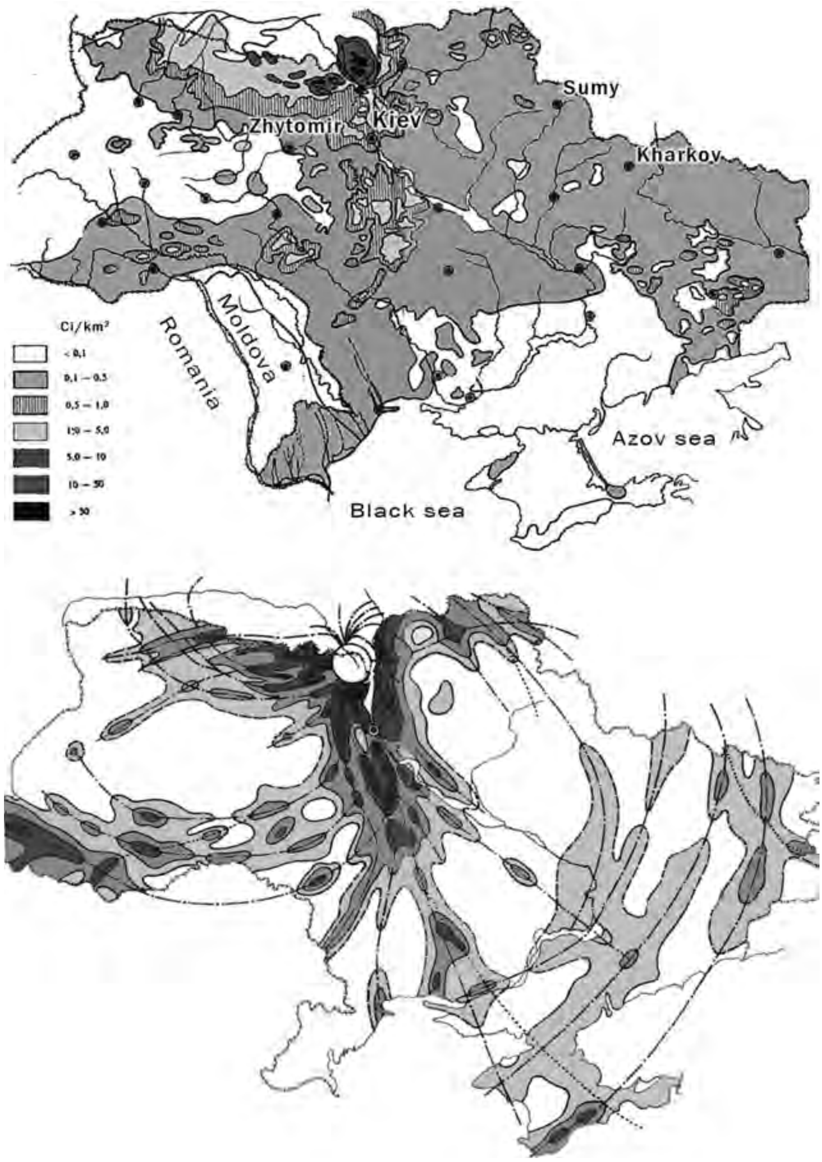

Figure 1.13. Contamination of Ukraine [Cs-137 (above) and Pu (below)] as a result of the Chernobyl catastrophe (National Report of Ukraine, 2006).

time when most of the short-lived radionuclides had decayed, was 50×10^6 Ci or 1.85×10^{18} Bq (Izrael, 1990, 1996). It was estimated that 3–4% of the fuel from the moment of meltdown (i.e., from 190.3 tons) was blown out of the reactor, a serious underestimation. Emissions continued after May 6, with intensity decreasing over 10 days until the graphite lining of the reactor stopped burning. Emission of radioactive substances into the atmosphere was prolonged. UNSCEAR (2000) estimated that the total activity of ejected radionuclides was 1.2×10^{19} Bq, including $1.2–1.7 \times 10^{18}$ Bq of I-131 and 3.7×10^{16} Bq of Cs-137.

UNSCEAR reports (1988, 2000) contain data (comparable with emissions of I-131) about an enormous volume of emissions of Te-132 (half-life 78 h and decaying into

TABLE 1.3. Radioactive Contamination of European Russia (≥1 Ci/km²) as a Result of the Chernobyl Catastrophe (Yaroshinskaya, 1996)

Province	Contaminated area, 1×10^3 km^2	Population, 10^3
Tula	11.5	936.2
Bryansk	11.7	476.5
Oryol	8.4	346.7
Ryazan	5.4	199.6
Kursk	1.4	140.0
Penza	3.9	130.6
Kaluga	4.8	95.0
Belgorod	1.6	77.8
Lipetsk	1.6	71.0
Ulyanovsk	1.1	58.0
Voronezh	1.7	40.4
Leningrad	1.2	19.6
Mordova	1.9	18.0
Tambov	0.5	16.2
Tatarstan	0.2	7.0[a]
Saratov	0.2	5.2[a]
Nizhniy Novgorod	0.1	3.7[a]
Chuvashiya	0.1	1.3[a]
Smolensk	0.1	1.1[a]
Total	56.0	2,644.8

[a]Authors' estimation based on average population density in each province.

radioactive iodine), as well as emissions of Zr-95 (half-life 64 days). According to calculations by Vukovic (1996) there were additional emissions of more than 0.5×10^6 Ci of Ag-110 (half-life 250 days).

Disputes concerning the amount of radionuclides released are important to estimate the collective dose. If only about 3% of the fuel (5 tons) was discharged then the Chernobyl catastrophe caused the world to be contaminated with 20 kg of Pu, a quantity sufficient to contaminate a territory of 20,000 km^2 forever. The half-life of Pu-239 is 24,000 years. If 30–40% of the fuel was released (Gofman, 1994; Medvedev, 1990; Sich, 1996; UNSCEAR, 2000; and others) allowing nearly 3×10^9 Ci to escape, or 80–90% was released (i.e., 7–8 $\times 10^9$ Ci; see Chernousenko, 1992; Kyselev *et al.*, 1996; Medvedev, 1991)—the manifold larger territories of the Northern Hemisphere will be contaminated forever. Table 1.5 shows some estimates of the total of the primary radionuclides emitted during the catastrophe.

All existing estimates of emitted radionuclides are rough calculations and indications are that we will be seeing an appreciable increase in these estimates as time goes on. It is indicative that even 20 years after the catastrophe there are new thoughts about the role of some of the radionuclides that initially were not taken into account at all, such as Cl-36 and Te-99 with half-lives of nearly 30,000 years and more than 23,000 years, respectively (Fairlie and Sumner, 2006).

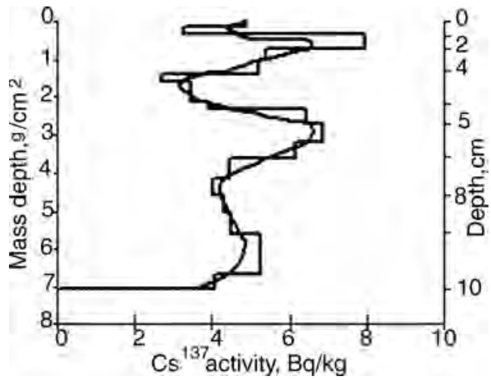

Figure 1.14. Activity of Cs-137 in sediments from Dabusupao Lake (northeast of China). The peak of radioactivity of sediment at a depth of about 6 centimeters is associated with atmospheric nuclear tests, and peaks at a depth of 1–2 centimeters, with the Chernobyl fallout (Xiang, 1998).

TABLE 1.4. Data on the May 1986 Peak Concentrations of Some Nuclides in Areas of the United States (RADNET, 2008)

Date	Place	Radionuclide
May 5, 1986	Forks, WA	Ru-103, Cs-134
May 5, 1986	Spokane, WA	Total
May 7–8, 1986	Augusta, ME	Total
May 8, 1986	Portland, ME	Total
May 11, 1986	Rexburg, ID	I-131, air
May 11, 1986	New York, NY	Cs-137
May 15, 1986	Chester, NJ	Total
May 16, 1986	Cheyenne, WY	Total

TABLE 1.5. Some Estimates of the Amount of Primary Radionuclides Emitted from April 26 to May 20, 1986, from the Fourth Chernobyl NPP Reactor (10^6 Ci)

Radionuclide (*half-life/full decay time, hours, days, months, years*)	Nuclear Energy Agency (1995)	Devell *et al.* (1995)	Medvedev (1991)	Guntay *et al.* (1996)
I-135 *(6.6 h/2.75 d)*			Several	
I-133 *(20.8 h/8.7 d)*	~1.5		140–150	
La-140 *(40.2 h/16.7 d)*			A lot of	
Np-239 *(2.36 d/23.6 d)*	25.6			45.9
Mo-99 *(2.75 d/27.5 d)*	>4.6	4.5		5.67
Te-132 *(3.26 d/32.6 d)*	~37.1	31	A lot of	27.0
Xe-133 *(5.3 d/53 d)*	175.7	180	170	175.5
I-131 *(8.04 d/2.7 mo)*	~47.6	48	>85[b]	32.4–45.9
Ba-140 *(12.8 d/4.3 mo)*	6.5	6.4		4.59
Cs-136 *(12.98 d/4.3 mo)*		0.644[a]		
Ce-141 *(32.5 d/10.8 mo)*	5.3	5.3		5.40
Ru-103 *(39.4 d/1 y 1 mo)*	>4.6	4.5		4.59
Sr-89 *(50.6 d/1.39 y)*	~3.1	3.1		2.19
Zr-95 *(64.0 d/1.75 y)*	5.3	5.3		4.59
Cm-242 *(162.8 d/4.6 y)*	~0.024	0.024		0.025
Ce-144 *(284 d/7.8 y)*	~3.1	3.1		3.78
Ru-106 *(367 d/10 y)*	>1.97	2.0		0.81
Cs-134 *(2.06 y/20.6 y)*	~1.5	1.5	—	1.19–1.30
Kr-85 *(10.7 y/107 y)*	0.89	—	—	0.89
Pu-241 *(14.7 y/147 y)*	~0.16	0.16		0.078
Sr-90 *(28.5 y/285 y)*	~0.27	0.27		0.22
Cs-137 *(30.1 y/301 y)*	~2.3	12.3	*c*	1.89–2.30
Pu-238 *(86.4 y/864 y)*	0.001	0.001	—	0.0001
Pu-240 *(6,553 y/65,530 y)*	0.001	0.001		0.001
Pu-239 *(24,100 y/241,000 y)*	0.023	0.001		0.0001

[a]Cort and Tsaturov (1998).
[b]Nesterenko (1996)—more than 100.
[c]Nesterenko (1996)—total emission of Cs-136 and Cs-137 is up to 420×10^{15} Bq (1.14×10^6 Ci).

1.4. Ecological Features of Contamination

The three most important factors in connection with the Chernobyl contamination for nature and public health are: spotty/uneven deposits of contamination, the impact of "hot particles," and bioaccumulation of radionuclides (also see Chapter III).

1.4.1. Uneven/Spotty Contamination

Until now the uneven/spotty distribution of the Chernobyl radioactive fallout has attracted too little attention. Aerogamma studies, upon which most maps of contamination are based, give only average values of radioactivity for 200–400 m of a route, so small, local, highly radioactive "hot spots" can exist without being marked. The character of actual contamination of an area is shown on Figure 1.15. As can be seen, a distance of 10 m can make a sharp difference in radionuclide concentrations.

"Public health services of the French department Vosges found out that a hog hit by one of local hunters 'was glowing.' Experts, armed with supermodern equipment, conveyed a message even more disturbing: practically the entire mountain where the dead animal had just run is radioactive at a level from 12,000 to 24,000 Bq/m^2. For comparison, the European norm is 600 Bq/m^2. It was remembered that radioactive mushrooms were found

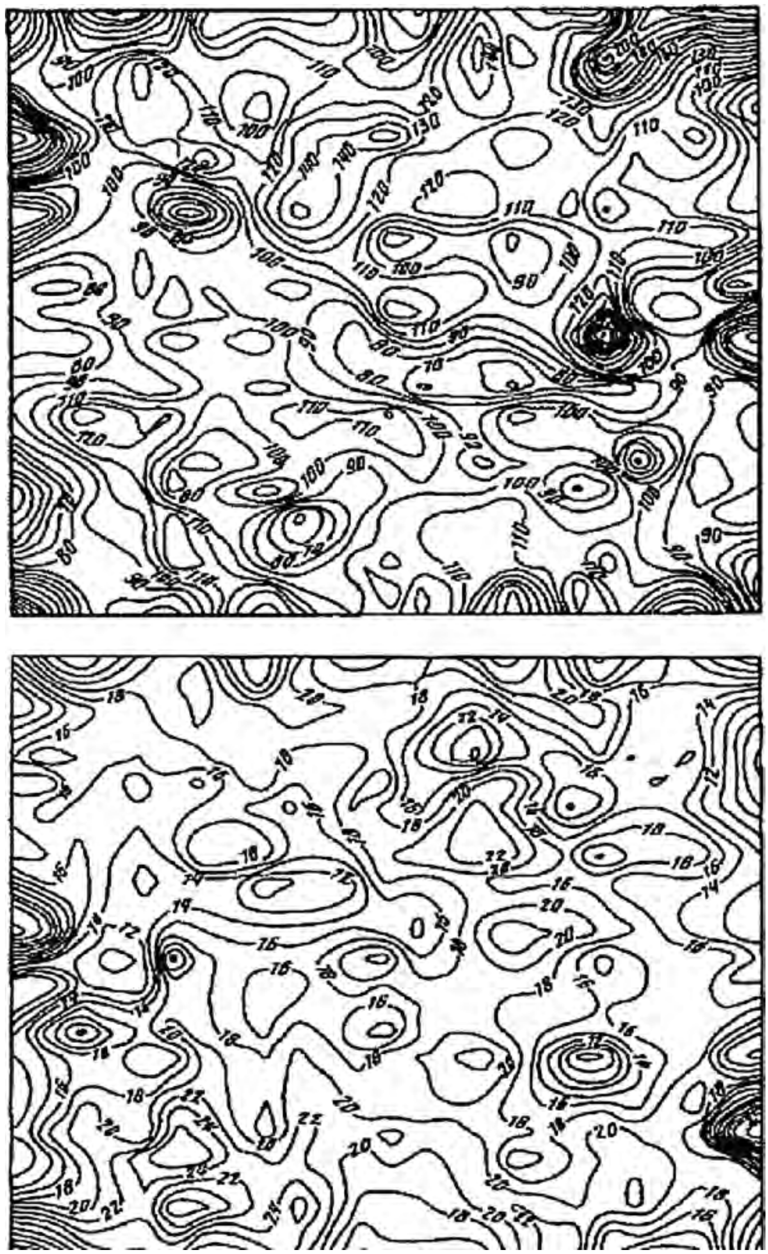

Figure 1.15. Spotty concentration (Ci/km^2) of Cs-137 (above) and Ce-144 (below) in the forest bedding in the 30-km Chernobyl zone. Scale 1:600 (Tscheglov, 1999).

> in these forests last autumn. The level of Cs-137 in chanterelles, boleros and stalks of mushrooms exceeded the norm by approximately forty times . . ." (Chykin, 1997)

There is still uncertainty in regard to contamination not only by Cs-137 and Sr-90, but also by other radionuclides, including beta and alpha emitters. Detailed mapping of territories for the varying spectra of radioactive contamination could not be done owing to the impossibility of fast remote detection of beta and alpha radionuclides.

Typical Chernobyl hot spots measure tens to hundreds of meters across and have levels of radioactivity ten times higher than the surrounding areas. The concentration density of Cs-137 can have several different values even within the limits of the nutrient area of a single tree (Krasnov *et al.*, 1997). In Poland, Ru-106 was the predominant hot spot nuclide in 1986, although a few hot spots were due to Ba-140 or La-140 (Rich, 1986).

Figure 1.16. shows distinct large-scale spotty radioactive distribution of Sb, Cs, and Ag in areas of continental Greece.

1.4.2. Problem of "Hot Particles"

A fundamental complexity in estimating the levels of Chernobyl radioactive contamination is the problem of so-called "hot particles" or "Chernobyl dust." When the reactor exploded, it expelled not only gases and aerosols (the products of splitting of U (Cs-137, Sr-90, Pu, etc.), but also particles of U fuel melted together with other radionuclides—firm hot particles. Near the Chernobyl NPP, heavy large particles of U and Pu dropped out. Areas of Hungary, Germany, Finland, Poland, Bulgaria, and other European countries saw hot particles with an average size of about 15 μm. Their activity mostly was determined to be (UNSCEAR, 2000) Zr-95 (half-life 35.1 days), La-140 (1.68 days), and Ce-144 (284 days). Some hot particles included beta-emitting radionuclides such as Ru-103 and Ru-106 (39.3 and 368 days, respectively) and Ba-140 (12.7 days). Particles with volatile elements that included I-131, Te-132, Cs-137, and Sb-126 (12.4 days) spread over thousands of kilometers. "Liquid hot particles" were formed when radionuclides became concentrated in raindrops:

> "Hot particles" were found in new apartment houses in Kiev that were to be populated in the autumn of 1986. In April and May they stood without roofs or windows, so they absorbed a lot of a radioactive dust, which we found in concrete plates of walls and ceilings, in the carpenter's room, under plastic covers on a floor, etc. For the most part these houses are occupied by staff of the Chernobyl atomic power station. While planning occupancy the special dosimeter commands I developed (I then was the deputy chief engineer of Chernobyl NPP on radiation safety and was responsible for the personnel in areas found to be contaminated) carried out a radiation check on the apartments. As a result of these measurements I sent a report to the Governmental Commission advising of the inadmissibility of inhabiting these "dirty" apartments. The sanitation service of the Kiev municipality . . . answered with a dishonest letter in which it agreed that there was radioactivity in these apartments, but explained it away as dirt that was brought in by tenants." (Karpan, 2007 by permission)

Radioactivity of individual hot particles reached 10 kBq. When absorbed into the body (with water, food, or inhaled air), such particles generate high doses of radiation even if an individual is in areas of low contamination. Fine particles (smaller than 1 μm) easily penetrate the lungs, whereas larger ones (20–40 μm) are concentrated primarily in the upper respiratory system (Khruch *et al.,* 1988; Ivanov *et al.*, 1990; IAEA, 1994). Studies concerning the peculiarities of the formation and disintegration of hot particles, their properties, and their impact on the health of humans and other living organisms are meager and totally inadequate.

1.5. Changes in the Radionuclide Dose Spectrum

To understand the impact of Chernobyl contamination on public health and the environment it is necessary to consider the essential changes in the radionuclide spectrum during of the first days, weeks, months, and decades after the Chernobyl catastrophe. The maximum level of activity from Chernobyl's fallout in the first days and weeks, which was due mostly to short-lived radionuclides, exceeded background levels by more than 10,000-fold (Krishev and Ryazantsev, 2000; and many others). Today radioactive contamination is only a

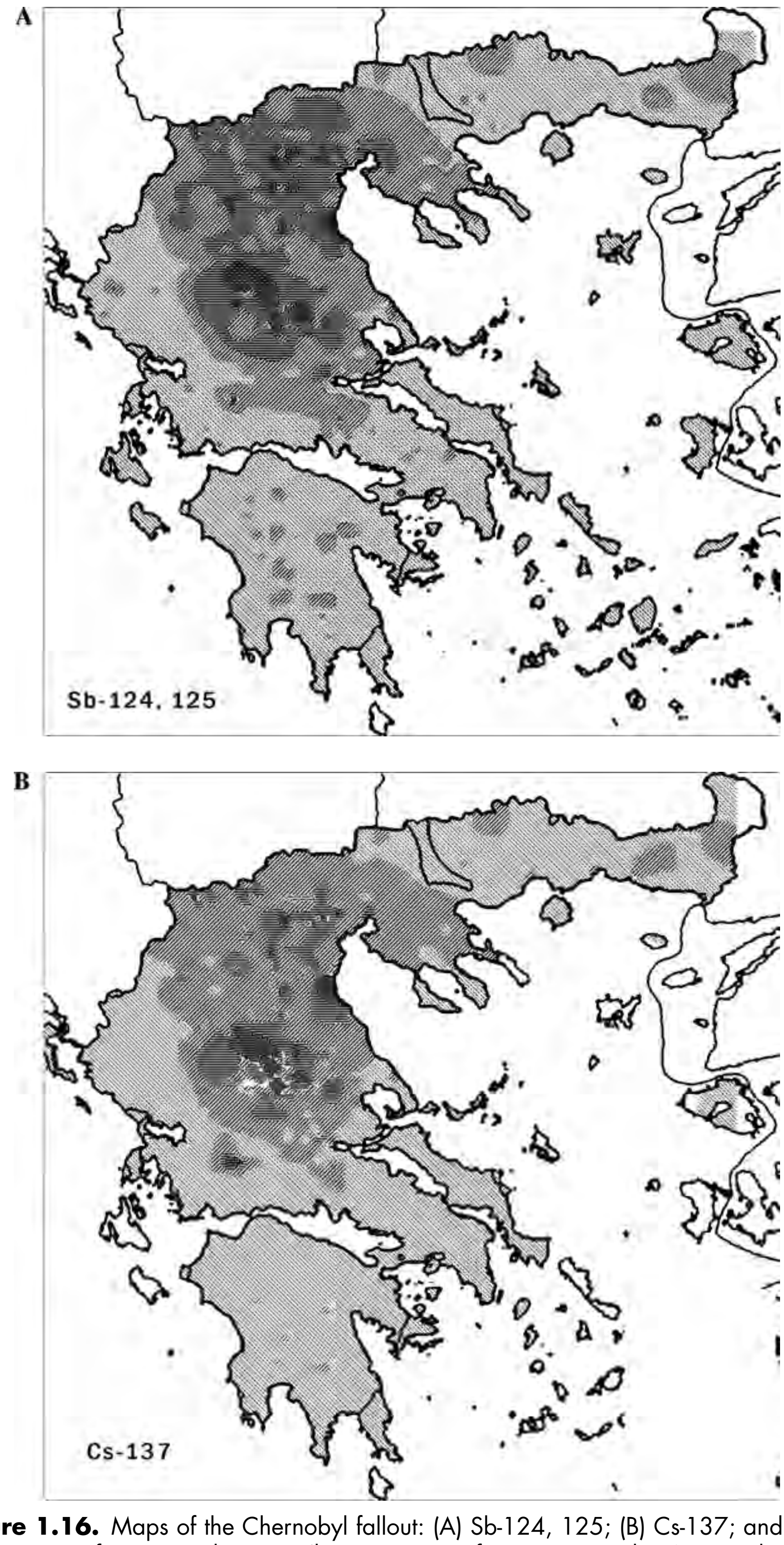

Figure 1.16. Maps of the Chernobyl fallout: (A) Sb-124, 125; (B) Cs-137; and (C) Ag-125m in areas of continental Greece (by permission of S. E. Simopoulos, National Technical University of Athens; arcas.nuclear.ntua.gr/apache2-default/radmaps/page1.htm).

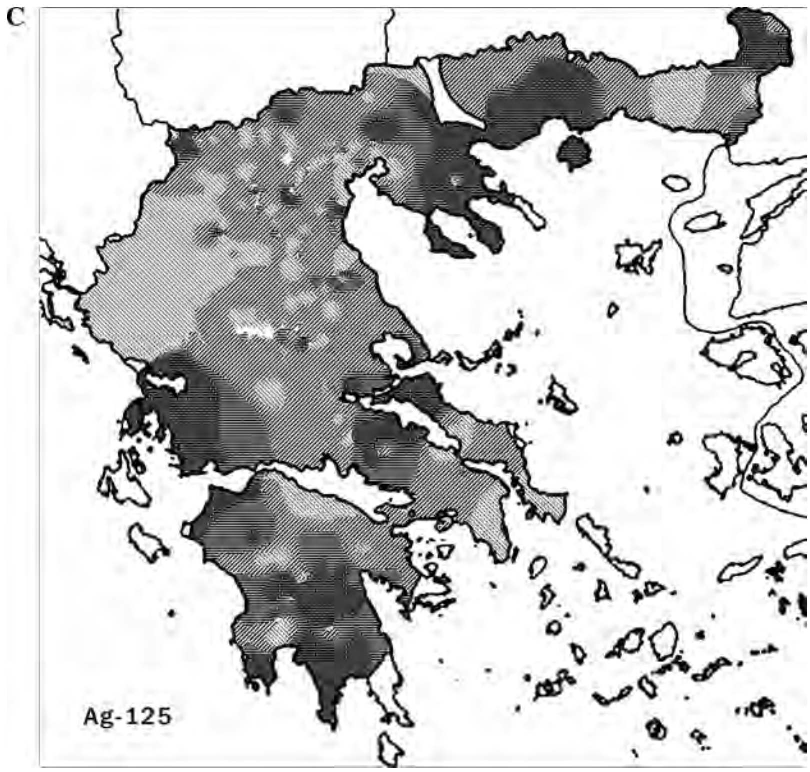

Figure 1.16. *Continued.*

small part of all the radiation emitted during the catastrophe. Based on data from Sweden and Finland, ratios of Cs-137 and other radionuclide fallout in the first days and weeks allows for reconstruction of the relative value of the various nuclides that make up the total external dose (Figure 1.17).

During the first days after the explosion the share of total external radiation due to Cs-137 did not exceed 4%, but the level of radiation from I-131, I-133, Te-129, Te-132, and several other radionuclides was hundreds of times higher. Within the succeeding months and the first year after the explosion the major external radiation was due to isotopes of Ce-141, Ce-144, Ru-103, Ru-106, Zr-95, Ni-95, Cs-136, and Np-239. Since 1987, most external radiation levels have been defined by Cs-137, Sr-90, and Pu. Today these radionuclides, which are found mostly in soil, seriously impact agricultural production (for details see Chapters III.9 and IV.13).

Timescales of radiation contamination can be determined by an analysis of tooth enamel. Such analyses were conducted by experts with the German group "Physicians of the World for the Prevention of Nuclear War." They tested

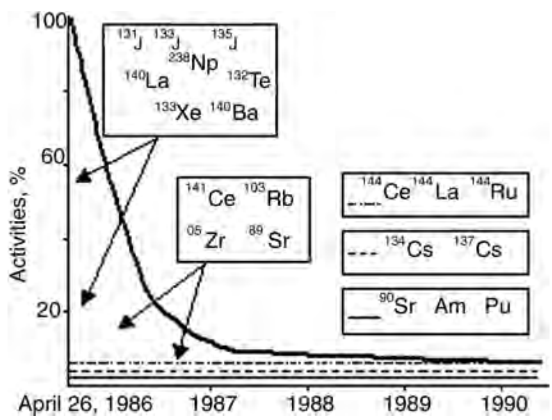

Figure 1.17. Dynamics of radioisotope structure of Chernobyl's contamination, percentage of total activity (Yablokov, 2002, from Sokolov and Krivolutsky, 1998).

the teeth of 6,000 children and found that children born soon after the Chernobyl catastrophe had 10 times more Sr-90 in their teeth compared with children born in 1983 (Ecologist, 2000).

Problem of Americium-241. The powerful alpha radiation emitter Am-241, formed as a result of the natural disintegration of Pu-241, is a very important factor in the increasing levels of contamination in many areas located up to 1,000 km from the Chernobyl NPP. The territory contaminated by Pu today, where the level of alpha radiation is usually low, will again become dangerous as a result of the future disintegration of Pu-241 to Am-241 in the ensuing tens and even hundreds of years (see also Chapter III.9). An additional danger of Am-241 is its higher solubility and consequent mobility into ecosystems compared with Pu.

1.6. Lead Contamination

During operations to quench the fires in the fourth reactor of the Chernobyl NPP, helicopters dumped 2,400 tons of Pb into the reactor (Samushia *et al.*, 2007; UNSCEAR, 2000); according to other data, the figure was 6,720 tons (Nesterenko, 1997). During several subsequent days, a significant part of the Pb was spewed out into the atmosphere as a result of its fusion, boiling, and sublimation in the burning reactor. Moreover, Pb poisoning is dangerous in itself, causing, for example, retardation in children (Ziegel and Ziegel, 1993; and many others).

1. Blood Pb levels in both children and adults in Belarus have noticeably increased over the last years (Rolevich *et al.*, 1996). In the Brest Province of Belarus, for example, of 213 children studied, the level of Pb was 0.109 ± 0.007 mg/liter, and about half of these children had levels of 0.188 ± 0.003 mg/liter (Petrova et al., 1996), whereas the World Health Organization (WHO) norm for children is no more than 0.001 mg/liter.
2. In Ukraine in the Poles'e District of Kiev Province, levels of Pb in the air breathed by operators of agricultural machinery was up to 10 times or more, exceeding maximum permissible concentrations. Increased levels of Pb were apparent in the soil and atmosphere and in the urine and the hair of adults and children in Kiev soon after the explosion (Bar'yakhtar, 1995).
3. Pb contamination added to radiation causes harm to living organisms (Petin and Synsynys, 1998). Ionizing radiation causes biochemical oxidation of free radicals in cells. Under the influence of heavy metals (such as Pb) these reactions proceed especially intensively. Belarussian children contaminated with both Cs-137 and Pb have an increased frequency of atrophic gastritis (Gres and Polyakova, 1997).

1.7. Evaluation of Chernobyl's Population Doses

The International Atomic Energy Agency (IAEA) and WHO (Chernobyl Forum, 2005) estimated a collective dose for Belarus, Ukraine, and European Russia as 55,000 persons/Sv. By other more grounded estimates (see Fairlie and Sumner, 2006) this collective dose is 216,000–326,000 persons/Sv (or even 514,000 persons/Sv only for Belarus; National Belarussian Report, 2006). The worldwide collective dose from the Chernobyl catastrophe is estimated at 600,000–930,000 persons/Sv (Table 1.6). However, it is now clear that these figures for collective doses are considerably underestimated.

1.8. How Many People Were and Will Be Exposed to Chernobyl's Contamination?

The first official forecasts regarding the health impact of the Chernobyl catastrophe

TABLE 1.6. Total Collective Effective Dose (persons/Sv) of Additional Irradiation from the Chernobyl Catastrophe (Fairlie and Sumner, 2006)

	U.S. Department of Energy[a]	UNSCEAR[b]
Belarus, Ukraine, European Russia	326,000	216,000
Other European countries	580,000	318,000
Rest of the world	28,000	66,000
Total	930,000	600,000

[a]Anspaugh *et al.* (1988).
[b]Bennett (1995, 1996).

included only several additional cases of cancer over a period of some 10 years. In 20 years it has become clear that no fewer than 8 million inhabitants of Belarus, Ukraine, and Russia have been adversely affected (Table 1.7).

One must understand that in areas contaminated above 1 Ci/km^2 (a level that undoubtedly has statistical impact on public health) there are no fewer than 1 million children, and evacuees and liquidators have had no fewer than 450,000 children. It is possible to estimate the number of people living in areas subject to Chernobyl fallout all over the world. Some 40% of Europe has been exposed to Chernobyl's Cs-137 at a level 4–40 kBq/m^2 (0.11–1.08 Ci/km^2; see Table 1.2). Assuming that about 35% of the European population lives in this territory (where radionuclides fell on sparsely populated mountain areas) and counting the total European population at the end of the 1980s, we can calculate that nearly 550 million people are contaminated. It is possible to consider that about 190 million Europeans live in noticeably contaminated areas, and nearly 15 million in the areas where the Cs-137 contamination is higher than 40 kBq/m^2 (1.08 Ci/km^2).

Chernobyl fallout contaminated about 8% of Asia, 6% of Africa, and 0.6% of North

TABLE 1.7. Population Suffering from the Chernobyl Catastrophe in Belarus, Ukraine, and European Russia

	Individuals, 10^3		
Group	Country	Different sources	Cardis *et al.*, 1996
Evacuated and moved[b]	Belarus	135,000[a]	135,000
	Ukraine	162,000[a]	—
	Russia	52,400[a]	—
Lived in territory contaminated by Cs-137 > 555 kBq|m^2 (>15 Ci/km^2)			270,000
Lived in territory contaminated by ^{7}Cs-137 > 37 kBq/m^2 (>1 Ci/km^2)	Belarus	2,000,000[a]	6,800,000
	Ukraine	3,500,000[a]	—
	Russia	2,700,000[a]	—
Liquidators	Belarus	130,000	200,000 (1986–1987)
	Ukraine	360,000	—
	Russia	250,000	—
	Other countries	Not less than 90,000[c]	—
Total		9,379,400	7,405,000

[a]Report of the UN Secretary General (2001). Optimization of international efforts in study, mitigation, and minimization of consequences of the Chernobyl catastrophe (http://daccessdds.un.org/doc/UNDOC/GEN/N01/568/11/PDF/N0156811.pdf>).

[b]Evacuated from city of Pripyat and the railway station at Janov: 49,614; evacuated from 6 to 11 days from 30-km zone in Ukraine: 41,792, in Belarus: 24,725 (Total 116, 231); evacuated 1986–1987 from territories with density of irradiation above 15 Ci/km^2—Ukraine: 70,483, Russia: 78,600, Belarus: 110,275. The total number of people forced to leave their homes because of Chernobyl contamination was nearly 350,400.

[c]Kazakhstan: 31,720 (Kaminsky, 2006), Armenia: >3,000 (Oganesyan *et al.*, 2006), Latvia: >6,500, Lithuania: >7,000 (Oldinger, 1993). Also in Moldova, Georgia, Israel, Germany, the United States, Great Britain, and other countries.

TABLE 1.8. Estimation of the Population (10^3) outside of Europe Exposed to Chernobyl Radioactive Contamination in 1986

Continent	Share of the total Chernobyl Cs-137 fallout,%	Total population, end of 1980s	Population under fallout of 1–40 kBq/m^2
Asia	8	2,500,000,000	Nearly 150,000,000
Africa	6	600,000,000	Nearly 36,000,000
America	0.6	170,000,000	Nearly 10,000,000
Total	14.6%	3,270,000,000	Nearly 196,000,000

America, so by similar reasoning it appears that outside of Europe the total number of individuals living in areas contaminated by Chernobyl Cs-137 at a level up to 40 kBq/m^2 could reach nearly 200 million (Table 1.8).

Certainly, the calculated figures in Table 1.8 are of limited accuracy. The true number of people living in 1986 in areas outside of Europe with noticeable Chernobyl contamination can be no fewer than 150 million and no more than 230 million. This uncertainty is caused, on the one hand, by calculations that do not include several short-lived radionuclides, such as I-131, I-133, Te-132, and some others, which result in much higher levels of radiation than that due to Cs-137. These include Cl-36 and Te-99 with half-lives of nearly 30,000 years and more than 21,000 years, respectively (Fairlie and Sumner, 2006). The latter isotopes cause very low levels of radiation, but it will persist for many millennia. On the other hand, these calculations are based on a uniform distribution of population, which is not a legitimate assumption. In total, in 1986 nearly 400 million individuals (nearly 205 million in Europe and 200 million outside Europe) were exposed to radioactive contamination at a level of 4 kBq/m^2 (0.1 Ci/km^2).

Other calculations of populations exposed to Chernobyl radiation have been based on the total collective dose. According to one such calculation (Table 1.9) the number of people who were exposed to additional radiation at a level higher than 2.5×10^{-2} mSv might be more than 4.7 billion and at a level of higher than 0.4 mSv more than 605 million.

1.9. Conclusion

Most of the Chernobyl radionuclides (up to 57%) fell outside of the former USSR and caused noticeable radioactive contamination over a large area of the world—practically the entire Northern Hemisphere.

TABLE 1.9. Population Suffering from Chernobyl Radioactive Contamination at Different Levels of Radiation Based on Collective Doses (Fairlie, 2007)

Group	Number of individuals	Average individual dose, mSv
USSR liquidators[a]	240,000	100
Evacuees	116,000	33
USSR heavily contaminated areas	270,000	50
USSR less contaminated areas	5,000,000	10
Other areas in Europe	600,000,000	$\geq$0.4
Outside Europe	4,000,000,000	$\geq 2.5 \times 10^{-2}$

[a]Presumably 1986–1987 (A.Y.).

Declarations that Chernobyl radioactivity adds *only* 2% to the natural radioactive background on the surface of the globe obscures the facts because this contamination exceeded the natural background in vast areas, and in 1986 up to 600 million men, women, and children lived in territories contaminated by Chernobyl radionuclides at dangerous levels of more than 0.1 Ci/km^2.

Chernobyl radioactive contamination is both dynamic and long term. The dynamic is delineated as follows: First is the natural disintegration of radionuclides so that levels of radioactive contamination in the first days and weeks after the catastrophe were thousands of times higher than those recorded 2 to 3 years later. Second is the active redistribution of radionuclides in ecosystems (for details see Chapter III). Third is the contamination that will exist beyond the foreseeable future—not less than 300 years for Cs-137 and Sr-90, more than 200,000 years for Pu, and several thousands of years for Am-241.

From the perspective of the 23 years that have passed since the Chernobyl catastrophe, it is clear that tens of millions of people, not only in Belarus, Ukraine, and Russia, but worldwide, will live under measurable chronic radioactive contamination for many decades. Even if the level of external irradiation decreases in some areas, very serious contamination in the first days and weeks after the explosion together with decades of additional and changing conditions of radioactivity will have an inevitable negative impact on public health and nature.

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Chapter II. Consequences of the Chernobyl Catastrophe for Public Health

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2. Chernobyl's Public Health Consequences

Some Methodological Problems

Alexey V. Yablokov

Problems complicating a full assessment of the effects from Chernobyl included official secrecy and falsification of medical records by the USSR for the first 3.5 years after the catastrophe and the lack of reliable medical statistics in Ukraine, Belarus, and Russia. Official data concerning the thousands of cleanup workers (Chernobyl liquidators) who worked to control the emissions are especially difficult to reconstruct. Using criteria demanded by the International Atomic Energy Agency (IAEA), the World Health Organization (WHO), and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) resulted in marked underestimates of the number of fatalities and the extent and degree of sickness among those exposed to radioactive fallout from Chernobyl. Data on exposures were absent or grossly inadequate, while mounting indications of adverse effects became more and more apparent. Using objective information collected by scientists in the affected areas—comparisons of morbidity and mortality in territories characterized by identical physiography, demography, and economy, which differed only in the levels and spectra of radioactive contamination—revealed significant abnormalities associated with irradiation, unrelated to age or sex (e.g., stable chromosomal aberrations), as well as other genetic and nongenetic pathologies.

The first official forecasts of the catastrophic health consequences of the Chernobyl meltdown noted only a limited number of additional cases of cancer over the first decades. Four years later, the same officials increased the number of foreseeable cancer cases to several hundred (Il'in *et al.*, 1990), at a time when there were already 1,000 people suffering from Chernobyl-engendered thyroid cancer. Twenty years after the catastrophe, the official position of the Chernobyl Forum (2006) is that about 9,000 related deaths have occurred and some 200,000 people have illnesses caused by the catastrophe.

A more accurate number estimates nearly 400 million human beings have been exposed to Chernobyl's radioactive fallout and, for many generations, they and their descendants will suffer the devastating consequences. Globally, adverse effects on public health will require special studies continuing far into the future. This review concerns the health of the populations in the European part of the former USSR (primarily, Ukraine, Belarus, and European Russia), for which a very large body of scientific literature has been published of which but little is known in the Western world.

The aim of the present volume is not to present an exhaustive analysis of all available facts concerning Chernobyl's disastrous effects—analyzing all of the known effects of the Chernobyl catastrophe would fill many full-size monographs—but rather to elucidate the known scale and spectrum of its consequences.

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2.1. Difficulties in Obtaining Objective Data on the Catastrophe's Impact

For both subjective and objective reasons, it is very difficult to draw a complete picture of Chernobyl's influence on public health.

The subjective reasons include:

1. The official secrecy that the USSR imposed on Chernobyl's public health data in the first days after the meltdown, which continued for more than 3 years—until May 23, 1989, when the ban was lifted. During those 3 years an unknown number of people died from early leukosis. Secrecy was the norm not only in the USSR, but in other countries as well, including France, Great Britain, and even the United States. After the explosion, France's official Service Central de Protection Contre les Radiations Ionisantes (SCPRI) denied that the radioactive cloud had passed over France (CRIIRAD, 2002) and the U.S. Department of Agriculture failed to disclose that dangerous levels of Chernobyl radionuclides had been found in imported foods in 1987 and 1988. The first public announcement of these contaminations was not made until 8 years later (RADNET, 2008, Sect. 6 and Sect. 9, part 4).
2. The USSR's official irreversible and intentional falsification of medical statistics for the first 3.5 years after the catastrophe.
3. The lack of authentic medical statistics in the USSR and after its disintegration in 1991, as well as in Ukraine, Belarus, and Russia, including health data for hundreds of thousands of people who left the contaminated territories.
4. The expressed desire of national and international official organizations and the nuclear industry to minimize the consequences of the catastrophe.

> The number of persons added to the Chernobyl state registers continues to grow, even during the most recent years, which casts doubt on the completeness and accuracy of documentation. Data about cancer mortality and morbidity are gathered from many and various sources and are coded without taking into account standard international principles . . . public health data connected to the Chernobyl accident are difficult to compare to official state of health statistics . . . (UNSCEAR, 2000, Item 242, p. 49).

The situation of the liquidators is indicative. Their total number exceeds 800,000 (see Chapter I). Within the first years after the catastrophe it was officially forbidden to associate the diseases they were suffering from with radiation, and, accordingly, their morbidity data were irreversibly forged until 1989.

> EXAMPLES OF OFFICIAL REQUIREMENTS THAT FALSIFIED LIQUIDATORS' MORBIDITY DATA:
>
> 1. ". . . For specified persons hospitalized after exposure to ionizing radiation and having no signs or symptoms of acute radiation sickness at the time of release, the diagnosis shall be 'vegetovascular dystonia.'" [From a letter from the USSR's First Deputy Minister of Public Health O. Shchepin, May 21, 1986, # 02–6/83–6 to Ukrainian Ministry of Public Health (cit. by V. Boreiko, 1996, pp. 123–124).]
> 2. ". . . For workers involved in emergency activities who do not have signs or symptoms of acute radiation sickness, the diagnosis of vegetovascular dystonia is identical to no change in their state of health in connection with radiation (i.e., for all intents and purposes healthy vis-à-vis radiation sickness). Thus the diagnosis does not exclude somatoneurological symptoms, including situational neurosis . . . ." [From a telegram of the Chief of the Third Main Administration of the USSR's Ministry of Health, E. Shulzhenko, # "02 DSP"-1, dated January 4, 1987 (cit. by L. Kovalevskaya, 1995, p. 189).]
> 3. "(1) For remote consequences caused by ionizing radiation and a cause-and-effect relationship, it is necessary to consider: leukemia or leukosis 5–10 years after radiation in doses exceeding 50 rad. (2) The presence of acute somatic illness and activation of chronic disease in

persons who were involved in liquidation and who do not have ARS (acute radiation sickness – Ed.), the effect of ionizing radiation should not be included as a causal relationship. (3) When issuing certificates of illness for persons involved in work on ChNPP who did not suffer ARS in point "10" do not mention participation in liquidation activities or the total dose of radiation that did not reach a degree of radiation sickness." [From an explanatory note of the Central Military-Medical Commission of the USSR Ministry of Defense, # 205 dated July 8, 1987, directed by the Chief of 10th MMC Colonel V. Bakshutov to the military registration and enlistment offices (cit. by L. Kovalevskaya, 1995, p. 12).]

Data from the official Liquidators Registers in Russia, Ukraine, and Belarus cannot be considered reliable because the status of "liquidator" conveyed numerous privileges. We do not know if an individual described as a "liquidator" was really directly exposed to radiation, and we do not know the number of individuals who were in the contaminated zone for only a brief time. At the same time, liquidators who served at the site and were not included in official registers are just now coming forward. Among them are the military men who participated in the Chernobyl operations but lack documentation concerning their participation (Mityunin, 2005). For example, among nearly 60,000 investigated military servicemen who participated in the clean-up operations in the Chernobyl zone, not one (!) had notice of an excess of the then-existing "normal" reading of 25 R on his military identity card. At the same time a survey of 1,100 male Ukrainian military clean-up workers revealed that 37% of them have clinical and hematological characteristics of radiation sickness, which means that these men received more than 25 R exposure (Kharchenko *et al.*, 2001). It is not by chance that 15 years after the catastrophe up to 30% of Russian liquidators did not have radiation dose data on their official certificates (Zubovsky and Smirnova, 2000).

Officially it is admitted that "the full-size personal dosimeter control of liquidators in the Chernobyl Nuclear Power Plant (ChNPP) zone managed to be adjusted only for some months" (National Russian Report, 2001, p. 11). It was typical to use so-called "group dosimetry" and "group assessment." Even official medical representatives recognize that a number of Russian liquidators could have received doses seven times (!) higher than 25 cGy, the level specified in the Russian state register (Il'in *et al.*, 1995). Based on official data, this evidence makes the liquidators' "official" dose/sickness correlation obsolete and unreliable.

Two Examples of Concealment of True Data on the Catastrophe's Consequences

1. "(4) To classify information on the accident... (8) To classify information on results of medical treatment. (9) To classify information on the degree of radioactive effects on the personnel who participated in the liquidation of the ChNPP accident consequences." [From the order by the Chief of Third Main Administration of the USSR's Ministry of Health E. Shulzhenko concerning reinforcing the secrecy surrounding the activities on liquidation of the consequences of the nuclear accident in ChNPP, #U-2617-S, June 27, 1986 (cit. by L. Kovalevskaya, 1995, p. 188).]
2. "(2) The data on patients' records related to the accident and accumulated in medical establishments should have a 'limited access' status. And data generalized in regional and municipal sanitary control establishments, ... on radioactive contamination of objects, environment (including food) that exceeds maximum permissible concentration is 'classified'." [From Order # 30-S by Minister of Health of Ukraine A. Romanenko on May 18, 1986, about reinforcing secrecy (cit. by N. Baranov'ska, 1996, p. 139).]

Comparison of the data received via individual biodosimetry methods (by the number of chromosomal aberrations and by electron paramagnetic resonance (EPR) dosimetry) has shown that officially documented doses of radiation can be both over- and underestimated

(Elyseeva, 1991; Vinnykov *et al.*, 2002; Maznik *et al.*, 2003; Chumak, 2006; and others). The Chernobyl literature widely admits that tens of thousands of the Chernobyl liquidators who worked in 1986–1987, were irradiated at levels of 110–130 mSv. Some individuals (and, accordingly, some groups) could have received doses considerably different than the average. All of the above indicates that from a strictly methodological point of view, it is impossible to correlate sickness among liquidators with the formally documented levels of radiation. Official data of thyroid-dosimetric and dosimetric certification in Ukraine were revised several times (Burlak *et al.*, 2006).

In addition to the subjective reasons noted above, there are at least two major objective reasons for the difficulty in establishing the true scale of the catastrophe's impact on public health. The first impediment is determining the true radioactive impact on individuals and population groups, owing to the following factors:

- Difficulty in reconstructing doses from the radionuclides released in the first days, weeks, and months after the catastrophe. Levels of radioisotopes such as I-133, I-135, Te-132, and a number of other radionuclides having short half-lives were initially hundreds and thousand of times higher than when Cs-137 levels were subsequently measured (see Chapter I for details). Many studies revealed that the rate of unstable and stable chromosome aberrations is much higher—by up to one to two orders of magnitude—than would be expected if the derived exposures were correct (Pflugbeil and Schmitz-Feuerhake, 2006).
- Difficulty in calculating the influence of "hot particles" for different radionuclides owing to their physical and chemical properties.
- Difficulty determining levels of external and internal radiation for the average person and/or group because "doses" were not directly measured and calculations were based on dubious assumptions. These assumptions included an average consumption of a set of foodstuffs by the "average" person, and an average level of external irradiation owing to each of the radionuclides. As an example, all official calculations of thyroid irradiation in Belarus were based on about 200,000 measurements done in May–June 1986 on fewer than 130,000 persons, or only about 1.3% of the total population. All calculations for internal irradiation of millions of Belarussians were made on the basis of a straw poll of several thousand people concerning their consumption of milk and vegetables (Borysevich and Poplyko, 2002). Objective reconstruction of received doses cannot be done on the basis of such data.
- Difficulty determining the influence of the spotty distribution of radionuclides (specific for each one; see Chapter I for details) and, as a result, the high probability that the individual doses of personal radiation are both higher and lower than "average" doses for the territory.
- Difficulty accounting for all of the multiple radionuclides in a territory. Sr-90, Pu, and Am can also contaminate an area counted as contaminated solely by Cs-137. For instance, in 206 samples of breast milk, from six districts of the Gomel, Mogilev, and Brest provinces (Belarus), where the official level of radiation was defined only by Sr-90 contamination, high levels of Cs-137 were also found (Zubovich *et al.*, 1998).
- Difficulty accounting for the movement of radionuclides from the soil to food chains, levels of contamination for each animal species and plant cultivar. The same difficulties exist for different soil types, seasons, and climatic conditions, as well as for different years (see Chapter III of this volume for details).
- Difficulty determining the health of individuals who have moved away from contaminated areas. Even considering

the incomplete official data for the period 1986–2000 for only Belarus, nearly 1.5 million citizens (15% of the population) changed their place of residence. For the period 1990–2000 more than 675,000 people, or about 7% of the population left Belarus (National Belarussian Report, 2006).

The second objective barrier to determining the true radioactive impact on individuals and/or population groups is the inadequacy of information and, in particular, incomplete studies of the following:

- Specificity of the influence of each radionuclide on an organism, and their effect in combination with other factors in the environment.
- Variability of populations and individuals in regard to radiosensitivity (Yablokov, 1998; and others).
- The impact of the ultralow doses (Petkau, 1980; Graeub, 1992; Burlakova, 1995; ECRR, 2003).
- The influences of internally absorbed radiation (Bandazhevsky *et al.*, 1995; Bandazhevsky, 2000).

The above are the factors that expose the scientific fallacy in the requirements outlined by the International Atomic Energy Agency (IAEA), the World Health Organization (WHO), and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and similar official national bodies that are associated with the nuclear industry. They demand a simple correlation—"a level of radiation and effect"—to recognize a link to adverse health effects as a consequence of Chernobyl's radioactive contamination. It is methodologically incorrect to combine imprecisely defined ionizing radiation exposure levels for individuals or groups with the much more accurately determined impacts on health (increases in morbidity and mortality) and to demand a "statistically significant correlation" as conclusive evidence of the deleterious effects from Chernobyl. More and more cases are coming to light in which the calculated radiation dose does not correlate with observable impacts on health that are obviously due to radiation (IFECA, 1995; Vorob'iev and Shklovsky-Kodry, 1996; Adamovich *et al.*, 1998; Drozd, 2002; Lyubchenko, 2001; Kornev *et al.*, 2004; Igumnov *et al.*, 2004; and others). All of these factors do not prove the absence of radiation effects but do demonstrate the inaccurate methodology of the official IAEA, WHO, and UNSCEAR approach.

2.2. "Scientific Protocols"

According to the Chernobyl Forum (2006), a common objection to taking into account the enormous body of data on the public health consequences of the Chernobyl catastrophe in Russia, Ukraine, and Belarus is that they were collected without observing the "scientific protocols" that are the norms for Western science. Usually this means that there was no statistical processing of the received data. Thus, valid distinctions among compared parameters, as for groups from heavily contaminated versus those from less contaminated territories or for groups from areas with different levels of radiation, have not demonstrated statistical significance. In the last decade—a sufficient time span for effects to become manifest—as information has accumulated, a range of values has been found to be within the limits of true "statistical significance."

One of the authors has considerable experience in statistical processing of biological material—the review *Variability of Mammals* (Yablokov, 1976) contains thousands of data calculations of various biological parameters and comparisons. In other reviews as *Introduction into Population Phenetics* (Yablokov and Larina, 1985) and *Population Biology* (Yablokov, 1987) methodical approaches were analyzed to obtain reliable statistically significant conclusions for various types of biological characteristics. Generalizing these and other factors concerning statistical processing of biological and epidemiological data, it is possible to formulate four positions:

1. The calculation "reliability of distinctions by Student," devised about a century ago for comparison of very small samples, is not relevant for large-size samples. When the size of the sample is comparable to the entire assembly, average value is an exact enough parameter. Many epidemiological studies of Chernobyl contain data on thousands of patients. In such cases the averages show real distinctions among the compared samples with high reliability.
2. To determine the reliability of distinctions among many-fold divergent averages, it is not necessary to calculate "standard errors." For example, why calculate formal "significance of difference" among liquidators's morbidities for 1987 and 1997 if the averages differ tenfold?
3. The full spectrum of the factors influencing one parameter or another is never known, so it does not have a great impact on the accuracy of the distinct factors known to the researcher. Colleagues from the nuclear establishment have ostracized one of the authors (A. Y.) for citing in a scientific paper the story from the famous novel *Chernobyl Prayer* (English translation *Voices from Chernobyl*, 2006) by Svetlana Aleksievich. Ms. Aleksievich writes of a doctor seeing a lactating 70-year-old woman in one Chernobyl village. Subsequently well-founded scientific papers reported the connection between radiation and abnormal production of prolactin hormone, a cause of lactation in elderly women.
4. When the case analysis of individual unique characteristics in a big data set does not fit the calculation of average values, it is necessary to use a probability approach. In some modern epidemiological literature the "case-control" approach is popular, but it is also possible to calculate the probability of the constellations of very rare cases on the basis of previously published data. Scientific research methodology will be always improved upon, and today's "scientific protocols" with, for example, "confidence intervals" and "case control," are not perfect.

It is correct and justified for the whole of society to analyze the consequences of the largest-scale catastrophe in history and to use the enormous database collected by thousands of experts in the radioactively contaminated territories, despite some data not being in the form of Western scientific protocols. This database must be used because it is impossible to collect other data after the fact. The doctors and scientists who collected such data were, first of all, trying to help the victims, and, second, owing to the lack of time and resources, not always able to offer their findings for publication. It is indicative that many of the medical/epidemiological conferences in Belarus, Ukraine, and Russia on Chernobyl problems officially were termed "scientific and practical" conferences. Academic theses and abstracts from these conferences were sometimes unique sources of information resulting from the examination of hundreds of thousands of afflicted individuals. Although the catastrophe is quickly and widely being ignored, this information must be made available to the world. Some very important data that were released during press conferences and never presented in any scientific paper are cited in this volume.

Mortality and morbidity are unquestionably higher among the medical experts who worked selflessly in the contaminated territories and were subject to additional radiation, including exposure to radioactive isotopes from contaminated patients. Many of these doctors and scientists died prematurely, which is one more reason that the medical results from Chernobyl were never published.

The data presented at the numerous scientifically practical Chernobyl conferences in Belarus, Ukraine, and Russia from 1986 to 1999 were briefly reported in departmental periodic journals and magazines and in various collections of papers ("*sborniks*"), but it is impossible to collect them again. We must reject the criticism of "mismatching scientific protocols," and search for ways to extract the valuable objective information from these data.

In November 2006 the German Federal Committee on Ionizing Radiation organized the BfS-Workshop on Chernobyl Health Consequences in Nuremberg. It was a rare opportunity for experts with differing approaches to have open and in-depth discussions and analyze the public health consequences of the catastrophe. One conclusion reached during this meeting is especially important for the past Chernobyl material: it is reasonable to doubt data lacking Western scientific protocols only when studies using the same or similar material diverge. From both scientific and social-ethical points of view, we cannot refuse to discuss data that were acquired in the absence of strict scientific protocols.

2.3. Dismissing the Impact of Chernobyl Radionuclides Is a Fallacy

Natural ionizing radiation has always been an element of life on Earth. Indeed, it is one of the main sources of on-going genetic mutations—the basis for natural selection and all evolutionary processes. All life on Earth—humans included—evolved and adapted in the presence of this natural background radiation.

Some have estimated that "the fallout from Chernobyl adds only about 2% to the global radioactive background." This "only" 2% mistakenly looks trivial: for many populations in the Northern Hemisphere the Chernobyl doses could be many times higher compared with the natural background, whereas for others (mostly in the Southern Hemisphere) it can be close to zero. Averaging Chernobyl doses globally is like averaging the temperature of hospital patients.

Another argument is that there are many places around of the world where the natural radioactive background is many times greater than the average Chernobyl fallouts and as humans successfully inhabit such areas, the Chernobyl radioactive fallout is not so significant. Let us discuss this argument in detail. Humans have a similar level of individual variation of radiosensitivity as do voles and dogs: 10–12% of humans have lower (and about 10–14% have a higher one) individual radiosensitivity than everyone else (Yablokov, 1998, 2002). Experiments on mammalian radiosensitivity carried out on voles showed that it requires strong selection for about 20 generations to establish a less radiosensitive population (Il'enko and Krapivko, 1988). If what is true for the experimental vole populations is also true for humans in Chernobyl contaminated areas, it means that in 400 years (20 human generations) the local populations in the Chernobyl-contaminated areas can be less radiosensitive than they are today. Will individuals with reduced radioresistance agree that their progeny will be the first to be eliminated from populations?

One physical analogy can illustrate the importance of even the smallest additional load of radioactivity: only a few drops of water added to a glass filled to the brim are needed to initiate a flow. The same few drops can initiate the same overflow when it is a barrel that is filled to the brim rather than a glass. Natural radioactive background may be as small as a glass or as big as a barrel. Irrespective of its volume, we simply do not know when *only* a small amount of additional Chernobyl radiation will cause an overflow of damage and irreversible change in the health of humans and in nature.

All of the above reasoning makes it clear that we cannot ignore the Chernobyl irradiation, even if it is "only" 2% of the world's average background radiation.

2.4. Determining the Impact of the Chernobyl Catastrophe on Public Health

It is clear that various radionuclides caused radiogenic diseases owing to both internal and external radiation. There are several ways to determine the influence of such radiation:

- Compare morbidity and mortality and such issues as students' performance in different territories identical in environmental, social, and economic features, but differing in the level of radioactive contamination (Almond *et al.*, 2007). This is the most usual approach in the Chernobyl studies.
- Compare the health of the same individuals (or genetically close relatives—parents, children, brothers, and sisters) before and after irradiation using health indices that do not reflect age and sex differences, for example, stable chromosomal aberrations.
- Compare the characteristics, mostly morbidity, for groups with different levels of incorporated radionuclides. In the first few years after the catastrophe, for 80–90% of the population, the dose of internal radiation was mostly due to Cs-137; thus for those not contaminated with other radionuclides, comparison of diseases in people with different levels of absorbed Cs-137 will give objective results of its influence. As demonstrated by the work of the BELRAD Institute (Minsk), this method is especially effective for children born after the catastrophe (see Chapter IV for details).
- Document the aggregation of clusters of rare diseases in space and time and compare them with those in contaminated territories (e.g., study on the specific leukoses in the Russian Bryansk Province; Osechinsky *et al.*, 1998).
- Document the pathological changes in particular organs and subsequent diseases and mortality with the levels of incorporated radionuclides, for instance, in heart tissue in Belarus' Gomel Province (Bandazhevski, 2000).

It is methodologically flawed for some specialists to emphasize "absence of proof" and insist on "statistically significant" correlation between population doses and adverse health effects. Exact calculations of population dose and dose rate are practically impossible because data were not accurately collected at the time. If we truly want to understand and estimate the health impact of the Chernobyl catastrophe in a methodologically correct manner, it will be demonstrated in populations or intrapopulation group differences varying by radioactive levels in the contaminated territories where the territories or subgroups are uniform in other respects.

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3. General Morbidity, Impairment, and Disability after the Chernobyl Catastrophe

Alexey V. Yablokov

In all cases when comparing the territories heavily contaminated by Chernobyl's radionuclides with less contaminated areas that are characterized by a similar economy, demography, and environment, there is a marked increase in general morbidity in the former. Increased numbers of sick and weak newborns were found in the heavily contaminated territories in Belarus, Ukraine, and European Russia.

There is no threshold for ionizing radiation's impact on health. The explosion of the fourth reactor of the Chernobyl Nuclear Power Plant (NPP) dispersed an enormous amount of radionuclides (see Chapter I for details). Even the smallest excess of radiation over that of natural background will statistically (stochastically) affect the health of exposed individuals or their descendants, sooner or later. Changes in general morbidity were among the first stochastic effects of the Chernobyl irradiation.

In all cases when territories heavily contaminated by Chernobyl radionuclides are compared with less contaminated areas that are similar in ethnography, economy, demography, and environment, there is increased morbidity in the more contaminated territories, increased numbers of weak newborns, and increased impairment and disability. The data on morbidity included in this chapter are only a few examples from many similar studies.

3.1. Belarus

1. The general morbidity of children noticeably increased in the heavily contaminated territories. This includes deaths from common as well as rare illnesses (Nesterenko *et al.*, 1993).

2. According to data from the Belarussian Ministry of Public Health, just before the catastrophe (in 1985), 90% of children were considered "practically healthy." By 2000 fewer than 20% were considered so, and in the most contaminated Gomel Province, fewer than 10% of children were well (Nesterenko, 2004).

3. From 1986 to 1994 the overall death rate for newborns was 9.5%. The largest increase (up to 205%), found in the most contaminated Gomel Province (Dzykovich *et al.*, 1996), was due primarily to disease among the growing number of premature infants.

4. The number of children with impaired physical development increased in the heavily contaminated territories (Sharapov, 2001).

5. Children from areas with contamination levels of 15–40 Ci/km^2 who were newborn to 4 years old at the time of the catastrophe have significantly more illnesses than those from places with contamination levels of 5–15 Ci/km^2 (Kul'kova *et al.*, 1996).

6. In 1993, only 9.5% of children (0 to 4 years old at the time of the catastrophe) were healthy in areas within the Kormyansk and Chechersk districts of Gomel Province, where soil Cs-137 levels were higher than 5 Ci/km^2. Some 37% of the children there suffer from chronic diseases. The annual increase in disease (per 1,000, for 16 classes of illnesses) in the

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TABLE 3.1. Radioactive and Heavy Metal Contamination in Children from the Heavily and Less Contaminated Areas (Arinchin *et al.*, 2002)

	Heavily contaminated: 73 boys, 60 girls, avg. age 10.6 years		Less contaminated: 101 boys, 85 girls, avg. age 9.5 years	
	First survey (a)	Three years later (b)	First survey (c)	Three years later (d)
mSv	0.77	0.81	0.02**	0.03***
Pb, urine, mg/liter	0.040	0.020*	0.017**	0.03*
Cd, urine, mg/liter	0.035	0.025	0.02**	0.015
Hg, urine, mg/liter	0.031	0.021*	0.022**	0.019

*b-a, d-c ($P < 0.05$); **c-a ($P < 0.05$); ***d-b ($P < 0.05$).

heavily contaminated areas reached 102–130 cases, which was considerably higher than for less contaminated territories (Gutkovsky *et al.*, 1995; Blet'ko *et al.*, 1995).

7. In the 8 years after the catastrophe, in the heavily contaminated Luninetsk District, Brest Province, illnesses per 1,000 children increased 3.5 times—1986–1988: 166.6; 1989–1991: 337.3; 1992–1994: 610.7 (Voronetsky, 1995).

8. For children of the Stolinsk District, Brest Province, who were radiated *in utero* from ambient Cs-137 levels up to 15 Ci/km^2, morbidity was significantly higher for the primary classes of illnesses 10 years later. Disease diagnoses were manifest at ages 6 to 7 years (Sychik and Stozharov, 1999).

9. The rates of both premature neonates and small-for-gestational-age babies in Belarus as a whole were considerably higher in the more radioactive contaminated territories for 10 years following the catastrophe (Tsimlyakova and Lavrent'eva, 1996).

10. Newborns whose mothers had been evacuated from a zone of the strict control ($\geq$15 Ci/km^2) had a statistically significant longer body, but a smaller head and a smaller thorax circumference (Akulich and Gerasymovich, 1993).

11. In the Vetca, Narovly, and Hoyniky districts of Gomel Province and the Kalinkovich District of Mogilev Province, spontaneous abortions and miscarriages and the numbers of low-birth-weight newborns were significantly higher in the heavily contaminated territories (Izhevsky and Meshkov, 1998).

12. Table 3.1 shows the results of two groups of children from the heavily and less contaminated territories surveyed for the years from 1995 to 2001. The state of their health was obtained by subjective (self-estimation) and objective (based on clinical observations) studies. Each child was followed for 3 years, and individual contamination determined by measuring the level of incorporated radionuclides (using an individual radioactivity counter) and the levels of Pb and other heavy metals. Data from Table 3.1 show that within groups the level of radioactive contamination did not change statistically over 3 years, whereas heavy metals levels were slightly reduced, with the exception of the Pb level, which increased in controls.

13. Table 3.2 shows the results of children's self-estimation of health. It is clear that children living in the heavily contaminated areas complain more often of various illnesses. The number of complaints in the group living in heavily contaminated areas was noticeably greater than in less contaminated places. Although the number of complaints increased in both the heavily contaminated and the less contaminated groups after 3 years of observation, most of the parameters were higher among the heavily contaminated.

Data in Table 3.3 show that children living in heavily contaminated areas differed noticeably from those in less contaminated places for

TABLE 3.2. Frequency of Complaints (%) on State of Health—Same Children as Table 3.1 (Arinchin *et al.*, 2002)

	Heavily contaminated areas		Less contaminated areas	
	First survey	Three years later	First survey	Three years later
Complaints of state of health	72.2	78.9	45.7**	66.1*, ***
Weakness	31.6	28.6	11.9**	24.7*
Dizziness	12.8	17.3	4.9**	5.8***
Headache	37.6	45.1	20.7**	25.9***
Fainting	0.8	2.3	0	0
Nose bleeds	2.3	3.8	0.5	1.2
Fatigue	27.1	23.3	8.2**	17.2*
Heart arrhythmias	1.5	18.8*	0.5	0.8*,***
Stomach pain	51.9	64.7*	21.2**	44.3*,***
Vomiting	9.8	15.8	2.2**	12.6*
Heartburn	1.5	7.5*	1.6	5.8*
Loss of appetite	9.0	14.3	1.1**	10.3*
Allergy	1.5	3.0	0.5	5.8*

*b-a; d-c ($P < 0.05$); **c-a ($P < 0.05$); ***d-b ($P < 0.05$).

practically all diseases in both the first and the second survey.

The findings in both Table 3.2 and Table 3.3 give a convincing picture of sharply worsening health for children in the heavily contaminated areas. The authors of this research defined this condition as "ecological disadaptation syndrome" which may be another definitive Chernobyl effect (Gres' and Arinchin, 2001).

14. According to official statistics in 1993–1994 primary morbidity was significantly higher in territories with Cs-137 levels above 15 Ci/km^2 (Kozhunov *et al.*, 1996).

15. Primary invalidism in contaminated territories of Belarus noticeably increased after 1993, especially during 1997 and 1998 (Figure 3.1).

16. The number of invalids was noticeably higher in the more contaminated Gomel and Mogilev provinces than in the country as a whole. In the Gomel Province the relative number of invalids was higher, but in Mogilev Province there were more sick children (Kozhunov *et al.*, 1996).

17. According to official data (Medical Consequences, 2003) morbidity of Belarus

TABLE 3.3. Frequency of Clinical Syndromes and Diagnoses (%)—Same Children as in Tables 3.1 and 3.2 (Arinchin *et al.*, 2002)

	Heavily contaminated areas		Lees contaminated areas	
Syndrome/diagnosis	First survey	Three years later	First survey	Three years later
Chronic gastroenteric pathology	44.2	36.4	31.9	32.9
Including chronic duodenitis	6.2	4.7	1.5	1.4
Including chronic gastroduodenitis	17.1	39.5*	11.6	28.7*
Gallbladder inflammation	43.4	34.1	17.4**	12.6***
Vascular dystonia and heart syndrome	67.9	73.7	40.3**	52.2*,***
Asthenia-neurosis	20.2	16.9	7.5**	11.3
Tonsil hypertrophy and chronic tonsillitis	11.1	9.2	13.6	17.2***
Tooth caries	58.9	59.4	42.6**	37.3***
Chronic periodontitis	6.8	2.4	0**	0.6

*b-a; d-c ($P < 0.05$); **c-a ($P < 0.05$); ***d-b ($P < 0.05$).

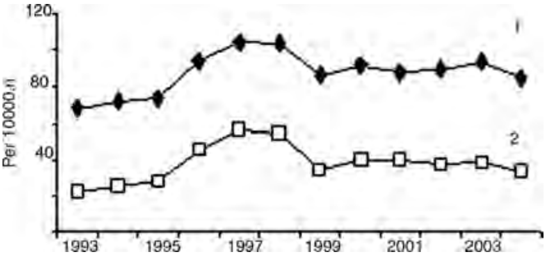

Figure 3.1. Dynamics of primary invalidism in Belarus that is officially connected with the catastrophe in heavily (*top curve*) and less contaminated provinces (Sosnovskaya, 2006).

liquidators 1986–1987 was significantly higher than for a similarly aged group. The annual disease rate among this group of liquidators was up to eight times higher than for the adult population of Belarus as a whole (Antypova *et al.*, 1997).

3.2. Ukraine

1. For the first 10 years after the catastrophe, general morbidity in Ukrainian children increased sixfold (TASS, 1998) followed by a slight reduction, but 15 years after the catastrophe it was 2.9 times higher than in 1986 (Table 3.4).

2. In 1988, there was no indication of significant differences in general morbidity among children living in heavily contaminated versus less contaminated areas, but comparison of the same groups in 1995 showed that morbidity was significantly higher in the highly contaminated areas (Baida and Zhirnosecova, 1998; Law of Ukraine, 2006).

TABLE 3.4. Primary and General Morbidity of Children (0 to 14 Years) in the Heavily Contaminated Territories of Ukraine, per 1,000 (Grodzinsky, 1999; Moskalenko, 2003; Horishna, 2005)

Year	Primary morbidity	General morbidity
1987	455	787
1994	1,139	1,652
2001	n/a	2,285
2004	1,423 (1384[a])	n/a

[a]By Stepanova (2006).

3. Children radiated *in utero* had lower birth weight and more diseases during the first year of life as well as irregularities in their physical development (Stepanova and Davydenko, 1995; Zakrevsky *et al.*, 1993; Zapesochny *et al.*, 1995; Ushakov *et al.*, 1997; Horishna, 2005).

4. From 1997 to 2005 the number of the "practically healthy" children in heavily contaminated areas decreased more than sixfold—from 3.2 to 0.5% (Horishna, 2005).

5. There was appreciably retarded growth in children from 5 to 12 years of age at the time of the survey in the heavily contaminated territories (Arabskaya, 2001).

6. In 1999 there were fourfold more sick children in contaminated territories than the average of such children in Ukraine (Prysyazhnyuk *et al.*, 2002).

7. At the beginning of 2005 the percentage of invalid children in contaminated territories was more than fourfold that of the average among children in other populations (Omelyanets, 2006).

8. Among 252 children in contaminated territories officially recognized as invalids in 2004, 160 had congenital malformations and 47 were cancer victims (Law of Ukraine, 2006).

9. From 1987 to 1989, it was typical for children from heavily contaminated territories to suffer from functional disturbances of various organ systems, indicative of hormonal and immune imbalance. By 1996 those functional disturbances had become chronic pathological processes with long-term relapses that were relatively resistant to treatment (Stepanova *et al.*, 1998).

10. In spite of the intensive social and medical programs in place from 1986 to 2003, the number (percentage) of "practically healthy" children in affected territories decreased 3.7 times (from 27.5 to 7.2%), and the number (percentage) of "chronically ill" children increased from 8.4% in 1986–1987 to 77.8% in 2003 (Figure 3.2). The percent of children with chronic diseases increased steadily—from 8.4%

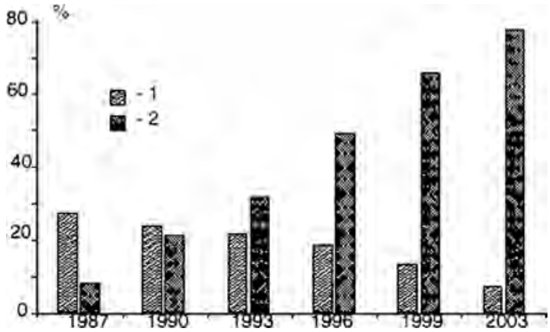

Figure 3.2. Number (percentage) of "practically healthy" children (1) and those with "chronic pathologies" (2) in affected territories in Ukraine from 1987 to 2003 (Stepanova, 2006a).

in 1986–1987 to 77.8% in 2004 (Stepanova, 2006a). At the same time in less contaminated areas the percentage of healthy children has been constant during the last 20 years—up to 30% (Burlak *et al.*, 2006).

11. In Ukraine in the 15 to 18 years after the catastrophe there has been a steady increase in the numbers of invalid children: 3.1 (per 1,000) in 2000, 4.0 in 2002, 4.5 in 2003, and 4.57 in 2004 (Stepanova, 2006a; Figure 3.3).

12. The level of general morbidity among evacuee children increased 1.4 times from 1987 to 1992 (from 1,224 to 1,665 per 1,000). The prevalence of diseases for this period rose more than double (1,425 up to 3,046). General morbidity increased 1.5 to 2.4 times in the contaminated territories from the period before the catastrophe until 1992. At the same time, across the whole of Ukraine child morbidity showed a

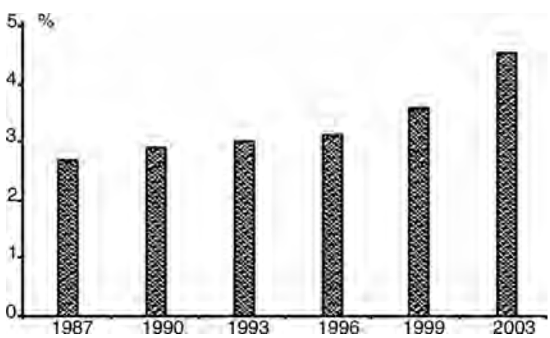

Figure 3.3. Number of invalids (per 1,000) among children in Ukraine from 1987 to 2003 (Stepanova, 2006a).

marked increase (Lukyanova *et al.*, 1995). This trend is continuing: 455.4 per 1,000 in 1987; 866.5 in 1990; 1,160.9 in 1995; 1,367.2 in 2000; and 1,422.9 in 2004 (Stepanova, 2006b).

13. After the catastrophe the number (percentage) of "practically healthy" children in contaminated territories declined markedly and the number of sick children significantly increased (Table 3.5).

14. According to annual surveys during the period from 1988 to 2005 there were severalfold fewer children of liquidators considered "practically healthy" than were found in the control group (2.6–9.2% compared with 18.6–24.6%); furthermore these liquidators' children were statistically significantly taller and more overweight (Kondrashova *et al.*, 2006).

15. Children in contaminated territories were undersized and had low body weight (Kondrashova *et al.*, 2006).

16. In the years from 1988 to 2002, among adult evacuees the number of "healthy" fell from 68 to 22% and the number "chronically ill" rose from 32 to 77% (National Ukrainian Report, 2006).

17. Morbidity among adults and teenagers in the heavily contaminated territories increased fourfold: from 137.2 per 1,000 in 1987 to 573.2 in 2004 (Horishna, 2005).

18. In 1991 the prevailing primary physical disabilities in the contaminated territories were due to circulatory problems (39.0%) and diseases of the nervous system (32.3%). Since 2001 the primary disability is neoplasm (53.3% in 2005). For the period 1992 to 2005 disability due to neoplasm increased nearly fourfold. The current second set of primary disabilities in the contaminated territories is due to circulatory disease (32.5% in 2005; Table 3.6).

19. According to official Ukrainian data, at the beginning of 2005 there were 148,199 people whose invalidism resulted from the Chernobyl catastrophe; among them were 3,326 children (Ipatov *et al.*, 2006).

20. From 1988 to 1997 increased morbidity related to radiation levels was more apparent in the heavily contaminated territories: up to

TABLE 3.5. Children's Health (percent in each healthy group) in Contaminated Territories in Ukraine, 1986–1991 (Luk'yanova *et al.*, 1995)

Health group	1986	1987	1988	1989	1990	1991
First (healthy)	56.6	50.9	54.9	39.9	25.9	19.5
Second	34.2	39.1	34.7	41.7	29.3	28.0
Third	8.4	8.9	9.2	16.8	43.1	50.2
Fourth	0.8	1.1	1.2	1.6	1.7	2.3

4.2 times in a zone with more than 15 Ci/km^2, up to 2.3 times in a zone with 5–15 Ci/km^2, and up to 1.4 times in a zone with 1–5 Ci/km^2 (Prysyazhnyuk *et al.*, 2002).

21. During the period from 1988 to 2004 the number of liquidators who were healthy decreased 12.8 times: from 67.6 to 5.3%, and the number with chronic illnesses increased 6.2 times: from 12.8 to 81.4% (National Ukrainian Report, 2006; Law of the Ukraine, 2006).

22. Among adult evacuees the occurrence of nonmalignant diseases increased 4.8 times (from 632 to 3,037 per 10,000) from 1988 to 2002. Beginning in 1991–1992 the occurrence and prevalence of these diseases was above the average for the country (Figure 3.4).

23. From 1988 to 2002 physical disabilities among adult evacuees increased 42-fold (from 4.6 to 193 per 1,000; National Ukrainian Report, 2006).

24. From 1988 to 2003 disabilities among liquidators increased 76-fold (from 2.7 to 206 per 1,000; Buzunov *et al.*, 2006).

25. From 1988 to 1999 primary morbidity among the populations in the contaminated territories doubled (from 621 to 1,276 and from 310 to 746 per 1,000). Beginning in 1993 these parameters have continually exceeded the Ukrainian norms (Prysyazhnyuk *et al.*, 2002; National Ukrainian Report, 2006) and are still increasing (Tables 3.7 and 3.8).

26. In the heavily contaminated districts of Chernygov Province, the general morbidity significantly exceeded that in areas with less contamination; the general morbidity for the entire province was significantly higher 10 years after the catastrophe as compared with 10 years before (Donets, 2005).

27. The general morbidity of Ukrainian liquidators increased 3.5 times in the 10 years following the catastrophe (Serdyuk and Bobyleva, 1998).

28. Typical complaints in the contaminated territories in the first year after the catastrophe included rapidly developing fatigue (59.6%), headache (65.5%), blood pressure instability (37.8%), abnormal dreaming (37.6%), and aching joints (30.2%) (Buzunov *et al.*, 1995).

TABLE 3.6. Primary Diseases (%) Resulting in Invalidism Connected with the Chernobyl Catastrophe, 1992 to 2005 (Ipatov *et al.*, 2006)

Illness	1992	2001	2005
Neoplasms	8.3	43.0	53.3
Nervous system diseases	40.9	4.5	4.5
Circulatory diseases	30.6	41.0	32.5

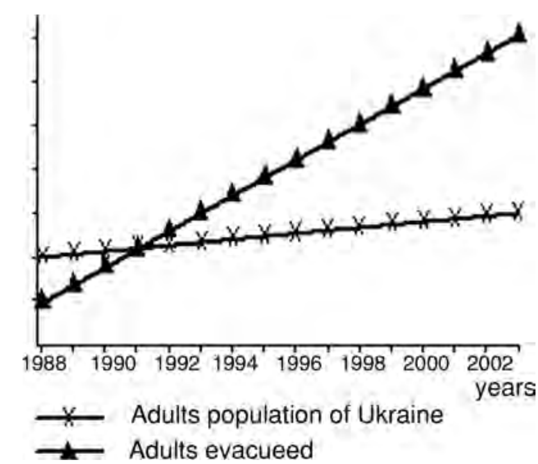

Figure 3.4. Prevalence and occurrence of nonmalignant diseases among adult evacuees and the population of Ukraine from 1988 to 2002 (National Ukrainian Report, 2006).

TABLE 3.7. Percent of "Practically Healthy" Individuals in Three Categories of Chernobyl Victims in Ukraine, 1987–1994 (Grodzinsky, 1999)

Year	Liquidators	Evacuees	Children born to irradiated parents
1987	82	59	86
1988	73	48	78
1989	66	38	72
1990	58	29	62
1991	43	25	53
1992	34	20	45
1993	25	16	38
1994	19	18	26

29. Since 1987 the number of liquidators in the category of "ill" has consistently increased: 18, 27, 34, 42, 57, 64, 75, to 81% (Grodzinsky, 1999). In the 18 years after the catastrophe the number of "sick" liquidators exceeded 94%. In 2003, some 99.9% of the liquidators were officially "sick" in Kiev; 96.5% in Sumy Province were sick and 96% in Donetsk Province (LIGA, 2004; Lubensky, 2004).

30. For the period from 1988 to 1994 there was a manifold increase in primary disabilities (invalidism) among liquidators and evacuees, which exceeded the Ukrainian norms (Table 3.9).

31. Disability among liquidators began to increase sharply from 1991 and by the year 2003 had risen tenfold (Figure 3.5).

3.3. Russia

1. The total measure of the "health of the population" (the sum of invalidism and morbidity) in the Russian part of the European Chernobyl territories worsened up to threefold during the 10 years after the catastrophe (Tsyb, 1996).

TABLE 3.8. Morbidity (per 1,000) in Radioactive Contaminated Territories of Ukraine (Grodzinsky, 1999; Law of Ukraine, 2006)

Year	Adults and teenagers
1987	421.0
1994	1,255.9
2004	2,097.8

TABLE 3.9. Primary Invalidism (per 1,000) in Ukraine, 1987–1994 (Grodzinsky, 1999)

Year	Liquidators	Evacuees	Ukraine
1987	9.6	2.1	0.5
1994	23.2	9.5	0.9

2. Children from radioactive contaminated provinces became ill much more often than children in "clean" regions. The greatest differences in morbidity are expressed in the class of illness labeled "symptoms, phenomena, and inexact designated conditions" (Kulakov *et al.*, 1997).

3. From 1995–1998 the annual prevalence of all registered diseases of children in the southwest districts of Bryansk Province (Cs-137 > 5 Ci/km^2), was 1.5–3.3 times the provincial level as well as the level across Russia (Fetysov, 1999; Kuiyshev *et al.*, 2001). In 2004 childhood morbidity in these districts was double the average for the province (Sergeeva *et al.*, 2005).

4. Childhood morbidity in the contaminated districts of Kaluga Province 15 years after the catastrophe was noticeably higher (Ignatov *et al.*, 2001).

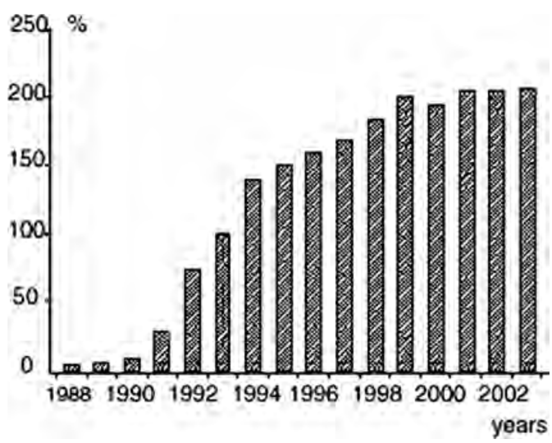

Figure 3.5. Invalidism as a result of nonmalignant diseases in Ukrainian liquidators (1986—1987) from 1988 to 2003 (National Ukrainian Report, 2006).

TABLE 3.10. Initially Diagnosed Children's Morbidity ($M \pm m$ per 1,000) in the Contaminated Districts of Kaluga Province, 1981–2000 (Tsyb *et al.*, 2006)

Districts	1981–1985	1986–1990	1991–1995	1996–2000
Three heavily contaminated	128.2 ± 3.3	198.6 ± 10.8**	253.1 ± 64.4**	130.1 ± 8.5
Three less contaminated	130.0 ± 6.4*	171.6 ± 9.0*	176.3 ± 6.5*	108.9 ± 16.8
Province, total	81.5 ± 6.3	100.4 ± 5.6	121.7 ± 3.2	177.1 ± 10.0

*Significantly different from province's average; **significantly different from province's average and from the period before the catastrophe.

5. Initially diagnosed childhood illnesses measured in 5-year periods for the years from 1981 to 2000 show an increase in the first two decades after the catastrophe (Table 3.10).

6. The frequency of spontaneous abortions and miscarriages and the number of newborns with low birth weight were higher in the more contaminated Klintsy and Novozybkov districts of Bryansk Province (Izhevsky and Meshkov, 1998).

7. The number of low-birth-weight children in the contaminated territories was more than 43%; and the risk of birth of a sick child in this area was more than twofold compared with a control group: 66.4 ± 4.3% vs. 31.8 ± 2.8% (Lyaginskaya *et al.*, 2002).

8. Children's disability in all of Bryansk Province in 1998–1999 was twice that of three of the most contaminated districts: 352 vs. 174 per 1,000 (average for Russia, 161; Komogortseva, 2006).

9. The general morbidity of adults in 1995–1998 in the districts with Cs-137 contamination of more than 5 Ci/km^2 was noticeably higher than in Bryansk Province as a whole (Fetysov, 1999; Kukishev *et al.*, 2001).

10. The general morbidity of the Russian liquidators (3,882 surveyed) who were "under the age of 30" at the time of the catastrophe increased threefold over the next 15 years; in the group "31–40 years of age" the highest morbidity occurred 8 to 9 years after the catastrophe (Karamullin *et al.*, 2004).

11. The morbidity of liquidators exceeds that of the rest of the Russian population (Byryukov *et al.*, 2001).

12. In Bryansk Province there was a tendency toward increased general morbidity in liquidators from 1995 to 1998 (from 1,506 to 2,140 per 1,000; Fetysov, 1999).

13. All the Russian liquidators, mostly young men, were initially healthy. Within 5 years after the catastrophe 30% of them were officially recognized as "sick"; 10 years after fewer than 9% of them were considered "healthy," and after 16 years, only up to 2% were "healthy" (Table 3.11).

14. The total morbidity owing to all classes of illnesses for the Russian liquidators in 1993–1996 was about 1.5 times above that for corresponding groups in the population (Kudryashov, 2001; Ivanov *et al.*, 2004).

15. The number of diseases diagnosed in each liquidator has increased: up until 1991 each liquidator had an average of 2.8 diseases; in 1995, 3.5 diseases; and in 1999, 5.0 diseases (Lyubchenko and Agal'tsov, 2001; Lyubchenko, 2001).

16. Invalidism among liquidators was apparent 2 years after the catastrophe and increased torrentially (Table 3.12).

TABLE 3.11. State of Health of Russian Liquidators: Percent Officially Recognized as "*Sick*" (Ivanov *et al.*, 2004; Prybylova *et al.*, 2004)

Years after the catastrophe	Percent "sick"
0	0
5	30
10	90–92
16	98–99

TABLE 3.12. Disability in Liquidators (%) Compared to Calculated Radiation Doses, 1990–1993 (Ryabzev, 2008)

Year	Disabled (%)		
	0–5 cGy	5–20 cGy	>20 cGy
1990	6.0	10.3	17.3
1991	12.5	21.4	31.1
1992	28.6	50.1	57.6
1993	43.5	74.0	84.7

17. In 1995 the level of disability among liquidators was triple that of corresponding groups (Russian Security Council, 2002), and in 1998 was four times higher (Romamenkova, 1998). Some 15 years after the catastrophe, 27% of the Russian liquidators became invalids at an average age of 48 to 49 (National Russian Report, 2001). By the year 2004 up to 64.7% of all the liquidators of working age were disabled (Zubovsky and Tararukhina, 2007).

3.4. Other Countries

1. FINLAND. There was an increase in the number of premature births just after the catastrophe (Harjulehto *et al.*, 1989).

2. GREAT BRITAIN. In Wales, one of the regions most heavily contaminated by Chernobyl fallout, abnormally low birth weights (less than 1,500 g) were noted in 1986–1987 (Figure 3.6).

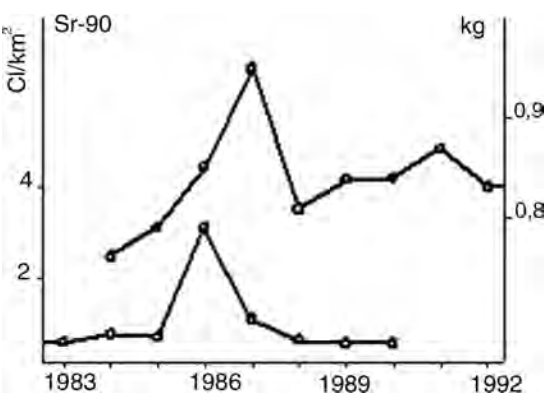

Figure 3.6. Percent of newborns with birth weight less than 1,500 g from 1983 to 1992 (*top curve*) and a level of Sr-90 in soil (*bottom curve*) in Wales (Busby, 1995).

3. HUNGARY. Among infants born in May–June 1986 there was a significantly higher number of low-birth-weight newborns (Wals and Dolk, 1990).

4. LITHUANIA. Among liquidators (of whom 1,808 survived) morbidity was noticeably higher among those who were 45 to 54 years of age during their time in Chernobyl (Burokaite, 2002).

5. SWEDEN. The number of newborns with low birth weight was significantly higher in July 1986 (Ericson and Kallen, 1994).

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It is clear that there is significantly increased general morbidity in territories heavily contaminated by the Chernobyl fallout and higher rates of disability among liquidators and others who were exposed to higher doses of radiation than the general population or corresponding nonradiated groups. Certainly, there is no direct proof of the influence of the Chernobyl catastrophe on these figures, but the question is: What else can account for the increased illness and disability that coincide precisely in time and with increased levels of radioactive contamination, if not Chernobyl?

The IAEA and WHO suggested (Chernobyl Forum, 2006) that the increased morbidity is partly due to social, economic, and psychological factors. Socioeconomic factors cannot be the reason because the compared groups are identical in social and economic position, natural surroundings, age composition, etc. and differ only in their exposure to Chernobyl contamination. Following scientific canons such as Occam's Razor, Mills's canons, and Bradford Hill criteria, we cannot discern any reason for this level of illness other than the radioactive contamination due to the Chernobyl catastrophe.

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4. Accelerated Aging as a Consequence of the Chernobyl Catastrophe

Alexey V. Yablokov

Accelerated aging is one of the well-known consequences of exposure to ionizing radiation. This phenomenon is apparent to a greater or lesser degree in all of the populations contaminated by the Chernobyl radionuclides.

1. Children living in all the Belarussian territories heavily contaminated by Chernobyl fallout evidence a characteristic constellation of senile illnesses (Nesterenko, 1996; and many others).
2. Children from the contaminated areas of Belarus have digestive tract epithelium characteristic of senile changes (Nesterenko, 1996; Bebeshko *et al.*, 2006).
3. Of 69 children and teenagers hospitalized in Belarus from 1991 to 1996 diagnosed with premature baldness (alopecia), 70% came from the heavily contaminated territories (Morozevich *et al.*, 1997).
4. The biological ages of inhabitants from the radioactive contaminated territories of Ukraine exceed their calendar ages by 7 to 9 years (Mezhzherin, 1996). The same phenomenon is observed in Russia (Malygin *et al.*, 1998).
5. Men and women categorized as middle aged living in territories with Cs-137 contamination above 555 kBq/m^2 died from heart attacks 8 years younger than the average person in Belarus (Antypova and Babichevskaya, 2001).
6. Inhabitants of Ukrainian territories heavily contaminated with radiation developed abnormalities of accommodation and other senile eye changes (Fedirko, 1999; Fedirko and Kadochnykova, 2007).
7. Early aging is a typical characteristic seen in liquidators, and many of them develop diseases 10 to 15 years earlier than the average population. The biological ages of liquidators calculated by characteristics of aging are 5 to 15 years older than their calendar ages (Gadasyna, 1994; Romanenko *et al.*, 1995; Tron'ko *et al.*, 1995; Ushakov *et al.*, 1997).
8. Chernobyl radiation induced premature aging of the eyes (Fedirko and Kadochnykova, 2007).
9. Presenile characteristics of liquidators include (Antypova *et al.*, 1997a,b; Zhavoronkova *et al.*, 2003; Kholodova and Zubovsky, 2002; Zubovsky and Malova, 2002; Vartanyan *et al.*, 2002; Krasylenko and Eler Ayad, 2002; Kirke, 2002; Stepanenko, 2003; Kharchenko *et al.*, 1998, 2004; Druzhynyna, 2004; Fedirko *et al.*, 2004; Oradovskaya *et al.*, 2006):

- Multiple illnesses characteristic of senility in individuals at early ages (10.6 diseases diagnosed in one liquidator is 2.4 times higher that the age norm).
- Degenerate and dystrophic changes in various organs and tissues (e.g., osteoporosis, chronic cholecystitis, pancreatitis, fatty liver, and renal dystrophy).
- Accelerated aging of blood vessels, including those in the brain, leading to senile

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encephalopathy in those 40 years of age, and generalized arteriosclerosis.

- Ocular changes, including early senile cataracts and premature presbyopia.
- Decline in higher mental function characteristic of senility.
- Development of Type II diabetes in liquidators younger than 30 years of age.
- Loss of stability in the antioxidant system.
- Retina vessel arteriosclerosis.
- Hearing and vestibular disorders at younger ages.

10. Evidence of accelerated biological time in liquidators is the shortened rhythm of intracircadian arterial pressure (Talalaeva, 2002).
11. Findings indicating accelerated aging in practically all liquidators are changes in blood vessel walls leading to the development of atherosclerosis. Changes are also found in epithelial tissue, including that of the intestines (Tlepshukov *et al.*, 1998).
12. An accelerated rate of aging, measured in 5-year intervals, marked by biological and cardiopulmonary changes (and for 11 years by physiological changes) was found in 81% of men and 77% of women liquidators (306 surveyed). Liquidators younger than 45 years of age were more vulnerable. The biological age of liquidators who worked at the Chernobyl catastrophe site in the first 4 months after the meltdown exceeds the biological age of those who labored there subsequently (Polyukhov *et al.*, 2000).
13. It is proposed that the accelerated occurrence of age-related changes in organs of liquidators is a radiation-induced *progeroid syndrome* (Polyukhov *et al.*, 2000; Bebeshko *et al.*, 2006).

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5. Nonmalignant Diseases after the Chernobyl Catastrophe

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This section describes the spectrum and the scale of the nonmalignant diseases that have been found among exposed populations. Adverse effects as a result of Chernobyl irradiation have been found in every group that has been studied. Brain damage has been found in individuals directly exposed—liquidators and those living in the contaminated territories, as well as in their offspring. Premature cataracts; tooth and mouth abnormalities; and blood, lymphatic, heart, lung, gastrointestinal, urologic, bone, and skin diseases afflict and impair people, young and old alike. Endocrine dysfunction, particularly thyroid disease, is far more common than might be expected, with some 1,000 cases of thyroid dysfunction for every case of thyroid cancer, a marked increase after the catastrophe. There are genetic damage and birth defects especially in children of liquidators and in children born in areas with high levels of radioisotope contamination. Immunological abnormalities and increases in viral, bacterial, and parasitic diseases are rife among individuals in the heavily contaminated areas. For more than 20 years, overall morbidity has remained high in those exposed to the irradiation released by Chernobyl. One cannot give credence to the explanation that these numbers are due solely to socioeconomic factors. The negative health consequences of the catastrophe are amply documented in this chapter and concern millions of people.

5.1. Blood and Lymphatic System Diseases

For both children and adults, diseases of the blood and the circulatory and lymphatic systems are among the most widespread consequences of the Chernobyl radioactive contamination and are a leading cause of morbidity and death for individuals who worked as liquidators.

5.1.1. Diseases of the Blood and Blood-Forming Organs

5.1.1.1. Belarus

1. The incidence of diseases of the blood and blood-forming organs was 3.8-fold higher among evacuees 9 years after the catastrophe. It was 2.4-fold higher for inhabitants of the contaminated territories than for all of the population of Belarus; these rates were, respectively, 279, 175, and 74 per 10,000 (Matsko, 1999).

2. In 1995, for the Belarus liquidators, incidence of diseases of the blood and blood-forming organs was 4.4-fold higher than for corresponding groups in the general population (304 and 69 per 10,000; Matsko, 1999; Kudryashov, 2001).

3. The incidence of hematological abnormalities was significantly higher among 1,220,424 newborns in the territories contaminated by Cs-137 at levels above 1 Ci/km^2 (Busuet *et al.*, 2002).

4. Incidence of diseases of the blood and the lymphatic system was three- to five-fold higher in the most contaminated Stolinsk and Luninetsk districts in Brest Province in 1996 than in less contaminated districts (Gordeiko, 1998).

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TABLE 5.1. Statistics of the Annual Cases of Belarussian Children with Depression of the Blood-Forming Organs after the Catastrophe (Gapanovich *et al.*, 2001)

	1979–1985	1986–1992	1993–1997
Number of cases	9.3	14.0	15.6
Cases per 10,000	0.60 ± 0.09	0.71 ± 0.1*	
	1.00	1.46*	1.73*

*$p < 0.05$.

5. The activity of serum complement and the number of effective C4 component cells was significantly lower among 350 children from the Belarus area contaminated by Cs-137; in more contaminated areas (>15 Ci/km^2) there was a significantly lower level of C3 component cells (Zafranskaya *et al.*, 1995).

6. Myelotoxic activity of the blood (MTA) and the number of T lymphocytes were significantly lower in multiple sclerosis patients from areas with Cs-137 contamination from 5–15 Ci/km^2 (Fyllypovich, 2002).

7. Absolute and relative numbers of lymphocytes, as a percent of basophilic cells were significantly higher among adults and teenagers living in Gomel Province territories with a level of Cs-137 contamination from 15–40 Ci/km^2 (Miksha and Danylov, 1997).

8. Evacuees and those still living in heavily contaminated territories have a significantly lower percent of leukocytes, which have expressed pan-D cellular marker CD3 (Baeva and Sokolenko, 1998).

9. The leukocyte count was significantly higher among inhabitants of Vitebsk and Gomel provinces who developed infectious diseases in the first 3 years after the catastrophe compared with those who already were suffering from these diseases (Matveenko *et al.*, 1995).

10. The number of cases of preleukemic conditions (myelodysplastic syndrome and aplastic anemia) increased significantly during the first 11 years after the catastrophe (Table 5.1).

11. Significant changes in the structure of the albumin layer of erythrocyte membranes (increased cell fragility) occurred in liquidators' children born in 1987 (Arynchin *et al.*, 1999).

12. There is a correlation between increased Fe-deficient anemia in Belarus and the level of radioactive contamination in the territory (Dzykovich *et al.*, 1994; Nesterenko, 1996). In the contaminated areas of Mogilev Province the number of people with leukopenia and anemia increased sevenfold from 1986 to 1988 compared to 1985 (Gofman, 1994).

13. Primary products of lipid oxidation in the plasma of children's blood (0 to 12 months) from Mogilev (Krasnopolsk District), Gomel (Kormyansk District), and Vitebsk (Ushachy District) provinces contaminated with Cs-137 statistically significantly declined from 1991 to 1994. The amount of vitamins A and E in babies' blood from the more contaminated territories (up to 40 Ci/km^2) decreased 2.0- to 2.7-fold (Voznenko *et al.*, 1996).

14. Children from Chechersk District (Gomel Province) with levels of 15–40 Ci/km^2 of Cs-137 and from Mtzensk and Bolkhovsk districts (Oryol Province, Russia) with levels of 1–15 Ci/km^2 have lipid oxidation products that are two- to sixfold higher. The levels of irreplaceable bioantioxidants (BAO) were two- to threefold lower than norms for the corresponding age ranges. Contaminated children have rates of metabolism of BAO two- to tenfold higher than the age norms (Baleva *et al.*, 2001a).

15. For boys irradiated *in utero* there was a reduction in direct and an increase in free bilirubin in blood serum over 10 years. For girls there was a reduced concentration of both direct and indirect bilirubin (Sychik and Stozharov, 1999a,b).

5.1.1.2. Ukraine

1. Children in the heavily contaminated territories have a level of free oxidizing radicals in their blood that is significantly higher than in those in the less contaminated territories: 1,278 ± 80 compared with 445 ± 36 measured as impulses per minute (Horishna, 2005).

2. Children of liquidators living in the contaminated territories had two- to threefold higher blood and blood-forming-organ morbidity compared to children from noncontaminated territories (Horishna, 2005).

3. Diseases of the blood and circulatory system for people living in the contaminated territories increased 11- to 15-fold for the first 12 years after the catastrophe (1988–1999; Prysyazhnyuk *et al.*, 2002).

4. In 1996, morbidity of the blood-forming organs in the contaminated territories was 2.4-fold higher than for the rest of Ukraine (12.6 and 3.2 per 10,000; Grodzinsky, 1999).

5. For the first 10 years after the catastrophe the number of cases of diseases of blood and blood-forming organs among adults in the contaminated territories of Zhytomir Province increased more than 50-fold: from 0.2 up to 11.5% (Nagornaya, 1995).

6. For a decade after the catastrophe, morbidity of the blood and blood-forming organs in adults and teenagers living in contaminated territories increased 2.4-fold: from 12.7 in 1987 to up to 30.5 per 10,000 in 1996. For the remaining population of Ukraine this level remained at the precatastrophe level (Grodzinsky, 1999).

7. During the acute iodic period (the first months after the catastrophe) abnormal blood cell morphology was found in more than 92% of 7,200 surveyed children living in the area, and 32% of them also had abnormal blood counts. Abnormalities included mitochondrial swelling and stratification of nuclear membranes, expansion of the perinuclear spaces, pathological changes in cell surfaces, decreased concentration of cellular substances, and increase in the volume of water. The last is an indication of damage to the cellular membranes (Stepanova and Davydenko, 1995).

8. During 1987–1988 qualitative changes in blood cells were found in 78.3% of children from zones with radiation levels of 5–15 Ci/km^2 (Stepanova and Davydenko, 1995).

9. In the contaminated territories, anemia was found in 11.5% of 1,926 children examined in 1986–1998 (Bebeshko *et al.*, 2000).

5.1.1.3. Russia

1. Diseases of the blood and blood-forming organs caused much greater general morbidity in children from contaminated areas (Kulakov *et al.*, 1997).

2. Morbidity owing to abnormalities of the blood and the circulatory system has more than doubled in children in the contaminated districts of Tula Province and has increased in all the contaminated districts in comparison with the period before the catastrophe (Sokolov, 2003).

3. In 1998 the annual general morbidity from blood, blood-forming organs, and the circulatory system of children in the contaminated districts of Bryansk Province significantly exceeded the provincial level (19.6 vs. 13.7 per 1,000; Fetysov, 1999a).

4. For liquidators, the morbidity from blood and blood-forming organs grew 14.5-fold between 1986 and 1993 (Baleva *et al.*, 2001).

5. Critically low lymphocyte counts were seen in children in the contaminated districts of Bryansk Province over a 10-year survey after the catastrophe (Luk'yanova and Lenskaya, 1996).

6. In almost half of the children, blood hemoglobin levels exceeded 150 g/liter in the settlements of Bryansk Province that had high levels of Cs-137 soil contamination and a level of contamination from Sr-90 (Lenskaya *et al.*, 1995).

7. Individuals living in the contaminated areas have fewer lymphocytes with adaptive reaction, and the number of people with higher lymphocytes radiosensitivity increased (Burlakova *et al.*, 1998).

8. The numbers of leukocytes, erythrocytes, lymphocytes, and thrombocytes in liquidators' peripheral blood were markedly different (Tukov *et al.*, 2000). The number of large granulocytic lymphocytes decreased by 60–80% 1 month after the liquidators began work and

TABLE 5.2. Dynamics of the Interrelation by Lymphopoietic Type (in %, See Text) in Russian Liquidators (Karamullin *et al.*, 2004)

Time after the catastrophe	Lymphopoietic types		
	Quasi-normal	Hyperregeneratory	Hyporegeneratory
0 to 5 years	32	55	13
5 to 9 years	38	0	62
10 to 15 years	60	17	23
Control group	76	12	12

stayed at a lower level for at least 1 year (Antushevich and Legeza, 2002).

9. The glutathione level in blood proteins and cytogenic characteristics of lymphocytes were markedly different in children born 5 to 7 years after the catastrophe in the contaminated Mtsensk and Bolkhov districts, Oryol Province, Russia, and in Chechersk District, Gomel Province, Belarus (Ivanenko *et al.*, 2004).

10. In the contaminated territories of Kursk Province changes in lymphocyte counts and functional activity and the number of circulating immune complexes were seen in the blood of children 10 to 13 years of age and in pregnant women (Alymov *et al.*, 2004).

11. Significant abnormal lymphocytes and lymphopenia was seen more often in children in the contaminated territories (Sharapov, 2001; Vasyna *et al.*, 2005). Palpable lymph nodes occurred with greater frequency and were more enlarged in the heavily contaminated territories. Chronic tonsillitis and hypertrophy of the tonsils and adenoids were found in 45.4% of 468 children and teenagers examined (Bozhko, 2004).

12. Among the liquidators, the following parameters of the blood and lymphatic system were significantly different from controls:

- Average duration of nuclear magnetic resonance relaxation (NPMR) of blood plasma (Popova *et al.*, 2002).
- Receptor–leukotrene reaction of erythrocyte membranes (Karpova and Koretskaya, 2003).
- Quantity of the POL by-products (by malonic aldehyde concentration) and by viscosity of membranes and on a degree of the lipids nonsaturation (Baleva *et al.*, 2001a).
- Imbalance of the intermediate-size molecules in thrombocytes, erythrocytes, and blood serum (Zagradskaya, 2002).
- Decreased scattering of the granular component of lymphocyte nuclei reduction of the area and perimeter of the perigranular zones; and increased toothlike projection of this zone (Aculich, 2003).
- Increased intravascular thrombocyte aggregation (Tlepshukov *et al.*, 1998).
- Increased blood fibrinolyic activity and fibrinogen concentration in blood serum (Tlepshukov *et al.*, 1998).

13. Liquidators' lymphopoesis remained nonfunctional 10 years after the catastrophe (Table 5.2).

It is known that Japanese juvenile atomic bomb victims suffer from diseases of the blood-forming organs 10 times more often than control groups, even in the second and third generations (Furitsu *et al.*, 1992). Thus it can be expected that, following the Chernobyl catastrophe, several more generations will develop blood-forming diseases as a result of the radiation.

5.1.2. Cardiovascular Diseases

Cardiovascular diseases are widespread in all the territories contaminated by Chernobyl emissions.

5.1.2.1. Belarus

1. Cardiovascular disease increased nationwide three- to fourfold in 10 years compared to the pre-Chernobyl period and to an even greater degree in the more heavily contaminated areas (Manak *et al.*, 1996; Nesterenko, 1996).

2. Impaired cardiovascular homeostasis is characteristic for more newborns in the first 4 days of life in districts with contamination levels higher than 15–40 Ci/km^2 (Voskresenskaya *et al.*, 1996).

3. Incidence of hemorrhages in newborns in the contaminated Chechersky District of the Gomel Province is more than double than before the catastrophe (Kulakov *et al.*, 1997).

4. Correlated with levels of radiation, changes in the cardiovascular system were found in more than 70% of surveyed children aged 3 to 7 years from contaminated territories of Gomel Province (Bandazhevskaya, 1994).

5. In 1995, cardiovascular system morbidity among the population in the contaminated territories and evacuees was threefold higher than for Belarus as a whole (4,860 and 1,630 per 100,000; Matsko, 1999).

6. More than 70% of newborn to 1-year-old children in territories with Cs-137 soil contamination of 5–20 Ci/km^2 have had cardiac rhythm abnormalities (Tsybul'skaya *et al.*, 1992; Bandazhevsky, 1997). Abnormalities of cardiac rhythm and conductivity correlated with the quantity of incorporated radionuclides (Bandazhevsky *et al.*, 1995; Bandazhevsky 1999). There were significantly higher incidence and persistence of abnormalities of cardiac rhythm in patients with ischemic heart disease in contaminated territories (Arynchyna and Mil'kmanovich, 1992).

7. Both raised and lowered arterial blood pressure were found in children and adults in the contaminated areas (Sykorensky and Bagel, 1992; Goncharik, 1992; Nedvetskaya and Lyalykov, 1994; Zabolotny *et al.*, 2001; and others). Increased arterial pressure occurred significantly more often in adults in the Mogilev Province, where contamination was above 30 Ci/km^2 (Podpalov, 1994). Higher arterial pressure in children correlated with the quantity of the incorporated Cs-137 (Bandazhevskaya, 2003; Kienya and Ermolitsky, 1997).

8. Compared to healthy children, brain arterial vessels in children 4 to 16 years old were more brittle among children in contaminated areas in Gomel (Narovlyansky, Braginsk, El'sk, and Khoiniky districts), Mogilev (Tchernikovsk, Krasnopol'sk, and Slavgorodsk districts), and Brest provinces (Arynchin *et al.*, 1996, 2002; Arynchin, 1998).

9. Morbidity of the circulatory system among children born to irradiated parents was significantly higher from 1993 to 2003 (National Belarussian Report, 2006).

10. The volume of blood loss during Caesarean birth was significantly higher for women from Gomel Province living in the territories contaminated by Cs-137 at levels of 1–5 Ci/km^2 compared to those from uncontaminated areas (Savchenko *et al.*, 1996).

11. Blood supply to the legs, as indicated by vasomotor reactions of the large vessels, was significantly abnormal for girls age 10 to 15 years who lived in areas with a level of Cs-137 contamination higher than 1–5 Ci/km^2 compared with those in the less contaminated territories (Khomich and Lysenko, 2002; Savanevsky and Gamshey, 2003).

12. The primary morbidity of both male and female liquidators was high blood pressure, acute heart attacks, cerebrovascular diseases, and atherosclerosis in of the arms and legs, which increased significantly in 1993–2003, including in the young working group (National Belarussian Report, 2006).

13. In the observation period 1992–1997 there was a 22.1% increase in the incidence of fatal cardiovascular disease among liquidators compared to 2.5% in the general population (Pflugbeil *et al.*, 2006).

TABLE 5.3. Cardiovascular Characteristics of Male Liquidators in Voronezh Province (Babkin *et al.*, 2002)

Parameter	Liquidators ($n = 56$)	Inhabitants of contaminated territory ($n = 60$)	Control ($n = 44$)
AP–a systole	151.9 ± 1.8*	129.6 ± 2.1	126.3 ± 3.2
AP–diastole	91.5 ± 1.5*	83.2 ± 1.8	82.2 ± 2.2
IBH, %	9.1*	46.4	33.3
Insult, %	4.5*	16.1*	0
Thickness of carotid wall, mm*	1.71 ± 0.90*	0.81 ± 0.20	0.82 ± 0.04
Overburdening heredity, %	25	25	27.3

*Statistically significant differences from control group.

5.1.2.2. Ukraine

1. The morbidity from circulatory diseases in 1996 in the contaminated territories was 1.5-fold higher than in the rest of Ukraine (430 vs. 294 per 10,000; Grodzinsky, 1999).

2. Symptoms of early atherosclerosis were observed in 55.2% of children in territories contaminated at a level of 5–15 kBq \ m^2 (Burlak *et al.* 2006).

3. Diseases of the cardiovascular system occurred significantly more often in children irradiated *in utero* (57.8 vs. 31.8%, $p < 0.05$; Prysyazhnyuk *et al.*, 2002).

4. Incidence of hemorrhage in newborns in the contaminated Polessk District, Kiev Province, has more than doubled since the catastrophe (Kulakov *et al.*, 1997). Atherosclerosis and ischemic disease of the heart are seen significantly more often in young evacuees and in those living in contaminated territories (Prokopenko, 2003).

5. Liquidators' morbidity from vegetal-vascular dystonia (tachycardia, hyperthyroidism, and neuropathy) was 16-fold higher than the average for Ukraine in the first 10 years after the catastrophe (Serdyuk and Bobyleva, 1998).

5.1.2.3. Russia

1. For the three heavily contaminated districts in Bryansk Province, morbidity in children from circulatory system problems is three- to fivefold higher than the average (Komogortseva, 2006).

2. The incidence of hemorrhages among newborns in the contaminated Mtsensk and Volkovsk districts, Oryol Province, is double what it was prior to the catastrophe (Kulakov *et al.*, 1997).

3. For liquidators, morbidity from circulatory disease increased 23-fold between 1986 and 1994 (Baleva *et al.*, 2001). In 1995–1998 morbidity in Bryansk Province liquidators increased 2.2-fold (Fetysov, 1999b). According to other data, for 1991–1998 morbidity increased 1.6-fold (Byryukov *et al.*, 2001). Some 13 years after the catastrophe cardiovascular morbidity among liquidators was fourfold higher than in corresponding groups of the population (National Russian Report, 1999).

4. The health of liquidators differs significantly from that of control groups, the former having higher arterial blood pressure, more ischemic heart disease, and increased cardiac wall thickness characteristic of atherosclerosis. The liquidators living in contaminated territories of Voronezh Province differed from control groups also in the number of strokes (cerebral vascular accidents) and the cases of ischemic heart disease (Table 5.3).

5. Ten years after the catastrophe there was an increase in the incidence of high arterial blood pressure among a large group of liquidators who worked from April to June 1986 (Kuznetsova *et al.*, 2004). Increased systolic

blood pressure was characteristic for all the liquidators examined (Zabolotny *et al.*, 2001).

6. From 1991 to 1998 the incidence of ischemic heart disease in liquidators increased threefold, from 20 to 58.9% (Zubovsky and Smirnova, 2000). Ischemic heart disease developed in one-third of 118 liquidators under observation for 15 years (Noskov, 2004). From 1993 to 1996 another group of liquidators demonstrated a significant increase in ischemic heart disease, from 14.6 to 23.0% (Strukov, 2003). Morbidity and the frequency of occurrence of ischemic heart disease in liquidators and in the general population of the contaminated territories continue to grow (Khrysanfov and Meskikh, 2001).

7. For all the liquidators examined, it was typical to find lowered tonus of arterial vessels in the circle of Willis in the brain (Kovaleva *et al.*, 2004).

8. Impairment of blood circulation in the brain (neurocirculatory dystonia) was found in a majority of the liquidators examined in 1986–1987, and the number of such cases is increasing (Romanova, 2001; Bazarov *et al.*, 2001; Antushevich and Legeza, 2002; Kuznetsova *et al.*, 2004; and others). These changes occur mainly owing to disease of small arteries and arterioles (Troshyna, 2004) and occurred more frequently in young liquidators (Kuznetsova *et al.*, 2004). Impairment of blood circulation in the brain among liquidators is sometimes defined as dyscirculatory encephalopathy (DCE), a chronic cerebral vascular pathology leading to functional and organic destruction of the central nervous system. DCE was found in 40% of the cases of structural brain circulatory disease in Russian liquidators in 2000. This pathological condition is specific for the impact caused by small doses of Chernobyl radioactivity and is not listed in the international classification of illnesses (Khrysanfov and Meskikh, 2001).

9. Hypertension is seen markedly more often among both liquidators and people living in the contaminated territories. High blood pressure accounted for 25% of the cases of pathology in liquidators in 2000 (Khrysanfov and Meskikh, 2001). Hypertension morbidity in a group of liquidators increased from 18.5% in 1993 to 24.8% in 1996 (Strukov, 2003). Hypertension is seen even more often in children of liquidators (Kulakov *et al.*, 1997).

10. After a second evaluation in 2000–2001, atherosclerosis of the brachiocephalic arteries was found in several members of the same large group of the liquidators originally examined in 1993–1994 (Shamaryn *et al.*, 2001).

11. Left-heart ventricular mass was significantly larger in liquidators although arterial pressures were normal (Shal'nova *et al.*, 1998).

12. Typically abnormalities persisted in liquidators for a long time after the catastrophe (Shamaryn *et al.*, 2001; Khrysanfov and Meskikh, 2001; Kuznetsova *et al.*, 2004).

13. Abnormal vascular circulation of the eye was found in all of the liquidators examined (Rud' *et al.*, 2001; Petrova, 2003). Liquidators were also found to suffer from diminished antimicrobial properties of vessel walls (Tlepshukov *et al.*, 1998).

14. Liquidators with ischemic heart disease differ significantly in many homodynamic parameters compared with other patients of the same age (Talalaeva, 2002).

5.1.2.4. Other Countries

MOLDOVA. Liquidators from Chisinau evidence a triple increase in cardiovascular diseases over the last years and the incidence among them is now double that of control groups. Some 25% of the liquidators examined developed thickening of the aortic wall, and 22% have left ventricular hypertrophy (Kirkae, 2002).

5.1.3. Conclusion

Diseases of blood, blood-forming organs, and the circulatory system are, undoubtedly, major components of the general morbidity of inhabitants of the territories contaminated by the Chernobyl radiation, including evacuees, migrants, and liquidators and their children. In spite of the fact that the general picture of the blood and circulatory systems is still far from complete, it is clear that one of the common reasons for these functional impairments is radioactive destruction of the endothelium, the covering surface of vessels.

The severe impact of radioactive contamination from Chernobyl resulting in increasing morbidity of the blood and circulatory system cannot be doubted.

5.2. Genetic Changes

Changes in genetic structures in both reproductive and somatic cells determine and define the occurrence of many diseases. Ionizing radiation causes damage to hereditary structures. The huge collective dose from the Chernobyl catastrophe (127–150 million persons/rad) has resulted in damage that will span several generations, causing changes in genetic structures and various types of mutations: genomic mutations (change in the number of chromosomes), chromosomal mutations (damage to the structure of chromosomes—translocations, deletions, insertions, and inversions), and small (point) mutations.

Twenty-two years after the catastrophe data concerning genetic damage linked to additional Chernobyl irradiation was released. This section presents data not only on the various types of mutations that have resulted from the catastrophe (Section 5.2.1), but also on genetically caused congenital developmental anomalies (Section 5.2.4) and the health of the subsequent generation, the children born to irradiated parents (Section 5.2.5).

5.2.1. Changes in the Frequency of Mutations

There are many convincing studies showing increased frequency of chromosomal and genomic mutations, including changes in the structure and normal number of chromosomes in those radiated by Chernobyl fallout. Accumulated data show genetic polymorphism of proteins and changes in satellite DNA.

5.2.1.1. Chromosomal Mutations

Ionizing radiation causes various changes in the general structure of chromosomes: nonstable aberrations (dicentrics, centric rings, noncentric fragments), which are rather quickly eliminated in subsequent cell generations, and stable aberrations (different types of translocations at separate chromosomal sites), which are retained for many years. The frequency of chromosomal aberrations in somatic cells, obtained by studying lymphocytes, reflects the general status of chromosomes throughout the body, including increasing dicentric and ring chromosome abnormalities in mothers and their newborns in the contaminated territories (Matsko, 1999).

Histological analysis of peripheral blood lymphocytes reveals structural and chromosomal number aberrations. Presence of cells with several aberrations (multiaberrant cells) may indicate the level of the impact of Pu (Il'inskikh *et al.*, 2002). An additional parameter of genetic variability is the so-called mitosis index, the number of mitoses per 100 cells.

Occurrence of a chromosomal aberration does not necessarily mean development of disease, but it does signal both the likely emergence of various tumors, owing to somatic cell impairment (e.g., in blood cells), and also impaired reproductive cells. Altered structure of generative chromosomes (in sperm and ova) indicates genetic predisposition to various diseases in the next generation.

The incidence of chromosomal aberrations is significantly higher in all of the territories contaminated by the Chernobyl nuclear fallout (Lazyuk *et al.*, 1990; Stepanova and Vanyurikhyna, 1993; Pilinskaya, 1994; Sevan'kaev *et al.*, 1995a; Vorobtsova *et al.*, 1995; Mikhalevich, 1999; and others; Table 5.4). The Chernobyl fallout caused a further increase in the already elevated number of

TABLE 5.4. Incidence of (%, M ± m) Aberrant Cells and Chromosomal Aberrations (per 100 Lymphocytes) before and after the Chernobyl Catastrophe (Bochkov *et al.*, 1972, 2001; Pilinskaya, 1992; Bezdrobna *et al.*, 2002)

	Aberrant cells, *n*	Chromosomal aberrations, *n*
Ukraine, early 1970s	n/a	1.19 ± 0.06
Ukraine, before 1986	1.43 ± 0.16	1.47 ± 0.19
Average in the world, 2000	2.13 ± 0.08	2.21 ± 0.14
Ukraine, Kiev, 1998–1999	3.20 ± 0.84	3.51 ± 0.97
30-km Chernobyl zone, 1998–1999	5.02 ± 1.95	5.32 ± 2.10

chromosomal mutations observed worldwide that is associated with the atmospheric nuclear weapons testing that was carried out until the 1980s.

5.2.1.1.1. Belarus

1. The number of chromosomal aberrations is higher than the norms among children living in areas with elevated levels of radiation (Nesterenko, 1996; Goncharova, 2000). The genetic changes are especially common among individuals who were younger than 6 years of age at the time of the catastrophe (Ushakov *et al.*, 1997). Frequency of chromosomal aberrations (dicentrics and centric rings) in women and newborns from the contaminated areas of Mogilev Province are significantly higher than in a control group, and the frequency of such abnormal chromosomes is more than double in schoolboys from the contaminated areas of Brest Province compared with those from less contaminated Minsk (Lazyuk *et al.*, 1994). Some 52% of surveyed children from the contaminated territories of Brest Province, where the Cs-137 levels are 5–15 Ci/km^2, have a significantly higher number of chromosomal aberrations. These cytogenic changes are accompanied by molecular-genetic, cytological, and biochemical changes in peripheral blood (Mel'nov and Lebedeva, 2004).

2. The average incidence of DNA mutations was twice as high in 79 children born in 1994 in Belarus to parents who continued to live in contaminated territories after the catastrophe. This was more than twice that in the DNA of children from 105 controls (families in Great Britain) and has been correlated with the level of radioactive contamination in the district where the parents lived (Dubrova *et al.*, 1996, 1997, 2002).

3. The same children examined 1 year and 2 years after the catastrophe had significant increases in the number of chromosomal aberrations (5.2 + 0.5% in 1987 and 8.7 + 0.6% in 1988). During the same evaluation, a significant increase in the number of multiaberrant cells with two to four aberrations was found (16.4 + 3.3% in 1987 and 27.0 + 3.4% in 1988). The occurrence of cells with three to four aberrations was especially higher in children from the more contaminated Khoiniky and Braginsk districts (Mikhalevich, 1999).

4. Elevated chromosomal aberrations are found in children born 5 to 7 years after the catastrophe in the contaminated Chechersk City, Gomel Province (Ivanenko *et al.*, 2004).

5. There was a sixfold increase in dicentrics and centric ring frequencies in the blood cells of the same individual before and after the catastrophe (Matsko, 1999).

6. For liquidators, micronuclei numbers in peripheral lymphocytes increased many years after their exposure to the radiation (Table 5.5).

TABLE 5.5. Number of Micronuclei in Lymphocytes of Belarussian Liquidators 15 Years after the Catastrophe (Mel'nov, 2002)

	Frequency of micronuclei (per 1,000 cells)*	
Dose, Gy	Liquidators, 47.6 ± 1.3 years old	Controls, 40.8 ± 1.7 years old
0.01	2.7 ± 1.1	15.2 ± 2.3
0.1	24.9 ± 4.4	29.4 ± 2.6
0.2	45.4 ± 5.0	47.1 ± 15.4
0.3	69.6 ± 10.3	47.2 ± 12.2
0.4	108.0 ± 16.0	67.2 ± 14.1
0.5	149.9 ± 21.1	108.0 ± 26.0

*All distinctions are statistically significant.

TABLE 5.6. Incidence of Various Types of Chromosomal Aberrations (per 100 Lymphocytes) among "Samosels" (Self-Settlers) and in the Kiev Area (Bezdrobna *et al.*, 2002)

	Incidence, per 100 cells	
Type of aberration	"Samosels"	Kiev area
Dicentrics + centric rings	3.0 ± 0.2	2.3 ± 0.1
Breaks	0.13 ± 0.04	0.02 ± 0.01
Exchanges*	3.1 ± 0.2	2.3 ± 0.1
Fragments	1.6 ± 0.2	0.9 ± 0.1
Insertions	0.02 ± 0.02	0.04 ± 0.02
Deletions with fragments	0.22 ± 0.05	0.08 ± 0.03
Deletions without fragments	0.10 ± 0.03	0.05 ± 0.02
Total abnormal	0.33 ± 0.06	0.13 ± 0.03
Monocentrics	0.23 ± 0.05	0.12 ± 0.03
Total	2.2 ± 0.2	1.2 ± 0.1

*Pre-Chernobyl level: 1.1.

5.2.1.1.2. Ukraine

1. In a survey of more than 5,000 children radiated at age 0 to 3 years, the number of aberrant cells and stable and nonstable chromosomal aberrations was higher (Stepanova and Skvarskaya, 2002; Stepanova *et al.*, 2002a,b).

2. The incidence of aberrant cells and chromosomal aberrations is significantly higher in children radiated *in utero* (Stepanova *et al.*, 2002a,b; Stepanova *et al.*, 2007).

3. Children evacuated from Pripyat City had higher incidences of chromatid aberration 10 years after the catastrophe, both as individuals (0.5–5.5 per 100 cells) and as a group (1.2–2.6 per 100 cells; Pilinskaya, 1999). For children from the village of Narodichi, where the Cs-137 contamination was 15 Ci/km^2, the frequency of occurrence of nonstable chromosomal aberrations was maintained at a more-or-less constant level for more than 10 years, whereas that of stable chromosomal aberrations increased (Pilinskaya *et al.*, 2003a).

4. The children of liquidators have an increased incidence of chromosomal aberrations (Horishna, 2005).

5. In 12 to 15 years after the catastrophe, the level of chromosomal aberrations and the number of multiaberrant cells significantly increased in "samosels" (self-settlers—the people who moved into the prohibited 30-km zone; Tables 5.6, 5.7, and 5.8). The frequency of occurrence of single-hit acentrics and the presence of two-hit dicentrics and circular rings (see Table 5.6) demonstrate the prolonged effect of low dose, low linear-energy-transfer of radiation (so-call low-LET radiation).

TABLE 5.7. Frequency of Chromosomal Aberrations (per 100 Lymphocytes) of the Same 20 "Samosels" (Self-Settlers) in 1998–1999 and 2001 Surveys (Bezdrobna *et al.*, 2002)

	Incidence, per 100 cells	
Type of aberrations	1998–1999	2001
Breaks and exchanges	0.16 ± 0.07	0.29 ± 0.07
Insertions	1.8 ± 0.3	0.8 ± 0.1*
Deletions	0.025 ± 0.025	0.07 ± 0.03
Without fragments	0.10 ± 0.04	0.18 ± 0.06
Total abnormal	0.39 ± 0.09	0.45 ± 0.09
Monocentrics	0.32 ± 0.08	0.25 ± 0.06
Total	2.6 ± 0.4	1.6 ± 0.2*

*Differences are statistically significant.

6. During the first year after their evacuation from the 30-km zone, the level of nonstable chromosomal aberrations among evacuees significantly exceeded control values and gradually decreased during the next 14 years. Incidence of this cytogenic damage was not sex-dependent, and the frequency of occurrence of dicentrics and rings correlated with duration of residence in a contaminated zone (Maznik, 2004).

TABLE 5.8. Comparison of the Incidence of Chromosomal Aberrations (per 100 Lymphocytes) from a 30-km Zone of Kiev Province, Ukraine, and from the Heavily Contaminated Territories of Gomel Province, Belarus, 1986–1988 (Bezdrobna *et al.*, 2002; Mikhalevich, 1999)

	Person, *n*	Cells, *n*	Aberrant cells, *n*	Aberrations, *n*
30-km zone	33	11,789	5.0 ± 2.0	5.3 ± 2.1
Kiev	31	12,273	3.2 ± 0.8	3.5 ± 1.0
Gomel area	56	12,152	6.4 ± 0.7	8.7 ± 0.6

7. For the majority surveyed in the contaminated territories, with Cs-137 levels in soil of 110–860 kBq/m^2, and among evacuated young men, the incidence of stable aberrations was significantly higher (Maznik and Vinnykov, 2002; Maznik *et al.*, 2003).

8. Radiation-induced cytogenic effects were maintained in 30–45% of surveyed liquidators for 10 to 12 years after the catastrophe. There was stabilization of the number of dicentric and ring chromosomes at a level of 0.5–1 per 100 cells, with controls at 0.2 and increased incidence of stable cytogenetic changes at 0.5–4.5 per 100 cells, with controls at 0.1 (Pilinskaya, 1999).

9. The level of stable chromosomal aberrations in liquidators increased for 10 to 15 years after the catastrophe (Mel'nikov *et al.*, 1998; Pilinskaya *et al.*, 2003b).

10. The phenomenon of genetic instability is found in children of liquidators (Stepanova *et al.*, 2006).

5.2.1.1.3. Russia

1. The level of chromosomal aberrations among children radiated *in utero* was significantly higher than in children who were born longer after the meltdown (Bondarenko *et al.*, 2004).

2. The index of genomic DNA repair is lower in the majority of children in the contaminated regions (Bondarenko *et al.*, 2004).

3. In 1989–1994 a higher incidence of nonstable chromosomal aberrations (dicentrics and circular rings) was found in 1,200 children from the contaminated areas of Bryansk and Kaluga provinces with Cs-137 levels from 100–1,000 kBq/m^2. The frequency of occurrence of these aberrations correlated with the level of contamination of the territory (Sevan'kaev *et al.*, 1995a,b; 1998).

4. An increased level of chromosomal aberrations is found in children of the Novozybkov District of Bryansk Province (Kuz'myna and Suskov, 2002).

TABLE 5.9. Level of Chromosomal Aberrations in Children and Teenagers from the Contaminated Territories 17 Years after the Catastrophe (Cs-137: 111–200 kBq/m^2) (Sevan'kaev *et al.*, 2005)

	Aberration (per 100 cells)	
	Contaminated areas	Control
Acentric fragments	0.40	0.22
Dicentrics and centric rings	0.04–0.19	0.03

5. An increased incidence of chromosomal aberrations is found in children born 5 to 7 years after the catastrophe in the contaminated Mtsensk District and Bolkhov City, Oryol Province (Ivanenko *et al.*, 2004).

6. DNA repair activity (tested by reactivation and induced mutagenesis of smallpox vaccine viruses) was impaired in children born after the catastrophe in territories with Cs-137 contamination levels above 5 Ci/km^2 (Unzhakov *et al.*, 1995).

7. The number of aberrant cells and chromosomal aberrations (pair fragments and rings) and the size of index chromosome breaks in newborns correlated with dose levels and dose rates at the time of the births (Kulakov *et al.*, 1993).

8. Seventeen years after the catastrophe there was an increased number of chromosomal aberrations in 30–60% of children and teenagers from territories contaminated by Cs-137 to a level of 111–200 kBq/m^2 (Table 5.9) (Sevan'kaev *et al.*, 2005).

9. There was a correlation between living in the contaminated territories (Bryansk, Tula, and Kaluga provinces, 1991–1997) and a delay in psychomotor development, congenital defects, and/or microanomalies and extremely elevated amount of near-centromer C-heterochromatin (Vorsanova *et al.*, 2000).

10. The frequency of occurrence of chromosomal aberrations increased two- to fourfold among those individuals in Chernobyl territories with Cs-137 levels of contamination above 3 Ci/km^2 (Bochkov, 1993).

TABLE 5.10. Number of Mutant Cells and Incidence of Chromosomal Aberrations (per 100 Metaphases) among Women with Uterine Myoma in the Contaminated Territories of Tula and Bryansk Provinces (Tsyb *et al.*, 2006)

	Metaphases, n	Mutant cells, n	Aberrations, n	Contamination, Bq/m^2
Novozybkovsky District ($n = 22$)	No data	6.2 ± 0.3*	No data	708
Klintsovsky District ($n = 97$)	18,703	5.3 ± 0.5*	4.27 ± 0.3*	322
Uzlovaya Station ($n = 100$)	19,600	4.6 ± 0.3	2.30 ± 0.1	171
Obninsk ($n = 42$)	12,779	4.0 ± 0.2	2.12 ± 0.1	Control

*Differences from the control are significant.

11. The number of lymphocytes with mutations of T-locus (TCR) and the number of chromosomal aberrations correlated with a level of radiation contamination in women with uterine tumors (myomas) who continued to live in the heavily contaminated Novozybkov and Klintsy districts, Bryansk Province, and in Uzlovaya Station, Tula Province (Table 5.10).

12. The number of chromosomal aberrations among inhabitants of the contaminated territories in Bryansk Province is higher than among people living in less contaminated areas (Table 5.11).

13. Inhabitants of the heavily contaminated Klintsy and Vyshkov districts of Bryansk Province demonstrate a significantly higher mitotic index in comparison with controls (Pelevina *et al.*, 1996).

14. Among 248 individuals aged 15 to 28 years surveyed, the incidence of dicentrics and centric rings is two- to fourfold higher than among control groups. Among those radiated *in utero*, the frequency of occurrence of such aberrations is fivefold higher than in controls (Sevan'kaev *et al.*, 2006).

15. Among inhabitants of four contaminated districts of Oryol Province, the incidence of gene mutations on locus T-cellular receptor (TCR) and on locus glycophorin (GPA) is higher than in controls (Sevan'kaev *et al.*, 2006).

16. Among 336 surveyed fertile women from the contaminated Uzlovaya Station, Tula Province, and Klintsy District, Bryansk Province, the incidence of chromosomal exchange aberrations was 0.13 ± 0.03 and 0.37 ± 0.07 compared to controls, which was two- to sixfold less (0.6 ± 0.04; Ivanova *et al.*, 2006).

17. The number of lymphocytic and marrow chromosomal mutations correlated with the radiation dose among liquidators and inhabitants of Pripyat City within 3 months after the catastrophe and were manifestly higher than among controls (Table 5.12) (Shevchenko *et al.*, 1995; Svirnovsky *et al.*, 1998; Bezhenar', 1999; Shykalov *et al.*, 2002; and others).

18. The number of nonstable (dicentrics, acentric fragments, and centric rings) and stable aberrations (translocations and insertions) in liquidators was significantly higher in the first year after the catastrophe (Shevchenko *et al.*, 1995; Shevchenko and Snegyreva, 1996; Slozina and Neronova, 2002; Oganesyan *et al.*, 2002; Deomyna *et al.*, 2002; Maznik, 2003; and others; Figure 5.1).

TABLE 5.11. Incidence of Chromosomal Aberrations among Inhabitants of the Contaminated Territories of Bryansk Province (Snegyreva and Shevchenko, 2006)

	Individuals, n	Cells, n	Aberrations, n	Including dicentrics
Bryansk Province	80	21,027	$1.43 + 0.08$*	$0.10 + 0.02$*
Control	114	51,430	0.66 ± 0.04	0.02 ± 0.01

*Differences from control are significant.

TABLE 5.12. Chromosomal Mutations among Various Groups of Liquidators within the First 3 Months after the Catastrophe (Shevchenko and Snegyreva, 1999)

Group	Cells, *n*	Aberrations, *n*	Including dicentric and centric rings
Construction crew for the sarcophagus** ($n = 71$)	4,937	32.4 ± 2.5*	4.4 ± 0.9*
Radiation supervisors ($n = 23$)	1,641	31.1 ± 4.3	4.8 ± 1.7
NPP staff ($n = 83$)	6,015	23.7 ± 2.0	5.8 ± 1.0
Drivers ($n = 60$)	5,300	14.7 ± 1.7	3.2 ± 0.8
Pripyat City civilians ($n = 35$)	2,593	14.3 ± 2.4	1.9 ± 0.8
Doctors ($n = 37$)	2,590	13.1 ± 2.3	2.7 ± 1.0
Control ($n = 19$)	3,605	1.9 ± 0.7	0.0

*For all groups differences with controls are significant.

**Sarcophagus is the huge concrete construct that covers the exposed Chernobyl reactor.

19. In the first 8 to 9 years after the catastrophe the number of cells with translocations among liquidators was more than twice that in controls (Table 5.13).

20. The number of translocations in liquidators was significantly higher than in controls (Table 5.14).

21. In the first 6 to 8 years after the catastrophe the number of chromosomal aberrations in liquidators from the Russian Federal Nuclear Center in Sarov City was significantly higher than in controls (Table 5.15).

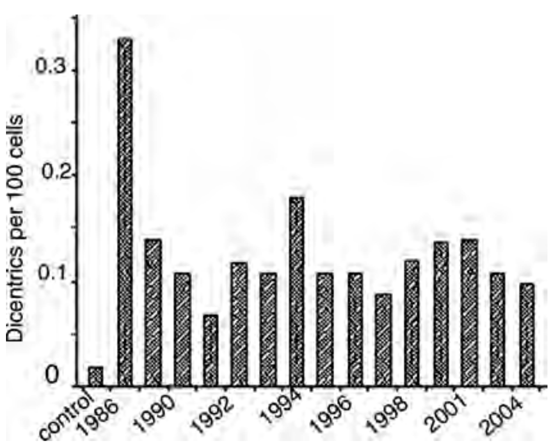

Figure 5.1. Average frequency of dicentrics in a group of 1986 liquidators examined within 18 years after the catastrophe (Snegyreva and Shevchenko, 2006).

22. Ten years after the catastrophe 1,000 liquidators had a significantly higher average frequency of occurrence of chromosomal aberrations (especially high in liquidators from 1986) (Sevan'kaev *et al.*, 1998).

23. The incidence of dicentrics in liquidators rose during the first 8 to 12 years after the catastrophe (Slozina and Neronova, 2002). More than 1,500 liquidators were examined and even after 15 years the frequency of occurrence of dicentrics was considerably higher than in control groups (Snegyreva and Shevchenko, 2002).

5.2.1.1.4. Other Countries

1. YUGOSLAVIA. Among newborns conceived in the months postcatastrophe, the number of chromosomal aberrations increased from 4.5% (1976–1985 average) to 7.1% (Lukic *et al.*, 1988).

2. AUSTRIA. In 1987 among 17 adults examined there was a four- to sixfold increase in the number of chromosomal aberrations, and in two individuals, examined before and 1 year after the catastrophe, there was an 11-fold increase (Pohl-Rüling *et al.*, 1991).

3. GERMANY (southern areas). Among 29 children and adults examined in 1987–1991 there was a two- to sixfold increase in the number of chromosomal aberrations (Stephan and Oestreicher, 1993).

TABLE 5.13. Number of Chromosomal Aberrations in Lymphocytes of Liquidators, 1990–1995 (Shevchenko and Snegyreva, 1999; Snegyreva and Shevchenko, 2006)

Year	Number of individuals, *n*	Cells, *n*	Aberrations, *n*	Including dicentrics and central rings
1986	443	41,927	23.2 ± *	0.33 ± 0.01*
1990	23	4,268	14.9 ± 1.9*	1.0 ± 0.5*
1991	110	20,077	19.7 ± 1.0*	0.9 ± 0.2*
1992	136	32,000	31.8 ± 1.0*	1.4 ± 0.2*
1993	75	18,581	34.8 ± 1.4*	0.9 ± 0.2*
1994	60	18,179	31.8 ± 1.3*	1.8 ± 0.3*
1995	41	12,160	18.8 ± 1.2*	0.4 ± 0.02*
Control	82	26,849	10.5 ± 0.6	0.02 ± 0.01

*All differences with the control are significant ($p < 0.01$–0.05).

4. NORWAY (northern areas). In 1991, a 10-fold increase in the number of chromosomal aberrations was found in 56 adults compared to controls (Brogger *et al.*, 1996; see review by Schmitz-Feuerhake, 2006).

5.2.1.2. Genomic Mutations

Trisomies of chromosomes 13, 18, and 21, which are genomic mutations showing change in the number of chromosomes, have been found in the contaminated territories.

5.2.1.2.1. Trisomy 21 (Down Syndrome)

1. BELARUS. Analysis of annual and monthly incidences of Down syndrome in 1981–1999 (2,786 cases) revealed an annual increase in 1987 for the whole country and monthly increases in January 1987 in Minsk City and in Gomel and Minsk provinces (Lazjuk *et al.*, 2002). There was also a 49% increase in the most contaminated 17 districts in 1987–1988 (Table 5.16) and an increase of 17% for the whole country for the period from 1987 to 1994 (Lazjuk *et al.*, 1997). Detailed analysis revealed a sharp increase in the incidence of Down syndrome in December 1986 and a peak in January 1987 (Figure 5.2).

2. GERMANY. In West Berlin, among babies conceived in May 1986, the number of newborns with Down syndrome increased 2.5-fold (Wals and Dolk, 1990; Sperling *et al.*, 1991, 1994; and others; Figure 5.3). In southern Germany an increase in the number of trisomy 21 cases was determined by amniocentesis (Sperling *et al.*, 1991; Smitz-Fuerhake, 2006).

3. SWEDEN. There was a 30% increase in the number of newborns with Down syndrome in the northeast of the country, which was the area most contaminated by Chernobyl radionuclides (Ericson and Kallen, 1994).

4. GREAT BRITAIN. There was a doubling in the number of newborns with Down syndrome

TABLE 5.14. Frequency of Translocations (per 100 Cells) among Liquidators (Snegyreva and Shevchenko, 2006)

	Individuals, *n*	Cells, *n*	Translocations
Liquidators	52	44,283	1.20 ± 0.16*
Control	15	21,953	0.47 ± 0.09

*$p < 0.05$.

TABLE 5.15. Number of Chromosomal Aberrations among Liquidator Personnel of the Russian Federal Nuclear Center in Sarov (Khaimovich *et al.*, 1999)

	Liquidators ($n = 40$)	Controls ($n = 10$)
All aberrations, per 100 cells	4.77 ± 0.42	0.90 ± 0.30
Dicentrics	0.93 ± 0.19	0
% Polyploidy cells	1.43 ± 0.23	0

TABLE 5.16. Incidence of Down Syndrome (per 1,000 Newborns) in 17 Heavily and 30 Less Contaminated Districts of Belarus, 1987–2004 (National Belarussian Report, 2006)

	1987–1988	1990–2004
Heavily contaminated	0.59	1.01
Less contaminated	0.88	1.08

in Lothian, Scotland, one of territories contaminated by Chernobyl (Ramsey *et al.*, 1991).

5.2.1.2.2. Trisomy 13 and Other Genomic Mutations

1. Photos from the contaminated areas of Belarus and Ukraine indicated that there are many cases of newborns with characteristics of Patau syndrome (trisomy 13). The anomalies included: polydactly, developmental anomalies of the eyes (microphthalmia, congenital cataracts, coloboma of the iris), trigonocephaly, cleft lip and palate, defects of the nose, etc. Statistics regarding such cases are not available.

2. From clinical descriptions of children born in the contaminated territories there are known cases of other genomic mutations: Edward's syndrome (trisomy 18), Kleinfelter syndrome (additional X-chromosome), Turner's syndrome (absence of the X-chromosome), XXX chromosomes in females, and XYY chromosomes in males. Statistics regarding such cases are not available.

5.2.2. Genetic Polymorphism of Proteins and Other Genetic Disorders

Genetic polymorphism of proteins is an important parameter of intrapopulation genetic variability. In children radiated *in utero* and born after Chernobyl, the level of genetic polymorphism of proteins is lower compared with children born before the catastrophe. This lower level of genetic polymorphism in structural proteins is negatively correlated with levels of congenital malformations and allergies, and may be a factor in the persistent current background of anemia, lymphadenopathies, and infections (Kulakov *et al.*, 1993).

Children born after the catastrophe who were irradiated *in utero* have a lower level of genetic polymorphism of proteins compared to children born before the catastrophe from the same territories (Kulakov *et al.*, 1993, 1997). They also had significantly lower levels of DNA repair both in the short and the long term after the catastrophe (Bondarenko *et al.*, 2004).

Proliferation was sharply reduced in HeLa cell culture 6 days after the explosion in the 30-km zone (beginning with a total dose up to 0.08 Gr), with this effect continuing for seven

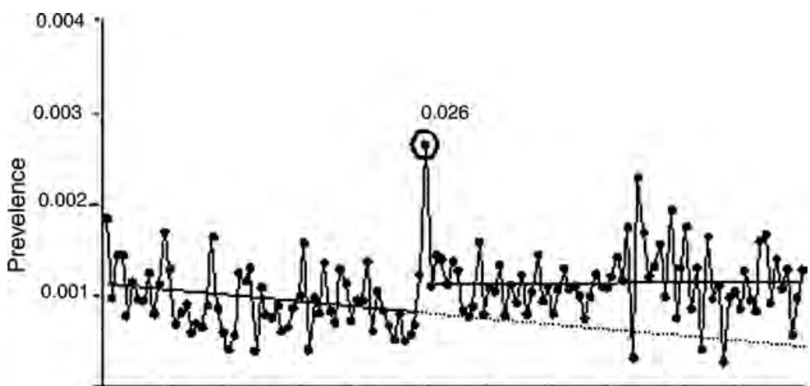

Figure 5.2. Prevalence of trisomy 21 in Belarus from 1982 to 1992 (N = 1,720,030; n = 1,791) and change-point model (see text) allowing for a significant ($p < 0.0001$) jump and a "broken stick" in December 1986 and a peak in January 1987 (Sperling *et al.*, 2008).

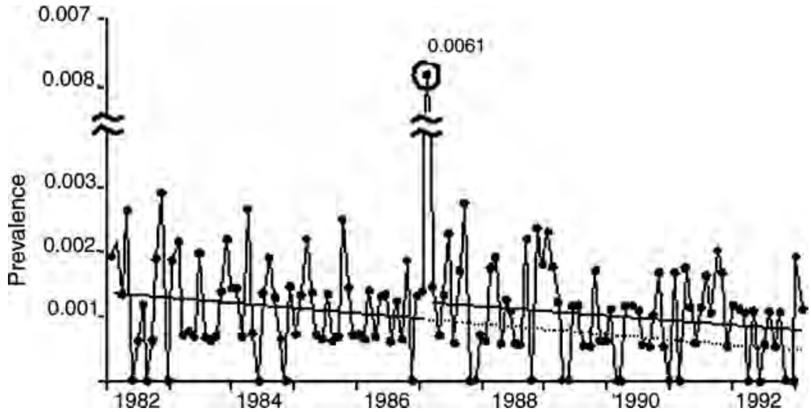

Figure 5.3. Prevalence of trisomy 21 in West Berlin from 1982 to 1992 ($N = 218{,}497$; $n = 237$) and change-point model allowing for a significant ($p < 0.0001$) jump in December 1986 and a peak in January 1987 (Sperling *et al.*, 2008).

cell generations after the irradiation. Numbers of large cells arising persisted for more than 20 cell generations after irradiation and clonogenicity was lower for 24 generations (Nazarov *et al.*, 2007).

DNA repair activity (tested by reactivation and induced mutagenesis of small-pox vaccine viruses) was impaired in children born after the catastrophe in territories with contamination levels of Cs-137 above 5 Ci/km^2 (Unzhakov *et al.*, 1995).

5.2.3. Changes in Satellite DNA

The number of mutations due to Chernobyl radiation has increased not only in somatic, but also in germ cells. The level of small mutations in minisatellite DNA in children born to irradiated parents and living in the contaminated territories of Belarus and Ukraine is almost twice that of children from Great Britain (Dubrova, 2003).

5.2.4. Genetically Caused Congenital Developmental Anomalies

It is estimated that from 50 to 90% of all congenital malformations (CMs) and congenital developmental anomalies (CDAs) result from mutations. Therefore the birth of newborns with anomalies can reveal the presence of genetic disorders, including the influence of additional irradiation. More than 6,000 genetically caused developmental anomalies are known (McKusick, 1998). Medical statistics consider only about 30 of the commonest CDAs. Some CDAs have appeared anew in a population as mutations *de novo*. *De novo* mutations determine such CDAs as polydactyly, change in the size of arms or legs, and so-called plural CDAs. These CDAs occur more often in the heavily contaminated Belarussian territories, where levels are higher than 15 Ci/km^2 (Lazjuk *et al.*, 1999a).

Genetically caused CDAs in newborns are but the tip of the iceberg. They are evidence of mutations that are not eliminated at previous stages of individual development in gametes (spermatozoa and ova); among impregnated ova up to and during implantation; and in the process of embryonic development.

Most mutations result in termination of embryonic development at an early stage (Nykytin, 2005). Thus it is reasonable to assume that the increase in the frequency of occurrence of genetically caused CDAs reflects an increase in tens (if not in hundreds) of times the rate of mutations at the gamete stage. That these processes occur in the radiation contaminated territories is testified to by: (a) an increase in the number abnormal spermatozoids; (b) an increase in the incidence of spontaneous abortions, which reflects increased embryonic mortality; (c) an increase in *de novo* mutations in aborted fetuses and those with CDAs; and (d) the greater proportion of CDAs, defined by mutations *de novo*, that occur in the most contaminated territories (Lazjuk *et al.*, 1999).

5.2.5. Children of Irradiated Parents

There are more and more data showing poorer health status in children born to irradiated parents.

1. Among children of the Belarus liquidators irradiated during 1986–1987 who received 5 cSv or more, there is a higher level of morbidity, a larger number of CDAs (Figure 5.4), and more sick newborns in comparison with children whose fathers received a dose less than 5 cSv (Lyaginskaya *et al.*, 2002, 2007).

2. A survey of a group of 11-year-old children born in 1987 to families of 1986 Belarus liquidators revealed significant differences in the incidence of blood disease and immune status (Table 5.17).

3. The annual general morbidity among children born to irradiated fathers from 2000 to 2005 was higher in Ukraine as a whole (1,135–1,367 per 10,000 vs. the Ukraine average of 960–1,200). Among these children only 2.6–9.2% were considered "practically healthy" (vs. 18.6–24.6% in the control group; National Ukrainian Report, 2006).

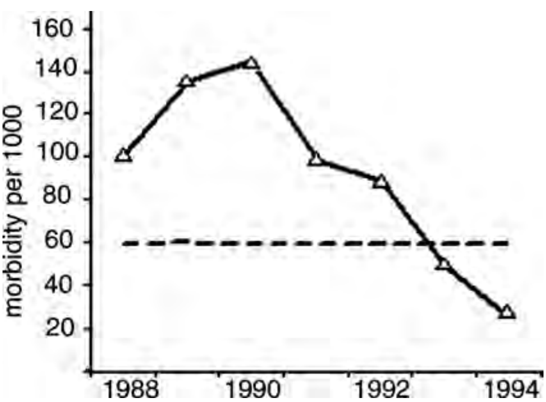

Figure 5.4. Prevalence of congenital developmental anomalies (CDAs) among infants born to families of liquidator (1986–1987) fathers who worked for the Russian nuclear industry from 1988 to 1994 (Lyaginskaya *et al.*, 2007). Broken line: level of CDA by UNSCEAR (1988).

TABLE 5.17. Health Statistics in 1987 for 11-Year-Old Children Born to Belarussian Liquidators Exposed in 1986 (Arynchin *et al.*, 1999)*

	Children of liquidators ($n = 40$)	Control group ($n = 48$)
Chronic gastroduodenitis	17 (42.5%)	13 (21.7%)
Dysbacteriosis	6 (15%)	0
Impaired development	8 (20%)	2 (4.2%)
Number of B lymphocytes	14.1 ± 0.7	23.3 ± 1.9
Number of T lymphocytes	16.9 ± 1.1	28.4 ± 1.6
Concentration of IgG, g/liter	9.4 ± 0.4	14.2 ± 0.7

*All differences are significant.

4. There are more congenital malformations and developmental anomalies among children born to irradiated fathers (National Ukrainian Report, 2006).

5. Children irradiated *in utero* in the Kaluga Province have a significantly higher level of general morbidity, including thyroid gland diseases (sixfold above the provincial level); CDAs (fourfold above the provincial level); plus urogenital tract, blood circulation, and digestive system diseases (Tsyb *et al.*, 2006a).

6. Among the children of liquidators in the Ryazan area there was an increased incidence of sick newborns, CDAs, birth weights below 2,500 g, delays in intrauterine development, higher morbidity, and impaired immunity (Lyaginskaya *et al.*, 2002, 2007).

7. Liquidators' children up to 10 years of age in Kaluga Province had an incidence of thyroid gland disease that was fivefold higher that the provincial level, a triple increase in CDAs, a fourfold increase in mental disorders, double the occurrence of circulatory system diseases, and a high incidence of chronic diseases (Tsyb *et al.*, 2006).

8. Children of liquidators have a high incidence of chronic laryngeal diseases, red blood cell changes, functional impairment of the nervous system, multiple tooth caries, chronic catarrhal gingivitis, and dental anomalies (Marapova and Khytrov, 2001).

9. Children of liquidators have more chromosomal aberrations (deletions, inversions, rings, isochromatids, single fragments, and gaps) and more polyploid cells (Ibragymova, 2003). "... In families of liquidation participants [in the Tula Province] there were 473 children born after the Chernobyl catastrophe. At first sight they differed from other kids in hyperexcitability. They cry, neither from that nor from this, and do not sit easily in place. ..." (Khvorostenko, 1999).

10. Children of liquidators have higher levels of digestive, respiratory, nervous, and endocrine system diseases; more CDAs and hereditary diseases; and increased incidence of infectious diseases (Ponomarenko *et al.*, 2002).

11. Among 455 children of liquidators from Bryansk Province who were born between 1987 and 1999 general morbidity increased from 1988 to 2000 (Table 5.18). From the table it is obvious that there has been a reduction in the occurrence of diseases of the blood and blood-forming organs and a significant increase in all other illnesses. Even more apparent is the morbidity of children of liquidators of Bryansk Province compared to other children in the area. Table 5.19 presents data showing a significant difference between children of liquidators and children from the Bryansk area as a whole.

TABLE 5.18. First Reports Concerning Illnesses (per 1,000) among Children of Liquidators in Bryansk Province (Matveenko *et al.*, 2005)*

Illness	Number of cases 1988–1990	1991–1995	1996–2000
Blood and blood-forming organs	52.2	30.6	8.3
Mental disorders	0	5.9	12.2
Neoplasms	0	0	3.3
Respiratory system	790	1,009	1,041
Digestive system	5.3	59.2	93.7
Muscle and bone	0	16.2	75.9
Urogenital tract	5.3	14.7	20.5
Infectious and parasitic diseases	15.9	83.6	71.5
Total	1,052	1,343	1,667

*Listed illnesses are those for which there are obvious trends over time.

TABLE 5.19. Primary Morbidity (per 1,000) among Children of Bryansk Liquidators and All the Children in Bryansk Province, 1996–2000 (Matveenko *et al.*, 2005)

Illnesses	Children of liquidators: Bryansk Province	Children of liquidators: Russia (RSMDR)*	Children of Bryansk Province
Circulatory system	6.7	19.7	3.5
Mental disorders	12.2	25.1	3.3
Digestive system	93.7	83.0	68.7
Muscle and bone	75.9	45.8	43.2
Congenital anomalies	11.6	12.6	3.0

*Russian State Medical Dosimetric Register.

12. There is lowered cellular immunity in children of Russian liquidators, demonstrated by decreases in both absolute and relative cell parameters. They have a relative increase in cellular immunity (higher numbers of CD4 cells, moderately lower levels of immunoglobulin-A, and increased basal neutrophilic activity; Kholodova *et al.*, 2001).

13. Children of liquidators and children irradiated *in utero* have a higher frequency of stable chromosomal aberrations, lower levels of repair activity, and a decrease in individual heterozygosis (Sypyagyna, 2002).

The second and the third generations of children whose parents were irradiated by the atomic bomb explosions in Japan in 1945 suffered 10-fold more circulatory system diseases and impaired liver function, and 3.3-fold more respiratory system illness than a control group (Furitsu *et al.*, 1992). It is likely that the health problems experienced by children born to parents irradiated by Chernobyl will continue in subsequent generations.

5.2.6. Chromosomal Aberrations as Indicators of Health Status

The response of the International Atomic Energy Agency (IAEA) and the World Health

Organization (WHO) (Chernobyl Forum, 2005) to the occurrence of chromosomal changes induced by the catastrophe is that these changes do not in any way affect the state of health—which is scientifically untrue. Chromosomal changes observed in peripheral blood cells can reflect general damage to genetic and ontogenetic processes. There are correlations between the level of chromosomal aberrations and a number of pathological conditions. There are many examples of such links in the Chernobyl territories. Among them are the following.

1. The number of chromosomal aberrations in 88% of liquidators coincides with the level of psychopathological illnesses and the expression of secondary immunosuppression (Kut'ko *et al.*, 1996).

2. The number of chromosomal aberrations is noticeably higher in those with psycho-organic syndromes, and the number of chromatid aberrations is noticeably higher in individuals with asthenia and obsessive–phobic syndromes (Kut'ko *et al.*, 1996).

3. The number of dicentrics and chromatid exchanges correlates with congenital developmental anomalies (Kulakov *et al.*, 1997).

4. The number of chromosome breaks correlates with hypothyroidism and a number of stigma associated with embryogenesis (Kulakov *et al.*, 2001).

5. The frequency of occurrence of aberrant cells, pair fragments, rings, and chromosomal breaks coincides with the level of immunoregulatory system imbalance in newborns (Kulakov *et al.*, 1997).

6. The incidence of congenital malformations defined by mutations *de novo* is significantly higher in territories with contamination levels of 15 Ci/km^2 or higher (Lazjuk *et al.*, 1999b).

7. The number of chromosomal aberrations, number of micronuclei, and incidence of spot mutations are considerably higher in children with thyroid cancer (Mel'nov *et al.*, 1999; Derzhitskaya *et al.*, 1997).

8. The frequency of occurrence of aberrations is higher in both tumor cells and in "normal" tissue in individuals who live in the contaminated territories (Polonetskaya *et al.*, 2001).

9. The incidence of spermatozoid structure abnormalities correlates with the frequency of occurrence of chromosomal aberrations (Kurilo *et al.*, 1993; Vozylova *et al.*, 1997; Domrachova *et al.*, 1997; Evdokymov *et al.*, 2001).

10. The level of antioxidant activity for various groups of liquidators correlates with the number of chromosomal aberrations (Table 5.20).

11. The prevalence of febrile infections correlates with the level of chromosomal aberrations (Degutene, 2002).

12. In the contaminated territories of Bryansk and Tula provinces there is a correlation between number of aberrant and multiaberrant cells and the development of uterine myoma (Ivanova *et al.*, 2006).

13. The frequency of cardiovascular and gastroenteric diseases in liquidators correlates with the level of chromosomal aberrations (Vorobtsova and Semenov, 2006).

All these correlations demonstrate that the increase in chromosomal damage, which is observable everywhere in the contaminated territories, is a measure of high genetic risk, as well as the risk of developing many illnesses.

5.2.7. Conclusion

Somatic chromosomal mutations, mutations causing congenital malformations, genetic polymorphism of proteins, and mutations in minisatellite DNA are only some of the genetic changes resulting from radionuclides released from Chernobyl. The overwhelming majority of Chernobyl-induced genetic changes will not become apparent for several generations. A fuller account of other genetic changes will come with progress in scientific methods. Today it is obvious that changes in the genetic structure of cells were the first dangerous signs of the Chernobyl catastrophe. The changes occurred in the first days after the

TABLE 5.20. Average Value of Antioxidant Characteristics among Groups of Russian Liquidators with Various Levels of Chromosomal Aberrations (Baleva *et al.*, 2001)[a]

	Control	Groups of liquidators with various numbers of aberrations				
Aberrations, *n*	0.11	0.18	0.68	1.15	1.66	2.64
GT	16.70	823.82	17.57	824.50	21.98*	25.66*
SOD	113.12	115.23	120.09	101.08*	136.5	107.76
Hem 1	6.78	7.86	11.14*	5.59	7.74	6.70
Hem 2	7.27	9.22	10.99*	5.88	6.86	8.17
MDA 1	2.08	2.41	2.74*	1.88	2.67*	1.83
MDA 2	2.07	2.58*	2.28*	2.10	2.88*	1.85
t_1	1.01	1.37*	1.24	1.39*	1.15	1.50*
CP	1.16	1.01*	0.92*	1.15	1.18	1.20
FR	0.69	1.20*	1.05	1.02	0.92	1.04

[a]GT: restored glucation; SOD: superoxide-dismutase; Hem 1, Hem 2: hematopoietic proteins; MDA 1: malondialdehyde in erythrocytes; MDA 2: malondialdehyde in erythrocytes after POL-initiation; t_1: time of rotary correlation of spin probe N_1 in erythrocyte membranes; CP: ceruloplasmin; FR: free radicals with the g-factor 2.0.

* $p < 0.05$.

release of radiation and increased the occurrence of various diseases.

Even if the Chernobyl radiation persisted only a short time (as in Hiroshima and Nagasaki), its consequences, according to the laws of genetics, would affect some generations of humans (Shevchenko, 2002). Only 10% of all expected Chernobyl genetic damage occurred in the first generation (Pflugbeil *et al.*, 2006). The Chernobyl radiation is genetically much more dangerous than that released in Hiroshima and Nagasaki as the quantity of radionuclides emitted from the Chernobyl meltdown was several-hundred-fold higher and there were more different kinds of radionuclides.

The genetic consequences of the Chernobyl catastrophe will impact hundreds of millions of people, including: (a) those who were exposed to the first release of short-lived radionuclides in 1986, which spread worldwide (see Chapter 1 for details); (b) those who live and will continue to live in the territories contaminated by Sr-90 and Cs-137, as it will take no fewer than 300 years for the radioactive level to decrease to background; (c) those who will live in the territories contaminated by Pu and Am, as millennia will pass before that deadly radioactivity decays; and (d) children of irradiated parents for as many as seven generations (even if they live in areas free from Chernobyl radionuclide fallout).

5.3. Diseases of the Endocrine System

Radioactive fallout from Chernobyl has had serious adverse effects on every part of the endocrine system of irradiated individuals. Among adults, the thyroid gland concentrates up to 40% of a radioactive iodine dose, and in children up to 70% (Il'in *et al.*, 1989; Dedov *et al.*, 1993). The hypophysis (pituitary gland) actively incorporates radioactive iodine at levels 5 to 12 times higher than normal (Zubovsky and Tararukhina, 1991). These two major portions of the endocrine system were overirradiated during the "iodine" period, the first weeks after the catastrophe.

All physiological functions such as the onset of puberty and the closing of bone epiphyses that are dependent on the organs of internal secretion—the pancreas, parathyroids, thyroid, and adrenal glands and the ovaries and the testes—which control multiple functions must coordinate to sustain normal development. Thus Chernobyl's radioactive contamination has adversely impacted the function of the entire endocrine system.

Adequate and timely thyroid function is necessary for physical and intellectual development. Damage to the thyroid gland of the fetus or the neonate may doom that individual to a life of diminished mental capacity. In pregnant women, synthesis of cortisol, an adrenal hormone, and testosterone correlated with the level of internal irradiation (Duda and Kharkevich, 1996). Children in the contaminated territories had significantly lower cortisol blood levels (Petrenko *et al.*, 1993). Measurements of immunity in children and teenagers with Hashimoto autoimmune thyroiditis correlated with the level of environmental radioactive contamination (Kuchinskaya, 2001).

Review of many similar examples clearly shows that Chernobyl radiation dangerously impacted the endocrine system. But what is the scale of such impacts? Concrete examples are presented in this section to answer some of these questions. After a brief review of material about endocrine system diseases (Section 5.3.1), we deal with the central problem of endocrine illnesses linked to the Chernobyl catastrophe—functional impairment of the thyroid gland (Section 5.3.2).

5.3.1. Review of Endocrine System Disease Data

Endocrine system diseases are widespread in all of the territories that were exposed to the Chernobyl radioactive fallout (Baleva *et al.*, 1996; and many others). Compared with data from normal people, individuals living in the contaminated territories have 50% lower sympathetic activity and 36% lower adrenal cortical activity. In 28% of surveyed newborns in contaminated areas, disorders in the hypophyseal–thyroid system, expressed as thyroid dysfunction, during the end of the first and the beginning of the second week of life ultimately resulted in hypothyroidism with its attendant mental and physiological abnormalities (Kulakov *et al.*, 1997).

5.3.1.1. Belarus

1. A sharp increase in endocrine diseases in all Belarussian contaminated territories was observed some years after the catastrophe (Lomat' *et al.*, 1996; Leonova and Astakhova, 1998; and many others). According to the State Register, in 1994 endocrine system morbidity reached 4,851 per 100,000 (Antypova *et al.*, 1995).

2. Children from heavily contaminated territories had blood cortisol levels that were significantly lower than the norm. Cortisol is an adrenal hormone that is released under stress (Petrenko *et al.*, 1993). In Gomel and Mogilev provinces, the levels of umbilical blood cortisol and estriol in areas having Cs-137 contamination of less than 1–15 Ci/km^2 were significantly higher than the level from heavily contaminated territories (15–40 Ci/km^2; Danil'chik *et al.*, 1996). Overtly healthy newborns in Gomel and Mogilev provinces had elevated cortisol levels where contamination was less than 15 Ci/km^2 and decreased levels in heavily contaminated areas (Danil'chik *et al.*, 1996). The number of children with impaired hormone secretion (cortisol, thyroxin, and progesterone) was significantly higher in heavily contaminated territories (Sharapov, 2001).

3. Children from heavily contaminated territories had lower levels of testosterone, a hormone associated with physical development, with low levels linked to impaired reproductive function (Lyalykov *et al.*, 1993).

4. Many girls of pubertal age, 13 to 14 years, from the contaminated territories with autoimmune thyroiditis had accelerated sexual development with significantly increased blood serum concentrations of gonadotropic hormones in the lutein phase of their menstrual cycles (Leonova, 2001).

5. Children aged 10 to 14 years born to irradiated parents diagnosed from 1993 to 2003 showed significantly more morbidity from goiter and thyroiditis (National Belarussian Report, 2006).

6. In some areas where congenital diabetes had not been seen at all before the catastrophe,

there were occurrences afterward and the number of cases has increased since 1986 (Marples, 1996).

7. In Gomel and Minsk provinces the frequency off occurrence of Type-I diabetes rose significantly after the catastrophe, with the highest incidence in the most contaminated districts of Gomel Province (Borysevich and Poplyko, 2002).

8. Six years after the catastrophe incidence of endocrine organ illnesses was threefold higher in the heavily contaminated territories (Shilko *et al.*, 1993). Endocrine pathology was the number one illness diagnosed in a survey of more than 8,000 children in 1993–1994 in the Slavgorod District of Mogilev Province (Suslov *et al.*, 1997).

9. Nine years after the catastrophe, endocrine organ morbidity among evacuees and in those from heavily contaminated territories was double that of the general population of Belarus (Matsko, 1999).

10. Occurrence of Type-I diabetes increased significantly in all of Belarus after the catastrophe (Mokhort, 2003) and to an even greater degree in the heavily contaminated territories (Table 5.21).

11. Among 1,026,046 nursing mothers examined, the incidence of diabetes was significantly higher in the women from territories with Cs-137 contamination above 1 Ci/km^2 (Busuet *et al.*, 2002).

12. At the time of delivery, women from more contaminated territories of Gomel and Vitebsk provinces had significantly higher concentrations of T4 and TCG hormones and lower concentrations of T3 hormone (Dudinskaya and Suryna, 2001).

13. From 1993 to 2003 in the contaminated territories, among men younger than 50 years of age and women of all ages, there was a significant increase in morbidity owing to nontoxic single-node and multinode goiters and autoimmune thyroiditis (National Belarussian Report, 2006).

14. Endocrine morbidity among evacuees was double that of the general population of Belarus (1,125 vs. 583) even 9 years after the catastrophe (Matsko, 1999).

15. There was a correlation between the level of incorporated Cs-137 and prolactin concentration in the serum of young women continuing to live in an area with radioactive contamination of 1–5 Ci/km^2 (Gomel City) during the first and second phases of their menstrual cycles, as well as a correlation between levels of incorporated Cs-137 and progesterone concentrations during the second menstrual cycle phase (Yagovdik, 1998).

16. Belarus liquidators and evacuees had a 2.5- to 3-fold increase in the number of individuals with Type-II diabetes and impaired glucose tolerance and a 1.4- to 2.3-fold increase in hyperinsulinemia (Aderikho, 2003).

17. Ten years after the catastrophe, Belarus liquidators had decreased function of the hypophyseal/thyroid axis; depression of insulin function; exhaustion of the pituitary/adrenal system; and higher levels of progesterone, prolactin, and renin (Table 5.22).

TABLE 5.21. Occurrence of Type-I Diabetes per 100,000 Children and Teenagers before and after the Catastrophe in Heavily and Less Contaminated Territories in Belarus (Zalutskaya *et al.* 2004)

Years	1980–1986	1987–2002
Heavily contaminated (Gomel Province)	3.2 ± 0.3	7.9 ± 0.6*
Less contaminated (Minsk Province)	2.3 ± 0.4	3.3 ± 0.5

*$p < 0.05$.

TABLE 5.22. Hormone Concentrations in Male Belarussian Liquidators* (Bliznyuk, 1999)

	Liquidators	Controls
Aldosterone	193.1 ± 10.6	142.8 ± 11.4
Cortisol	510.3 ± 37.0	724.9 ± 45.4
Insulin	12.6 ± 1.2	18.5 ± 2.6
ACTH	28.8 ± 2.6	52.8 ± 5.4
Prolactin	203.7 ± 12.3	142.2 ± 15.2
Progesterone	2.43 ± 0.18	0.98 ± 0.20
Renin	1.52 ± 0.14	1.02 ± 0.18

*All differences are significant.

5.3.1.2. Ukraine

1. The noticeable increase in endocrine diseases (autoimmune thyroiditis, thyrotoxicosis, diabetes) began in 1992 in all the contaminated territories (Tron'ko *et al.*, 1995). In 1996 endocrine illnesses in areas contaminated at levels higher than 5 Ci/km^2 occurred markedly more often than within the general Ukrainian population (Grodzinsky, 1999). From 1988 to 1999 endocrine system morbidity in contaminated territories increased up to eightfold (Prysyazhnyuk *et al.*, 2002).

2. Endocrine illnesses were the main cause of medical disability among children in the contaminated territories (Romanenko *et al.*, 2001). Some 32% of girls irradiated *in utero* became infertile (10.5% among controls; $p < 0.05$) owing to damage to the endocrine system (Prysyazhnyuk *et al.*, 2002).

3. Within the first 2 years after the catastrophe hormonal imbalance became typical among people in heavily contaminated territories. Both boys and girls in contaminated areas developed increased insulin synthesis, and girls developed elevated testosterone levels (Antipkin and Arabskaya, 2003).

4. In the contaminated territories onset of puberty in girls was late and menstrual cycles among the women were disrupted (Vovk and Mysurgyna, 1994; Babich and Lypchanskaya, 1994). In the territories contaminated with Sr-90 and Pu, there was a 2-year delay in puberty for boys and a 1-year delay for girls, whereas sexual development was accelerated in territories contaminated by Cs-137 (Paramonova and Nedvetskaya, 1993).

5. The incidence of endocrine disorders in irradiated children increased markedly after 1988 (Luk'yanova *et al.*, 1995).

6. Evaluation of more that 16,000 pregnant women from 1986 to 1993 in the contaminated territories revealed significantly higher levels of thyrotrophic hormone and thyroxin (TSH and T-4) 2 years after the catastrophe. From 1988 to 1990 levels of the principal thyroid hormones were close to normal, but in 1991–1992 the levels of the TSH, T-4, and T-3 were reduced. In 1993 hyperthyroidism in pregnant women and newborns was observed for the first time (Dashkevich *et al.*, 1995; Dashkevich and Janyuta, 1997).

7. Some 30% of women older than 50 years of age living in contaminated territories are subclinically hypothyroid (Panenko *et al.*, 2003).

8. The level of endocrine morbidity among adult evacuees is considerably higher than for the overall population of Ukraine (Prysyazhnyuk *et al.*, 2002).

9. A significant increase in diabetes mellitus was observed in the contaminated territories some years after the catastrophe (Gridjyuk *et al.*, 1998).

10. A significant impairment of the pituitary–adrenal system was seen in a majority of 500 surveyed liquidators in the first years after the catastrophe; 6 years later there was normalization of the relevant measurements in the others at rest, but not in the functional levels (Mytryaeva, 1996).

11. Liquidators with generalized periodontal disease had significantly lower levels of calcium metabolic hormones, including parathormone, calcitonin, and calcitriol (Matchenko *et al.*, 2001).

12. Practically all liquidators had characteristic hormonal system changes expressed first as impaired cortisone and insulin secretion (Tron'ko *et al.*, 1995). For some, hormonal system normalization occurred 5 to 6 years after they were irradiated. At the same time more than 52% of those examined still had an increased frequency of occurrence of autoimmune endocrine diseases including thyroiditis, diabetes mellitus, and obesity (Tron'ko *et al.*, 1995).

5.3.1.3. Russia

1. Hormonal imbalance (estradiol, progesterone, luteotrophin, testosterone) became widespread in the contaminated territories 5 to 6 years after the catastrophe (Gorptchenko *et al.*, 1995).

2. Endocrine diseases increased in the contaminated territories during the first 10 years after the catastrophe (Tsymlyakova and Lavrent'eva, 1996).

3. The number of children with endocrine diseases increased in the heavily contaminated zones (Sharapov, 2001). For children in the contaminated areas of Tula Province, endocrine morbidity was fivefold higher in 2002 compared to the period before the catastrophe (Sokolov, 2003).

4. In 1995 the number of children with endocrine morbidity peaked as a whole in the contaminated areas of Bryansk Province. In spite of some decrease in the level of endocrine morbidity from 1995 to 1998, it remained twice as high as for Russia as a whole. At the same time in the heavily contaminated Gordeevka, Novozybkov, and Klymovo districts it remained highly elevated in 1998 (Table 5.23).

5. A total of 17.7% of pregnant women in the contaminated territories had significantly increased levels of prolactin with associated termination of menstruation and loss of fertility (Strukov, 2003).

6. In the contaminated districts of the Kaluga Province, which as a whole was less contaminated than Bryansk Province, juvenile endocrine morbidity was 5.8 to 16.1 per 1,000, which was 1.4- to 3.2-fold more than that of districts with less contamination (Borovykova *et al.*, 1996).

TABLE 5.23. Overall Endocrine Morbidity (per 1,000) among Children of Bryansk Province, 1995– 1998, in Areas with Cs-137 Contamination above 5 Ci/km^2 (Fetysov, 1999b: table 6.1)

	Number of cases			
District	1995	1996	1997	1998
Klymovo	21.6	29.9	25.5	83.3
Novozybkov	133.4	54.5	55.0	109.6
Klintsy	28.9	31.4	34.6	28.9
Krasnogorsk	31.4	69.2	41.3	25.3
Zlynka	65.0	43.8	49.7	24.9
Gordeevka	410.2	347.5	245.0	158.5
Southwest*	104.4	97.1	67.2	68.5
Province total	102.2	74.2	47.2	47.3
Russia	21.4	23.4	25.6	n/a

*All heavily contaminated districts of Bryansk Province.

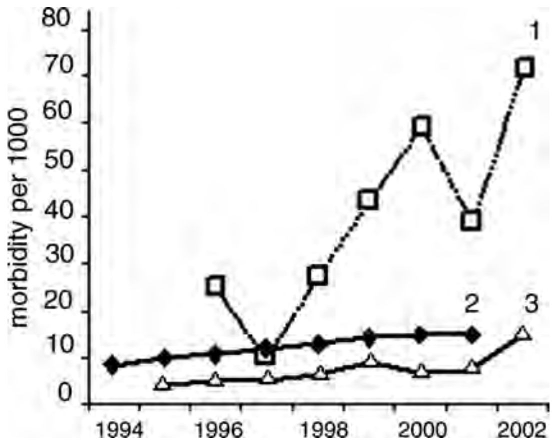

Figure 5.5. Incidence of endocrine and metabolic diseases (per 1,000) among children of liquidators (1) in Obninsk City, Kaluga Province (Borovykova, 2004); (2) children, City; (3) children, Russia.

7. Endocrine morbidity in children born to liquidators in Kaluga Province sharply increased in the first 12 years after the catastrophe (Figure 5.5).

8. The rate of increase in overall endocrine illnesses in adults in the heavily contaminated territories was higher than that of children from 1995 to 1998, and in most of the heavily contaminated districts of Bryansk Province was noticeably higher than for the province and for Russia as a whole (Table 5.24).

9. Twelve years after the catastrophe overall adult endocrine system morbidity in the heavily contaminated southwest districts of Bryansk Province and liquidators' morbidity both significantly exceeded the provincial norms (Table 5.25). The provincial morbidity for liquidators was noticeably higher than the Russian average.

10. Fifteen years after the catastrophe overall endocrine system morbidity in the contaminated territories exceeded the provincial level 2.6-fold (Sergeeva *et al.*, 2005).

TABLE 5.24. General Endocrine Morbidity (per 1,000) among Adults in Bryansk Province in Territories with Cs-137 Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999a: tables 5.1 and 5.2)

	Number of cases			
District	1995	1996	1997	1998
Klymovo	70.8	95.5	109.3	112.2
Novozybkov	54.5	77.9	67.5	40.9
Klintsy	48.0	83.2	75.5	74.1
Krasnogorsk	38.2	40.4	54.0	81.1
Zlynka	33.9	51.4	52.0	57.7
Gordeevka	32.8	46.3	57.6	72.4
Southwest*	43.2	58.6	64.2	66.6
Province as a whole	32.1	35.0	38.5	41.2
Russia	28.2	29.8	31.2	n/A

*All heavily contaminated districts of Bryansk Province.

11. There is an association between Chernobyl irradiation and impaired exocrine and endocrine testicular function, which includes low testosterone plasma levels, an increased level of follicle-stimulating hormone (FSH), and decreased luteinizing hormone (LH; Byryukov *et al.*, 1993).

12. Endocrine system morbidity of Russian liquidators increased sharply from 1986 to 1993 (Table 5.26).

13. By 1999, endocrine system morbidity among Russian liquidators was 10-fold higher than in corresponding groups of the population (National Russian Report, 1999).

14. Severe changes in hypophyseal function and changes in hormonal levels were found in liquidators (Drygyna, 2002).

15. High levels of prolactin were found in 22% of surveyed male liquidators, levels typically observed only in young women (Strukov, 2003).

16. Women liquidators have had consistent and significantly higher levels of gonadotropic and steroidal sex hormones than controls, as well as abnormal levels of cortisol, testosterone, thyrotrophic hormone (TGH), triiodothyronine (T-3), and thyroxine (Bezhenar, 1999; Bezhenar *et al.*, 2000).

TABLE 5.25. General Endocrine Morbidity (per 1,000) among Adults and Liquidators in Territories with Cs-137 Contamination above 5 Ci/km^2 in Bryansk Province, 1995–1998 (Fetysov, 1999a: tables 4.1 and 4.2)

	Number of cases				
	1994	1995	1996	1997	1998
Southwestern districts*	49.9	53.3	58.6	64.2	147.4
Liquidators	92.7	124.5	92.1	153.0	195.0
Province as a whole	31.6	32.1	35.0	38.5	41.2
Russia	27.8	28.2	29.8	31.2	n/a

*All heavily contaminated districts.

" . . . Last summer Dr. Vvedensky and a group of colleagues went to the "chemical filaments" state factory sanatorium, located several hundred kilometers from Gomel City. Since the accident in the Chernobyl nuclear power station, this sanatorium has been a place to rehabilitate children from the most contaminated areas of Belarus . . . Doctors chose to study 300 girls who were born in 1986–1990 . . . For 1.5 years of the survey doctors saw surprising results. Anthropometrical research: measurements of growth, weights, volume of thorax, hips, and legs have shown that among girls from a Chernobyl zone all the parameters were below the norms. However, the width of shoulders exceeded the norm and their forearms, shoulders, and legs were very hairy.

Other scientists have come up against more serious pathologies. As a rule, at the age of 12–13 years girls begin to menstruate. Not one of the 300 girls in the study had done so. Ultrasound examinations showed that their uteruses and ovaries were underdeveloped . . . "Our results could be wildly accidental, Dr. Vvedensky said, but among these 300 girls there was one who had no internal reproductive organs at all. . . . While we have no right to draw any scientific conclusions—if we had found at least three out of 10,000 girls with the same developmental anomaly, then it would be possible to speak about a terrible physiological catastrophe." However, we doctors do not have money for more detailed and extensive studies. Vvedensky's group has come to the conclusion that the reason for the changes is hormonal imbalance. Under the

TABLE 5.26. Endocrine Morbidity among Russian Liquidators (per 10,000) (Baleva *et al.*, 2001)

Year	1986	1987	1988	1989	1990	1991	1992	1993
Number of cases, *n*	96	335	764	1,340	2,020	2,850	3,740	4,300

influence of irradiation a large amount of testosterone develops in the female organism. Testosterone is a male hormone that is normally present only in very small quantities in females, but when a woman has too much of it she can lose her female characteristics. . . ." (Ulevich, 2000)

5.3.2. Impairment of Thyroid Gland Function

Adequate and timely thyroid function is necessary for physical and intellectual development of the fetus. Damage to the thyroid gland of the unborn or the neonate may result in diminished mental capacity for life.

Radiation from I-131 and other radionuclides damages the glandular epithelium, which is demonstrated by nodular formations. Autoimmune thyroiditis is one of the first functional consequences of irradiation (Mozzhukhyna, 2004). Among the subsequent thyroid illnesses are hypo- and hyperthyroidism, myxedema, and nonmalignant and malignant tumors. Thyroid gland impairment leads to decreased production of the glands' three hormones—thyroxin, triiodothyronine, and calcitonin—which control, for example, growth and development, thermoregulation, and calcium exchange.

In all of the contaminated territories, there is a marked increase in nonmalignant thyroid diseases (Gofman, 1994; Dedov and Dedov, 1996). Associated illnesses include: delayed healing of wounds and ulcers, delay in growth of hair, dryness, fragility, hair loss, increased susceptibility to respiratory infections, night blindness, frequent dizziness, ringing in the ears, headaches, fatigue and lack of energy, lack of appetite (anorexia), delayed growth in children, male impotence, increased bleeding (including menstrual menorrhagia), lack of gastric hydrochloric acid (achlorhydria), and mild anemia.

Among hypothyroid symptoms that are not necessarily recorded as illnesses, but are seen with increased frequency in the contaminated territories, are: facial and eyelid swelling; increased sensitivity to cold; decreased perspiration; drowsiness; tongue swelling, slowed speech, and rough and hoarse voice; muscular pains and weakness and impaired muscle coordination; joint stiffness; dry, rough, pale, and cold skin; poor memory and slowed thinking; difficult respiration (dyspnoea); and deafness (Gofman, 1990; and others).

Pathological changes in the thyroid gland are closely linked to those in the parathyroid glands. Parathyroid function was destroyed in 16% of the individuals that underwent thyroid gland surgery (Demedchik *et al.*, 1996). Many symptoms attributed to parathyroid impairment were observed in the Chernobyl territories. Among them: hypogonadism in men and women, impaired normal somatic and sexual development, hypophyseal tumors, osteoporosis, vertebral compression fractures, stomach and duodenal ulcers, urolithiasis, and calcium cholecystitis (Dedov and Dedov, 1996; Ushakov *et al.*, 1997).

5.3.2.1. Belarus

1. By the year 2000 several hundred thousand people had been registered as having thyroid pathologies (nodular goiter, thyroid cancer, thyroiditis). Annually some 3,000 people require thyroid surgery (Borysevich and Poplyko, 2002).

2. Morbidity among children owing to autoimmune thyroiditis increased almost threefold during the first 10 years after the catastrophe (Leonova and Astakhova, 1998). By 1995 there was an apparent increase in the number

of cases of autoimmune thyroiditis in the less contaminated Vitebsk, Minsk, and Brest provinces (Khmara *et al.*, 1993).

3. In Gomel Province, which was one of the most contaminated, more than 40% of the children examined in 1993 had enlarged thyroid glands. Here endemic goiter increased sevenfold from 1985 to 1993, and autoimmune thyroiditis increased more than 600-fold from 1988 to 1993 (Astakhova *et al.*, 1995; Byryukova and Tulupova, 1994).

4. Screening of 328 children ages 11 to 14 years in Khoiniky City, Gomel Province, in 1998 revealed that 30% had enlarged thyroid glands (Drozd, 2002).

5. Children irradiated *in utero* during the first trimester have small thyroid glands and are frequently diagnosed with latent hypothyroidism (Drozd, 2002).

6. Surveys disclosed thyroid gland pathology in 43% of 4- to 5-month-old embryos from mothers from areas contaminated with Cs-137 at levels of 1–15 Ci/km^2 (Kapytonova *et al.*, 1996).

7. Children irradiated *in utero* from the Stolinsk District, Brest Province, which had levels of Cs-137 contamination up to 15 Ci/km^2, had thyroid gland impairment even after more than 10 years, which included: lowered production of thyroxin-binding globulin (T-4), increased production of triiodothyronine, increased production of thyroglobulin in girls, and lowered production of thyroxin in boys (Sychik and Stozharov, 1999a).

8. Enlarged thyroid glands were found in 47% of 3,437 children examined in Mozyr District, Gomel Province (Vaskevitch and Tchernysheva, 1994).

9. Levels of immunity in children and teenagers with autoimmune thyroiditis have been correlated with a district's level of radioactive contamination (Kuchinskaya, 2001).

10. Early sexual maturation was observed in girls from contaminated territories who had autoimmune thyroiditis and was associated with a significant increase in gonadotropic hormone concentration in the luteil phase of their menstrual cycles (Leonova, 2001).

11. Among 119,178 children from Ukraine, Belarus, and Russia under 10 years of age at the time of catastrophe who were examined within the framework of the "Sasakava" project, there were 62 cases of thyroid cancer and 45,873 cases of other thyroid pathology (Yamashita and Shibata, 1997).

12. There was a significant correlation between environmental Cs-137 contamination and the incidence of thyroid diseases among 1,026,046 pregnant women (Busuet *et al.*, 2002).

13. From 1993 to 2003 primary nontoxic multinodular and uninodular goiters and autoimmune thyroiditis significantly increased among female evacuees (National Belarussian Report, 2006).

14. From 1993 to 1995 thyroid gland hyperplasia was found in 48% of juvenile immigrants from the Bragin District and in 17% of juvenile immigrants from the Stolinsk District, Brest Province (Belyaeva *et al.*, 1996).

15. Thyroid gland pathology in the Chernobyl-contaminated territories correlated with diseases of the gums and teeth (Konoplya, 1998).

16. In 1996 thyroid gland illnesses were observed 11.9-fold more often among liquidators than in the general adult population (Antypova *et al.*, 1997a,b).

17. The incidence of thyroid gland anatomic changes in male liquidators who worked in 1986–1987 was noticeably higher in 1994 compared with 1992 (Table 5.27).

TABLE 5.27. Thyroid Gland Structural Changes (% of a Total of 1,752 Cases Examined Annually) in Belarussian Male Liquidators (1986–1987) (Lyasko *et al.*, 2000)

	1992	1994
Nodular	13.5	19.7
Hyperplasia	3.5	10.6
Thyroiditis	0.1	1.9

5.3.2.2. Ukraine

1. Thyroid gland dysfunction has been observed in the contaminated territories since 1986–1987, and since 1990–1991 there has been an increase in chronic autoimmune thyroiditis (Stepanova, 1999; Cheban, 1999, 2002).

2. Eight years after *in utero* irradiation, thyroid gland hormone production was low, but it was also low in children irradiated during the first weeks after birth (Gorobets, 2004).

3. Children with secondary thyroid hyperplasia have two to three times more incidence of allergies, blood vessel pathology, immune disorders, intestinal illnesses, caries, and high blood pressure (Table 5.28).

4. In thyroid surgical pathology specimens in 1989, the incidence of goiter was found to be sharply higher compared with the pre-Chernobyl period (Horishna, 2005).

5. From 1992 to 2000 the incidence of chronic thyroiditis increased in teenagers and adults, especially among liquidators and evacuees (Figure 5.6).

6. Thyroid gland changes were found in 35.7% of 3,019 teenagers living in Vinnitsa and Zhytomir provinces who had been 6 to 8 years old at the time of the catastrophe (Fedyk, 2000).

7. Thyroid gland pathology is twice as common in children from heavily contaminated territories compared to those from less contaminated areas: 32.6 vs. 15.4% (Stepanova, 1999).

8. Among 1,825 children and teenagers living in Kiev Province who were born before the catastrophe (1984–1986) the frequency of thyroid gland pathology did not decrease in 11 to 14 years following the catastrophe (Syvachenko *et al.*, 2003).

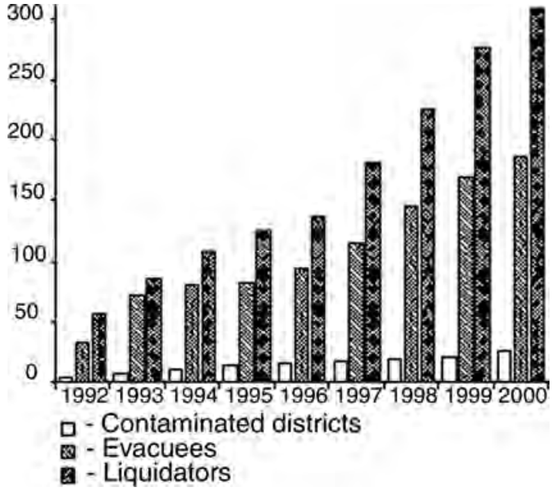

Figure 5.6. Occurrence of chronic thyroiditis among teenagers and adults from Ukraine from 1992 to 2000 (National Ukrainian Report, 2006: fig. 5.10).

9. Among 119,178 children of Ukraine, Belarus, and Russia who were younger than 10 years of age at the time of the catastrophe examined within the framework of the "Sasakava" project, there were 740 abnormal thyroid pathologies for each case of thyroid cancer (Yamashita and Shibata, 1997). In another study in which 51,412 children were examined, 1,125 thyroid pathologies were found for each case of cancer (Foly, 2002).

10. Among more than 50,000 children with psychological problems who were evaluated, 15% have thyroid gland pathology (Contis, 2002).

11. Chronic thyroiditis morbidity significantly increased among Ukrainian liquidators

TABLE 5.28. Incidence (%) of Somatic Pathology among Children with Various Degrees of Thyroid Hyperplasia (Luk'yanova *et al.*, 1995)

	VSD*	Allergies	Circulation	Infections	Caries	Intestinal
0	7.2	1.4	3.5	5.0	32.7	20.4
I degree	12.4	4.8	4.3	5.8	45.8	29.3
II degree	27.8	12.6	9.4	14.7	63.9	35.8

*Vegetocircular dystonia (autonomic nervous system dysfunction).

between 1992 and 2001 (Moskalenko, 2003).

12. Some 150,000 Ukrainians developed thyroid gland diseases in 10 years that were related to the catastrophe (ITAR–TASS, 1998).

5.3.2.3. Russia

1. Children in territories with high levels of radioactive contamination have a significantly higher incidence of second-degree thyroid gland hyperplasia and nodular and diffuse forms of goiter (Sharapov, 2001).

2. There is a correlation between the level of incorporated radionuclides and hyperplasia of the thyroid gland (Adamovich *et al.*, 1998).

3. Every second child in the heavily contaminated districts of Bryansk Province has had some thyroid gland pathology (Kashyryna, 2005).

4. From 1998 to 2004 in Bryansk Province, there were 284 cases of thyroid cancer and 7,601 cases of other types of thyroid pathology (Karevskaya *et al.*, 2005).

5. In the heavily contaminated districts of Bryansk Province up to 60% of children have thyroid gland hyperplasia (Table 5.29).

6. In Voronezh Province, where eight districts were officially registered as being contaminated with radioactivity, the incidence of enlarged thyroids increased in children in the first 10 years after the catastrophe. At age 11, boys who were born in Voronezh Province in 1986 were significantly shorter than boys of the same age who were born in 1983, most probably owing to thyroid hormone imbalance (Ulanova *et al.*, 2002).

7. In 1998 every third child in the city of Yekaterinburg, located in the heavily industrialized Ural area that was exposed to Chernobyl fallout, had abnormal thyroid gland development (Dobrynina, 1998).

TABLE 5.29. Cases of First and Second Degree Thyroid Gland Hyperplasia in Children (per 1,000) in Heavily Contaminated (Cs-137 > 5 Ci/km^2) Districts of Bryansk Province, 1995–1998 (Fetysov, 1999b: table 6.2)

	Number of cases			
District	1995	1996	1997	1998
Klymovo	600.5	295.9	115.1	52.3
Novozybkov	449.0	449.5	385.9	329.4
Klintsy	487.6	493.0	413.0	394.3
Krasnogorsk	162.2	306.8	224.6	140.1
Zlynka	245.1	549.3	348.7	195.0
Southwest*	423.4	341.0	298.7	242.7

*All heavily contaminated districts.

5.3.2.4. Other Countries

POLAND. Of the 21,000 individuals living in the southeast part of the country contaminated by Chernobyl fallout who were examined, every second woman and every tenth child had an enlarged thyroid. In some settlements, thyroid gland pathology was found in 70% of the inhabitants (Associated Press, 2000).

5.3.3. Conclusion

Despite information presented so far, we still do not have a total global picture of all of the people whose hormone function was impaired by radiation from the Chernobyl catastrophe because medical statistics do not deal with such illnesses in a uniform way.

At first sight some changes in endocrine function in those subjected to Chernobyl radiation were considered controversial. We have learned, however, that hormone function may be depressed in a territory with a low level of radioactive contamination and increased owing to an increasing dose rate in a neighboring contaminated area. Diseases of the same organ may lead to opposing signs and symptoms depending upon the timing and extent of the damage. With the collection of new data, we hope that such contradictions can be resolved. Careful research may uncover the explanation as to whether the differences are due to past influences of different isotopes, combinations of different radioisotopes, timing of exposures, adaptation of various organs, or factors still to be uncovered.

The analysis of remote, decades-old data, from the southern Ural area contaminated by radioactive accidents in the 1950s and 1960s indicates that low-dose irradiation *in utero*, which was similar to that from Chernobyl, may cause impairment of neuroendocrine and neurohumoral regulation. Using those data, researchers reported vertebral osteochondrosis, osteoarthritic deformities of the extremities, atrophic gastritis, and other problems in the exposed population (Ostroumova, 2004).

An important finding to date is that for every case of thyroid cancer there are about 1,000 cases of other kinds of thyroid gland pathology. In Belarus alone, experts estimate that up to 1.5 million people are at risk of thyroid disease (Gofman, 1994; Lypyk, 2004).

From the data collected from many different areas by many independent researchers, the spectrum and the scale of endocrine pathology associated with radioactive contamination are far greater than had been suspected. It is now clear that multiple endocrine illnesses caused by Chernobyl have adversely affected millions of people.

5.4. Immune System Diseases

One result of many studies conducted during the last few years in Ukraine, Belarus, and Russia is the clear finding that Chernobyl radiation suppresses immunity—a person's or organism's natural protective system against infection and most diseases.

The lymphatic system—the bone marrow, thymus, spleen, lymph nodes, and Peyer's patches—has been impacted by both large and small doses of ionizing radiation from the Chernobyl fallout. As a result, the quantity and activity of various groups of lymphocytes and thus the production of antibodies, including various immunoglobulins, stem cells, and thrombocytes, are altered. The ultimate consequences of destruction of the immune system is immunodeficiency and an increase in the frequency and seriousness of acute and chronic diseases and infections, as is widely observed in the Chernobyl-irradiated territories (Bortkevich *et al.*, 1996; Lenskaya *et al.*, 1999; and others). The suppression of immunity as a result of this radioactive contamination is known as "Chernobyl AIDS."

On the basis of review of some 150 scientific publications the conclusion is that depression of thymus function plays the leading role in postradiation pathology of the immune system (Savyna and Khoptynskaya, 1995). Some examples of adverse effects of Chernobyl contamination on the immune system as well as data showing the scale of damage to the health of the different populations are described in what follows.

5.4.1. Belarus

1. Among 3,200 children who were examined from 1986 to 1999 there was a significant decrease in B lymphocytes and subsequently in T lymphocytes, which occurred within the first 45 days after the catastrophe. In the first 1.5 months, the level of the G-immunoglobulin (IgG) significantly decreased and the concentration of IgA and IgM as circulating immune complexes (CIC) increased. Seven months after the catastrophe there was a normalization of most of the immune parameters, except for the CIC and IgM. From 1987 to 1995 immunosuppression was unchanged and a decrease in the number of T cells indicators was seen. A total of 40.8 ± 2.4% of children from the contaminated territories had high levels of IgE, rheumatoid factor, CIC, and antibodies to thyroglobulin. This was especially prominent in children from the heavily contaminated areas. The children also had increased titers of serum interferon, tumor necrosis factor (TNF-a), R-proteins, and decreased complement activity. From 1996 to 1999 T cell system changes showed increased $CD3^+$ and $CD4^+$ lymphocytes and significantly decreased CD22 and HLA-DR lymphocytes. Children from areas heavily contaminated with Cs-137 had significantly more eosinophils, eosinophilic

protein X concentration in urine, and eosinophilic cation protein concentration in serum (Tytov, 2000).

2. There was a strong correlation between the level of Cs-137 contamination in the territories and the quantity of the $D25^{+}$ lymphocytes, as well as concentration-specific IgE antibodies to grass and birch pollen (Tytov, 2002).

3. There was an increasing concentration of the thyroid autoantibodies in 19.5% of "practically healthy" children and teenagers living in Khoiniky District, Gomel Province. The children and teenagers with thyroid autoimmune antibodies living in the contaminated territories have more serious and more persistent changes in their immune status (Kuchinskaya, 2001).

4. The number of B lymphocytes and the level of serum IgG began to increase in children from the contaminated areas of the Mogilev and Gomel provinces a year after the catastrophe. The children were 2 to 6 years of age at the time of the catastrophe (Galitskaya *et al.*, 1990).

5. In children from the territories of Mogilev Province contaminated by Cs-137 at levels higher than 5 Ci/km^2 there was a significant decrease in cellular membrane stability and impaired immunity (Voronkin *et al.*, 1995).

6. The level of T lymphocytes in children who were 7 to 14 years of age at the time of the catastrophe correlated with radiation levels (Khmara *et al.*, 1993).

7. Antibody formation and neutrophilic activity were significantly lower for the first year of life in newborns in areas with Cs-137 levels higher than 5 Ci/km^2 (Petrova *et al.*, 1993).

8. Antitumor immunity in children and evacuees was significantly lower in heavily contaminated territories (Nesterenko *et al.*, 1993).

9. Immune system depression occurred in healthy children in the Braginsk District near the 30-km zone immediately after the catastrophe with normalization of some parameters not occurring until 1993 (Kharytonik *et al.*, 1996).

10. Allergy to cow's milk proteins was found in more children living in territories more heavily contaminated by Sr-90 than in children from less contaminated areas: 36.8 vs. 15.0% (Bandazhevsky *et al.*, 1995; Bandazhevsky, 1999).

11. Among 1,313 children examined from an area contaminated by Cs-137 at a level of 1–5 Ci/km^2 some developed immune system problems, which included lowered neutrophil phagocytic activity, reduced IgA and IgM, and increased clumping of erythrocytes (Bandazhevsky *et al.*, 1995).

12. The immune changes in children of Gomel Province are dependent upon the spectrum of radionuclides: identical levels of Sr-90 and Cs-137 radiation had different consequences (Evets *et al.*, 1993).

13. There was correlation among children and adults between the level of radioactive contamination in an area and the expression of the antigen APO-1/FAS (Mel'nikov *et al.*, 1998).

14. There are significant competing differences in the immune status of children from territories with different Cs-137 contamination loads (Table 5.30).

15. Levels of immunoglobulins IgA, IgM, IgG, and A(sA) in mother's milk were significantly lower in the contaminated areas. Acute respiratory virus infections (ARV), acute bronchitis, acute intestinal infections, and anemia were manifoldly higher in breast-fed babies from the contaminated areas (Zubovich *et al.*, 1998).

16. Significant changes in cellular immunity were documented in 146 children and teenagers operated on for thyroid cancer in Minsk. These changes included: decrease in the number of T lymphocytes (in 30% of children and 39% of teens), decreased levels of B lymphocytes (42 and 68%), decreased T lymphocytes (58 and 67%), high titers of antibodies to thyroglobulin (ATG), and neutrophilic leukocytosis in 60% of the children (Derzhitskaya *et al.*, 1997).

17. Changes in both cellular and humoral immunity were found in healthy adults living in territories with a high level of contamination (Soloshenko, 2002; Kyril'chik, 2000).

TABLE 5.30. Immune Status of Children with Frequent and Prolonged Illnesses from the Contaminated Territories of Belarus (Gurmanchuk *et al.*, 1995)

District/radiation level	Parameters of immunity
Pinsk, Brest Province, 1–5 Ci/km^2 ($n = 67$)	Number of T lymphocytes, T suppressors (older children), suppression index, T helpers (all groups) is lowered. The level of the CIC, IgM (all groups), and IgA (children up to 6 years of age) is raised.
Bragin, Gomel Province, 40–80 Ci/km^2 ($n = 33$)	Number of T lymphocytes is raised (all groups), fewer T-lymphocyte helpers (older children), increased T suppressors (in oldest children).
Krasnopolsk, Mogilev Province, up to 120 Ci/km^2 ($n = 57$)	All children have humoral cellular depression, fewer B lymphocytes, CIC levels raised, complement overactive, and levels of IgG and IgA phagocyte activity lowered.

18. The levels of IgA, IgG, and IgM immunoglobulins were increased in the postpartum period in women from districts in Gomel and Mogilev provinces contaminated with Cs-137 at a level higher than 5 Ci/km^2 and the immune quality of their milk was lowered (Iskrytskyi, 1995). The quantity of IgA, IgG, and IgM immunoglobulins and secretory immunoglobulin A(sA) were reduced in women in the contaminated territories when they began lactating (Zubovich *et al.*, 1998).

19. The number of T and B lymphocytes and phagocytic activity of neutrophilic leukocytes was significantly reduced in adults from the contaminated areas (Bandazhevsky, 1999).

20. Significant changes in all parameters of cellular immunity (in the absence of humoral ones) were found in children born to liquidators in 1987 (Arynchin *et al.*, 1999).

21. A survey of 150 Belarus liquidators 10 years after the catastrophe showed a significant decrease in the number of T lymphocyte, T suppressor, and T helper cells (Table 5.31).

22. In a group of 72 liquidators from 1986, serum levels for autoantibodies to thyroid antigens (thyroglobulin and microsomal fraction of thyrocytes) were raised 48%. Autoantibodies to lens antigen were increased 44%; to CIC, 55%; and to thyroglobulin, 60%. These shifts in immune system function are harbingers of pathology of the thyroid gland and crystalline lens of the eye (Kyseleva *et al.*, 2000).

5.4.2. Ukraine

1. Immune deficiency was seen in 43.5% of children radiated *in utero* (vs. 28.0% in the control group; $P < 0.05$) within the first 2 years after the catastrophe (Stepanova, 1999).

2. A total of 45.4% of 468 children and teenagers who were examined had chronic tonsillitis, hypertrophy of the adenoid glands and tonsils, and increased frequency of neck lymphadenopathies. All of these pathologies were expressed more in the areas with higher levels of contamination (Bozhko, 2004).

3. Quantitative and functional parameters of the immune status of children correlated with the level of background radiation in areas of permanent residency. These included impaired T- and B-cellular immunity, stimulation of Th[2]-cells and increased IgE, absolute and relative number of B lymphocytes, and levels of immunoglobulins in blood and saliva (Kyril'chik, 2000).

4. Periodic changes in humoral and cellular immunity were found in healthy children from the Komarin settlement, Braginsk District, near

TABLE 5.31. Numbers of T and B Lymphocytes in 150 Belarussian Male Liquidators in 1996 (Bliznyuk, 1999)

	Liquidators	Controls
T lymphocytes	723.5 ± 50.6	1,401.0 ± 107.4*
B lymphocytes	215.7 ± 13.9	272.5 ± 37.3*

*Differences are significant.

the 30-km Chernobyl zone. In 1986 the level of interferon in 40.8 ± 6.2% of children was significantly below the level of controls. The greatest immune system depression involved a decrease in EAC-POK, especially in children aged 4 to 6 years, a decreased level of T lymphocytes, and an index of suppression (IS) especially for children aged 11 to 14 years. In 1988 the levels of IgM and CIC remained raised, as were those of T lymphocytes and T helper cells. Levels of T suppressor cells significantly decreased, whereas interferon activity increased. By 1993 there was a normalization of a number of immune parameters, but for children 7 to 14 years of age T lymphocytes and T helper cells were decreased (Kharytonik *et al.*, 1996).

5. Immunological status of evacuees' children in the first 2 years was characterized by impaired humoral and cellular immunity. These parameters stabilized only 5 years later (Romanenko *et al.*, 1995a,b).

6. The number of T and B lymphocytes (36 ± 3.5% and 24 ± 1.4%), T helpers, immune-regulating index Tx:Tc (2.4 ± 0.19 vs. 1.9 ± 0.14), and IgG levels were significantly higher in patients with chronic pyelonephritis living in the contaminated areas of Polessk and Ivankov districts of Kiev Province (Vozianov *et al.*, 1996).

7. The number of peripheral blood leukocytes in evacuees remained significantly lower even 7 to 8 years after the catastrophe (Baeva and Sokolenko, 1998).

8. The influences of internal and external radiation on the character of neurohumoral reactions are sharply different: with internal radiation there is a gradual development of autoimmune reactions, whereas with external radiation, development is rapid (Lysyany and Lyubich, 2001).

9. A total of 45% of more than 450,000 children living in contaminated territories had lowered immune status 10 years after the catastrophe (TASS, 1998).

10. Significant impairment of cellular and humoral immunity, expressed by decreased numbers of T- and B-rosette forming cells, T suppressors, and IgA and IgG globulins and an increased index of T helpers/T suppressors, was found in areas with higher levels of radionuclides (Soloshenko, 2002).

11. Liquidators from 1986–1987 had impaired immunity expressed as depressed humoral and cellular immunity and poor resistance to infection 6 to 8 years after the catastrophe (Chumak and Bazyka, 1995).

12. In the 10 to 15 years after the catastrophe many liquidators had quantitative changes in cellular and humoral immunity and altered immune status (Korobko *et al.*, 1996; Matveenko *et al.*, 1997; Potapnev *et al.*, 1998; Grebenjuk *et al.*, 1999; Gazheeva *et al.*, 2001; Malyuk and Bogdantsova, 2001; Tymoshevsky *et al.*, 2001; Shubik, 2002; Bazyka *et al.*, 2002; Novykova, 2003; Mel'nov *et al.*, 2003). These changes are expressed as:

- Changes in the ratio of subpopulations of T lymphocytes—T helpers/T suppressors.
- Decrease in the general number of T and B lymphocytes.
- Decrease in the level of serum IgA, IgG, and IgM immunoglobulins.
- Impaired production of cytokines.
- Activation of neutrophilic granulocytes.

13. Pathological changes in neutrophil ultra structure, which included destruction of cell contents, hypersegmentation of nuclei, abnormal polymorphic forms and lymphocytes with increased segmentation, changes in membrane contour, and chromatin and nuclei segmentation, were found in a majority of 400 liquidators examined (Zak *et al.*, 1996).

5.4.3. Russia

1. Children living in heavily contaminated territories have generalized and specific immunity suppression and malfunction of their antioxidant and sympathetic adrenal systems (Terletskaya, 2003).

2. A survey of 144 children and teenagers of Krasnogorsk District, Bryansk Province, with Cs-137 levels up to 101.6 Ci/km^2 have decreased relative and absolute numbers of T cells; increased immune-regulatory index (T4/T8); and reduced relative numbers of lymphocytes, T helpers (CD4$^+$), and relative and absolute numbers of T suppressors (CD8$^+$; Luk'yanova and Lenskaya, 1996).

3. During a survey of 113 children from the Krasnogorsk District, Bryansk Province, from 1987 to 1995, parameters of intensive granular reaction in lymphocytes peaked in 1991, decreased almost to their norms in 1992–1993, and increased again in 1994–1995. The number of children with critically low lymphocyte counts also rose in 1994–1995. There were correlations between an intensive granular reaction in children and additional internal radiation of more than 0.5 mSv annually (Luk'yanova and Lenskaya, 1996).

4. In territories of Krasnogorsk District with higher radioactive contamination there was significantly less activity of nonspecific esterase (a marker of immature T cells) and a significant increase in the number of medium-size lymphocytes with intensive granular reaction (Lenskaya *et al.*, 1995).

5. Children 11 to 13 years of age and pregnant women living in districts of Kursk Province with high levels of contamination had functional and quantitative lymphocyte changes and significantly increased circulating serum immune complexes (CICs; Alymov *et al.*, 2004).

6. By 2002 the frequency of occurrence of impaired immunity and metabolism in children had increased fivefold in the contaminated districts of Tula Province compared to pre-Chernobyl levels. At the same time, morbidity not related to radiation remained the same in both the clean and contaminated territories (Sokolov, 2003).

7. In the heavily contaminated districts of Bryansk Province, children and teenagers had markedly lowered relative and absolute numbers of T cells; significantly lowered relative numbers of lymphocytes, T helpers (CD4$^+$), and T suppressors (CD8$^+$); and a raised immune-regulatory index (T4 helpers/T8 suppressors). This index correlated significantly with the dose level *in utero* (Kulakov *et al.*, 1997).

8. Absolute levels of all lymphocyte populations were lower in all liquidators' children examined at 10 to 13 years of age, which indicated that these children had both absolute and relative deficiencies in their cellular immunity. Clinically, infections prevailed: frequent acute respiratory virus infections (ARV), bronchitis, pneumonia, otitis, and purulent infections of the mucous membranes and skin. For others, a relative measure of cellular immunity had a tendency to increase owing to an increase in the number of CD4$^+$ cells and there was a decrease in the subpopulation T cells and an increase in basophilic activity. The clinical picture of the second group comprised allergies, sensitivity to pollens, asthmatic bronchitis, and food allergies (Kholodova *et al.*, 2001).

9. In the contaminated territories the number of individuals with adaptive reaction lymphocytes is lower and the number of people with elevated lymphocyte radiosensitivity is higher (Burlakova *et al.*, 1998).

10. The number of large granulocytic lymphocytes (NK cells) decreased 60 to 80% in liquidators 1 month after beginning work in the contaminated zone and persisted at a low level for not less than 1 year (Antushevich and Legeza, 2002). After 3 to 4 years liquidators had persistent changes in T system immunity with a decrease in T cells and T helpers and a reduction in the helper/suppressor index. This combination was observed in varying degrees in 80% of cases with bacterial intestinal disease. After 5 years and then 13 to 15 years most of the parameters of cellular and humoral immunity in liquidators did not differ from normal, although there were changes in natural immunity with decreased activity of myeloperoxidase (MPO) in neutrophils, a markedly reduced subpopulation of active lymphocytes, and a substantial increase in abnormal erythrocytic forms (Antushevich and Legeza, 2002).

11. In the 7 to 9 years after the catastrophe, liquidators from Obninsk City, Kaluga Province, had a higher incidence of allergic diseases: rhinitis (6- to 17-fold) and nettle rash (4- to 15-fold) compared to the local population (Tataurtchykova *et al.*, 1996).

12. Four years after their participation in emergency work the normal levels of dermorphin was restored in only 17% of the liquidators examined. The levels of two other neuropeptides (leu- and methionine-encephalin) exceeded norms for more than 50% of the liquidators examined (Sushkevich *et al.*, 1995).

13. Liquidators with neuropsychological disorders developed secondary immunedeficiency conditions (T lymphopenia, loss of balance of subpopulations of T cells with impaired T helper/T suppressor ratios, etc.). The number of T helpers ($CD4^+$) decreased in 90% of surveyed liquidators, and 15% of those examined had a significantly reduced number of circulating T-suppressor cells. In these groups changes took place that were opposite in nature to changes in the immune-regulatory index CD4/CD8). The level of the CIC increased in all surveyed liquidators. Phagocytic activity of peripheral blood neutrophils was lower in 80% and macrophage activity was lower in 85% of those examined (Kut'ko *et al.*, 1996).

14. The immune index of liquidators correlated with the dose of radiation calculated by the level of chromosomal aberrations (Baleva *et al.*, 2001).

5.4.4. Conclusion

Data in this section demonstrate the powerful effects of the Chernobyl radioactive fallout on the immune system and its functions. Despite the fragmentary data, it is clear that the scale of the impacts is enormous. Apparently, impaired immunity triggered by Chernobyl radionuclides adversely affected all of the individuals, without exception, who were subjected to any additional radiation.

5.5. Respiratory System Diseases

There is a marked increase in respiratory system morbidity everywhere in the territories contaminated by Chernobyl fallout. Respiratory system diseases, which include those of the nasal cavity, throat, trachea, bronchial tubes, and lungs, were among the first apparent consequences of the irradiation and ranged from nose bleeds and tickling in the throat to lung cancer. Hot particles, or "Chernobyl dust," consist of particles containing radionuclides derived from nuclear fuel melted together with particles from metal construction, soil, etc. (see Chapter 1 for details). These persist for long periods in pulmonary tissue because of the low solubility of uranium oxides. In the first days after the catastrophe, respiratory problems in the mouth, throat, and trachea in adults were basically linked to the gaseous–aerosol forms of radionuclides. During this initial period I-131, Ru-106, and Ce-144 had the most serious impact on the respiratory system (IAEA, 1992; Chuchalin *et al.*, 1998; Kut'kov *et al.*, 1993; Tereshenko *et al.*, 2004). Further damage to the respiratory system was caused by hot particles and external irradiation, and was also a consequence of changes in the immune and hormonal systems. The smallest hot particles, up to 5 μm, easily reached the deepest parts of lungs, while larger particles were trapped in the upper respiratory tract (Khrushch *et al.*, 1988; Ivanov *et al.*, 1990; IAEA, 1994).

Bronchopulmonary morbidity increased quickly among liquidators in the contaminated territories (Kogan, 1998; Provotvorov and Romashov, 1997; Trakhtenberg and Chissov, 2001; Yakushin and Smirnova, 2002; Tseloval'nykova *et al.*, 2003; and others). Liquidators, whose health was supervised more carefully than that of the general population, developed marked restrictive lung disease due to a functional decrease in lung elasticity (Kuznetsova *et al.*, 2004). Chernobyl dust was found in liquidators' bronchial tubes, bronchioles, and alveoli for many years. The syndrome of "acute inhalation depression of the upper respiratory system" presents as a combination of a rhinitis, tickling in the throat, dry cough, and difficulty breathing (Chuchalin *et al.*, 1993; Kut'kov, 1998; Romanova, 1998; Chykyna *et al.*, 2001; and others).

5.5.1. Belarus

1. Children born to mothers in the Chernobyl contaminated territories who were pregnant at the time of the catastrophe have twice the incidence of acute respiratory diseases (Nesterenko, 1996).

2. Respiratory morbidity in children born at the time of the catastrophe in territories with contamination levels of 15–40 Ci/km^2 was significantly higher than in children of the same age from territories with contamination of 5–15 Ci/km^2 (Kul'kova *et al.*, 1996).

3. Respiratory diseases were found in 19% of liquidators' children up to 1 year of age, and 10% of the children had exudative-mucoid disease. In older children 60% had documented respiratory diseases (Synyakova *et al.*, 1997).

4. The number of children hospitalized for bronchial asthma was higher in the more contaminated territories and chronic nasopharyngeal pathology was seen twice as often compared to children from less contaminated areas (Sitnykov *et al.*, 1993; Dzykovich *et al.*, 1994; Gudkovsky *et al.*, 1995).

5. Among 2,335 surveyed evacuees' teenagers, respiratory morbidity was the third cause of overall morbidity 10 years after the catastrophe: 286 per 1,000 (Syvolobova *et al.*, 1997).

6. Among 4,598 children newborn to 4 years old at the time of the meltdown from Kormyansk and Chechersk districts, Gomel Province, which had contamination levels of 15–40 Ci/km^2, respiratory system morbidity was significantly higher than among children from areas with contamination levels of 5–15 Ci/km^2 (Blet'ko *et al.*, 1995; Kul'kova *et al.*, 1996).

7. In the first 3 years after the catastrophe respiratory illnesses in children from territories contaminated at a level of 15–40 Ci/km^2 were 3.5-fold more common than in less contaminated territories. From 1990 to 1993 children from heavily contaminated territories had 2.5-fold more illnesses (Gudkovsky *et al.*, 1995).

8. Respiratory morbidity among children from the Luninetsk District, Brest Province, was 72.9% from 1986 to 1988, 54.1% from 1989 to 1991, and 39.4% from 1992 to 1994. Among the most common illnesses were ARV infection, bronchitis, and chronic tonsillitis (Voronetsky *et al.*, 1995).

9. Among evacuees, respiratory morbidity in 1995 was 2,566 cases per 10,000 compared to the country average of 1,660 (Matsko, 1999).

5.5.2. Ukraine

1. In the first months after the catastrophe, more than 30% of children in the contaminated territories had breathing difficulties defined as a respiratory syndrome (Stepanova *et al.*, 2003). In 1986–1987, nearly 10,000 children from contaminated territories that were examined had breathing problems: (a) 53.6% had bronchial obstruction mainly of the small bronchial tubes (controls, 18.9%) and (b) 69.1% had latent bronchospasms (controls, 29.5%; Stepanova *et al.*, 2003).

2. Asphyxia was observed in half of 345 newborns irradiated *in utero* in 1986–1987 (Zakrevsky *et al.*, 1993).

3. Older children irradiated *in utero* had respiratory system pathologies significantly more often than controls: 26.0 vs. 13.7% (Prysyazhnyuk *et al.*, 2002).

4. In 1994 respiratory system morbidity among children from contaminated territories and among evacuees was as high as 61.6% and among adults and teenagers it reached 35.6% (Grodzinsky, 1999).

5. In 1995 respiratory illnesses in children from the heavily contaminated territories were reported twice as often as from less

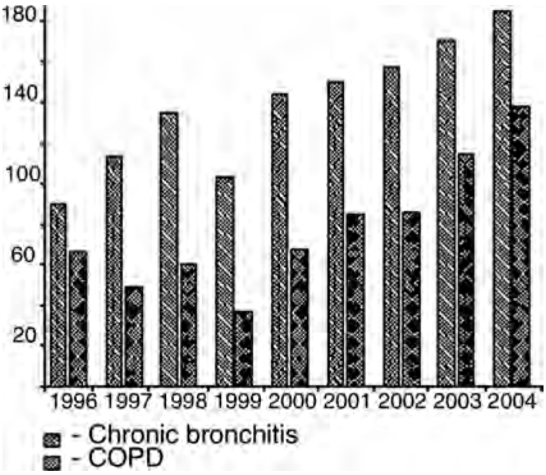

Figure 5.7. Chronic bronchitis and chronic obstructive pulmonary disease (COPD) morbidity among Ukrainian liquidators from 1996 to 2004 (Sushko *et al.*, 2007).

contaminated areas (Baida and Zhirnosekova, 1998).

6. According to the Ukrainian Ministry of Health, bronchitis and emphysema among teenagers, adults, and evacuees in the contaminated territories increased 1.7-fold from 1990 to 2004 (316.4 and 528.5 per 10,000), and bronchial asthma more than doubled (25.7 and 55.4 per 10,000; National Ukrainian Report, 2006).

7. Chronic bronchitis in liquidators more than doubled between 1996 and 2004, going from 84 to 181 cases per 1,000 (Figure 5.7).

8. In 80% of the cases of chronic nonspecific pulmonary disease among liquidators, atrophy of the mucous membrane covering of the trachea and bronchus was found, as well as ciliary flattening and epithelial metaplasia (Romanenko *et al.*, 1995a).

9. Of 873 male liquidators examined 15 years after the catastrophe, 84% had mucous membrane atrophy, usually accompanied by bronchial tree deformities (Shvayko and Sushko, 2001; Tereshchenko *et al.*, 2004).

10. Chronic bronchitis and bronchial asthma are two of the main reasons for morbidity, impairment, and mortality among liquidators. The majority of liquidators during their stay in the contaminated zone and immediately afterward suffered from a dry cough complicated by painful breathing. The subsequent development of disease was characterized by progressive obstruction and dyspnoea with shortness of breath and difficulty or pain in breathing. Subsequently, symptoms of chronic obstructive lung disease were observed: cough, sputum production, and dyspnoea in combination with obstructive, restrictive, and mixed ventilation disorders (Tereshchenko *et al.*, 2003; Sushko and Shvayko, 2003a).

11. From 1988 to 2006 clinical observation of 2,476 male liquidators ages 36.7 ± 8.5 years showed chronic obstructive lung disease and bronchitis in 79%, chronic nonobstructive bronchitis in 13%, and asthma in 8% (Tereshchenko *et al.*, 2004; Dzyublik *et al.*, 1991; Sushko, 1998, 2000). The occurrence of obstructive disease and bronchitis almost doubled in the second decade after the catastrophe (Figure 5.8).

12. Some 84% of 873 surveyed liquidators had tracheobronchial mucous membrane thinning and vascular atrophy; 12% had opposite changes in bronchial fiberscopic pathology, including hyperplasia, which consisted of

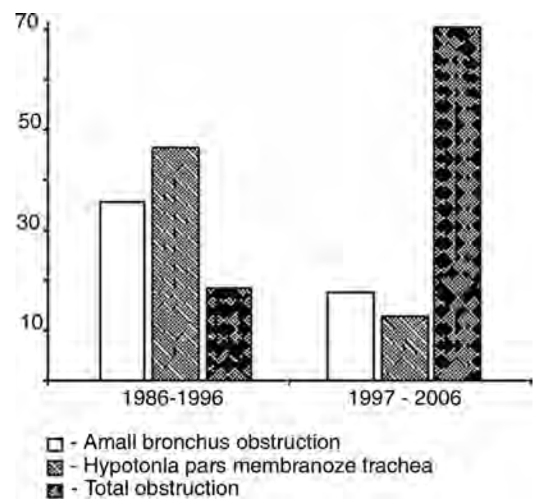

Figure 5.8. Bronchopulmonary illnesses in Ukrainian male liquidators over a 20-year period (Tereshchenko *et al.*, 2004; Sushko and Shvayko, 2003a,b).

thickening of the mucous membranes and narrowing of primary and secondary bronchial tubes; and 4% were observed to have both types of pathology—atrophic changes proximally and hyperplasia distally. In 80% of the group examined mucoid-sclerotic changes in the bronchial mucosa were accompanied by tracheobronchial tree deformity. The prevalence of mucoid-sclerotic changes correlates with endobronchial atrophy. Isolated sclerotic changes of bronchial mucosa were reported in 16% and mucoid changes in 4% (Tereshchenko *et al.*, 2004).

13. Years after the catastrophe three liquidators were found to have sclerotic pulmonary mucous membrane changes and bronchial deformities (Sushko *et al.*, 2007).

5.5.3. Russia

1. Broncopulmonary dysplasia was seen in premature newborns from Novozybkov City, Bryansk Province, and fetal lung dysplasia was more common in 1992–1993 compared with controls and compared with the number of cases observed in 1995 (Romanova *et al.*, 2004).

2. The incidence of asphyxia and complicated breathing problems in newborns correlated with the level of contamination in the territory (Kulakov *et al.*, 1997).

3. Noninfectious respiratory disorders in neonates born to mothers from the contaminated territories were encountered 9.6 times more often than before the catastrophe. The areas and contamination levels were: Polessk District, Kiev Province (20–60 Ci/km^2); Chechersk District, Gomel Province (5–70 Ci/km^2); and Mtsensk (1–5 Ci/km^2) and Volkhov (10–15 Ci/km^2) districts, Oryol Province (Kulakov *et al.*, 1997).

4. Children in the contaminated territories currently have more bronchial asthma and chronic bronchitis owing to irreversible structural lung changes. In the contaminated territories there is a marked increase in the incidence of both acute pneumonia and chronic broncopulmonary pathology, expressed as bronchial asthma and chronic bronchitis. In the first years after the catastrophe broncopulmonary illnesses were accompanied by moderate immunological changes and latent functional impairment; 10 to 15 years later the findings are pneumonia and lung scarring (Terletskaya, 2002, 2003).

TABLE 5.32. Respiratory Morbidity among Children of Bryansk Province Districts with a Level of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999b: table. 6.1)

	Number of cases			
	1995	1996	1997	1998
Klymovo	781.5	897.5	1,080.5	1,281.6
Novozybkov	1,435.3	1,750.0	2,006.0	1,743.9
Klintsy	303.4	342.9	481.3	728.5
Krasnogorsk	936.0	927.3	1,001.3	771.0
Zlynka	1,510.4	1,072.0	1,267.6	1,582.6
Southwest*	1,288.7	1,023.8	1,426.2	1,398.3
Province	855.1	774.8	936.6	918.7
Russia	767.2	715.1	790.9	n/a

*All contaminated districts.

5. Children's overall respiratory morbidity was much higher in the heavily contaminated districts of Bryansk Province 9 to 12 years after the catastrophe than in the rest of the province and in Russia as a whole (Table 5.32).

6. For adults in the more contaminated territories of Bryansk Province the general respiratory morbidity is much below that of children, but the same tendency toward increase was observed from 1995 to 1998, except in one district (Table 5.33).

7. A majority of the surveyed Russian liquidators who were exposed in 1986–1987 have developed progressive pulmonary function impairment (Chykyna *et al.*, 2002). Incidence of this respiratory abnormality increased continuously for the first 8 years after the catastrophe (Table 5.34).

8. A group of 440 liquidators with chronic bronchopulmonary pathology were examined at the Moscow Institute of Pulmonology. Radionuclides were found in their pulmonary systems 6 to 10 years after the catastrophe.

TABLE 5.33. Respiratory Morbidity among the Adult Population of Bryansk Province in Areas with a Level of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999a: table 5.1)

Territory	1995	1996	1997	1998
Klymovo	195.9	211.9	259.6	326.3
Novozybkov	302.3	288.9	238.0	233.1
Klintsy	142.5	126.2	336.8	474.5
Krasnogorsk	196.6	163.6	182.0	183.4
Zlynka	192.0	230.8	298.0	309.1
Gordeevka	134.0	167.6	192.0	237.0
Southwest	209.2	194.5	237.6	242.2
Province	197.4	168.3	199.2	192.6
Russia	213.6	196.6	219.2	n/a

Combined external radiation and incorporated radionuclide effects were expressed in a new form of chronic obstructive pulmonary disease syndrome (Chuchalin *et al.*, 1998).

9. Prolonged persistence of radioactive particles is associated with the appearance of cancer-related molecular abnormalities in the bronchial epithelium of former Chernobyl cleanup workers. These include: K-ras (codon 12) mutation; p16 (INK4A) promoter hypermethylation; microsatellite alterations at seven chromosomal regions; and allelic loss at 3p12, 3p14.2 (FHIT), 3p21, 3p22–24 (hMLH1), and 9p21 (p16INK4A). The incidence of 3p14.2 allelic loss was associated with decreased expression of the FHIT mRNA in the bronchial epithelium as compared with a control group of smokers (Chuchalin, 2002; Chizhykov and Chizhykov, 2002).

10. The frequency of the chronic bronchopulmonary illnesses in liquidators increased significantly over the first 15 years after the catastrophe, with an increase up to 10-fold for some illnesses. The diseases developed more rapidly and were more serious (Tseloval'nykova *et al.*, 2003).

5.5.4. Conclusion

Illnesses of the upper respiratory system (nasopharynx and bronchial tubes) were the initial consequences of Chernobyl irradiation for the general population and the liquidators in the first days and weeks after the catastrophe. In some years the incidence of bronchopulmonary illnesses decreased, but the severity increased, reflecting significant impairment of the immune and hormonal systems. Some 10 to 15 years later, respiratory morbidity in Belarus, Ukraine, and Russia remained significantly higher in the contaminated territories.

For children of the Japanese hibakusha who were not irradiated directly, the incidence of respiratory system illnesses was higher compared to controls some decades after the bombardments (Furitsu *et al.*, 1992). If such an increase is observed after a single short-term irradiation, it is possible to assume that the Chernobyl irradiation will cause increased respiratory system illnesses over the next several generations.

5.6. Urogenital Tract Diseases and Reproductive Disorders

Irradiation directly damages the kidneys, bladder, and urinary tract, as well as the ovaries and testicles, which not only are subject to direct radiation effects, but are indirectly affected through hormonal disruption. These disorders in structure and function result in damage to the reproductive process.

Although there have been some studies of the functional changes in the urogenital tract as a consequence of Chernobyl radiation, there is still not enough information to explain all of the serious changes. It was unexpected, for example, to find increased levels of male hormones

TABLE 5.34. Respiratory Morbidity (per 10,000) among Russian Liquidators for the First 8 Years after the Catastrophe (Baleva *et al.*, 2001)

Year	1986	1987	1988	1989	1990	1991	1992	1993
Morbidity	645	1,770	3,730	5,630	6,390	6,950	7,010	7,110

in females as a result of internally incorporated radionuclides (for a review see Bandazhevsky, 1999) and also unexpected to observe contrary effects of various radionuclides on the rate of sexual maturation (Paramonova and Nedvetskaya, 1993).

5.6.1. Belarus

1. From 1993 to 2003, there was a significant delay in sexual maturation among girls from 10 to 14 years of age born to irradiated parents (National Belarussian Report, 2006).

2. Up until 2000 children born after the catastrophe in heavily contaminated territories had more reproductive organ disorders than those born in less contaminated areas: fivefold higher for girls and threefold higher for boys (Nesterenko *et al.*, 1993).

3. In territories with heavy Chernobyl contamination, there are increased numbers of children with sexual and physical developmental disorders related to hormone dysfunction—cortisol, thyroxin, and progesterone (Sharapov, 2001; Reuters, 2000b).

4. Abnormal development of genitalia and delay in sexual development correlated with the levels of radioactive contamination in the Chechersk District, Gomel Province (5–70 Ci/km^2; Kulakov *et al.*, 1997).

5. Of 1,026,046 pregnant women examined, the level of urogenital tract disease was significantly higher in the more contaminated territories (Busuet *et al.*, 2002).

6. From 1991 to 2001, the incidence of gynecologic diseases in fertile women in the contaminated territories was considerably increased, as were the number of complication during pregnancy and birth (Belookaya *et al.*, 2002).

7. Increased gynecologic morbidity (including anemia during pregnancy and postnatal anemia) and birth anomalies correlated with the level of radioactive contamination in the Chechersky District, Gomel Province (5–70 Ci/km^2; Kulakov *et al.*, 1997).

8. In the contaminated territories, failed pregnancies and medical abortions increased (Golovko and Izhevsky, 1996).

9. Soon after the catastrophe the majority of fertile women from the contaminated territories developed menstrual disorders (Nesterenko *et al.*, 1993). Frequent gynecologic problems and delay in the onset of menarche correlated with the levels of radioactive contamination in the area (Kulakov *et al.*, 1997).

10. Abnormalities of menstrual function in nonparous women in areas with contamination of 1–5 Ci/km^2 (Gomel City) was linked to ovarian cystic-degenerative changes and increased endometrial proliferation. Ovarian size correlated with testosterone concentration in blood serum (Yagovdik, 1998).

11. The incidence of endometriosis increased almost 2.5-fold in Gomel, Mogilev, and Vitebsk cities from 1981 to 1995 (surgical treatment for 1,254 women), with the disease expressed most often in the first 5 years after the catastrophe. Among women who developed endometriosis, those in the more contaminated areas were 4 to 5 years younger than those from less contaminated areas (Al-Shubul and Suprun, 2000).

12. Primary infertility in the contaminated areas increased 5.5-fold in 1991 compared with 1986. Among the irrefutable reasons for infertility are sperm pathologies, which increased 6.6-fold; twice the incidence of sclerocystic ovaries; and a threefold increase in endocrine disorders (Shilko *et al.*, 1993).

13. Impotence in young men (ages 25 to 30 years) correlated with the level of radioactive contamination in a territory (Shilko *et al.*, 1993).

"... The doctors reminisce: 'In one village we found twelve lactating* elderly women, that is, women 70 years of age had milk in their breasts, as though they were nursing. Experts can argue about the effects of small doses of radiation, but the ordinary person cannot even begin to imagine such a thing. ...' " (Aleksievich, 1997).

*Lactation in the absence of pregnancy (termed galactoria or hyperprolactinemia) is an expression of pituitary gland dysfunction.

5.6.2. Ukraine

1. Urogenital diseases increased in children in the contaminated territories: 0.8 per 1,000 in 1987 to 22.8 per 1,000 in 2004 (Horishna, 2005).

2. From 1988 to 1999 the incidence of urogenital diseases in the population of contaminated territories more than doubled (Prysyazhnyuk *et al.*, 2002).

3. The level of alpha-radionuclides is significantly higher in bone tissue of aborted fetuses from mothers from the contaminated territories (Luk'yanova, 2003).

4. Girls have delayed puberty in the contaminated territories (Vovk and Mysurgyna, 1994). Sexual maturity was retarded in 11% of a group of 1,017 girls and teenagers from contaminated territories (Lukyanova, 2003).

5. In the territories contaminated by Sr-90 and Pu, puberty was delayed by 2 years in boys and by 1 year in girls. Accelerated rates of sexual development were observed in territories contaminated by Cs-137 (Paramonova and Nedvetskaya, 1993).

6. Abnormal genital development and delay in sexual development in the Polessk District, Kiev Province, correlated with the level of radioactive contamination (20–60 Ci/km^2) (Kulakov *et al.*, 1997).

7. Among 1,017 female children of evacuees (aged 8 to 18 years) examined after the catastrophe, 11% had delayed sexual development (underdevelopment of secondary sex characteristics, uterine hypoplasia, and late menarche), and 14% had disturbed menstrual function (Vovk, 1995).

8. Women who were irradiated as girls in 1986 have markedly more problems during childbirth (Table 5.35).

TABLE 5.35. Child-Bearing Data Concerning Women Irradiated as Children in 1986 in Contaminated Territories (Nyagy, 2006)

	Irradiated	Control
Normal delivery	25.8%	63.3%
Hypogalactia	33.8%	12.5%
Hypocalcemia	74.2%	12.5%

9. Neonates born to women who were irradiated as girls in 1986 have up to twice the incidence of physical disorders (Nyagy, 2006).

10. A survey of 16,000 pregnant women in the contaminated territories over an 8-year period after the catastrophe revealed the following: renal morbidity increased from 12 to 51%, oligohydramnios increased 48%, newborn respiratory disease increased 2.8-fold, the number of premature deliveries increased up to twofold, and there was early placental aging at 30–32 weeks gestation (Dashkevich *et al.*, 1995).

11. Increased gynecologic morbidity (including anemia during and after pregnancy) and birth anomalies in the Polessk District, Kiev Province, correlated with the level of radioactive contamination (20–60 Ci/km^2; Kulakov *et al.*, 1997).

12. Earlier onset and prolonged puberty and disorders of secondary sexual characteristics were found in girls born to liquidator fathers (Teretchenko, 2004).

13. Occurrence of chronic pyelonephritis, kidney stones, and urinary tract diseases in teenagers correlated with the level of contamination in the territories (Karpenko *et al.*, 2003).

14. The incidence of female genital disorders, including ovarian cysts and uterine fibromas, in the contaminated territories increased significantly for 5 to 6 years after the catastrophe (Gorptchenko *et al.*, 1995).

15. Menstrual cycle disorders are commonly diagnosed in the contaminated territories (Babich and Lypchanskaya, 1994). The number of menstrual disorders in the contaminated territories tripled compared with the precatastrophe period. In the first years after the catastrophe there was heavier menstruation, and after 5 to 6 years menstruation decreased or stopped (Gorptychenko *et al.*, 1995). Among 1,017 girls examined who had been exposed to irradiation, 14% had impaired menstruation (Luk'yanova, 2003; Dashkevich and Janyuta, 1997).

16. Dystrophic and degenerate changes of the placenta in liquidators and in other women living in the contaminated territories correlated with the level of Cs-137 incorporated in the placenta. These changes included uneven thickness of the placenta, presence of fibrous scaring, cysts, calcium inclusions, and undifferentiated and undeveloped fibroblasts in the terminal stromal villi, and resulted in lower weight of newborns (Luk'yanova, 2003; Luk'yanova *et al.*, 2005; Ivanyuta and Dubchak, 2000; Zadorozhnaya *et al.*, 1993).

17. Spontaneous interruption of pregnancy, late gestation, premature birth, and other pathologies of pregnancy occurred significantly more often in evacuees and in the contaminated territories 8 to 10 years after the catastrophe (Grodzinsky, 1999; Golubchykov *et al.*, 2002; Kyra *et al.*, 2003).

18. For 8 to 9 years after the catastrophe the incidence of menstrual disorders was significantly increased in female liquidators. A total of 84% of young women (average age 30.5 years in 1986–1987) developed hypermenstrual syndrome within 2 to 5 years after being exposed (41.2% had uterine fibromyoma, 19% had mammary fibroadenomatosis, and 16% had oliogomenses accompanied by persistent hyperprolactinemia (Bezhenar' *et al.*, 1999).

19. Female liquidators of perimenopausal age during the catastrophe had an early menopause (46.1 ± 0.9 years), and about 75% had climacteric syndrome and declining libido (Bezhenar *et al.*, 2000).

20. A total of 54.1% of pregnant women from the contaminated territories had preclampsia, anemia, and destruction of the placenta (controls 10.3%); 78.2% had birth complications and excess bleeding (2.2-fold higher than controls; Luk'yanova, 2003; Sergienko, 1997, 1998).

21. Miscarriages occurred especially often in the heavily contaminated territories of Kiev Province (Gerasymova and Romanenko, 2002). Risks of spontaneous abortions are higher in the contaminated territories (Lipchak *et al.*, 2003).

22. Women in the heavily contaminated areas have more frequent miscarriages, complications of pregnancy, aplastic anemia, and premature births (Horishna, 2005).

23. Some 96% of individuals in the contaminated territories with prostatic adenoma were found to have precancerous changes in the bladder urothelium (Romanenko *et al.*, 1999).

24. Among 250 married couples of liquidators observed in Donetsk City, 59 ± 5% have experienced sexual dysfunction caused by irradiation and 19 ± 3% owing to radiophobia. In an other study, 41% of 467 male liquidators (age 21 to 45 years) had sexual abnormalities: decreased testicular androgen function and increased estrogen and follicle-stimulating hormone levels (Bero, 1999).

25. In 7 to 8 years after the catastrophe, about 30% of liquidators had functional sexual disorders and sperm abnormalities (Romanenko *et al.*, 1995b).

26. Among 12 men with chronic radiation dermatitis caused by beta- and gamma-irradiation during and after the Chernobyl catastrophe two had erectile dysfunction and the others reported various impairments of sexual function. One had aspermia, two had azoospermia, one had oligospermia, and four had normal sperm counts. In three samples there was an increase in abnormal forms of spermatozoa and in three samples sperm motility was decreased (Byryukov *et al.*, 1993).

27. In 42% of surveyed liquidators sperm counts were reduced by 53%, the proportion of mobile sperm was lower (35–40% vs. 70–75% in controls), and the number of dead sperm increased up to 70% vs. 25% in controls (Gorptchenko *et al.*, 1995).

28. From 1988 to 2003 urogenital morbidity among male liquidators who worked in 1986–1987 increased 10-fold: 9.8 per 1,000 in 1988, 77.4 per 1,000 in 1999, and 98.4 per 1,000 in 2003 (Baloga, 2006).

TABLE 5.36. Urogenital Morbidity among Children (per 1,000) in Bryansk Province Districts with Levels of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999b: table 6.1)

	Number of cases			
	1995	1996	1997	1998
Klymovo	34.5	48.7	51.6	79.3
Novozybkov	40.2	43.3	44.8	60.1
Klintsy	8.0	10.8	11.2	10.8
Klintsy City	22.4	24.3	34.6	34.1
Krasnogorsk	56.7	51.4	44.2	26.0
Zlynka	66.8	38.7	44.8	46.2
Southwest*	30.1	33.5	36.7	41.6
Province	22.4	25.8	26.8	29.2

*All heavily contaminated districts.

TABLE 5.37. Urogenital Morbidity (per 1,000) among Adults in Bryansk Province Districts Contaminated above 5 Ci/km^2, 1995–1998 (Fetysov, 1999a: table 5.1)

	Number of cases			
Territory	1995	1996	1997	1998
Klymovo	72.1	71.4	64.1	60.1
Novozybkov	68.1	70.2	72.1	81.3
Klintsy	27.3	53.8	53.0	91.3
Klintsy City	45.5	76.1	75.2	79.2
Krasnogorsk	78.7	82.7	95.9	114.2
Zlynka	44.8	75.7	78.7	78.7
Gordeevka	52.3	67.8	72.9	80.2
Southwest*	54.9	88.7	78.4	75.9
Province	60.4	60.4	60.7	57.1

*All heavily contaminated districts.

5.6.3. Russia

1. Impaired genital and delayed sexual development correlated with the level of radioactive contamination in the Mtsensk (1–5 Ci/km^2) and Volkhov (10–15 Ci/km^2) districts of Oryol Province (Kulakov *et al.*, 1997).

2. Increased gynecologic morbidity (including anemia during pregnancy, postnatal anemia, and abnormal delivery) correlated with the level of radioactive contamination in the Mtsensk (1–5 Ci/km^2) and Volkhov (10–15 Ci/km^2) districts of Oryol Province (Kulakov *et al.*, 1997).

3. Overall, from 1995 to 1998, urogenital morbidity in children was higher in the majority of the contaminated districts of Bryansk Province than in the province as a whole (Table 5.36).

4. From 1995 to 1998 the overall urogenital morbidity in adults in Bryansk Province noticeably increased in all but one of the contaminated areas (Table 5.37).

5. The urogenital morbidity among women in some of the heavily contaminated territories of Bryansk and Tula provinces correlated with the levels of contamination (Table 5.38).

6. The frequency of occurrence of spontaneous abortions (miscarriages) in liquidator (1986–1987) families in Ryazan Province was significantly higher during the first 7 years after the catastrophe (Figure 5.9) and was fourfold higher (18.4 ± 2.2%) than that of the general population (4.6 ± 1.2%; Lyaginskaya *et al.*, 2007).

7. A total of 18% of all pregnancies registered among liquidators' families terminated in miscarriages (Lyaginskaya *et al.*, 2007).

8. The 1986 liquidators from Ryazan Province and other nuclear industry personnel went through a prolonged period of sterility, which was not revealed until recently (Lyaginskaya *et al.*, 2007).

9. Four years after the catastrophe up to 15% of liquidators (from 94 evaluated) had

TABLE 5.38. Occurrence of Reproductive System Illness and Precancer Pathologies among Women in Some Territories of the Tula and Bryansk Provinces Contaminated by Cs-137 (Tsyb *et al.*, 2006)

	Precancer pathologies, %*	All illnesses, %
Klintsy District ($n = 1{,}200$) 322 kBq/m^2	21.1	58.2
Novozybkov City ($n = 1{,}000$) 708 kBq/m^2	19.6	66.6
Uzlovaya Station ($n = 1{,}000$) 171 kBq/m^2	1.8	51.2

*Leukoplacias, displasias, polyps, etc.

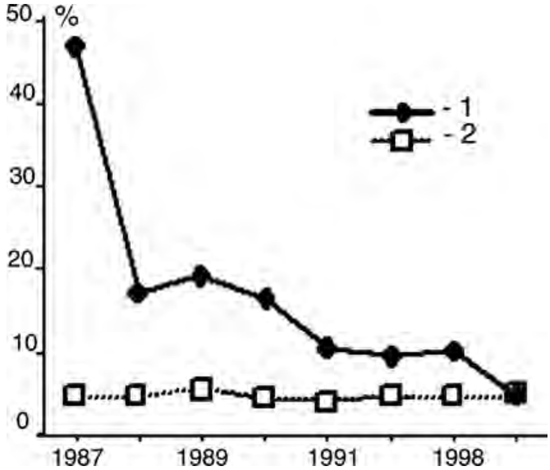

Figure 5.9. Incidence (%) of spontaneous abortions in liquidators' families (black rectangles) and in Ryazan' Province (white rectangles) from 1987 to 1994 (Lyaginskaya *et al.*, 2007).

significantly more dead sperm, lower sperm mobility, and increased acidic phosphatase levels in ejaculate compared with other males of the same age (Ukhal *et al.*, 1991).

10. Liquidators' virility was noticeably lower in the year after the catastrophe: up to 42% of sperm tests did not meet quantitative norms and up to 52.6% did not meet qualitative norms (Mikulinsky *et al.*, 2002; Stepanova and Skvarskaya, 2002).

11. Pathomorphological alterations occurred in testicular tissue of liquidators in Krasnodar Province, and autoimmune orchitis affecting spermatogenesis occurred soon after irradiation. Lymphoid infiltration developed in the seminiferous tubules 5 years after the catastrophe and in the interstitial tissue after 10 to 15 years.

12. Sexual potency was low in half of the male liquidators who were examined (Dubivko and Karatay, 2001).

13. The incidence of urogenital illnesses in male liquidators grew from 1.8 to 4% from 1991 to 1998 (Byryukov *et al.*, 2001).

14. Fifty liquidators who were examined had sperm counts significantly lower than the norms (Tsyb *et al.*, 2002).

15. Urogenital morbidity in liquidators increased more than 40-fold from 1986 to 1993 (Table 5.39).

16. A third of 116 liquidators examined had intercourse disorders (Evdokymov *et al.*, 2001).

17. A total of 21% of surveyed liquidators had sperm with reduced mobility and morphologic changes. Sperm of some liquidators contained 6–8% immature cells (the norm is 1–2%; Evdokymov *et al.*, 2001).

18. The level of abnormal spermatozoids in liquidators correlated with the level of chromosome aberrations (Kondrusev, 1989; Vozylova *et al.*, 1997; Domrachova *et al.*, 1997).

19. Sclerosis in 50% of seminiferous tubules and foci of Leydig cell regeneration was seen after the catastrophe (Cheburakov *et al.*, 2004).

5.6.4. Other Countries

1. Armenia. There were spermatogenesis disorders in the majority of the surveyed liquidators 10 years after the catastrophe (Oganesyan *et al.*, 2002). Among 80 children of liquidators who were examined there was increased incidence of pyelonephritis (Hovhannisyan and Asryan, 2003).

2. Bulgaria. Following the Chernobyl nuclear accident, an increase in maternal toxemia was associated with increased irradiation (Tabacova, 1997).

3. Czech Republic. The number of boys born monthly in Bohemia and Moravia, the Czech Republic territories that suffered most

TABLE 5.39. Dynamics of Urogenital Morbidity among Liquidators (per 10,000), 1986–1993 (Baleva *et al.*, 2001)

Year	1986	1987	1988	1989	1990	1991	1992	1993
Number of cases	34	112	253	424	646	903	1,180	1,410

from Chernobyl fallout changed only once over 600 months of observation (1950–1999). In November 1986, there were 457 fewer boys born than expected based on a long-term demographic trend (Perez, 2004). The change occurred among babies who were 7–9 weeks *in utero* at the time of the catastrophe.

4. ISRAEL. Significant differences in quantitative ultramorphological parameters of sperm heads were observed in liquidators who had emigrated compared with men of similar age who were not irradiated (Fischbein *et al.*, 1997).

5. OTHER COUNTRIES. There were long-term chronic effects of the catastrophe on sex ratios at birth in Denmark, Finland, Germany, Hungary, Norway, Poland, and Sweden between 1982 and 1992. The proportion of males increased in 1987 with a sex odds ratio of 1.0047 (95% CI: 1.0013–1.0081, $p < 0.05$). A positive association for the male proportion in Germany between 1986 and 1991 with radioactive exposure at the district level is reflected in a sex odds ratio of 1.0145 per mSv/year (95% CI: 1.0021 – 1.0271, $p < 0.05$) (Frentzel-Beyme and Scherb, 2007).

5.6.5. Conclusion

Clearly there is an increasingly wide spectrum of urogenital illnesses in men, women, and children from the territories contaminated by Chernobyl fallout. Although some claim that poor reproductive function is due solely to psychological factors (stressful conditions), it is difficult to blame stress for abnormalities in spermatozoa, reproductive failures, and birth abnormalities in children. The adverse influence of Chernobyl irradiation upon urogenital morbidity and reproductive function for liquidators and for millions of people living in the contaminated territories will continue in coming generations.

5.7. Bone and Muscle Diseases

Osteoporosis (decreasing density of bone tissue) results from an imbalance between the formation of bone and the natural reabsorption process. Such imbalance results from either hormonal disorders or direct damage by irradiation to the cellular predecessors of osteoclasts and osteoblasts (Ushakov *et al.*, 1997). Liquidators and inhabitants of contaminated territories often complain of bone and joint pain—the indirect indicators of the processes of osteoporosis.

5.7.1. Belarus

1. The number of newborns with developmental osteomuscular anomalies has increased in the contaminated territories (Kulakov *et al.*, 1997).

2. In 1995, osteomuscular morbidity in evacuees and inhabitants of the contaminated territories was 1.4-fold higher than for the general population (Matsko, 1999).

3. Osteomuscular illnesses were widespread among liquidators under 30 years of age (Antypova *et al.*, 1997a).

5.7.2. Ukraine

1. In recent years, stillbirths from the heavily contaminated territories had increased levels of alpha-radionuclides incorporated in bone tissue (Horishna, 2005).

2. Cs-137 incorporated in the placenta at a level of 0.9–3.25 Bq/kg leads to weakness of the tubular bone structures and destruction of spinal cartilage (Arabskaya *et al.*, 2006).

3. In the contaminated territories there have been cases of children born practically without bones ("jellyfish-children"), a condition seen previously only in the Marshall Islands after the nuclear tests of the 1950s.

4. Elevated placental radionuclide concentrations may be a factor in the death of newborns in contaminated territories (Table 5.40).

5. The bones of dead newborns demonstrate morphological defects: reduction in the number and size of osteoblasts, dystrophic changes in osteoblasts and osteoclasts, and a change in the osteoblast/osteoclast ratio (Luk'yanova, 2003; Luk'yanova *et al.*, 2005).

TABLE 5.40. Radionuclide Concentration (Bq/kg) in the Bodies of Pregnant Women and in Organs of Stillborns

	Horishna, 2005	Lukyanova *et al.*, 2005	Radionuclides
Mother's body	0.7 – 1.3	No data	Cs-137
Placenta	3.5	No data	Cs-137
	0.9	No data	Alpha
Liver	7.8	0.4 ± 0.05	Cs-137
Spleen	0.2	0.2 ± 0.03	Cs-137
Thymus	0.2	0.1 ± 0.02	Cs-137
Vertebrae	0.9	0.7 ± 0.02	Cs-137
Teeth	0.4	0.4 ± 0.02	Alpha
Ribs	No data	1.0 ± 0.24	Cs-137
Tubular bones	No data	0.3 ± 0.02	Cs-137

TABLE 5.41. Osteomuscular Morbidity (per 1,000) among Children in Bryansk Province Territories with Levels of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999b: table 6.1)

	Number of cases			
Territory	1995	1996	1997	1998
Klymovo	146.2	124.7	90.3	143.0
Novozybkov	31.3	32.7	37.9	29.6
Klintsy	40.4	41.3	69.9	63.5
Krasnogorsk	17.3	15.2	11.2	12.0
Zlynka	58.8	217.2	162.4	174.3
Southwest*	40.9	67.9	49.7	67.1
Province	22.6	25.4	27.0	29.7

*All heavily contaminated districts.

6. Osteomuscular morbidity among adult evacuees is higher than in the general population of the country (Prysyazhnyuk *et al.*, 2002).

7. In 1996 osteomuscular morbidity in territories with contamination of 5–15 Ci/km^2 was higher than for the population of the country as a whole (Grodzinsky, 1999).

8. From 1988 to 1999 osteomuscular morbidity in the contaminated territories more than doubled (Prysyazhnyuk *et al.*, 2002).

9. Muscular system and connective tissue diseases in liquidators increased 2.3-fold from 1991 to 2001 (Borysevich and Poplyko, 2002).

5.7.3. Russia

1. In the heavily contaminated districts of Bryansk Province, children's general osteomuscular morbidity was noticeably higher than that of the province as a whole (Table 5.41).

2. From 1995 to 1998 primary osteomuscular morbidity in children of Bryansk Province was higher in the contaminated areas (Table 5.42).

3. General osteomuscular morbidity of adults is higher in the heavily contaminated districts of Bryansk Province than in the province as a whole (Table 5.43).

4. Up to 62% of liquidators complain of back pain and pain in the bones of their hands, legs, and joints (Dedov and Dedov, 1996).

5. Osteoporosis was found in 30–88% of liquidators who were examined (Nykytyna, 2002; Shkrobot *et al.*, 2003; Kirkae, 2002; Druzhynyna, 2004).

6. Osteoporosis develops more often in liquidators than in comparable groups of the population (Nykytyna, 2005).

7. Osteoporosis in liquidators also affects the dental bone tissue (Matchenko *et al.*, 2001).

8. The most frequently occurring osteomuscular pathologies among 600 liquidators who were examined were osteochondrosis of various parts of vertebrae and diffuse osteoporosis. In 3.5% of cases the osteoporosis was accompanied by pathological bone fractures,

TABLE 5.42. Osteomuscular Morbidity among Adults in Bryansk Province Territories with Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999a: table 5.1)

	Number of cases			
Territory	1995	1996	1997	1998
Klymovo	173.8	118.9	216.0	236.7
Novozybkov	129.6	120.8	94.0	101.1
Klintsy	151.0	150.6	159.7	217.3
Krasnogorsk	136.0	141.1	109.7	89.7
Zlynka	110.2	110.2	102.0	103.0
Gordeevka	94.3	129.3	105.1	104.8
Southwest	100.7	109.4	111.7	111.9
Province	82.5	81.6	82.4	76.4

TABLE 5.43. Primary Osteomuscular Morbidity (per 1,000) among Children in Bryansk Province, 1995–1998 (Fetysov, 1999b: table 6.2)

Year	1995	1996	1997	1998
Southwest	19.5	39.2	24.5	42.4
Province	11.5	13.9	16.4	18.5

TABLE 5.44. Osteomuscular Morbidity (per 1,000) among Liquidators and the Adult Population of Bryansk Province Territories with Levels of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999a: table 4.1)

	Number of cases				
	1994	1995	1996	1997	1998
Liquidators	114.1	99.3	207.0	221.8	272.9
Southwest*	90.0	93.5	109.4	111.7	238.6
Province	80.5	82.5	81.6	82.4	76.4
Russia	80.3	81.5	87.2	87.2	n/a

*All heavily contaminated districts.

compression of nerve roots, and osteoalgia and arthralgias (Kholodova *et al.*, 1998).

9. The mineral density of bone in many liquidators is 16–37% lower than the age norms (Kholodova *et al.*, 1998). Some 62% of liquidators among the 274 who were examined had decreased skeletal mineralization and 8% had osteoporosis (Khartchenko *et al.*, 1995). Skeletal mineral losses in liquidators who worked in 1986 reached 42% (compared with peak age and weight); there was less loss among liquidators who worked in 1987–1988 (Khartchenko *et al.*, 1998).

10. Periodontal disease markers were found in all surveyed liquidators: 88.2% had diffuse osteoporosis of the jaw; 33.3% had thinning of the compact plate of the mandible; in addition, 37.3% also had osteoporosis of a vertebral body (Druzhynyna, 2004).

11. According to National Registry data, from 1991 to 1998 the osteomuscular morbidity of liquidators was significantly higher than for the population as a whole (650 vs. 562 per 10,000; Byryukov *et al.*, 2001).

12. From 1994 to 1998, osteomuscular morbidity in liquidators in Bryansk Province was noticeably higher than that of the general population of the heavily contaminated districts and differed considerably from of the population of the province and Russia as a whole (Table 5.44).

5.7.4. Conclusion

Data concerning the influence of Chernobyl contamination on the osteomuscular system are scarce, not because these diseases are insignificant but because they attract little attention in terms of survival. Bone and muscle diseases are not insignificant. The loss of teeth leads to deterioration in a person's ability to eat and secondary adverse dietary effects. Chronic bone and muscle pain leads to loss of function and curtailment of activities needed to sustain life. The effects are especially serious for children when osteomuscular defects impede growth and activity.

Undoubtedly, as new material is published, there will be new data on the effects of Chernobyl's radioactive contamination on bone and muscle. It is now clear that structural bone disorders (osteopenia, osteoporosis, and fractures) are characteristic not only of the majority of liquidators, but also of many residents of the contaminated territories, including children.

5.8. Diseases of the Nervous System and the Sense Organs and Their Impact on Mental Health

Thirty-plus years ago, the nervous system was considered the system most resistant to ionizing radiation, but this is apparently true only in respect to large doses (see, e.g., Gus'kova and Baisogolov, 1971). Accordingly, the report of the Chernobyl Forum (2005) attributed all neurological illnesses, increased levels of depression, and mental problems to post-traumatic stress (Havenaar, 1996; Havenaar *et al.*, 1997a,b).

Since the Chernobyl catastrophe it is clear that low doses and low dose rates of radiation have enormous impact on the fine structures of the nervous system, on higher nervous system activities, and ocular structures, as well as on neuropsychiatric disorders that are widespread in all the contaminated territories. There is a growing body of evidence supporting radiosensitivity of the brain (Nyagu and Loganovsky, 1998).

Mental health assessment in the Former Soviet Union dealt primarily with mental disorders as recorded in the national healthcare system, not with data obtained from well-designed psychiatric studies using standardized diagnostic procedures. Together with the ongoing changes in the way that the countries of the Former Soviet Union deal with psychiatric problems, this approach may have led to dramatic underestimation of mental disorders (Loganovsky, 2002). The first part of this section is devoted to the nervous system itself and the second to the sense organs.

5.8.1. Diseases of Nervous System

Twenty-two years after the Chernobyl catastrophe, it is apparent that low levels of ionizing radiation cause changes in both the central and the autonomic nervous systems and can precipitate radiogenic encephalopathy (for a review see Loganovsky, 1999). Some parts of the central nervous system (CNS) are especially susceptible to radiation damage.

5.8.1.1. Belarus

1. According to a longitudinal survey of pregnant women, maternity patients, newborns, and children in the contaminated territories of the Chechersk District, Gomel Province, with radiation levels of 185–2,590 kBq/m^2 (5–70 Ci/km^2), the incidence of perinatal encephalopathy after 1986 was two to three times higher than before the catastrophe (Kulakov *et al.*, 2001).

2. Morbidity from diseases of the nervous system and sense organs noticeably increased in all the contaminated territories (Lomat *et al.*, 1996).

3. The number of cases of congenital convulsive syndrome (epilepsy) grew significantly in the contaminated territories in the first 10 years after the catastrophe (Tsymlyakova and Lavrent'eva, 1996).

4. From 1993 to 2003 primary morbidity from nervous system disease and diseases of the eye and its appendages increased markedly among children aged 10 to 14 years born to irradiated parents (National Belarussian Report, 2006).

5. Nervous system morbidity in children increased in one of the most contaminated areas—the Luninetsk District of Brest Province (Voronetsky *et al.*, 1995). From 2000 to 2005 there was a tendency toward an increasing incidence of mental disorders among children in this district (Dudinskaya *et al.*, 2006).

6. Ten years after the catastrophe nervous system disorders were the second cause of morbidity among teenagers evacuated from contaminated territories, with 331 cases per 1,000 out of the 2,335 teens that were examined (Syvolobova *et al.*, 1997).

7. Neurological and psychiatric disorders among adults were significantly higher in the contaminated territories (31.2 vs. 18.0%). Impaired short-term memory and attention lapse were observed among high school students aged 16 to 17 and the seriousness of these conditions correlated directly with the levels of contamination (Ushakov *et al.* 1997).

8. In a comparison between 340 agricultural machine operators from the heavily contaminated Narovlya District, Gomel Province, and a similar group of 202 individuals from the vicinity of less contaminated Minsk, the first group exhibited a sixfold higher incidence of vascular-brain pathology (27.1 vs. 4.5%; Ushakov *et al.*, 1997).

9. Neurological morbidity of 1,708 adults in the Kostjukovichi District, Mogilev Province, which was contaminated with Cs-137 at levels higher than 1,110 kBq/m^2 (30 Ci/km^2), was noticeably higher than in 9,170 individuals examined from the less contaminated districts of Vitebsk Province (Lukomsky *et al.*, 1993).

10. From 1991 to 2000 there was a 2.2-fold increase in the incidence of nervous system and sense organ diseases among Belarussian liquidators (Borysevich and Poplyko, 2002).

5.8.1.2. Ukraine

1. According to a longitudinal survey of pregnant women, maternity patients, newborns, and children in contaminated territories of Polessk District, Kiev Province, which had radiation levels of 740–2,200 kBq/m^2 (20–60 Ci/km^2), the incidence of perinatal encephalopathy after 1986 was observed to be two to three times higher than before the catastrophe (Kulakov *et al.*, 2001).

2. The incidence of nervous system disease in children grew markedly in the contaminated territories 2 years after the catastrophe (Stepanova, 1999). By 1998 nervous system and sense organ diseases in children had increased sixfold compared to 1986 (TASS, 1998). Other data between 1988 and 1999 indicated that the incidence of neurological disease grew 1.8-fold during the 10-year period: from 2,369 to 4,350 per 10,000 children (Prysyazhnyuk *et al.*, 2002).

3. Greater fatigue and lowered intellectual capacity was found in middle and high school age children in the contaminated villages of the Chernygov Province 7 to 8 years after the catastrophe (Bondar *et al.*, 1995).

4. Electroencephalograms (EEGs) for 97% of 70 surveyed evacuees' children indicated structural and functional immaturity of subcortical and cortical brain structures; that is, only two out of these 70 children had normal EEGs (Horishna, 2005).

5. Children irradiated *in utero* have more nervous system illnesses and mental disorders (Igumnov *et al.*, 2004; Table 5.45).

6. The number of children with mental illness in the contaminated territories increased: in 1987 the incidence was 2.6 per 1,000, whereas by 2004 it was 5.3 per 1,000 (Horishna, 2005).

7. The incidence of nervous system asthenia and vegetative (autonomic) regulation disorders was more that fivefold higher in evacuees' children compared with a control group (Romanenko *et al.*, 1995a).

8. Irradiated children have lower IQs (Figure 5.10).

TABLE 5.45. Occurrence (%) of Neurological and Psychiatric Disorders among Children Irradiated *In Utero* (Nyagu *et al.*, 2004)

	Irradiated, $n = 121$	Controls, $n = 77$
Neurologically healthy	60.3	85.7
Predisposition to epilepsy (G40)	7.4	1.3
Migraine (G43)	2.5	0
Other headaches (G44)	25.6	13.0
Sleep disturbances (G47)	3.3	0
Other disorders of vegetative nervous system (G90)	2.5	0
Neurological complications	1.6	0
Intellectual health	15.7	58.4
Organic mental disorders (F06 and F07)	16.5	3.9
Neurotic, stress, and somatoform disorders (F40-F48)	46.3	26.0
Physiological developmental disorders (F80-F89)	7.4	0
Emotional disorders (F90-F98)	25.6	11.7
Learning disorders	17.2	3.9

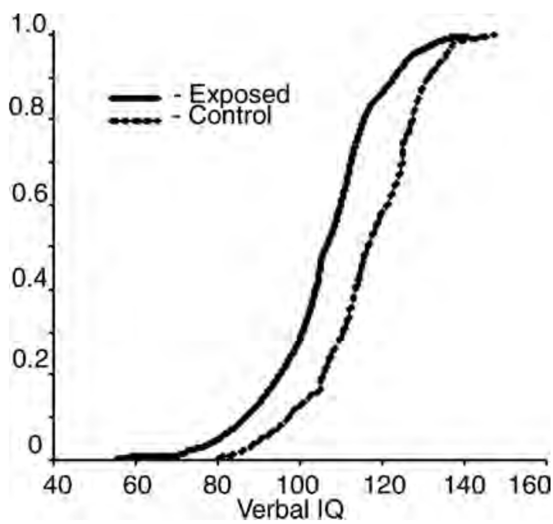

Figure 5.10. Intellectual development scores (IQs) for a group of heavily irradiated evacuee children from Pripyat City and for children from less irradiated Kiev (National Ukrainian Report, 2006).

TABLE 5.46. Quantitative Parameters of Intellectual Development of Heavily Irradiated Evacuees' Children from Pripyat City and Less Exposed Children from Kiev City (Yablokov *et al.*, 2006)

	Irradiated, $n = 108$	Controls, $n = 73$
Verbal intelligence	107	116
Distinctions pIQ-vIQ	10.4	2.9*

*$p < 0.05$.

9. Children exposed *in utero* at 16 to 25 weeks of gestation developed a range of conditions, including:

- Increased incidence of mental and personality disorders owing to brain injury or brain dysfunction (F06, F07).
- Disorders of psychological development (F80–F89).
- Paroxysmal states (headache syndromes, G44; migraine, G43; epileptiform syndromes, G40).
- Somatoform autonomic dysfunction (F45.3).
- Behavioral and emotional disorders of childhood (F90–F99).

10. Quantitative parameters of intellectual development (IQ) of the heavily irradiated evacuees' children from Pripyat City were worse than those of the less heavily irradiated children from Kiev City (Table 5.46).

11. A marked growth of adult nervous system morbidity was observed in the contaminated territories during the first 6 years after the catastrophe, especially after 1990 (Table 5.47).

12. Nervous system and sense organ morbidity in the contaminated territories increased 3.8- to 5-fold between 1988 and 1999. Among adult evacuees these illnesses occurred significantly more often than in the population as a whole (Prysyazhnyuk *et al.*, 2002). In 1994, nervous system illnesses in adults and teenagers and among evacuees accounted for 10.1% of the overall morbidity in the contaminated territories (Grodzinsky, 1999).

TABLE 5.47. Nervous System Morbidity (per 10,000 Adults) in the Contaminated Territories of Ukraine, 1987–1992 (Nyagu, 1995a)

	Number of cases					
	1987	1988	1989	1990	1991	1992
All nervous system diseases	264	242	356	563	1,504	1,402
Vasomotor dyscrasia*	128	43	32	372	391	312

*In Russian-language literature often named "vegetative vascular dystonia," also known as autonomic nervous system dysfunction.

13. From 93 to 100% of the liquidators have neuropsychiatric disorders, with predominantly organic symptomatic mental disorders (F00—F09) (Loganovsky, 1999, 2000). Posttraumatic stress disorder (PTSD), psychosomatic, organic, and abnormal schizoid personality development were documented according to local psychiatric classifications and ICD-10 and DSM-IV criteria (Loganovsky, 2002).

14. A total of 26 out of 100 randomly selected liquidators who suffered from fatigue met the chronic fatigue syndrome (CFS) diagnostic criteria. CFS may therefore be one of the most widespread consequences of the catastrophe for liquidators (Loganovsky, 2000b, 2003). Moreover, although CFS incidence decreased significantly ($p < 0.001$) (from 65.5% in 1990–1995 to 10.5% in 1996–2001), the frequency of occurrence of metabolic syndrome X (MSX—a group of risk factors for heart disease) increased significantly ($p < 0.001$) during the same period (from 15 to 48.2%). CFS and MSX are considered to be the first stages in the development of other pathologies, and CFS can transform into MSX neurodegeneration, cognitive impairment, and neuropsychiatric disorders (Kovalenko and Loganovsky, 2001; Volovik *et al.*, 2005).

15. A cross-sectional study was carried out on a representative cohort of liquidators within the frame of the Franco-German Chernobyl Initiative (Subproject 3.8) using a composite international diagnostic interview. The results

indicated an almost twofold increase in the incidence of all mental disorders (36%) in liquidators compared with the general Ukrainian population (20.5%), and a dramatic increase in the incidence of depression (24.5 vs. 9.1%). Anxiety (panic disorder) was also increased in liquidators (12.6 vs. 7.1%). At the same time, alcohol dependence among liquidators was not much higher than that in the total population (8.6 vs. 6.4%), ruling out a major contribution from this factor (Demyttenaere *et al.*, 2004; Romanenko *et al.*, 2004).

16. In 1996, nervous system and sense organ morbidity among liquidators was more than triple the country's average (Serdyuk and Bobyleva, 1998).

17. Nervous system morbidity among liquidators in 1986–1987 was twice as high as in 1988–1990 (Moskalenko, 2003).

18. In 1986, some 80 male Ukrainian liquidators with encephalopathy had both structural changes and functional impairment in the frontal and left temporal brain areas (Antipchuk, 2002, 2003).

19. Autonomic nervous system disorders among liquidators who worked in 1986–1987 differed from disorders in liquidators from 1988–1989 in stability, expressiveness, paroxysmal variants, presence of vestibular I–III dysfunction, and peripheral hemodynamic disturbances. Autonomic nervous system disorders are closely connected to disorders of neuropsychiatric behavior such as asthenia, disturbed memory, attention deficits, emotional disturbance, neuroses, hypochondriasis, and depression (Romamenko *et al.*, 1995).

20. Increased rates of neuropsychiatric disorders and somatic pathology (F00–F09) were observed among liquidators who worked in 1986–1987, especially in those who spent several years working within the Chernobyl exclusion zone (Loganovsky, 1999).

21. Among liquidators the typical structural brain disorder involves the frontal and left temporal lobes with their cortical–subcortical connections and the deep structures of the brain. The cerebral homodynamic disorders are caused by atherosclerotic changes. With hypertonic vascular tone, cerebral hemisphere asymmetry, and poor circulation on the left, there is a high incidence of stenotic processes. Pathologic radiographic changes in brain structure include atrophy, enlargement of cerebral ventricles, and focal brain lesions (Loganovsky *et al.*, 2003; Nyagu and Loganovsky, 1998).

22. The EEG patterns and topographical distribution of spontaneous and evoked brain bioelectrical activity of liquidators differed significantly from those of the control groups (Nyagu *et al.*, 1992; Noshchenko and Loganovsky, 1994; Loganovsky and Yuryev, 2001). In some cases, organic brain damage was verified by clinical neuropsychiatric, neurophysiological, neuropsychological, and neuroimaging methods (Loganovsky *et al.*, 2003, 2005b). The cerebral basis for deterioration of higher mental activity causing such disorders following a limited period of irradiation is pathology in the frontal and temporal cortex of the dominant hemisphere and the midline structures with their cortical–subcortical connections (Loganovsky, 2002; Loganovsky and Bomko, 2004).

23. The average age of both male and female Ukrainian liquidators with encephalopathy was 41.2 ± 0.83 years, noticeably younger than for the population as a whole (Stepanenko *et al.*, 2003).

24. From 1990 there were reports of a significant increase in the incidence of schizophrenia among the Chernobyl exclusion zone personnel compared to the general population (5.4 vs. 1.1 per 10,000 in the Ukraine in 1990; Loganovsky and Loganovskaya, 2000). Irradiation occurring in the contaminated territories causes brain damage, with cortical–limbic system dysfunction and impairment of informative processes at the molecular level that can trigger schizophrenia in predisposed individuals or cause schizophrenia-like disorders (Loganovsky *et al.*, 2004a, 2005).

25. A longitudinal study of the cognitive effects of the Chernobyl catastrophe on the liquidators and forestry and agricultural

workers living within 150 km of Chernobyl was conducted in 1995–1998. The 4-year averaged levels of accuracy and efficiency of cognitive performance of the exposed groups (especially the liquidators) were significantly lower than those of the controls (healthy Ukrainians residing several hundred kilometers away from Chernobyl). Longitudinal analyses of performance revealed significant declines in accuracy and efficiency, as well as psychomotor slowing, for all exposed groups over the 4-year period. These findings strongly indicate impairment of brain function resulting from both acute and chronic exposure to ionizing radiation (Gamache *et al.*, 2005).

TABLE 5.48. General Nervous System and Sense Organ Morbidity among Children in Bryansk Province Districts with Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999b: table 6.1)

	Number of cases			
Territory	1995	1996	1997	1998
Klymovo	109.2	111.2	109.2	125.7
Novozybkov	124.0	155.0	140.8	158.0
Klintsy	49.2	59.9	79.0	54.2
Klintsy City	213.3	212.3	178.1	173.6
Krasnogorsk	275.1	237.8	242.8	107.5
Zlynka	187.2	102.8	144.0	125.8
Gorgdeevo	71.2	64.2	70.1	71.0
Southwest*	143.0	134.7	134.6	131.4
Province	123.6	128.6	133.4	135.2
Russia	143.8	154.0	159.0	n/a

*All heavily contaminated districts.

5.8.1.3. Russia

1. According to a longitudinal survey of pregnant women, maternity patients, newborns, and children in the contaminated territories of the Mtsensk (1–5 Ci/km^2) and Volkhov (10–15 Ci/km^2) districts, Orel Province, the incidence of perinatal encephalopathy observed after 1986 was double that prior to the catastrophe (Kulakov *et al.*, 2001).

2. Electroencephalographic (EEG) studies of children of different ages from heavily contaminated territories revealed increased functional activity of the diencephalic structures. Ultrasound studies of babies' brains from these territories revealed ventricular hypertrophy in almost one-third (Kulakov *et al.*, 2001).

3. Children irradiated *in utero* had the highest indices of mental disability and were more likely to display borderline intelligence and mental retardation linked to their prenatal irradiation (Ermolyna *et al.*, 1996).

4. In the contaminated territories a lower level of nonverbal intelligence is found in children radiated in the 15th week of intrauterine development (Rumyantseva *et al.*, 2006).

5. Although data on children's neurological morbidity in the heavily contaminated districts of Bryansk Province are contradictive (Table 5.48), the level of this morbidity in Klintsy City and Krasnogorsk District surpasses that of the province and the rest of Russia by a significant margin.

6. Impaired short-term memory and attention deficit in pupils 16 to 17 years of age in the contaminated territories correlated with the level of contamination (Ushakov *et al.*, 1997).

7. Borderline adult neuropsychological disorders occurred noticeably more often in the contaminated territories (31 vs. 18%; Ushakov *et al.*, 1997).

8. There are increasing instances of a phenomenon termed "Chernobyl dementia," which includes disorders of memory, writing, convulsions, and pulsing headaches, caused by destruction of brain cells in adults (Sokolovskaya, 1997).

9. From 1986 to 1993 neurological morbidity in liquidators increased 42-fold (Table 5.49).

10. The occurrence of an encephalopathy in liquidators increased 25% from 1991 to 1998, and by 2004 the increase was up to 34% (Zubovsky and Tararukhyna, 2007).

11. In 1995, nervous system and sense organ morbidity in liquidators exceeded the country's average 6.4-fold (Russian Security Council, 2002).

12. Over 40% of the more than 2,000 liquidators that have been observed over many

TABLE 5.49. Dynamics of Nervous System and Sense Organ Morbidity (per 1,000) among Russian Liquidators, 1986–1993 (Baleva *et al.*, 2001)

Year	1986	1987	1988	1989	1990	1991	1992	1993
Number of cases	23	79	181	288	410	585	811	989

years suffer from organic brain diseases of vascular or mixed origin. These illnesses are the result of long-lasting cerebral-ischemia, disruption of central regulatory functions, and possibly of damage to the endothelium of small blood vessels (Rumyantseva *et al.*, 1998). Of more than 1,000 liquidators evaluated up until 2005, some 53.7% had mental impairment caused by damage or dysfunction of the brain or somatic illness (F06, F07). These disorders became clearly apparent 10 to 12 years after the catastrophe, are more significant with every passing year, and are characteristic of diffuse organic brain lesions with localization mainly in the frontal area (Rumyantseva *et al.*, 2006).

13. Autoimmune and metabolic thyroid gland pathologies are also major factors in the mental disorders found among liquidators (Rumyantseva *et al.*, 2006).

14. Nervous system and sense organ morbidity among liquidators of Bryansk Province was noticeably higher than for the general population (Table 5.50).

15. A total of 12% of surveyed liquidators had polyneuropathy, expressed as excruciating burning pains, and limb atrophy (Kholodova *et al.*, 1998).

16. According to data from the Russian Interdepartmental Expert Council for the years 1999–2000, neuropsychological illnesses were the second cause of overall morbidity in 18% of 1,000 surveyed liquidators (Khrysanfov and Meskikh, 2001).

17. The incidence of encephalopathy and proven organic pathology increased from 20 to 34% as compared with 1991–1997 and 2000, and neurological diagnoses became more serious by diagnostic criteria (Khrysanfov and Meskikh, 2001).

18. Neuropsychological pathology among Russian liquidators in 1999–2000 included: 34% encephalopathy, 17% organic disorders of the central nervous system, 17% vegetative vascular dystonia (vasomotor dyscrasia), and 17% neurocirculatory dystonia (Khrysanfov and Meskikh, 2001).

19. In 150 male liquidators 44.5 ± 3 years of age there was an increase in slow forms of EEG activity, intercerebral asymmetry, decreased quality of performance on all cognitive tests, impaired memory, and other functional disorders (Zhavoronkova *et al.*, 2002). Observations on liquidators revealed that changes in brain asymmetry and interhemispheric interaction can be produced not only by a dysfunction of subcortical limbic–reticular and mediobasal brain structures, but also by damage to the white matter, including the corpus callosum (Zhavoronkova *et al.*, 2000). The EEG findings suggested subcortical disorders at different levels (diencephalic or brainstem) and functional failure of either the right or left hemispheres long after radiation exposure had ceased (Zhavoronkova *et al.*, 2003).

TABLE 5.50. Nervous System and Sense Organ Morbidity among Liquidators and the Adult Population of Bryansk Province Territories with Contamination Levels above 5 Ci/km^2, 1994–1998 (Fetysov, 1999a: table 4.1)

Group/ Territory	Number of cases				
	1994	1995	1996	1997	1998
Liquidators	312.9	312.5	372.5	376.9	467.6
Southwest*	118.6	104.2	130.5	124.2	314.6
Province	127.3	136.5	134.6	131.6	134.2
Russia	126.6	129.7	136.5	136.5	n/a

*All heavily contaminated districts.

20. There were many reports concerning neurophysiological, neuropsychological, and neuroimaging abnormalities in liquidators (Danylov and Pozdeev, 1994; Zhavoronkova *et al.*, 1994, 2000; Vyatleva *et al.*, 1997; Khomskaja, 1995; Khartchenko *et al.*, 1995; Kholodova *et al.*, 1996; Voloshyna, 1997). These data strongly support clinical findings of organic brain damage caused by radiation (Chuprykov *et al.*, 1992; Krasnov *et al.*, 1993; Romodanov and Vynnyts'ky, 1993; Napreyenko and Loganovsky, 1995, 2001; Revenok, 1998; Zozulya and Polischuyk, 1995; Morozov and Kryzhanovskaya, 1998).

21. Many liquidators had complex organic disorders of the brain, including: (a) hypometabolic centers localized in white and gray matter and in deep subcortical formations; (b) ventricular enlargement, often asymmetric; (c) expansion of the arachnoid cavity; (d) decreased density of the white brain substance; (e) thinning of the corpus callosum; and (f) diffuse singular or multiple localized space-occupying lesions of the brain tissue (Kholodova *et al.*, 1998; Ushakov *et al.*, 1997; Nyagy and Loganovsky, 1998; Loganovsky, 2002; and others).

22. Four hundred liquidators 24 to 59 years of age with organic disorders of the central nervous system have irreversible structural brain defects: structural changes in the frontal lobe, the left temporal area, and the connections in the cortex–subcortex (Khartchenko *et al.*, 1995; Antipchuk, 2002, 2003; Zhavoronkova *et al.*, 2002; Antonov *et al.*, 2003; Tsygan, 2003).

23. Typical complaints from liquidators include severe headaches, not relieved by medications, impaired memory of current events, general weakness, fatigue, diminished capacity for work, generalized sweating, palpitations, bone and joint pains and aches that interfere with their sleep, sporadic loss of consciousness, sensation of fever or heat, difficulty in thinking, heart seizures, flashes, loss of vision, and numbness in hands and feet (Sokolova, 2000; Kholodova, 2006).

24. The neurological damage suffered by liquidators includes well-marked autonomic nervous system dysfunction expressed as acrocyanosis, acrohyperhydrosis, and common hyperhydrosis, sponginess and puffiness of soft tissues, facial redness, diffuse dermographism, asthenia, and depressive syndromes. Other organic nervous system impairments include cranial nerve abnormalities, marked hyperreflexia, the presence of pathological reflexes, and abnormal Romberg test scores (Kholodova, 2006).

25. Characteristic dysfunction in liquidators involves deep parts of the brain: diencephalic areas, deep frontal and temporal lobes, and occipitoparietal parts of the cerebral hemispheres (Kholodova, 2006).

26. Liquidators demonstrate impaired task performance, a shortening of attention span, and problems with short-term memory and operative thinking. These features correspond to skill levels typical of 10- to 11-year-old children and cannot be attributed to social factors—they clearly testify to radiation-induced brain damage (Kholodova, 2006).

27. EEG brain activity demonstrates two types of pathologies: high-amplitude slowed alpha- and theta-wave bands, reflecting pathology of the visceral brain, and diffuse decreases in bioelectric activity, reflecting diffuse cortex and subcortical area damage (Kholodova, 2006).

28. The seriousness of brain pathology in liquidators correlates with impaired blood circulation in various cortical white substance sites and deep subcortical formations (Kholodova, 2006).

5.8.1.4. Other Countries

1. ESTONIA. After Chernobyl, suicide was the leading cause of death among liquidators living in Estonia (Rahu *et al.*, 2006).

2. LITHUANIA. Age-adjusted mortality from suicide increased among the Chernobyl liquidators compared to the general Lithuanian population (Kesminiene *et al.*, 1997).

3. Sweden. A comprehensive analysis of a data set of 562,637 Swedes born from 1983 to 1988 revealed that the cohort *in utero* during the catastrophe had poorer school outcomes than those born shortly before and shortly after this period. This impairment was greatest for those exposed 8 to 25 weeks postconception. Moreover, more damage was found among students born in regions that received more fallout; students from the eight most affected municipalities were significantly (3.6 percentage points) less likely to qualify for high school (Almond *et al.*, 2007). These findings correspond to those concerning reduced IQ hibakusha who were irradiated 8 to 25 weeks after ovulation (Otake and Schull, 1984).

5.8.1.5. Conclusion

Previous views claiming resistance of the nervous system to radiation damage are refuted by the mounting collective data that demonstrate nervous system illnesses among the populations of the contaminated territories, especially liquidators. Even rather small amounts of nuclear radiation, considered harmless by former measures of radiation protection, have resulted in marked organic damage. Clearly, the existing radiation levels in the contaminated territories have harmed the central nervous system of countless people.

For many inhabitants of the contaminated territories, especially persons that were radiated *in utero* and liquidators, nervous system functions, including perception, short-term memory, attention span, operative thinking, and dreaming, are deteriorating. These conditions are associated with deep cerebral hemispheric damage: diencephalic areas, deep frontal, and temporal lobes, and occipitoparietal parts of the cerebral hemisphere. Low-dose radiation damages the vegetative (autonomic) nervous system. The fact that intellectual retardation is found in 45% of children born to mothers who went through the Hiroshima and Nagasakai nuclear bombardment is a very troubling concern (Bulanova, 1996).

5.8.2. Diseases of Sense Organs

Throughout the more contaminated territories, visual and hearing abnormalities occur with greater frequency than in the less contaminated areas: premature cataracts, vitreous degeneration, refraction errors, uvitis, conjunctivitis, and hearing loss.

5.8.2.1. Belarus

1. A survey of pregnant women, maternity patients, newborns, and children in the Chechersk District, Gomel Province, with Cs-137 contamination of the soil at levels of 5–70 Ci/km^2 showed an increase in the number of sensory organ development abnormalities, including congenital cataracts in neonates (Kulakov *et al.*, 2001).

2. In heavily contaminated territories there is a noticeably higher incidence of congenital malformations, including cataracts, microphthalmia, malpositioned ears, and extra ear tissue (Kulakov *et al.*, 2001).

3. Cataracts in children are common in the territories with contamination levels above 15 Ci/km^2 (Paramey *et al.*, 1993; Edwards, 1995; Goncharova, 2000).

4. Retinal pathology in children in the Khoiniky and Vetka districts, Gomel Province (4,797 people examined), increased about threefold: from 6 to 17% in the first 3 years after the catastrophe compared to 1985 (Byrich *et al.*, 1999).

5. From 1988 to 1989 the incidence of congenital eye malformation in children (3 to 4 years after the catastrophe) was fourfold higher in the heavily contaminated Gomel Province (1.63%) than from 1961 to 1972 in Minsk (0.4%; Byrich *et al.*, 1999).

6. Clouding of the lens, an early symptom of cataracts, was found in 24.6% of exposed children compared with 2.9% in controls (Avkhacheva *et al.*, 2001).

7. Children under 5 years of age who were exposed have more problems with eye accommodation and more overall eye diseases than controls (Serduchenko and Nostopyrena, 2001).

TABLE 5.51. Incidence of Cataracts (per 1,000) in Belarus, 1993–1995 (Matsko, 1999; Goncharova, 2000)

Year	Belarus	Contaminated territories, Ci/km^2 1–15	>15	Evacuees
1993	136	190	226	355
1994	146	196	366	425
1995	147	n/a	n/a	443

8. Eye disease significantly increased from 1993 to 2003 among children 10 to 14 years of age born to irradiated parents (National Belarussian Report, 2006).

9. The level of absorbed Cs-137 correlates with the incidence of cataracts in children from the Vetka District, Gomel Province (Bandazhevsky, 1999).

10. From 1993 to 1995, cataracts were markedly more common in the more contaminated territories and among evacuees than in the general population (Table 5.51).

11. Eye diseases were more common in the more contaminated districts of Gomel Province and included cataracts, vitreous degeneration, and refraction abnormalities (Bandazhevsky, 1999).

12. Bilateral cataracts occurred more frequently in the more contaminated territories (54 vs. 29% in controls; Arynchin and Ospennikova, 1999).

13. Crystalline lens opacities occur more frequently in the more radioactive contaminated territories (Table 5.52) and correlate with the level of incorporated Cs-137 (Figure 5.11).

14. Increased incidence of vascular and crystalline lens pathology, usually combined with neurovascular disease, was found in 227 surveyed liquidators and in the population of contaminated territories (Petrunya *et al.*, 1999).

15. In 1996, incidence of cataracts among Belarussian evacuees from the 30-km zone was more than threefold that in the population as a whole: 44.3 compared to 14.7 per 1,000 (Matsko, 1999).

TABLE 5.52. Incidence (%) of Opacities in Both Crystalline Lenses among Children Living in Territories with Various Levels of Contamination, 1992 (Arynchin and Ospennikova, 1999)

	Incidence of opacities, % 1–5	6–10	>10
Brest Province, 137–377 kBq/m^2 ($n = 77$)	57.5	17.9	6.7
Vitebsk Province, 3.7 kBq/m^2 ($n = 56$)	60.9	7.6	1.1

16. From 1993 to 2003 cataract morbidity increased 6% annually among male liquidators (National Belarussian Report, 2006).

5.8.2.2. Ukraine

1. A survey of pregnant women, maternity patients, newborns, and children in contaminated territories in the Polessk District, Kiev Province (soil Cs-137 contamination 20–60 Ci/km^2) showed an increase in the number of sensory organ development defects, including congenital cataracts in neonates (Kulakov *et al.*, 2001).

2. Hearing disorders are found in more than 54% of inhabitants of the contaminated territories, a level noticeably higher than that of the general population (Zabolotny *et al.*, 2001).

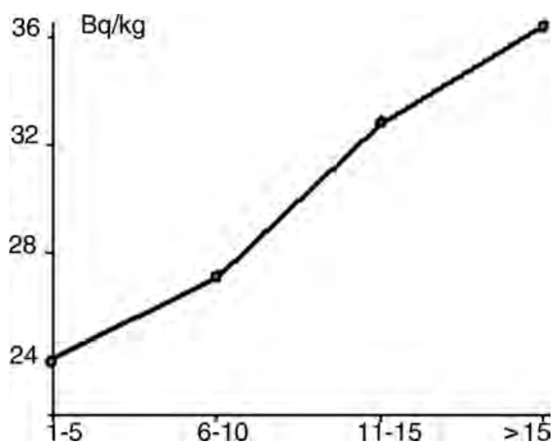

Figure 5.11. Number of bilateral lens opacities and level of incorporated Cs-137 in Belarussian children (Arynchin and Ospennikova, 1999).

3. In 1991 a group of 512 children 7 to 16 years of age from four villages in the Ivankiv District, Kiev Province, was examined. The villages differed only in the degree of Cs-137 contamination of the soil:

(a) First village: average 12.4 Ci/km^2 (maximum 8.0 Ci/km^2; 90% of the territory, 5.4 Ci/km^2).
(b) Second village: average 3.11 Ci/km^2 (maximum 13.8 Ci/km^2; 90% of the territory, 4.62 Ci/km^2).
(c) Third village: average 1.26 Ci/km^2 (maximum 4.7 Ci/km^2; 90% of the territory, 2.1 Ci/km^2).
(d) Fourth village: average 0.89 Ci/km^2 (maximum 2.7 Ci/km^2; 90% of the territory, 1.87 Ci/km^2).

Typical lens pathologies were detected in 51% of those examined, and the incidence of lens pathology was higher in villages with higher levels of soil contamination. Atypical lens pathologies were observed in 61 children (density of the posterior subcapsular layers, dimness in the form of small spots and points between the posterior capsule and the core, and vacuoles) and were highly ($r = 0.992$) correlated with the average and maximum levels of soil contamination. In 1995 the incidence of atypical lens pathologies in the first and second villages (with average soil contamination over 2 Ci/km^2) increased significantly to 34.9%. Two girls (who had early changes of cortical layer density in 1991) were diagnosed with dim vision, suggesting the development of involutional cataracts (Fedirko and Kadoshnykova, 2007).

4. In 1992–1998 children from Ovruch City (soil Cs-137 contamination 185–555 kBq/m^2) had significantly higher subclinical lens changes (234 per 1,000, of 461 examined) than children from Boyarka City (soil Cs-137 contamination 37–184.9 kBq/m^2 or 149 per 1,000, of 1,487 examined). In Ovruch the incidence of myopia and astigmatism was significantly higher (Fedirko and Kadoshnykova, 2007).

5. Children who were exposed before they were 5 years of age have more problems with eye accommodation (Burlak *et al.*, 2006).

6. Individuals from contaminated territories and liquidators had premature involutional and dystrophic changes in the eyes, development of ocular vascular diseases, increasing incidence of chorioretinal degeneration such as age-dependent macular degeneration (AMD), and benign neoplasm of the eyelids. Central chorioretinal degeneration with clinical symptoms of AMD was the most frequently occurring form of delayed retinal pathology: 136.5 ± 10.7 per 1,000 in 1993 and 585.7 ± 23.8 per 1,000 in 2004. Involutional cataracts increased from 294.3 ± 32.0 per 1,000 in 1993 to 766.7 ± 35.9 per 1,000 in 2004 (Fedirko, 2002; Fedirko and Kadoshnykova, 2007).

7. Individuals from contaminated territories and liquidators had a marked decrease in ocular accommodation (Sergienko and Fedirko, 2002).

8. In the heavily contaminated territories, among 841 adults examined from 1991 to 1997, retinal pathologies, involutional cataracts, chronic conjunctivitis, and vitreous destruction were observed more often than in the less contaminated areas, and cataracts were seen in persons younger than 30 years of age, which has never been observed in less contaminated areas (Fedirko and Kadochnykova, 2007).

9. The occurrence of involutional cataracts in the contaminated territories increased 2.6-fold from 1993 to 2004: from 294.3 ± 32.0 to 766.7 ± 35.9 per 1,000 (Fedirko, 1999).

10. Among 5,301 evacuees examined, eye pathology was diagnosed in 1,405. One cataract occurred for every four cases of other eye pathologies (Buzunov *et al.*, 1999).

11. Two new syndromes have been seen in liquidators and in those from the contaminated territories:

- Diffraction grating syndrome, in which spots of exudate are scattered on the central part of the retina. This was observed in liquidators who were within direct sight

of the exposed core of the fourth reactor (Fedirko, 2002).
- Incipient chestnut syndrome, named for the shape of a chestnut leaf, expressed as new chorioretinopathy, changes of retinal vessels with multiple microaneurisms, dilations, and sacs in the retinal veins around the macula (Fedirko, 2000).

12. The frequency of central chorioretinal degradation increased among the liquidators 4.3-fold from 1993 to 2004: from 136.5 ± 10.7 to 585.7 ± 23.8 per 1,000 (Buzunov and Fedirko, 1999).

13. The incidence of cataracts was significantly higher for male liquidators compared with female liquidators (Ruban, 2001).

14. Retinal pathology was markedly higher than the norm among 2002 liquidators' children who were born after the catastrophe and examined between 1999 and 2006 (Fedirko and Kadoshnykova, 2007).

5.8.2.3. Russia

1. A survey of pregnant women, maternity patients, newborns, and children in the Mtsensk and Volkhovsk districts, Orel Province, contaminated with Cs-137 levels of 1–5 and 10–15 Ci/km^2 showed an increase in the number of sensory organ developmental deficiencies, including congenital cataracts in neonates (Kulakov *et al.*, 2001).

2. A total of 6.6% of 182 surveyed liquidators had cataracts (Lyubchenko and Agal'tsev, 2001).

3. More than 52% of 500 surveyed liquidators had retinal vascular abnormalities (Nykyforov and Eskin, 1998).

4. Some 3% of liquidators under 40 years of age had cataracts, an incidence 47-fold that in a similar age group of the general population; 4.7% had glaucoma (Nykyforov and Eskin, 1998).

5. Between 46 and 69% of surveyed liquidators had some hearing disorder (Zabolotny *et al.*, 2001; Klymenko *et al.*, 1996). Liquidators suffer from defects in different parts of the auditory system resulting in progressive hearing loss and a stuffy sensation and noise in the ears (Zabolotny *et al.*, 2000).

6. High-frequency audiometry revealed that the most abnormalities occurred in liquidators with vocal problems (Kureneva and Shidlovskaya, 2005).

5.8.2.4. Other Countries

1. Israel. A 2-year follow-up study of immigrants to Israel from the Former Soviet Union revealed that the proportion of those reporting chronic visual and hearing problems was statistically higher for immigrants from contaminated territories (304 individuals) compared with immigrants from noncontaminated (217 individuals) and other areas (216 individuals; Cwikel *et al.*, 1997).

2. Norway. Cataracts in newborns occurred twice as often 1 year after the catastrophe (Irgens *et al.*, 1991).

5.8.3. Conclusion

There is little doubt that specific organic central and peripheral nervous system damage affecting various cognitive endpoints, as observed in both individuals from the contaminated territories and liquidators, is directly related to Chernobyl's ionizing radiation. In differing degrees, these conditions affect all liquidators and practically every person living in the contaminated territories.

Among the consequences of the damage to the nervous system caused by the Chernobyl catastrophe are cognitive, emotional, and behavioral disorders. Adverse effects also include neurophysiological abnormalities in the prenatally exposed and neurophysiological, neuropsychological, and neuroimaging abnormalities in liquidators, manifested as left frontotemporal limbic dysfunction, schizophreniform syndrome, chronic fatigue syndrome, and, combined with psychological stress, indications of schizophrenia and related disorders.

Only after 2000 did medical authorities begin to recognize the radiogenic origin of a universal increase in cataracts among liquidators and evacuees from the Chernobyl territories. Official recognition occurred 10 years (!) after doctors began to sound the alarm and 13 years after the problem was first registered.

5.9. Digestive System and Visceral Organ Diseases

Digestive system diseases are among the leading causes of illness in the contaminated territories. Compared to other illnesses, it is more difficult to classify these with certainty as being caused by a radiogenic component; however, the collected data from the contaminated territories point to a solid basis for such a conclusion.

5.9.1. Belarus

1. The number of digestive organ malformations in newborns increased in the contaminated territories (Kulakov *et al.*, 2001).

2. There was a twofold general increase in chronic gastritis in Brest Province in 1996 compared to 1991. In 1996 the occurrence of chronic gastritis in children was up to threefold higher in the heavily contaminated territories than in the less contaminated areas. In the Stolinsk District in 1996 the incidence of this disease was more than fourfold that seen in 1991 (Gordeiko, 1998).

3. Of 135 surveyed juvenile evacuees from Bragin City and the highly contaminated territories of Stolinsk District, Brest Province, 40% had gastrointestinal tract illnesses (Belyaeva *et al.*, 1996).

4. Of 2,535 individuals examined in 1996, digestive system illnesses were the first cause of general morbidity in teenage evacuees (556 per 1,000; Syvolobova *et al.*, 1997).

5. Digestive system morbidity increased from 4.6% in 1986 to 83.5% in 1994 and was the second cause of overall morbidity of children in the Luninetsk District, Brest Province (Voronetsky *et al.*, 1995).

6. Of 1,033 children examined in the heavily contaminated territories from 1991 to 1993 there was a significantly higher incidence of serious caries and lowered acid resistance of tooth enamel (Mel'nichenko and Cheshko, 1997).

7. Chronic upper gastrointestinal disease was common in children of liquidators (Arynchin *et al.*, 1999).

8. Gastrointestinal tract pathology is connected to morphologic and functional thyroid gland changes in children from territories contaminated by Cs-137 at levels of 1–15 Ci/km^2 (Kapytonova *et al.*, 1996).

9. Digestive diseases in adults and liquidators are more common in the contaminated territories. From 1991 to 1996 stomach ulcers among the population increased 9.6%, while among liquidators the increase was 46.7% (Kondratenko, 1998).

10. In 1995, the incidence of diseases of the digestive system among liquidators and evacuees in the contaminated territories was 4.3- and 1.8-fold higher than in the general population of the country: respectively, 7,784; 3,298; and 1,817 per 100,000 (Matsko, 1999).

11. Ten years after the catastrophe digestive illnesses were fourfold more common among liquidators than in the general adult population of the country (Antypova *et al.*, 1997a).

12. From 1991 to 2001 digestive system illnesses among liquidators increased 1.65-fold (Borisevich and Poplyko, 2002).

13. Of 2,653 adults and teenagers examined, the incidence of acute hepatitis-B, chronic hepatitis-C, and hepatic cirrhosis diseases was significantly higher in the heavily contaminated territories of Gomel Province than in the less contaminated Vitebsk Province. By 1996 the incidence of these diseases had increased significantly, with chronic hepatitis in liquidators 1.6-fold higher than in 1988–1995 (Transaction, 1996).

5.9.2. Ukraine

1. The number of digestive system diseases in children rose markedly within the first 2 years after the catastrophe (Stepanova, 1999; and others).

2. The incidence of digestive diseases in children correlated with the level of contamination of the area (Baida and Zhirnosekova, 1998).

3. Premature tooth eruption was observed in girls born to mothers irradiated during childhood (Tolkach *et al.*, 2003).

4. Tooth caries in boys and girls as young as 1 year are more common in the contaminated territories (Tolkach *et al.*, 2003).

5. Digestive system morbidity in children more than doubled from 1988 to 1999—4,659 compared to 1,122 per 10,000 (Korol *et al.*, 1999; Romanenko *et al.*, 2001).

6. Children irradiated *in utero* had significantly higher incidence of gastrointestinal tract pathology than controls—18.9 vs. 8.9% (Stepanova, 1999).

7. Atrophy of the stomach mucosa occurred five times more often, and intestinal metaplasia twice as often in children living in areas contaminated at a level of 5–15 kBq/m^2 than in a control group (Burlak *et al.*, 2006).

8. In 1987 and 1988 functional digestive tract illnesses were prevalent in evacuees' children, and from 1989 to 1990 allergies, dyspeptic syndromes, and biliary problems were rampant (Romanenko *et al.*, 1995).

9. Peptic ulcer, chronic cholecystitis, gallstone disease, and pancreatitis occurred noticeably more often in inhabitants of territories with higher levels of contamination (Yakymenko, 1995; Komarenko *et al.*, 1995).

10. From 1993 to 1994 digestive system diseases were second among overall morbidity (Antypova *et al.*, 1995).

11. There were significantly increased levels of hepatic, gallbladder, and pancreatic diseases in 1993 and 1994 in the heavily contaminated territories (Antypova *et al.*, 1995).

12. Digestive system morbidity in adult evacuees considerably exceeds that of the general population of the country (Prysyazhnyuk *et al.*, 2002).

13. In 1996 digestive system morbidity of inhabitants in territories with contamination greater than 15 Ci/km^2 was noticeably higher than for the country as a whole (281 vs. 210 cases per 1,000; Grodzinsky, 1999).

14. Only 9% of the liquidators evaluated in 1989 and 1990 had normal stomach and duodenal mucous membranes (Yakymenko, 1995).

15. The incidence of stomach ulcers among Ukrainian liquidators in 1996 was 3.5-fold higher than the country average (Serdyuk and Bobyleva, 1998).

16. In 1990 ulcers and gastric erosion were found in 60.9% of liquidators (Yakymenko, 1995).

17. After the catastrophe pancreatic abnormalities in liquidators were diagnosed through echograms (Table 5.53).

18. In 7 to 8 years after the catastrophe up to 60% of the liquidators examined had chronic digestive system pathology, which included structural, motor, and functional secretory disorders of the stomach. For the first 2.5 to 3 years inflammation was the most prevalent symptom, followed by indolent erosive hemorrhagic ulcers (Romanenko *et al.*, 1995).

TABLE 5.53. Pancreatic Echogram Abnormalities in Male Ukrainian Liquidators (% of Those Examined) (Komarenko *et al.*, 2002; Komarenko and Polyakov, 2003)

	1987–1991	1996–2002
Thickening	31	67
Increased echo density	54	81
Structural change	14	32
Contour change	7	26
Capsular change	6	14
Pancreatic duct dilatation	4	10
All echogram abnormalities	37.6 (1987)	87.4 (2002)

19. In 7 to 8 years after the catastrophe liquidators had increasing numbers of hepatobiliary illnesses, including chronic cholecystitis, fatty liver, persistent active hepatitis, and chronic hepatitis (Romamenko *et al.*, 1995).

5.9.3. Russia

1. Children and the teenagers living in the contaminated territories have a significantly higher incidence of dental caries (Sevbytov, 2005).

2. In Voronez Province there was an increased number of odontomas in children who were born after 1986. Tumors were found more often in girls and the complex form was most common (Vorobyovskaya *et al.*, 2006).

3. Periodontal pathology was more common in children from contaminated territories and occurred more often in children born after the catastrophe (Sevbytov, 2005).

4. Children who were irradiated *in utero* in the contaminated territories are significantly more likely to develop dental anomalies (Sevbytov, 2005).

5. The frequency of the occurrence of dental anomalies is markedly higher in children in the more contaminated territories. Of 236 examined who were born before the catastrophe 32.6% had normal dentition, whereas of 308 examined who were born in the same territories after the catastrophe only 9.1% had normal structure (Table 5.54).

6. The incidence of general and primary digestive system diseases in children in the heavily contaminated districts of Bryansk Province is noticeably higher than the average for the province and for Russia as a whole (Tables 5.55 and 5.56).

7. In general, digestive system morbidity in adults increased in the majority of the heavily contaminated districts of Bryansk Province (except in the Krasnogorsk District). This increase occurred against a background of reduced morbidity in the province and across Russia (Table 5.57).

TABLE 5.54. Incidence of Dental Anomalies (%) among Children Born before and after the Catastrophe Exposed to Different Levels of Contamination in Tula and Bryansk Provinces* (Sevbytov *et al.*, 1999)

	<5 Ci/km^2	5–15 Ci/km^2	15–45 Ci/km^2	Time of birth
Tooth anomalies	3.7	2.4	2.8	Before 1986 ($n = 48$)
	4.2	4.6	6.3	After 1986 ($n = 82$)
Dentition deformities	0.6	0.4	0.6	Before 1986 ($n = 8$)
	0.6	0.6	1.7	After 1986 ($n = 15$)
Occlusion	2.6	2.4	2.2	Before 1986 ($n = 39$)
	4.4	5.2	6.3	After 1986 ($n = 86$)
Age norm	5.3	5.7	3.1	Before 1986 ($n = 77$)
	2.6	2.0	0.6	After 1986 ($n = 28$)

*5 Ci/km^2: Donskoy City, Tula Province (n = 183); 5–15 Ci/km^2: Uzlovaya Station, Tula Province (n = 183); 15–45 Ci/km^2: Novozybkov City, Bryansk Province (n = 178).

8. Digestive system morbidity in liquidators increased 7.4-fold over a 9-year period (Table 5.58).

9. The Russian National Register reported that digestive system morbidity among liquidators from 1991 to 1998 was markedly higher than in corresponding age groups in the country: 737 vs. 501 per 10,000 (Byryukov *et al.*, 2001).

TABLE 5.55. Overall Digestive System Morbidity (per 1,000) among Children in Bryansk Province Territories with Levels of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999b: table 6.1)

	Number of cases			
Territory	1995	1996	1997	1998
Southwest*	182.9	163.5	153.6	154.7
Province	94.5	88.9	90.9	91.0
Russia	114.9	115.6	114.9	n/a

*All heavily contaminated districts.

TABLE 5.56. Primary Digestive System Morbidity (per 1,000) among Children in Bryansk Province Territories with Levels of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999b: table 6.2)

	Number of cases			
Territory	1995	1996	1997	1998
Southwest*	103.5	81.7	84.2	83.1
Province	51.8	42.9	46.7	42.3
Russia	58.1	60.2	56.4	n/a

*All heavily contaminated districts.

10. Pathologic ultrastructural digestive tract changes were observed in liquidators: decreased activity and undifferentiated epithelial cells in the duodenum, endotheliocytes in stomach microvessels, and fibrosis of the gastric mucous membrane (Sosyutkin *et al.*, 2004; Ivanova, 2005).

11. Of 901 pathologies found in 182 liquidators, digestive system morbidity accounted for 28.2%. A total of 87.9% of the liquidators have had chronic gastritis and gastroduodenitis (often, the erosive type); 33.4% have superficial destruction of the mucous covering of the gastroduodenal junction, which is six- to eightfold higher than the norm (Lyubchenko and Agal'tsev, 2001).

TABLE 5.57. General Digestive System Morbidity (per 1,000) among Adults in Bryansk Province Territories with Levels of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999a: table 6.1)

	Number of cases			
Territory	1995	1996	1997	1998
Klymovo	88.6	98.5	84.9	157.3
Novozybkov	79.6	76.7	88.6	92.4
Klintsy	118.0	143.8	89.0	155.9
Krasnogorsk	90.7	74.0	46.3	57.9
Zlynka	65.8	72.2	78.1	82.8
Gordeevka	52.9	74.8	91.2	92.0
Southwest*	79.7	95.6	88.0	105.0
Province	69.0	65.6	63.2	64.4
Russia	97.3	93.8	91.5	n/a

*All heavily contaminated districts.

12. Of 118 surveyed liquidators, 60.2% have structural pancreatic changes, 40.6% have liver changes, and 29% have thickening of the gallbladder wall (Noskov, 2004).

13. Digestive system morbidity among both liquidators and the population of the contaminated territories of Bryansk Province noticeably increased from 1994 to 1998, which is especially significant against the background of a decrease in the province and in Russia as a whole (Table 5.59).

14. Ten years after the catastrophe a rapid increase in digestive organ diseases in liquidators began, together with circulatory, bone, and muscular diseases (Figure 5.12). Making fewer diagnoses of vegetovascular dystonia has turned this constellation of diseases into a more serious organic illness—discirculatory pathology.

15. Pathological tooth enamel erosion is widespread among liquidators (Pymenov, 2001).

16. Among 98 surveyed liquidators 82% have chronic periodontal disease, an incidence much more common than in corresponding age groups in the country as a whole (Druzhynyna, 2004; Matchenko *et al.*, 2001).

17. Chronic catarrhal gingivitis was present in 18% of 98 surveyed liquidators (Druzhynyna, 2004).

18. The expression of chronic pancreatitis in liquidators correlated with the level of irradiation and the degree of the lipid peroxidation (Onitchenko *et al.*, 2003).

5.9.4. Conclusion

The increase in the incidence of digestive system diseases as a result of Chernobyl irradiation cannot be doubted. In contaminated territories, where Cs-137 was easily detected, it was accompanied by Sr-90, which is taken up during intrauterine development and deposited in teeth and bones. Sr-90 decays to Y-90 via release of a beta particle, which is harmful to the developing teeth, and the resultant decay

TABLE 5.58. Digestive System Morbidity (per 10,000) among Russian Liquidators (Baleva *et al.*, 2001)

Year	1986	1987	1988	1989	1990	1991	1992	1993
Number of cases	82	487	1,270	2,350	3,210	4,200	5,290	6,100

isotope, Y-90, weakens the structural integrity of the teeth.

There was an immediate increase in the incidence of digestive tract diseases among liquidators and a rise in the number of congenital digestive system malformations in babies born in the contaminated territories. The assumption appears proven that low-level irradiation acts in some way to directly affect the function of the gastrointestinal tract epithelium—and not only during intrauterine development.

Considering the significantly increased digestive system morbidity among children of irradiated parents in Japan (Furitsu *et al.*, 1992), and in the southern Ural mountain area owing to radiation contamination (Ostroumova, 2004), it is logical to assume that similar consequences from Chernobyl irradiation will have a prolonged effect in territories where radioactive conditions persist.

5.10. Skin Diseases Associated with the Chernobyl Catastrophe

Diseases of the skin reflect not only the effect of external irritants, but also diseases of internal organs and the effects of organic and inorganic agents that are absorbed internally.

TABLE 5.59. General Digestive System Morbidity among Liquidators and the Adult Population of Bryansk Province Territories with Levels of Contamination above 5 Ci/km^2, 1994–1998 (Fetysov, 1999a: table 4.1)

Group/ Territory	Number of cases				
	1994	1995	1996	1997	1998
Liquidators	24.7	45.7	63.0	52.3	346.4
All of the Southwest	54.2	523.0	88.7	78.4	269.0
Province	71.8	69.0	65.6	63.2	64.4
Russia	95.8	97.3	91.5	91.5	n/a

The skin, a multilayered organ with multiple functions, is made up of the epidermis, the dermis, and various cells, including the keratinaceous structures that form nails and hair, plus melanocytes, and the sebaceous and sweat (eccrine) glands. The skin is richly supplied with nerves and blood vessels. Thus the skin and all of its subcutaneous components reflect internal damage to blood vessels and other tissues of the body, as is demonstrated by the research cited in this section.

5.10.1. Belarus

1. By 1994 skin and subcutaneous tissue diseases had increased among children in all of the heavily contaminated territories compared with 1988 (Lomat' *et al.*, 1996).

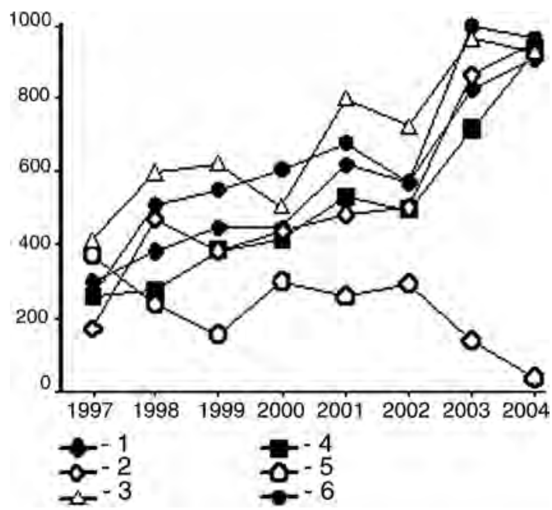

Figure 5.12. Digestive, circulatory, bone, and muscle diseases among liquidators from Moscow City and Moscow Province: (1) digestive system, (2) bone and muscle, (3) hypertension, (4) ischemic heart disease, (5) circulatory encephalopathy, and (6) autonomic nervous system dysfunction (Oradovskaya *et al.*, 2006, 2007).

2. Of 69 children and teenagers admitted to hospitals with various forms of alopecia, more than 70% came from the heavily contaminated territories (Morozevich *et al.*, 1997).

3. In Senkevichi Village, Luninets District, Brest Province, the incidence of children's skin and subcutaneous tissue diseases increased 1.7-fold from 2000 to 2005 (Dudinskaya *et al.*, 2006).

4. From 1986 to 1993 the incidence of skin disease among 4,598 children examined in Kormyansk and Chechersk districts, Gomel Province, where Cs-137 contamination was 15–40 Ci/km^2, was significantly higher compared to less contaminated districts (Gudkovsky *et al.*, 1995).

5. The incidence of skin disease among children who were newborn to 4 years old at the time of the catastrophe is significantly higher in territories with contamination levels of 15–40 Ci/km^2 than in children of the same age from territories with contamination of 5–15 Ci/km^2 (Kul'kova *et al.*, 1996).

6. Out of the first 9 years after the catastrophe, skin and subcutaneous morbidity was a maximum in 1993 (Blet'ko *et al.*, 1995).

5.10.2. Ukraine

1. Skin diseases among evacuees living in the heavily contaminated territories from 1988 to 1999 was more than fourfold higher than in the less contaminated areas (Prysyazhnyuk *et al.*, 2002).

5.10.3. Russia

1. Exudative diathesis (lymphotoxemia) in preschool children in the contaminated territories occurred up to four times more often than before the catastrophe (Kulakov *et al.*, 2001).

2. From 1995 to 1998 the incidence of overall and primary skin diseases in children in the heavily contaminated territories was noticeably higher than in the province and in Russia as a whole (Tables 5.60 and 5.61).

TABLE 5.60. Overall Skin Diseases among Children (per 1,000) in the Southwest Territories of Bryansk Province with Levels of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999b: table 6.1)

	Number of cases			
Territory	1995	1996	1997	1998
Southwest*	111.3	105.9	102.1	83.3
Province	83.4	80.8	78.3	76.2
Russia	81.9	84.6	86.0	n/a

*All heavily contaminated districts.

3. Dermatological pathology was found in 60% of children and teenagers in Gordeevka, Bryansk Province, which is one of the most contaminated districts (Kyseleva and Mozzherova, 2003).

4. In 1996 overall skin morbidity in adults in the heavily contaminated territories of Bryansk Province corresponded to parameters in the province as a whole (Tables 5.62 and 5.63).

5. Incidence of diseases of the skin and subcutaneous tissues among liquidators increased 6 years after the catastrophe and in 1992 exceeded the level of 1986 more than 16-fold (Table 5.64).

6. Skin pathology found among liquidators included thickening of the cornified and subcellular layers of the epidermis, endothelial

TABLE 5.61. Primary Skin Diseases among Children (per 1,000) in Southwestern Territories of Bryansk Province with Levels of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999b: table 6.2)

	Number of cases			
Territory	1995	1996	1997	1998
Southwest*	88.5	89.2	95.7	74.8
Province	71.7	69.6	65.3	63.2
Russia	73.1	71.3	68.6	n/a

*All heavily contaminated districts.

TABLE 5.62. Overall Skin Diseases among Adults (per 1,000) in the Southwestern Territories of Bryansk Province with Levels of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999a: table 6.1)

	Number of cases			
Territory	1995	1996	1997	1998
Southwest*	60.3	67.4	61.4	58.6
Province	68.5	62.4	53.0	54.0
Russia	50.4	48.9	46.3	n/a

*All heavily contaminated districts.

swelling, inflammatory lymphocytic infiltration accompanied by active panvasculitis of most of the small arteries; findings correlated with the level of the radiation load (Porovsky *et al.*, 2005).

7. Among the 97% of liquidators who developed psoriasis after the catastrophe, the psoriasis was always combined with functional impairment of the nervous system and with gastrointestinal disorders (Malyuk and Bogdantsova, 2001).

Undoubtedly the post-Chernobyl period has seen an increase in diseases of the skin and subcutaneous tissues in children and liquidators.

5.11. Infections and Parasitic Infestations

Ionizing radiation is a powerful mutagenic factor (see Section 5.2 above for details). Clouds from Chernobyl dropped a powerful cocktail of radionuclides over the entire Northern Hemisphere (see Chapter 1 for details). Chernobyl radionuclide contamination impacted microbial flora and fauna and other of our symbionts (parasites and commensals) and changed our biological community (see Chapter 11).

There is evidence of increased incidence and severity of diseases characterized by intestinal toxicoses, gastroenteritis, bacterial sepsis, viral hepatitis, and respiratory viruses in areas contaminated by Chernobyl radionuclides (Batyan and Kozharskaya, 1993; Kapytonova and Kryvitskaya, 1994; Nesterenko *et al.*, 1993; Busuet at al., 2002; and others). Genetic instability markedly increased in the contaminated territories and has resulted in increased sensitivity to viral and other types of infections (Vorobtsova *et al.*, 1995).

TABLE 5.63. Primary Skin Diseases among Adults (per 1,000) in the Southwestern Territories of Bryansk Province with Levels of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999a: table 6.1)

	Number of cases			
Territory	1995	1996	1997	1998
Southwest*	50.9	52.5	51.5	45.4
Province	54.1	50.2	42.2	45.0
Russia	40.6	38.7	36.7	n/a

*All heavily contaminated districts.

5.11.1. Belarus

1. Herpes virus activation in the heavily contaminated territories of Gomel Province resulted in increased intrauterine and infant death rates (Matveev *et al.*, 1995).

2. An increased incidence of whipworm (*Trichocephalus trichiurus*) infestation (trichocephalosis) correlated with the density of radioactive contamination in Gomel and Mogilev provinces (Stepanov, 1993).

3. In Senkevichi Village, Luninets District, Brest Province, the occurrence of infectious and parasitic illnesses in children increased 1.54-fold from 2000 to 2005 (Dudinskaya *et al.*, 2006).

4. Among 135 children living in the contaminated territories of Stolinsk District and Bragin City who were examined in 1993–1995, a total of 20% had chronic urogenital infections (Belyaeva *et al.*, 1996).

5. Data for 1,026,046 pregnant women from territories with contamination above 1 Ci/km^2 showed that incidence of the puerperal sepsis in heavily contaminated territories was significantly higher than in areas with less contamination (Busuet *et al.*, 2002).

TABLE 5.64. Skin and Subcutaneous Tissue Abnormalities among Russian Liquidators (per 10,000) (Baleva *et al.*, 2001)

Year	1986	1987	1988	1989	1990	1991	1992	1993
Number of cases	46	160	365	556	686	747	756	726

6. Neonates born to mothers from territories in the Chechersk District, Gomel Province, contaminated at a level of 5–70 Ci/km^2 had congenital infections 2.9-fold more often than before the catastrophe (Kulakov *et al.*, 1997).

7. In 1993, women with gestational herpes in Gomel Province with a Cs-137 contamination higher than 15 Ci/km^2 experienced 8.6-fold more infant deaths compared to less contaminated territories (Matveev *et al.*, 1995).

8. Among 784 preschool children examined from 1986 to 1991 in territories having contamination levels of 15–40 Ci/km^2, infections and infestations were significantly higher than in children from territories with contamination levels of 5–15 Ci/km^2, where 1,057 children were examined (Gutkovsky *et al.*, 1995; Blet'ko *et al.*, 1995).

9. Tuberculosis was more virulent in the more contaminated areas (Chernetsky and Osynovsky, 1993; Belookaya, 1993).

10. During 1991–1995 there was a serious increase in the incidence of tuberculosis in the heavily contaminated areas of Gomel Province, where there were drug-resistant forms and "rejuvenation" of the disease (Borschevsky *et al.*, 1996).

11. In the Mogilev and Gomel provinces, there was a noticeably higher level of cryptosporidium infestation: 4.1 vs. 2.8% in controls (Lavdovskaya *et al.*, 1996).

12. From 1993 to 1997 in Vitebsk Province the persistence of infectious hepatitis among adults and teenagers was noticeably higher than in control groups (Zhavoronok *et al.*, 1998a).

13. Herpes viral diseases doubled in the heavily contaminated territories of Gomel and Mogilev provinces 6 to 7 years after the catastrophe compared with the rest of the country (Matveev, 1993).

14. Activation of cytomegalovirus infections in pregnant women was found in the heavily contaminated districts of Gomel and Mogilev provinces (Matveev, 1993).

15. In all the heavily contaminated territories there was activation of herpes viruses (Voropaev *et al.*, 1996).

16. In Gomel Province hepatitis B and C infections in adults and teenagers rose significantly after 1986. Among 2,653 individuals examined, the incidence increased from 17.0 cases per 100,000 in 1986 to 35.0 in 1990 (Zhavoronok *et al.*, 1998b).

17. Among 2,814 individuals examined the incidence of specific markers of viral hepatitis HbsAg, anti-HBc, and anti-HCV was significantly higher in liquidators and evacuees than in inhabitants of less contaminated districts of Vitebsk Province (Zhavoronok *et al.*, 1998a).

18. From 1988 to 1995 chronic hepatitis in liquidators (1,626 individuals examined) increased from 221 to 349 per 100,000 (Zhavoronok *et al.*, 1998b).

5.11.2. Ukraine

1. By 1995, infectious and parasitic diseases in children were over five times more common in the heavily contaminated territories compared with less contaminated areas. In 1988 these territories did not differ in terms of the occurrence of such diseases (Baida and Zhirnosekova, 1998).

2. Congenital infections in neonates born to mothers in the Polessk District, Kiev Province, contaminated at a level of 20–60 Ci/km^2, occurred 2.9-fold more often than before the catastrophe (Kulakov *et al.*, 1997).

3. The incidence of kidney infections in teenagers significantly increased after the catastrophe and correlated with the level of contamination (Karpenko *et al.*, 2003).

5.11.3. Russia

1. Infectious disease deaths among infants were significantly correlated with irradiation *in utero* (Ostroumova, 2004).

2. Infantile infections are noticeably higher in three of the more contaminated districts of Kaluga Province (Tsyb *et al.*, 2006a).

3. The incidence of infections resulting in the death of children in the heavily contaminated districts of Kaluga Province has tripled in the 15 years since the catastrophe (Tsyb *et al.*, 2006).

4. A significantly higher level of cryptosporidium infestation (8 vs. 4% in controls) occurred in Bryansk Province (Lavdovskaya *et al.*, 1996).

5. The number of cases of pneumocystis was noticeably higher in children in the heavily contaminated territories of Bryansk Province (56 vs. 30% in controls; Lavdovskaya *et al.*, 1996).

6. The incidence of infectious and parasitic diseases in children, 0 to 4 years of age at the time of the catastrophe was significantly higher in the years 1986–1993 in territories with contamination levels of 15–40 Ci/km^2 than in children the same age from territories with contamination of 5–15 Ci/km^2 (Kul'kova *et al.*, 1996).

7. Congenital infections in neonates born to mothers from heavily contaminated territories of the Mtsensk and Volkhovsk districts, Oryol Province, contaminated at levels of 1–5 and 10–15 Ci/km^2, occurred 2.9-fold more often than before the catastrophe (Kulakov *et al.*, 1997).

8. The overall incidence of infectious and parasitic diseases in the heavily contaminated territories of Bryansk Province from 1995 to 1998 was highest in 1995, and higher than the incidence in the province as a whole (Table 5.65).

TABLE 5.65. Childhood Infectious and Parasitic Diseases (per 1,000) in Bryansk Province Territories with Levels of Contamination above 5 Ci/km^2, 1995–1998 (Fetysov, 1999b: table 6.1)

	Number of cases			
Territories	1995	1996	1997	1998
Southwest*	128.3	112.3	99.0	94.8
Province	104.1	79.0	68.8	71.6
Russia	121.6	107.4	102.7	n/a

*All heavily contaminated districts.

9. The prevalence and severity of Gruby's disease (ringworm), caused by the fungus microsporia *Microsporum* sp., was significantly higher in the heavily contaminated areas of Bryansk Province (Table 5.66).

10. One year after the catastrophe, infectious and parasitic diseases were the primary cause of illness among military men who were liquidators (Nedoborsky *et al.*, 2004).

11. Herpes and cytomegalovirus viruses were found in 20% of ejaculate samples from 116 liquidators who were examined (Evdokymov *et al.*, 2001).

5.11.4. Conclusion

The above data concerning infectious and parasitic diseases in liquidators and those living in contaminated territories reflect activation and dispersion of dangerous infections. Whether this is due to mutational changes in the disease organisms rendering them more virulent, impaired immunological defenses in the populations, or a combination of both is not

TABLE 5.66. Gruby's Disease (Ringworm) Incidence (per 100,000) in Bryansk Province, 1998–2002 (Rudnitsky *et al.*, 2003)

Year	Heavily contaminated districts	Less contaminated districts
1998	56.3	32.8
1999	58.0	45.6
2000	68.2	52.9
2001	78.5	34.6
2002	64.8	23.7

fully answered. It is clear that continued detailed observations are needed to document the spread and virulence of infectious and parasitic diseases among people in all of the contaminated territories.

5.12. Congenital Malformations

There are several thousand large and small congenital malformations or anomalies. One type has a strong genetic background (see Section 5.3 above for details) and the second type includes developmental anomalies resulting from impacts during embryonal development. Among them are the so-called "large" congenital malformations (CMs), which are often the only ones officially registered as anomalies. The other developmental anomalies arise as a result of damage during prenatal development and can be genetic, caused by mutations, or teratogenic, caused by toxic external influences, usually occurring up to the first 16 weeks of pregnancy.

Wherever there was Chernobyl radioactive contamination, there was an increase in the number of children with hereditary anomalies and congenital malformations. These included previously rare multiple structural impairments of the limbs, head, and body (Tsaregorodtsev, 1996; Tsymlyakova and Lavrent'eva, 1996; Goncharova, 2000; Hoffmann, 2001; Ibragymova, 2003; and others).

This section presents data concerning congenital malformations and developmental anomalies.

5.12.1. Belarus

1. The frequency of the occurrence of CMs, which was stable up to 1986, increased noticeably after the catastrophe. Although the increase in CMs is marked mainly in the heavily contaminated territories, significant increases in CM morbidity were registered for the whole country, including the less contaminated Vitebsk Province (Nykolaev and Khmel', 1998).

TABLE 5.67. Incidence (per 1,000 Births) of the Officially Accounted for Congenital Malformations in Belarussian Districts with Different Levels of Contamination, 1982–1992 (Lazjuk *et al.*, 1996a; Goncharova, 1997)

	Level of contamination		
Year	1–5 Ci/km^2	>15 Ci/km^2	<1 Ci/km^2
1982	5.74	3.06	5.62
1983	3.96	3.58	4.52
1984	4.32	3.94	4.17
1985	4.46	4.76	4.58
1982–1985	4.61	3.87	4.72
1987	5.54	8.14	5.94
1988	4.62	8.61	5.25
1989	6.32	6.50	5.80
1990	7.98	6.00	6.76
1991	5.65	4.88	5.52
1992	6.22	7.77	5.89
1987–1992	6.01*	7.09*	5.85*

*1982–1985 compared with 1987–1992; $p < 0.05$.

2. Analysis of more than 31,000 abortuses revealed that the incidence of officially registered CMs increased in all of the contaminated territories, but was especially significant in areas in Gomel and Mogilev provinces with Cs-137 levels of contamination higher than 15 Ci/km^2 (Lazjuk *et al.*, 1999b).

3. The incidence of CMs increased significantly from 5.58 per 1,000 before the catastrophe to 9.38 for the years from 2001 to 2004 (National Belarussian Report, 2006).

4. In 1990 the primary, initial diagnosis of CM in children was twice that of the illnesses in adolescents 15 to 17 years of age, but by 2001 it was fourfold higher (UNICEF, 2005: table 1.3).

5. Some 24% of the children in the so-called "clean" regions (<1 Ci/km^2) were born with CMs, in districts with Cs-137 contamination levels of 1–5 Ci/km^2 the figure was 30%, and in the districts with contamination levels above 15 Ci/km^2 the number reached 83% (Table 5.67).

6. There was a higher incidence of CM morbidity in the more contaminated areas than in less contaminated ones (Table 5.68).

TABLE 5.68. Incidence of Congenital Malformations (per 1,000 Live Births) in Heavily and Less Contaminated Areas of Belarus before and after the Catastrophe (National Belarussian Report, 2006: table 4.6.)

	Heavily contaminated areas			Less contaminated areas		
Years	1981–1986	1987–1989	1990–2004	1981–1986	1987–1989	1990–2004
Incidence of all CMs	4.08	7.82*	7.88*	4.36	4.99	8.00*
Anencephaly	0.28	0.33	0.75	0.36	0.29	0.71
Spinal hernia	0.57	0.88	1.15	0.69	0.96	1.41
Polydactyly	0.22	1.25*	1.10	0.32	0.50	0.91
Down syndrome	0.89	0.59	1.01	0.64	0.88	1.08
Multiple CMs	1.27	2.97*	2.31	1.35	1.23	2.32
Newborn and stillborn total	58,128	23,925	76,278	98,522	47,877	161,972
Children and stillbirths with CMs	237	187	601	430	239	1,295

*$p < 0.05$.

7. CM incidence increased in the whole of the country from 12.5 per 1,000 newborns in 1985 to 17.7 in 1994, with most of the cases in territories with Cs-137 contamination of above 15 Ci/km^2 (Lazjuk *et al.*, 1996a).

8. Annually in the country there are no fewer than 2,500 newborns with CMs. Since 1992 a program to interrupt pregnancy in accordance with medical and genetic parameters (500 to 600 cases in a year) has stabilized the birth of children with CMs (Lazjuk *et al.*, 1996a,b).

9. Nine years after the catastrophe the number of newborns who died because of nervous system developmental anomalies was statistically significant (Dzykovich *et al.*, 1996).

10. In Gomel Province congenital anomalies of the eye increased more than fourfold: from 0.4 to 1.63% from 1961–1972 to 1988–1989 (Byrich *et al.*, 1999).

11. In 1994, CMs were the second cause of infant mortality. The incidence was higher in Gomel Province (4.1%) than in the least contaminated Vitebsk Province (3.0%), and averaged 3.9% for the country as a whole (Bogdanovich, 1997).

12. The incidence of CMs increased significantly in 17 heavily contaminated districts (>5 Ci/km^2) and in 30 less contaminated districts (<1 Ci/km^2) compared to 5 years before and 5 years after the catastrophe. Heavily contaminated districts had increased frequency of occurrence of CMs compared with less contaminated ones only from 1987 to 1988 (Table 5.69).

13. There was an increased incidence of 26 officially registered CMs after the catastrophe; heavily and less heavily contaminated areas differed with some CMs increasing from 1987 to 1988, whereas others increased from 1990 to 2004. Polydactly and limb-reduction defects were significantly different in the heavier and less contaminated districts in 1987 and 1988. Eventually, there was less

TABLE 5.69. Incidence of Officially Registered Congenital Malformations (per 1,000 Live Born + Fetuses) in 17 Heavily and 30 Less Contaminated Districts of Belarus (National Belarussian Report, 2006)

Districts	1981–1986	1987–1988	1990–2004
A. Heavily contaminated	4.08	7.82	7.88**
B. Less contaminated	4.36	4.99*	8.00**

*$p < 0.05$, *A compared to B (1987–1988); **$p < 0.05$, 1981–1986 compared with 1990–2004.

TABLE 5.70. Incidence of Officially Registered Congenital Malformations (per 1,000 Live Births + Fetuses) in Contaminated Districts in Belarus. Top Line: Data for 17 Districts with Levels above 5 Ci/km^2; Bottom Line: Data for 30 Districts with Levels below 1 Ci/km^2 (National Belarussian Report, 2006)

	1981–1986	1987–1988	1990–2004
Anencephaly	0.28	0.33	0.75
	0.36	0.29	0.71
Spinal hernias	0.57	0.88	1.15
(Spina bifida)	0.69	0.96	1.41
Lip defects	0.65	1.09	1.08
	0.64	0.84	1.23
Polydactyly	0.22	1.25*	1.10
	0.32	0.50	0.91
Limb reduction	0.17	0.59*	0.49
	0.22	0.13	0.35
Esophageal and	0.14	0.21	0.21
anal atresia	0.19	0.27	0.23
Multiple CMs	1.27	2.97*	2.31
	1.35	1.23	2.32

*$p < 0.05$.

distinction between heavily and less contaminated districts and the incidence of CMs in the former decreased in comparison to that in the latter (Table 5.70).

14. The incidence of registered CMs noticeably increased in 14 out of 16 districts of Gomel and Mogilev provinces 1 to 2 years after the catastrophe. In five districts the increase was significant compared with precatastrophe data (Table 5.71).

15. Occurrence of the officially registered CMs correlated with the level of radioactive contamination of the territory (Table 5.72).

16. The occurrence of CMs in Gomel Province was sixfold higher in 1994 (Goncharova, 2000).

17. The frequency of occurrence of CMs from 1986 to 1996 in areas contaminated at a level greater than 15 Ci/km^2 was significantly higher than in Minsk, with the highest incidence of 9.87 occurring in 1992 (Lazjuk *et al.*, 1996b, 1999).

18. Compared with Minsk, the incidence of CMs among medical abortuses and fetuses in the contaminated areas of Mogilev and Gomel provinces was significantly higher in the first decade after the catastrophe (Table 5.73).

TABLE 5.71. Incidence of Registered Congenital Malformations (per 1,000 Live Births + Fetuses) in Gomel and Mogilev Provinces of Belarus before and after the Catastrophe (Lazjuk *et al.*, 1996a)

	Number of cases	
District	1982–1985	1987–1989
Gomel area		
Bragin	4.1 ± 1.4	9.0 ± 3.0
Buda—Koshelevo	4.7 ± 1.2	9.3 ± 2.0*
Vetka	2.8 ± 1.0	9.9 ± 2.7
Dobrush	7.6 ± 2.0	12.6 ± 2.6
El'sk	3.3 ± 1.4	6.4 ± 2.4
Korma	3.2 ± 1.2	5.9 ± 2.1
Lel'chitsy	3.3 ± 1.2	6.6 ± 2.0
Loev	1.6 ± 1.1	3.7 ± 2.1
Khoiniky	4.4 ± 1.2	10.2 ± 2.6*
Chechersk	1.0 ± 0.7	6.6 ± 2.3*
Mogilev area		
Bykhov	4.0 ± 1.1	6.5 ± 1.6
Klymovychy	4.8 ± 1.4	3.2 ± 1.4
Kostyukovychy	3.0 ± 1.2	12.0 ± 2.9*
Krasnopol'e	3.3 ± 1.5	7.6 ± 2.9
Slavgorod	2.5 ± 1.2	7.6 ± 2.7
Cherykov	4.1 ± 1.7	3.6 ± 1.8
Total	4.0 ± 0.3	7.2 ± 0.6*

*$p < 0.05$.

5.12.2. Ukraine

1. Before the Chernobyl catastrophe only one case of severe CMs in a newborn was seen

TABLE 5.72. Occurrence of Officially Registered Congenital Malformations (per 1,000 Live Births) and Different Levels of Contamination (Lazjuk *et al.*, 1996a; Matsko, 1999)

Level of contamination	Number of cases	
	1982–1985	1987–1992
<1 Ci/km^2	4.72 (4.17 – 5.62)	5.85 (5.25 – 6.76)
1–5 Ci/km^2	4.61 (3.96 – 5.74)	6.01 (4.62 – 7.98)
>15 Ci/km^2	3.87 (3.06 – 4.76)	7.09 (4.88 – 8.61)

*All differences are significant.

TABLE 5.73. Comparison of the Incidence (per 1,000) of Strictly Registered Congenital Malformations, Medical Abortuses, and Fetuses in Minsk Compared with Gomel and Mogilev Provinces Contaminated at Levels above 15 Ci/km^2 (Lazjuk *et al.*, 1999)

	Territories/period		
	Minsk	Contaminated districts	
Congenital malformations	1980–1985, $n = 10{,}168$	1986*–1996, $n = 20{,}507$	1986*–1995, $n = 2{,}701$
All CMs	5.60	4.90	7.21**
CNS anomalies	0.32	0.53	0.54
Polydactyly	0.63	0.53	0.79
Multiple limb defects	0.07	0.10	0.28

*Second half 1986; **$p < 0.05$.

in a 5-year period; afterward there were several cases a year (Horishna, 2005).

2. After 1986 the number of children with CMs increased in the contaminated territories (TASS, 1998; Golubchykov *et al.*, 2002).

3. Disability owing to congenital defects in children newborn to 15 years of age increased more than threefold in the Ukraine from 1992–1993 to 2000–2001: from 10 to 31 per 10,000 (UNISEF, 2005: table 1.5).

4. The peak incidence of CMs in the period from 1987 to 1994 occurred in 1990 (Orlov, 1995).

5. For children irradiated *in utero*, the occurrence of CMs increased significantly (5.52 ± 0.22 vs. 2.95 ± 0.18 in controls, $p < 0.001$) and the spectrum of CMs changed (Stepanova, 1999).

6. The number of the small congenital malformations (anomalies of development) correlated with the level of *in utero* irradiation (Stepanova *et al.*, 2002a).

7. Developmental anomalies in children from heavily contaminated districts occur up to 2.8-fold more frequently than in less contaminated areas (Horishna, 2005).

8. Previously rare multiple CMs and severe CMs such as polydactyly, deformed internal organs, absent or deformed limbs, and retarded growth increased significantly in the contaminated districts (Horishna, 2005).

9. Occurrence of officially registered CMs increased 5.7-fold during the first 12 years after the catastrophe (Grodzinsky, 1999).

10. The incidence of CMs is twice as high in contaminated districts (Horishna, 2005).

11. Ten years after the catastrophe, the level of congenital malformations in Rivne Province increased from 15.3 to 37.3 (per 1,000 neonates), most noticeably in the heavily contaminated northern districts (Evtushok, 1999).

12. Among the 13,136 children born to 1986–1987 liquidators, 9.6% had officially registered CMs. Common developmental anomalies include scoliosis; throat and tooth deformities; early tooth decay; dry, rough, and leathery skin; abnormally thin, tightly clustered hair; and alopecia (Stepanova., 1999, 2004; Horishna, 2005).

13. The highest incidence of CMs among children born to liquidator families was observed in 1987–1988, when there were up to 117 per 1,000. Thereafter the ratio began to decrease: 83–102 children in 1989–1991; 67 in 1992; and 24–60 in 1993–1997 (Figure 5.13).

14. According to the Neurosurgery Institute, National Ukrainian Medical Academy in Kiev, after the catastrophe 98% of central nervous system anomalies were due to hydrocephalus. The average annual increase in central nervous system defects was about 39% among 2,209 registered cases in the period from 1981 to 1985 compared with 4,925 cases from 1987 to 1994. From 1987 to 2004 the incidence of brain tumors in children up to 3 years of age doubled (Figure 5.14) and in infants it increased 7.5-fold (Orlov *et al.*, 2001, 2006).

15. The highest incidence of maxillofacial CMs (mostly cleft upper lip and palate) occurred in children born within 9 months after April 26, 1986, and was six- to tenfold more common in the more contaminated areas of Kiev City and Kiev and Zhytomir provinces compared with the less contaminated provinces of Vinnitsa and Khmelnitsk (Nyagu *et al.*, 1998).

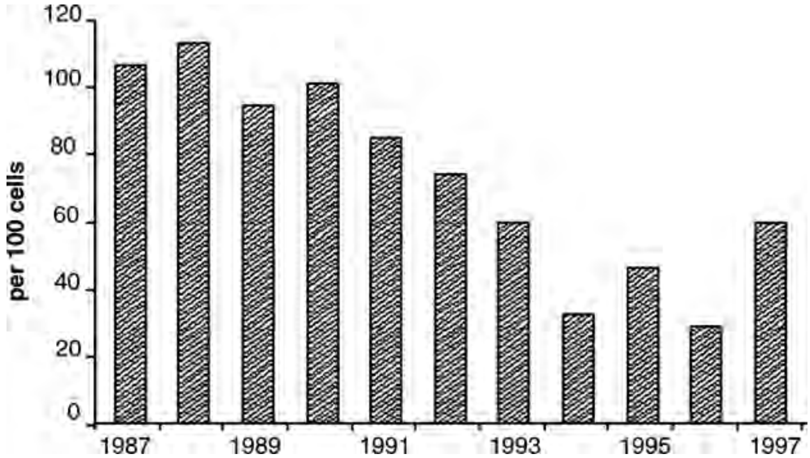

Figure 5.13. Incidence (per 1,000) of congenital malformations in children born to families of Ukrainian liquidators who worked in 1986–1987 (Stepanova, 2006).

16. Urogenital tract CMs accounted for more than 20% of all officially registered anomalies and were more frequent for the period from 1998 to 2001 (Sorokman, 1998; Sorokman *et al.*, 2002).

5.12.3. Russia

1. The number of CMs noticeably increased for several years after the catastrophe (Lyaginskaya and Osypov, 1995; Lyaginskaya *et al.*, 2007).

2. The number of CMs increased markedly for several years after the catastrophe in the heavily contaminated districts of Tula Province (Khvorostenko, 1999).

3. The heavily contaminated districts of Kaluga Province had an increase in the number of CMs after the catastrophe, which resulted in a twofold increase in children's deaths in these districts 15 years later (Tsyb *et al.*, 2006).

4. CMs in contaminated regions increased three- to fivefold in 1991 and 1992 compared with the precatastrophe level, with a noticeable increase in anomalies of the genitals, nervous

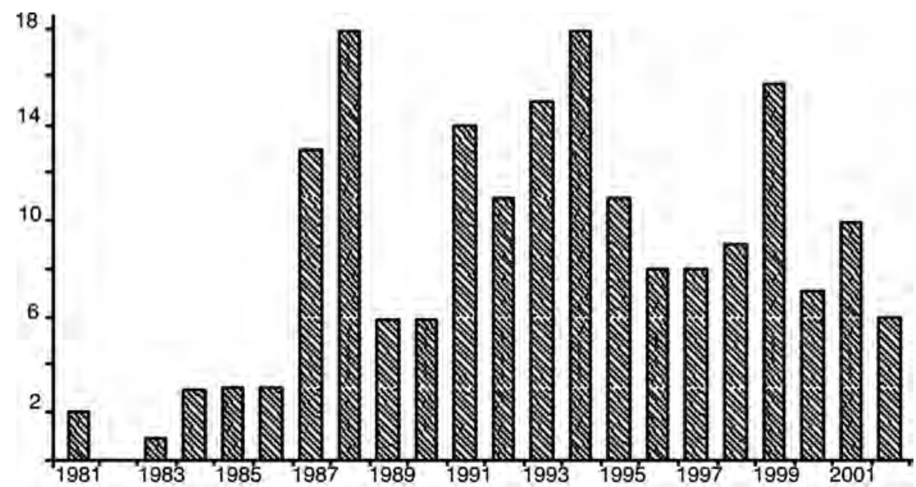

Figure 5.14. Number of cases of central nervous system tumors in children under 3 years of age from 1981 to 2002, taken from Kiev Institute of Neurosurgery data (Orlov and Shaversky, 2003).

TABLE 5.74. Congenital Malformation Morbidity (per 1,000 Live Births) in Bryansk Province Districts with Contamination Levels above 5 Ci/km^2, 1995–1998 (Fetysov, 1999b: table 6.1)

	Number of cases			
Territory	1995	1996	1997	1998
Southwest*	14.2	13.1	12.7	11.9
Province	7.9	8.1	8.6	8.9

*All heavily contaminated districts.

system, sense organs, bone, muscular and digestive systems, and congenital cataracts (Kulakov *et al.*, 2001).

5. Infant mortality in Bryansk Province due to structural CMs was fivefold the Russian average (Zhylenko and Fedorova, 1999).

6. The occurrence of officially registered CMs in the contaminated districts of Bryansk Province was significantly higher from 1995 to 1998 than for the province as a whole (Table 5.74).

7. According to the Russian State Registry, which included more than 30,000 children born to liquidators, 46.7 had congenital developmental anomalies and "genetic syndromes" with a prevalence of bone and muscular abnormalities. Occurrence of CMs among children of liquidators was 3.6-fold higher than corresponding Russian parameters (Sypyagyna *et al.*, 2006).

5.12.4. Other Countries

Official European registries of CMs (EUROCAT Registry, 1988) collectively cover only about 10% of the European population (Hoffmann, 2001). Underestimates are thought to be up to 30% for minor malformations and 15–20% for Down syndrome (Dolk and Lechat, 1993; Czeizel *et al.*, 1991). Most European countries do not routinely register prenatally diagnosed malformations that lead to induced abortions (Hoffmann, 2001).

1. AUSTRIA. More cases of central nervous system defects in newborns were observed in Austria after Chernobyl (Hoffmann, 2001).

2. BULGARIA. In Pleven Province there was a significant increase in CMs of the heart and central nervous system, as well as multiple anomalies following the Chernobyl contamination (Moumdjiev *et al.*, 1992 by Hoffmann, 2001).

3. CROATIA. Analysis of 3,541 autopsies at the University Clinic of Zagreb between 1980 and 1993 showed a significantly increased incidence of central nervous system anomalies during the post-Chernobyl period (Kruslin *et al.*, 1998, by Schmitz-Feuerhake, 2002).

4. CZECH REPUBLIC. For three pre-Chernobyl years, the rate of registered CMs was about 16.3 (per 1,000 total births) and 18.3 for three post-Chernobyl years. From 1986 to 1987 the rate of CMs increased significantly—about 26%, from 15 to 19 per 1,000 (UNICEF, 2005: from table 1.2, calculation by A. Y.)

5. DENMARK. More children in Denmark were born with central nervous system defects after Chernobyl (Hoffmann, 2001; Schmitz-Feuerhake, 2002).

6. FINLAND. Between February 1987 and December 1987, the number of cases of CMs were, respectively, 10 and 6% above expectation in the moderately and highly contaminated regions. Subgroups with higher incidence included malformations of the central nervous system and limb-reduction anomalies (Harjuletho *et al.*, 1989, 1991).

7. GEORGIA. The number of CM cases diagnosed as "harelip" and "wolf mouth" increased after the catastrophe, especially in what were probably the most contaminated areas of Ajaria Republic and Racha Province (Vepkhvadze *et al.*, 1998).

8. GERMANY. The Jena Regional Malformation Registry recorded an increase in CMs in 1986 and 1987 compared with 1985; isolated malformations leveled off during subsequent years (Lotz *et al.*, 1996, by Hoffmann, 2001). The increase was most pronounced for malformations of the central nervous system and anomalies of the abdominal wall. An analysis of the nationwide GDR Malformation Registry for the prevalence of cleft lip/palate revealed a

TABLE 5.75. Incidence (per 1,000 Births) of Neural Tube Defects in Turkey before and after the Catastrophe (Hoffmann, 2001; Schmitz-Feuerhake, 2006)

Location	Before	After	
Bursa, Western Turkey	5.8[1]	12.6[3]–20.0[2]	6.3[4]
Trabzon	2.12[5]	4.39[6]	
Elazig	1.7[7]	2.2 –12.5[8]	10.0[9]

[1]1983–1986; [2]Jan.–June 1987; [3]July–Dec. 1987; [4]Jan.–June 1988; [5]1981–1986; [6]1987–Oct. 1989; [7]1985–1986; [8]1987–1988; [9]1989.

9.4% increase in 1987 compared with the country's average for 1980 and 1986 (Zieglowski and Hemprich, 1999). This increase was most pronounced in three northern provinces of the GDR, those most affected by the Chernobyl fallout (Hoffmann, 2001).

9. HUNGARY. More cases of central nervous system defects in newborns were observed in Hungary after Chernobyl (Hoffmann, 2001; Schmitz-Feuerhake, 2002).

10. MOLDOVA. Out of 8,509 registered cases of CMs for the period from 1989 to 1996 the highest frequencies of occurrence of malformations (including Down syndrome, structural limb deformities, and embryonic hernias) were in the most contaminated southeast territories (Grygory *et al.*, 2003).

11. NORWAY. Data on all newborns conceived between May 1983 and April 1989 revealed a positive correlation between calculated total irradiation from Chernobyl and CMs such as hydrocephaly. There was a negative correlation with Down syndrome (Terje Lie *et al.*, 1992; Castronovo, 1999).

TABLE 5.76. Congenital Developmental Anomalies in Children Irradiated *In Utero* as a Result of the Chernobyl Catastrophe in Countries Other than Belarus, Ukraine, and European Russia (Hoffmann, 2001; Schmitz-Feuerhake, 2006; Pflugbeil *et al.*, 2006)

Country, territory	Congenital malformations	Reference
Austria	CMs	Hoffmann, 2001
Turkey (Bursa, Izmir, Black Sea coast)	Incidence of CNS among the newborns conceived in the second half of 1986	Akar *et al.*, 1988,1989; Caglayan *et al.*, 1990; Guvenc *et al.*, 1993; Mocan *et al.*, 1990
Bulgaria (Pleven)	Cardiac anomalies, CNS defects, multiple CMs	Moumdjiev *et al.*, 1992
Croatia (Zagreb)	CMs among stillbirths and neonatal deaths (including CNS anomalies)	Kruslin *et al.*, 1998
Denmark (Odense)	Neural tube defects (NTD)	EUROCAT, 1988
Finland	Malformations of the CNS and limb-reduction anomalies	Harjuletho-Mervaala *et al.*, 1992
Hungary	Congenital malformations	Czeizel, 1997
Scotland	Down syndrome (trisomy 21)	Ramsay *et al.*, 1991
Sweden	Down syndrome (trisomy 21)	Ericson and Kallen, 1994
East Germany	Cleft lip and/or palate, other CMs	Zieglowski and Hemprich, 1999; Scherb and Weigelt, 2004
Bavaria	In 7 months after the catastrophe CM incidence increased 4%	Korblein 2002, 2003a, 2004; Scherb and Weigelt, 2003
West Berlin	CMs among stillbirths noticeably increased in 1987	Hoffmann, 2001
Jena	Increase in CMs (including malformations of the CNS and anomalies of the abdominal wall)	Lotz *et al.*, 1996
Germany total	In 1987 CM incidence increased significantly	Korblein, 2000

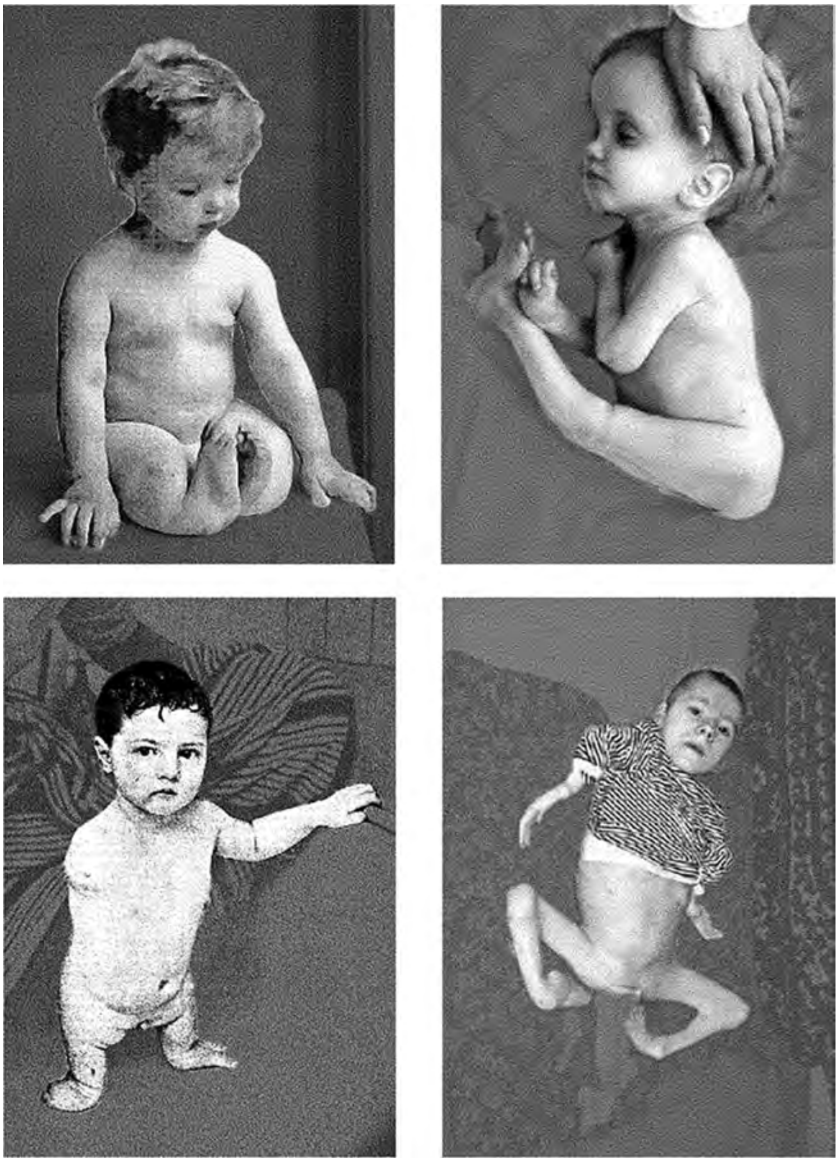

Figure 5.15. Typical examples of Chernobyl-induced congenital malformations with multiple structural deformities of the limbs and body (drawing by D. Tshepotkin from *Moscow Times* (April 26, 1991) and from www.progetto.humus).

12. TURKEY. At the beginning of 1987, an increased incidence of CMs was reported in western Turkey, which was particularly badly affected (Akar, 1994; Akar *et al.*, 1988, 1989; Güvenc *et al.*, 1993; Caglayan *et al.*, 1990; Mocan *et al.* 1990). Table 5.75 is a summary of data on the prevalence of neural tube defects (including spina bifida occulta and aperta, encephalocele, and anencephaly) in Turkey before and after the catastrophe.

13. Information on CMs in newborns irradiated *in utero* as a result of the catastrophe in various countries is presented in Table 5.76.

TABLE 5.77. Incidence (per 10,000) of 12 Disease Groups among Liquidators (Pflugbeil *et al.*, 2006)

Illness/organ group	1986	1988	1990	1992	1993	Increase
Blood and blood-forming organs	15	96	191	226	218	14.5-fold
Circulation	183	1,150	2,450	3,770	4,250	23.2-fold
Endocrine sytem	96	764	2,020	3,740	4,300	45.1-fold
Respiratory system	645	3,730	6,390	7,010	7,110	11.0-fold
Urogenital tract	34	253	646	1,180	1,410	41.4-fold
Nervous system and sense organs	232	1,810	4,100	8,110	9,890	42.6-fold
Psychological changes	621	1,580	3,380	4,540	4,930	7.9-fold
Digestive System	82	1,270	3,210	5,290	6,100	74.4-fold
Skin and subcutaneous tissue	46	365	686	756	726	15.8-fold
Infections and parasites	36	197	325	388	414	11.5-fold
Tumors	20	180	393	564	621	31.1-fold
Malignant growths	13	40	85	159	184	14.2-fold

5.12.5. Conclusion

The appreciable increase in newborns with both major and minor developmental anomalies is one of the undeniable consequences of the Chernobyl catastrophe. Everywhere in areas contaminated by Chernobyl radioactivity, increased numbers of children have been born with hereditary anomalies and congenital developmental malformations, including previously rare multiple structural deformities of the limbs, head, and body (Figure 5.15). The occurrence of congenital malformations continues to increase in several of the contaminated territories and correlates with the levels of irradiation. Thus the link between congenital and genetic defects and Chernobyl irradiation is no longer an assumption, but is proven.

Extrapolating available data on congenital malformations and the total number of children born in the territories contaminated by Chernobyl, we must assume that each year several thousand newborns in Europe will also bear the greater and smaller hereditary

TABLE 5.78. Incidence (per 100,000) of Juvenile Morbidity in Gomel Province, Belarus (Pflugbeil *et al.*, 2006 Based on Official Gomel Health Center Data, Simplified)

Morbidity group/Organ	1985	1990	1995	1997	Increase
Total primary diagnoses	9,771	73,754	127,768	124,440	12.7-fold
Blood and blood-forming organs	54	502	859	1,146	21.2-fold
Circulatory diseases	32	158	358	425	13.3-fold
Endocrinological, metabolic, and immune systems	3.7	116	3,549	1,111	300.0-fold
Respiratory system	760	49,895	81,282	82,689	108.8-fold
Urogenital tract	25	555	961	1,199	48.0-fold
Muscle and bones/connective tissue	13	266	847	1,036	79.7-fold
Mental disorders	95	664	908	867	9.1-fold
Neural and sense organs	645	2,359	7,649	7,040	10.9-fold
Digestive system	26	3,108	5,879	5,548	213.4-fold
Skin and subcutaneous tissue	159	4,529	7,013	7,100	44.7-fold
Infectious and parasitic illnesses	4,761	6,567	11,923	8,694	1.8-fold
Congenital malformations*	51	122	210	340	6.7-fold
Neoplasm**	1.4	323	144	134	95.7-fold

*High estimation of unreported cases through abortions; **1985 only malignant neuroplasms.

TABLE 5.79. Incidence (per 100,000) of Morbidity among Adults and Adolescents in Northern Ukraine, 1987–1992 (Pflugbeil *et al.*, 2006)

Illness/Organ	1987	1989	1991	1992	Increase
Endocrine system	631	886	4,550	16,304	25.8-fold
Psychological disturbances	249	576	5,769	13,145	52.8-fold
Neural system	2,641	3,559	15,518	15,101	5.7-fold
Circulatory system	2,236	4,986	29,503	98,363	44.0-fold
Digestive system	1,041	2,249	14,486	62,920	60.4-fold
Skin and subcutaneous tissue	1,194	1,262	4,268	60,271	50.5-fold
Muscles and bones	768	2,100	9,746	73,440	96.9-fold

anomalies caused by Chernobyl's radioactive fallout.

5.13. Other Diseases

1. Age-related changes found in liquidators included anoxic, fermentation-type metabolism and formation of pro-oxidation conditions (Vartanyan *et al.*, 2002).

2. In 58 children ages 7 to 14 from Stolinsk and Narovlya districts without clinical pathology, blood vitamin E levels were significantly lower than normal and were especially low in territories contaminated at a level above 6 Ci/km^2 (Zaitsev *et al.*, 1996).

3. In 153 pregnant women from the Bragin District, vitamin A levels were noticeably higher than normal and concentrations of vitamin E were significantly lower—up to eightfold (Zaitsev *et al.*, 1996).

5.14. Conclusion

Only when we know the full scope of the Chernobyl catastrophe can we prevent such a tragedy from ever happening again.

There was widespread damage to the people living in the contaminated territories. Nearly all physiological systems were adversely affected, resulting in consequences ranging from impairment to death. These disorders cannot be attributed to socioeconomic or behavioral stress factors. They are real and documented.

Liquidators were the most comprehensively observed group after the catastrophe. Table 5.77 presents dramatic data on the incidence of 12 groups of illnesses suffered by Russian liquidators.

It is reasonable to suggest that the state of public health in the affected territories may be even worse than that of the liquidators. Tables 5.78 and 5.79 provide a comprehensive view of the deterioration in public health in the affected territories of Belarus and Ukraine.

Existing data presented in this chapter are irrefutable proof that the frequency of occurrence of nonmalignant illnesses is obviously and significantly higher in the contaminated territories.

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6. Oncological Diseases after the Chernobyl Catastrophe

Alexey V. Yablokov

The most recent forecast by international agencies predicted there would be between 9,000 and 28,000 fatal cancers between 1986 and 2056, obviously underestimating the risk factors and the collective doses. On the basis of I-131 and Cs-137 radioisotope doses to which populations were exposed and a comparison of cancer mortality in the heavily and the less contaminated territories and pre- and post-Chernobyl cancer levels, a more realistic figure is 212,000 to 245,000 deaths in Europe and 19,000 in the rest of the world. High levels of Te-132, Ru-103, Ru-106, and Cs-134 persisted months after the Chernobyl catastrophe and the continuing radiation from Cs-137, Sr-90, Pu, and Am will generate new neoplasms for hundreds of years.

The oncological diseases include neoplasms and malignant (cancerous) and nonmalignant tumors as common consequences of ionizing radiation. There are varying periods of latency between the exposure and the appearance of a tumor. Data collected from the victims of Hiroshima and Nagasaki show radiation-induced malignancies becoming clinically apparent as follows:

- Leukemia (various blood cancers)—within 5 years
- Thyroid cancer—within 10 years
- Breast and lung cancers—in 20 years
- Stomach, skin, and rectal cancer—in 30 years

For people living in the areas contaminated by Chernobyl's radioactive fallout the cancer situation is much more complicated. Although there was not a single case due to direct exposure from the explosion that occurred in April 1986, the ongoing irradiation in the wake of the meltdown is responsible for an increase in malignant diseases. Given the ten half-lives that have to occur before many of the isotopes decay to safe levels, this means that Chernobyl radiation will engender new neoplasms for hundreds of years.

The initial forecasts insisted that there would be no significant increase in the occurrence of cancer after the catastrophe. As is demonstrated by data in this chapter, the Russian and Ukrainian oncological statistics were low and grossly underestimated the cancer morbidity. It is officially accepted that:

> . . . the main source of data for international statistics for cancer morbidity is the collection of papers "Cancer Disease on Five Continents," published by the International Agency for Research on Cancer (IARC). Each five years, since 1960 . . . these editions publish only those data which correspond to the established quality standards. In the first editions across the USSR . . . information has not been included. In last two editions of the collection, containing data for 1983–1987 and 1988–1992, data are included for Belarus, Estonia and Latvia; the first of these two collections also contained information from St. Petersburg and Kirghizia. Nevertheless, the authors of the collection warn

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> that all data from former republics of the USSR (except for Estonia) underestimate the occurrence of disease... (UNSCEAR, 2000, item 234, p. 48).

This chapter is divided into sections on the various cancers that have been found in territories contaminated by Chernobyl radionuclides. Section 6.1 deals with general oncological morbidity, 6.2 with thyroid cancer, 6.3 with leukemia, and 6.4 with all of the other malignant neoplasms. This chapter, as well as others in this book, is not an all-inclusive review, but does reflect the scope and the scale of the problem.

6.1. Increase in General Oncological Morbidity

There are two ways to define the scale of cancer morbidity associated with the Chernobyl catastrophe: (1) on the basis of calculated received doses (with application of appropriate risk factors) and (2) by direct comparison of cancer morbidity in the heavily and less contaminated territories.

6.1.1. Belarus

1. For the period 1990–2000 cancer morbidity in Belarus increased 40%. The increase was a maximum in the most highly contaminated Gomel Province and lower in the less contaminated Brest and Mogilev provinces: 52, 33, and 32%, respectively (Okeanov *et al.*, 2004).

2. A significant increase in morbidity for malignant and benign neoplasms occurred in girls aged 10 to 14 years born to irradiated parents in the years from 1993 to 2003 (National Belarussian Report, 2006).

3. The highest level of general oncological morbidity among persons 0 to 17 years of age from 1986 to 2000 occurred in the most contaminated Gomel Province; the lowest was in the least contaminated areas of the Vitebsk and Grodno provinces (Borysevich and Poplyko, 2002).

4. The level of the cancer morbidity in Gomel and Mogilev provinces correlated with the level of contamination of the areas (Table 6.1).

5. From 1987 to 1999 some 26,000 cases of radiation-induced malignant neoplasms (including leukemia) were registered. The average annual absolute risk of malignant disease calculated from these data is 434 per 10,000 person/Sv. The relative risk for cancer is 3–13 Sv^{-1}, an order of magnitude higher that of Hiroshima (Malko, 2002).

6. Cancer morbidity among liquidators (57,440 men and 14,400 women officially registered) sharply and significantly increased from 1993 to 2003 compared to individuals exposed to less contamination (Table 6.2).

7. Cancer morbidity among liquidators who worked in May–June 1986 (maximal doses and dose rate) is above that of liquidators who worked in July–December 1986, who received lower doses (Table 6.3).

8. Cancer mortality in the Narovlia District, Gomel Province, increased from 0.0 to 26.3%

TABLE 6.1. Occurrence of Cancers (per 100,000) in Belarussian Territories Contaminated by Cs-137 before and after the Catastrophe (Konoplya and Rolevich, 1996; Imanaka, 1999)

Contamination, Ci/km^2	Gomel Province		Mogilev Province	
	1977–1985	1986–1994	1977–1985	1986–1994
<5	181.0 ± 6.7	238.0 ± 26.8	248.8 ± 14.5	306.2 ± 18.0*
5–15	176.9 ± 9.0	248.4 ± 12.5*	241.8 ± 15.4	334.6 ± 12.2*
>15	194.6 ± 8.6	304.1 ± 16.5*	221.0 ± 8.6	303.9 ± 5.1*

*$P < 0.05$.

TABLE 6.2. Cancer Morbidity of Belarussian Liquidators (per 10,000), 1993–2003 (Okeanov *et al.*, 2004)

	Morbidity		Regression coefficient	
	Liquidators	Controls**	Liquidators	Controls**
All cancers	422.2 ± 20.6*	366.4 ± 5.3	13.15 ± 5.29*	4.69 ± 1.10
Stomach	41.1 ± 3.4	42.9 ± 1.2	1.99 ± 0.92	−0.99 ± 0.19
Rectal	19.1 ± 2.1	16.1 ± 0.4	1.14 ± 0.59*	0.24 ± 0.12
Lung	55.6 ± 5.4	53.6 ± 1.2	3.78 ± 1.26*	−0.38 ± 0.31
Kidney	15.7 ± 1.9*	10.8 ± 0.5	1.78 ± 0.27*	0.68 ± 0.16
Bladder	16.7 ± 1.2*	13.8 ± 0.8	0.89 ± 0.23	0.28 ± 0.12
Thyroid	28.4 ± 4.1*	10.1 ± 1.0	1.08 ± 1.03	0.8 ± 0.18

*$p < 0.05$; **From the less contaminated Vitebsk Province (excluding liquidators and those who migrated to the province from the contaminated regions).

in the years from 1986 to 1994 (Zborovsky *et al.*, 1995).

9. Calculated on the basis of official data for the years 1990 to 2004, Belarussian patients diagnosed with cancer for the first time has increased from 0.26 to 0.38% (up 46%), and in Gomel Province, from 0.25 to 0.42% (up 68%). This marked deviation from the long-term trend of cancer mortality is very likely connected to the Chernobyl contamination (Figure 6.1).

10. Up to 62,500 radiation-induced cancers are predicted to occur in Belarus over a period of 70 years after the catastrophe (Malko, 2007).

TABLE 6.3. Cancer Morbidity (per 10,000) in Two Belarussian Liquidator Groups Exposed in Different Periods in 1986, 1993–2003 (Okeanov *et al.*, 2004)

	Liquidators May–June 1986	Liquidators July–December 1986	Controls
All cancers	456.1 ± 10.3*	437.8 ± 10.3*	366.4 ± 5.3
Stomach	50.4 ± 3.4 *	42.6 ± 3.2	42.9 ± 1.2
Rectal	18.7 ± 2.1	25.5 ± 2.5*	16.1 ± 0.4
Lung	57.9 ± 3.7	67.1 ± 4.0*	53.6 ± 1.2
Kidney	20.3 ± 2.2*	20.6 ± 2.2*	10.8 ± 0.4
Bladder	20.6 ± 2.2*	16.6 ± 2.0*	13.8 ± 0.8
Thyroid	40.0 ± 3.1*	25.2 ± 2.5*	10.1 ± 1.0

*$p < 0.05$ from controls.

6.1.2. Ukraine

1. The cancer morbidity of evacuees from the heavily contaminated territories is noticeably higher than in the rest of the country (Tsimliakova and Lavrent'eva, 1996; Golubchykov *et al.*, 2002).

2. In the heavily contaminated territories cancer morbidity increased 18–22% in the 12 years following the catastrophe, and rose by 12% in the entire country (Omelyanets *et al.*, 2001; Omelyanets and Klement'ev, 2001).

3. For adults in the contaminated districts of Zhytomir Province cancer morbidity increased nearly threefold in 1986–1994: from 1.34 to 3.91% (Nagornaya, 1995).

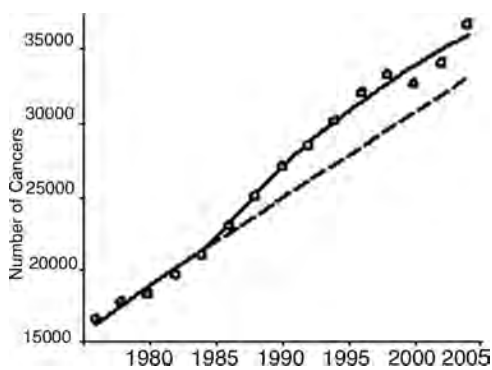

Figure 6.1. First-time-registered cases of cancer in Belarus from 1975 to 2005. Deviation from the trend after 1986 is very likely associated with additional Chernobyl-related cancers (Malko, 2007).

TABLE 6.4. Childhood Cancer Morbidity (per 100,000) in Tula Province under Various Levels of Contamination, 1995–1997 (Ushakova *et al.*, 2001)

Districts	Morbidity
"Clean"	7.2
≥3 Ci/km^2	18.8

4. Among male liquidators there were 5,396 cases of cancer from 1986 to 2004, whereas the expected number for that period was 793 (Prysyazhnyuk *et al.*, 2007).

5. Cancer morbidity for both men and women liquidators increased significantly from 1990 to 2004 (National Ukrainian Report, 2006).

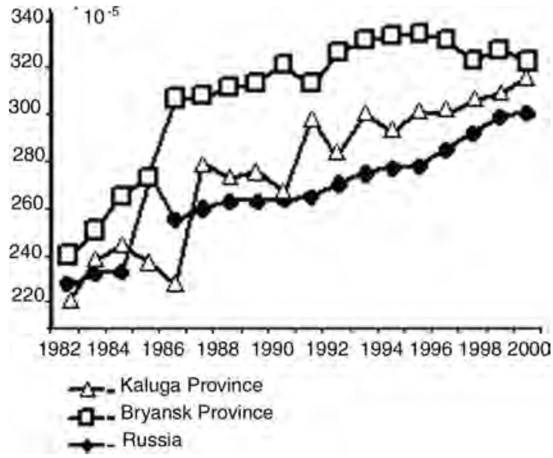

Figure 6.2. Comparison of the general cancer morbidity (per 100,000 for solid tumors) in heavily contaminated Bryansk Province to less contaminated Kaluga Province and to Russia (Ivanov and Tsyb, 2002).

6.1.3. Russia

1. In 1997 childhood cancer morbidity in the contaminated provinces of Bryansk, Oryol, Tula, Lipetsk, and Smolensk markedly exceeded that in all of Russia (Ushakova *et al.*, 2001).

2. Cancer morbidity in children from areas contaminated by Cs-137 of 3 Ci/km^2 or more in Tula Province increased 1.7-fold from 1995 to 1997 and was noticeably higher than in less contaminated areas (Table 6.4).

3. Within 5 years after the catastrophe the number of malignant neoplasms diagnosed for the first time in Bryansk and Oryol provinces increased 30% compared with the pre-Chernobyl period (Parshkov *et al.*, 2006).

4. In 1995 cancer morbidity in the heavily contaminated districts of Kaluga, Oryol, Tula, and Bryansk provinces was noticeably higher than in the less contaminated areas (Ushakov *et al.*, 1997).

5. General cancer morbidity for solid tumors in Bryansk Province has exceeded the country average since 1987, even according to official data (Figure 6.2).

6. Nine years after the catastrophe general cancer morbidity in districts contaminated by 15 Ci/km^2 or more in Bryansk Province was 2.7-fold higher than in the less contaminated areas (Ushakov *et al.*, 1997).

6.1.4. Other Countries

1. Bulgaria. According to official evaluations some 500 deaths were caused by Chernobyl-radiation-induced cancers (Dymitrova, 2007).

2. Poland. It has been estimated that during the next 50 years there will be an annual additional 740 to 6,600 cancer-related deaths owing to the catastrophe, which will account for about 1–9% of all cancer-related deaths in the country (Green Brigade, 1994).

3. Sweden. A multifaceted epidemiological study based on a comparison of hundreds of administrative units with different levels of Chernobyl Cs-137 contamination revealed unequivocally an increased incidence of all malignancies in northern Sweden, the most contaminated territory in that country (Tondel, 2007). "More than 1,000" cancer deaths in Norrland Province, Sweden, between 1986 and 1999 have been attributed to the Chernobyl fallout (Abdelrahman, 2007).

6.2. Thyroid Cancer

The initial reports of a rise in the incidence of thyroid cancer in 1991–1992 were criticized and the figures attributed to such factors as increased screening, random variation, and wrong diagnoses (for a review see Tondel, 2007).

The incidence of thyroid cancer requires special attention, as it is the most prevalent of all malignant neoplasms caused by the catastrophe. As the thyroid is a critical part of the endocrine system, the gland's dysfunction results in many other serious illnesses. The clinical and molecular features of thyroid cancers that developed following Chernobyl are unique. Chernobyl thyroid cancers virtually always occur in the papillary form, are more aggressive at presentation, and are frequently associated with thyroid autoimmunity. Furthermore, many have an unusual subtype with a large solid component, grow rapidly, and have high rates of local and remote metastases (Williams *et al.*, 2004; Hatch *et al.*, 2005; and many others). They also often precede or are accompanied by radiation-induced benign thyroid nodules, hypothyroidism, autoimmune thyroiditis, and thyroid insufficiency.

6.2.1. How Many People Have Thyroid Cancer?

In the first months after the catastrophe, only several additional cases were predicted, then hundreds, but then no more than several thousand. There is one common conclusion: without exception, numerous official forecasts were optimistic—all underestimated the figures for Chernobyl-induced thyroid cancers (*Economist*, 1996). The actual count of the thyroid cancer cases differs from one report and source to another, reflecting mostly real time changes but may also be due to more accurate diagnoses of the disease (Figure 6.3).

Figure 6.3. Annual thyroid cancer incidence rates in Belarus and Ukraine (per 100,000) for individuals who were children and adolescents in 1986 (Fairlie and Sumner, 2006).

6.2.1.1. Belarus

1. Thyroid cancer morbidity in children and adults has increased sharply in the country since 1990 (Figure 6.4).
2. Thyroid cancer morbidity in children and adults began to increase sharply after 1989, and childhood morbidity reached a maximum in 1995–1996, whereas that for adults continued upward until 2003 (Figure 6.5).
3. Childhood thyroid cancer morbidity increased 43-fold (~ 0.003–0.13 cases per 1,000) from 1989 to 1994 (Lomat' *et al.*, 1996).
4. After 20 years the incidence of thyroid cancer among individuals who were under 18 years

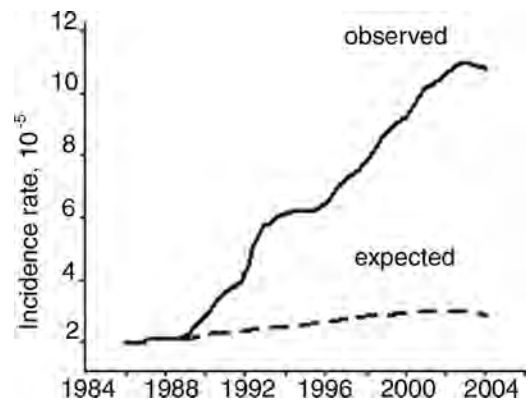

Figure 6.4. Prospective (by pre-Chernobyl data) and real data of thyroid cancer morbidity (per 100,000) for children and adults in Belarus (Malko, 2007).

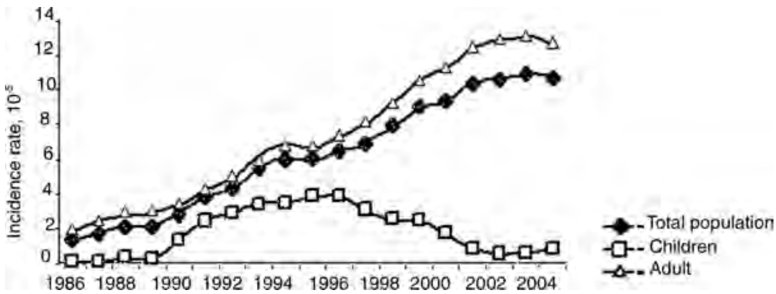

Figure 6.5. General thyroid cancer morbidity for Belarussian children and adults after the catastrophe (National Belarussian Report, 2006: fig. 4.1).

of age at the time of the catastrophe increased more than 200-fold (Figure 6.6).

5. Compared to the pre-Chernobyl period, by 2000 the number of cases of thyroid cancer in children had increased 88-fold; in teenagers, 12.9-fold; and in adults, 4.6-fold (Belookaya *et al.*, 2002).

6. By the year 2000, more than 7,000 people were registered as suffering from thyroid cancer, including more than 1,000 people who were children at the time of the catastrophe. Annually some 3,000 individuals undergo surgery for thyroid cancer (Borysevich and Poplyko, 2002).

7. Among 1,000 specially surveyed persons, 100 had thyroid nodules and among them two or three had cancer (Krysenko, 2002).

8. Congenital thyroid cancers have been diagnosed in newborns (Busby, 1995).

9. Summary data on some cases of thyroid cancer in Belarus are presented in Table 6.5.

Figure 6.6. Primary thyroid cancer morbidity among those age 0 to 18 years in 1986 (National Belarussian Report, 2006: fig. 4.2).

10. There were more cases of thyroid cancer in provinces that had a higher level of I-131 contamination (Figure 6.7).

6.2.1.2. Ukraine

1. Compared to the pre-Chernobyl period, the number of cases of thyroid cancer increased 5.8-fold from 1990 to 1995, 13.8-fold from 1996 to 2001, and 19.1-fold from 2002 to 2004 (Tronko *et al.*, 2006).

2. The prevalence of invasive forms of carcinoma (87.5%) indicates very aggressive tumor development (Vtyurin *et al.*, 2001). Clinically this is expressed by a short latency period, absence of general body signs or symptoms, and high lymphatic invasiveness. Some 46.9% of patients have their tumor spread beyond the thyroid. Regional metastasis into neck lymph nodes occurred in 55.0% of patients and these required repeated operations to remove residual metastases that appeared shortly after the initial operation. Moreover, 11.6% of patients developed remote lung metastases (Rybakov *et al.*, 2000; Komissarenko *et al.*, 2002).

3. Before the catastrophe, the occurrence of thyroid cancer among children and adolescents was 0.09 per 100,000; afterward, in 1990, it was 0.57–0.63 per 100,000. The greatest increase in morbidity was recorded in young people living in the most heavily contaminated districts of Kiev, Chernygov, Zhytomir, Cherkassk, and Rovno provinces (Komissarenko *et al.*, 1995). In these areas thyroid cancer morbidity reached 1.32 per 100,000 persons, which was five-fold higher than in other areas. Regression

TABLE 6.5. Number of Thyroid Cancer Cases in Belarus from Various Sources (Radiogenic Cases in Parentheses)

Number of cases, *n*	Period	Author	Comments
5,470 (3,748)	1987–1998	Ivanov & Tsyb, 2002: tab. 3.1, p. 213	Six most contaminated provinces (calculated by A. Yablokov, based on the pre-Chernobyl level)
(1,067)	1990–1998	UNSCEAR, 2000	In persons aged 0–17 years at the time of the meltdown
(4,409)	1986–2000	Malko, 2002	Including 700 in children
(674)	1986–2000	Demidchik *et al.*, 2002	In children aged 0–14 years
"More than 8,000"	1986–2000	Belookaya *et al.*, 2002	
"About 6,000 operated"	1997–2000	Drozd, 2001	Including 1,600 children
"More than 7,000" (1,000); 3,000 postsurgery cases annually	Up to 2001	Borysevich and Poplyko, 2002	In persons aged 0–17 years at the time of the meltdown
(2,430)	1986–2004		
(2,399)	1990–2004	National Belarussian Report, 2006*	In persons 0–18 years at the time of the meltdown
9,650 (4,560–6,840, average about 5,700)	Jan. 1987–Dec. 2002	Malko, 2004	In persons 0–14 years at the time of the meltdown
About 7,000	1986–2004	Malko, 2007	In persons 0–14 years at the time of the meltdown
8,161 (1,670)	1986–2001	Ostapenko, 2002	Belarussian Ministry of Health data
1,055 new cases	2002 alone	Postoyalko, 2004	
2,200 postsurgery children	1988–2004	Lypik, 2004	
More than 10,000 postsurgery (all ages)	1987–2004	Nesterenko, pers. comm.	Based on official data
12,136	1986–2004	Demidchik, 2006	

coefficients that reflect time trends are: all of Ukraine, 0.12 ± 0.01 (per 100,000 per year); Kiev Province, 0.41 ± 0.07; Kiev City, 0.52 ± 0.05; Zhytomir Province, 0.22 ± 0.03; other contaminated territories, 0.41 ± 0.06. The first cases of thyroid cancer in children under 14 years of age living in contaminated territories were registered in 1990. From 1980 to 1990 instances of this cancer were not tabulated and registered in the areas under study (Prysyazhnyuk *et al.*, 2005).

4. In the Chernygov, Kiev, and Zhytomir provinces from 1990 to 1999, where I-131 fallout was recorded, the incidence of thyroid cancer was dependent on the level of that fallout. Truncated age-standardized incidence rates in territories with contamination less than 100 kBq/m^2 did not exceed two and five cases per 100,000, respectively, in males and females. In territories with contamination greater than 100 kBq/m^2 the incidence was four and sixteen cases per 100,000, respectively, in males and females in 1998 and 1999 (Romanenko *et al.*, 2004; Prysyazhnyuk *et al.*, 2005).

5. A survey of 26,601 children in 1998 revealed that for each case of thyroid cancer there were 29 other thyroid pathologies (Shybata *et al.*, 2006).

6. According to the Ukrainian State Register for the period from 1982 to 2003 the incidence of thyroid cancer rose significantly after 1991 for three different cohorts studied: liquidators who worked 1986–1987, evacuees from Pripyat City and the 30-km exclusion zone, and residents in the radioactively contaminated areas (Prysyazhnyuk *et al.*, 2002).

7. Various estimations of the numbers of the thyroid cancer cases in Ukraine are presented in Table 6.6.

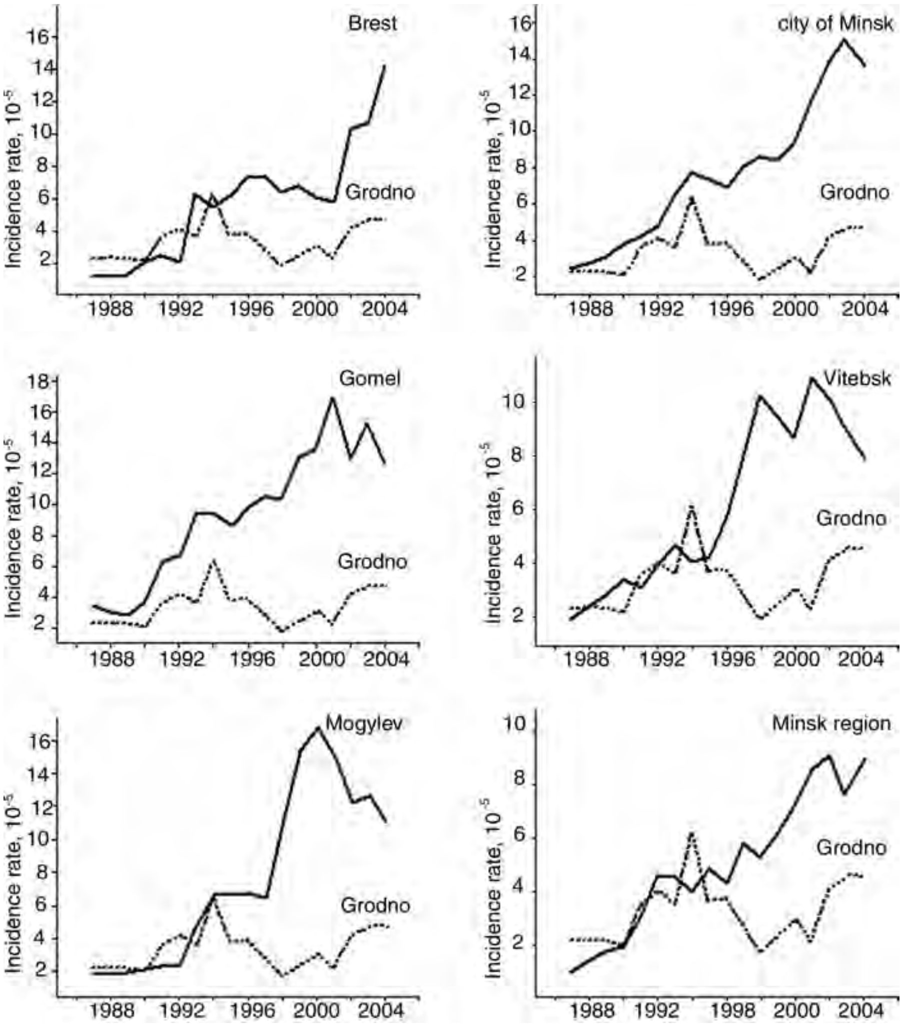

Figure 6.7. Thyroid cancer morbidity in five contaminated provinces of Belarus and Minsk compared to the least contaminated Grodno Province. The increase in cancer cases in the rather less contaminated Vitebsk Province and the city of Minsk may reflect the inflow of evacuees and refugees (Malko, 2007).

8. A sharp increase in cases of thyroid cancer began after 1989 in persons who were 0 to 18 years of age at the time of the catastrophe (Figure 6.8).

9. Thyroid cancer morbidity for women in the heavily contaminated territories is more than fivefold higher than for men (Figure 6.9).

10. In 1998–1999, thyroid cancer morbidity was significantly higher in territories contaminated at a level higher than 100 kBq/m^2 than in areas with levels of less than 100 kBq/m^2 (Prysyazhnyuk *et al.*, 2007). Incidence of thyroid cancer in various provinces is illustrated in Figure 6.10.

11. Thyroid cancer morbidity markedly increased in liquidators after 2001 (Law of Ukraine, 2006).

6.2.1.3. Russia

1. Thyroid cancer morbidity in the age group 0–30 years increased 1.5-fold from 1991 to 1998 (Ivanov and Tsyb, 2002).

2. From 1986 to 2000 thyroid cancer morbidity for the entire population of Bryansk

TABLE 6.6. Number of Thyroid Cancer Cases in Ukraine (Radiogenic Cases Parentheses)

Number of cases, *n*	Years	Author	Comments
1,420 (585)	1990–1997	UNSCEAR, 2000	Persons aged 0 – 15 years at the time of the meltdown
3,914	1986–1996	Dobyshevskaya *et al.*, 1996	Including 422 children
(937)	1986–1997	Interfax-Ukraine, 1998	Referring to official data
(1,217)	1986–1999	Associated Press, 2000	Referring to official data
(1,400)	1986–1999	Reuters, 2000	Referring to official data
(572)	1986–2000	Tronko *et al.*, 2002	Children aged 0–14 years
2,371 postsurgery	1986–2002	Tsheglova, 2004	Children aged 0–17 years at the time of the meltdown
2,674 postsurgery	1988–2004	Anonymous, 2005	Children
(585)	1990–2004	Prysyazhnyuk, 2007	
3,385	1986–2004	National Ukrainian Report, 2006: fig. 5.2	Children aged 0–18 years at the time of the meltdown (11 died)

Province increased 4.2-fold (3.3–13.8 cases per 100,000) and to 20.7 cases in children in the heavily contaminated districts (Kukishev *et al.*, 2001; Proshin *et al.*, 2005).

3. Thyroid cancer morbidity in Bryansk Province was twice that in Russia from 1988 to 1998 and triple that from 1999 to 2004 (Malashenko, 2005). The real level of thyroid cancer in Bryansk Province might be up to four times higher than the official 13.8 cases per 100,000 (Pylyukova, 2004).

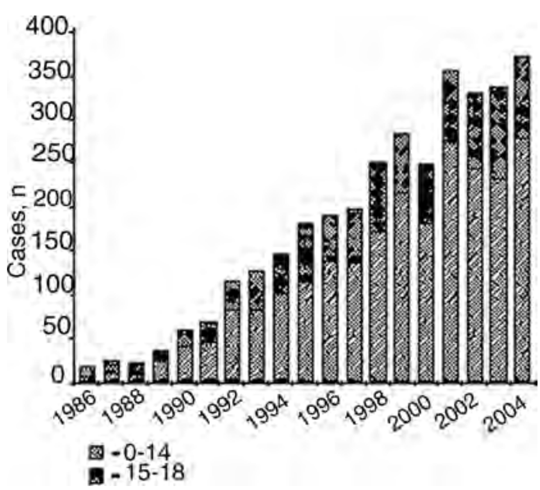

Figure 6.8. Number of thyroid cancer cases in Ukraine among persons who were 0 to 18 years of age at the time of the meltdown (National Ukrainian Report, 2006: fig. 5.2).

4. Since 1995 thyroid cancer morbidity in the southwest districts contaminated at a level higher than 5 Ci/km^2 has become significantly higher than the province's average (Kukishev *et al.*, 2001).

5. Thyroid cancer morbidity in children increased significantly in Tula Province from 1986 to 1997 compared with the years before the catastrophe (Ushakova *et al.*, 2001).

6. Since 1991, thyroid cancer morbidity in Bryansk Province began to increase sharply among individuals who were under 50 years of age at the time of the catastrophe. The relative risk of the disease for adults is twice that for children, and higher for women (Zvonova *et al.*, 2006).

7. There has been noticeable growth of thyroid cancer morbidity in children in the Ural region provinces since 1990 (Dobrynyna, 1998).

8. The thyroid cancer morbidity in Lipetsk City increased 3.4 times from 1989 to 1995 (Krapyvin, 1997).

9. In the 10 to 15 years after the catastrophe, thyroid cancer morbidity in Oryol Province increased eightfold (Parshkov *et al.*, 2006).

10. Thyroid cancer morbidity in both children and adults in Oryol Province increased sharply in the 6 to 8 years after the catastrophe (Kovalenko, 2004). The absolute number of cases in the province is shown in Figure 6.11.

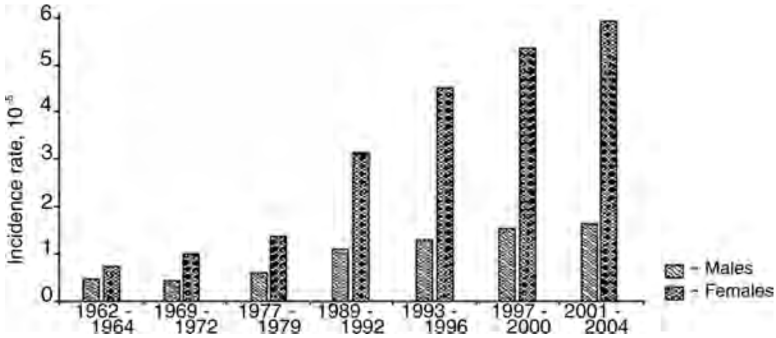

Figure 6.9. Thyroid cancer morbidity (per 100,000) in Ukraine for men and women from 1962 to 2004 (Prysyazhnyuk *et al.*, 2007).

11. The incidence of thyroid cancer in European Russia is presented in Table 6.7.

6.2.1.4. Other Countries

Globally an increased incidence of thyroid cancer has been reported in the last 20 years. Small tumors are discovered incidentally while exploring and treating benign thyroid diseases, which may be a reason for the increase, but this cannot account for most of the increase. For example, in the Marne-Ardennes French provinces, the percentage of malignant thyroid tumors smaller than 5 mm at diagnosis has increased 20% (from 7 to 27%) from 1975 to 2005. At the same time cancer incidence increased 360% in women and 500% in men (Cherie-Challine *et al.*, 2006).

A common argument against the "Chernobyl effect" of increasing thyroid cancer morbidity is that it does not correlate with the most contaminated areas in 1986. However, this argument is flawed. For example, the official view in France was that the I-131 contamination was primarily in the southeastern part of the county (Figure 6.12), but there are data showing that on some days there were heavier Chernobyl clouds over the northern part of the country, including the Marne-Ardennes provinces, where there was increasing incidence of thyroid cancer several years later. It is important to note that not only I-131, but other radionuclides can cause thyroid cancer.

1. Austria. An increase in the number of thyroid cancers began in 1990 and was especially high in the contaminated territories in 1995 (Weinisch, 2007).

2. Czech Republic. From 1976 to 1990 thyroid cancer morbidity grew 2% a year. From 1990 there was a significant increase in the rate of this cancer for both sexes to 4.6% a year (95% CI: 1.2–4.1, $P = 0.0003$). The values for women are markedly higher than those for men. Since Chernobyl there have been 426

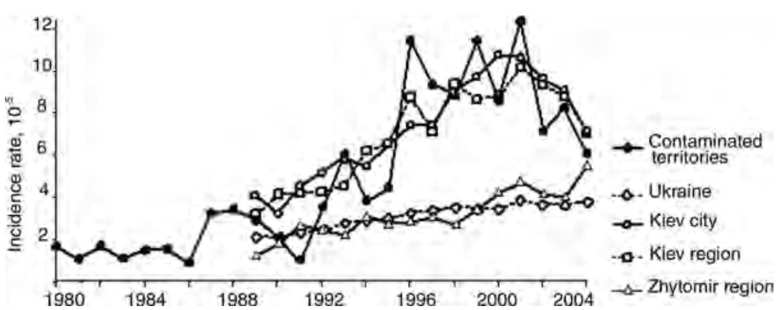

Figure 6.10. Thyroid cancer morbidity (per 100,000) in heavily contaminated Kiev Province and Kiev City and less contaminated Zhytomir Province (Prysyazhnyuk, 2007).

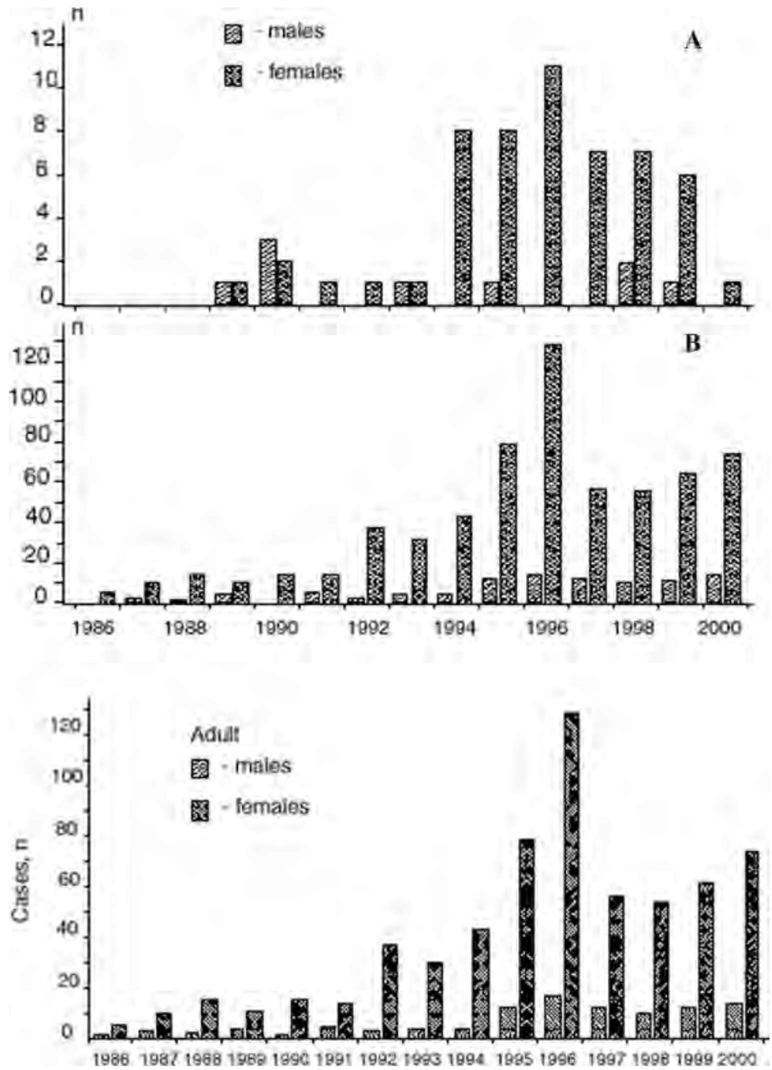

Figure 6.11. Absolute number of thyroid cancer cases in children and teenagers who were newborn to 18 years of age at the time of the meltdown (above) and among the adult population (below) in the Oryol Province from 1986 to 2000 (Golyvets, 2002).

TABLE 6.7. Number of Thyroid Cancer Cases in European Russia According to Various Sources (Radiogenic Cases in Parentheses)

Number of cases, *n*	Years	Author	Comments
4,173 (2,801)	1987–2000	Ivanov and Tsyb, 2002	Four most contaminated provinces (calculated by A. Yablokov based on the pre-Chernobyl level)
(205)	1990–1998	UNSCEAR, 2000	Whole country; persons aged 0–17 years at the time of the meltdown
1,591	1986–2000	Kukishev *et al.*, 2001	Bryansk Province (more than 50 times higher than for 1975–1985)
2,638	1986–2005	Malashenko, 2005	Bryansk Province
2,100 (1,071)	1991–2003	Tsheglova, 2004	Reference to A. F. Tsyb's oral message
("Nearly 1,800")	1986–1999	UNSCEAR, 2000	

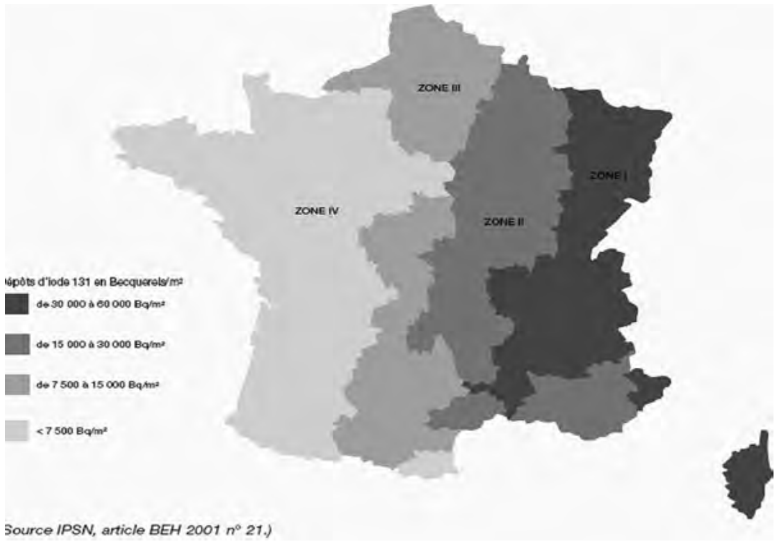

Figure 6.12. Total I-131 contamination of France originating from Chernobyl (Cherie-Challine *et al.*, 2006).

more cases of thyroid cancer in the Czech Republic alone (95% CI: 187–688) than had been predicted prior to the meltdown (Mürbeth *et al.*, 2004; Frentzel-Beyme and Scherb, 2007). After the catastrophe, the thyroid cancer incidence reveals an additional annual increase of up to 5% depending on age and gender (Frentzel-Beyme and Scherb, 2007).

3. FRANCE. From 1975 to 1995, the incidence of thyroid cancer increased by a factor of 5.2 in men and 2.7 in women (Verger *et al.*, 2003), but an association with the nuclear catastrophe was officially denied. By 1997–2001 the rate was significantly higher in Corsica for men and in Tarn for women. So, too, was the rate noticeably higher for women in Calvados and for men in Douds, Isere, and Marne-Ardennes provinces (Annual Report, 2006). Marne-Ardennes' data are especially interesting because they show the sharply increased incidence of thyroid cancer soon after the catastrophe (Figure 6.13), practically synchronous with the Belarussian data.

4. GREAT BRITAIN. Thyroid cancer morbidity noticeably increased in northern England and, especially, in the most contaminated areas of Cumbria, where it was up 12.2% (Cotterill *et al.*, 2001).

5. GREECE. For three years after the catastrophe, from 1987 to 1991, there was a significant increase in papillary thyroid cancer (more common in women), as well as mixed forms of cancer (Figure 6.14). An increased incidence of papillary carcinomas was seen after 1995, reaching the maximum value in the year 2000 and is likely associated with the Chernobyl fallout (Emmanuel *et al.*, 2007).

6. ISRAEL. Analysis of records of 5,864 patients from the Israel National Cancer

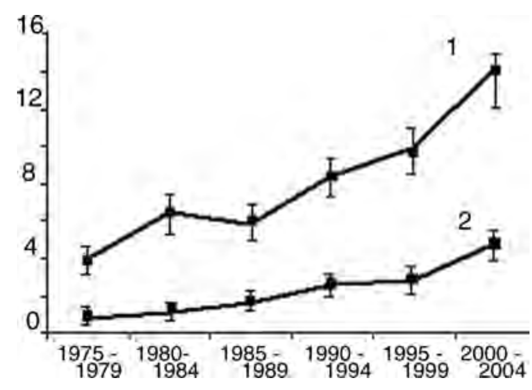

Figure 6.13. The thyroid cancer incidence (per 100,000) in the Marne-Ardenne provinces, France, for 1975–2004 (Cherie-Challine *et al.*, 2006). Upper curve – men, lower curve – women.

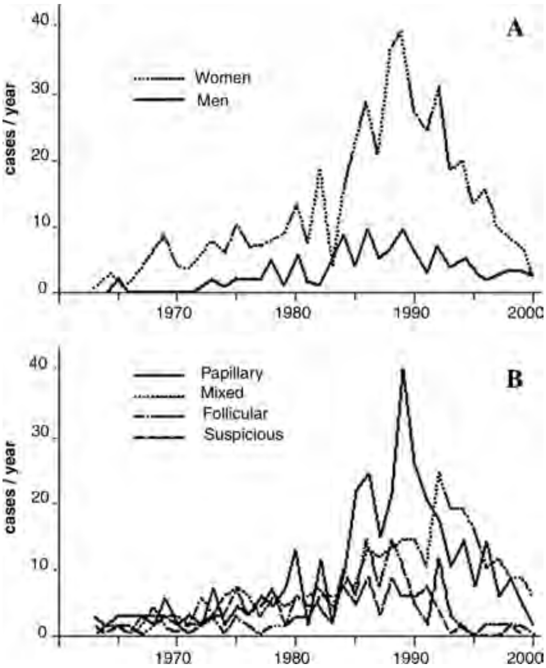

Figure 6.14. The incidence of the thyroid cancer by different histological types and by gender in Greece in 1963–2000 (Ilias *et al.*, 2002).

Registry reveal a significant increase in the age-standardized incidence rate (per 100,000) for thyroid cancer, due primarily to papillary carcinoma diagnosed between 1992 and 1996 in comparison with patients diagnosed earlier: 1982–1986 (86 vs. 78%, $P < 0.01$; Lubyna *et al.*, 2006). In spite of the author's conclusion that the reasons for this rise "may relate partly to increased diagnostic vigilance and changes in clinical practice," time trends, gender, and ethnicity do not preclude Chernobyl influence.

7. ITALY. There was a twofold increase in thyroid cancer morbidity from 1988 to 2002, especially expressed after 1992. It was claimed that this increased incidence was most likely due to improved and more powerful diagnostic techniques, not to Chernobyl-related factors, which "although possible, is not envisaged at this moment" (Pacini, 2007). However, it is noted that this conclusion was based on a cancer registry that included only 25.5% of the Italian population.

8. POLAND. There is a noticeable increase in thyroid cancer morbidity in contaminated territories among adolescents and adults (Szybinski *et al.*, 2001, 2005). Owing to the Chernobyl catastrophe an additional 80–250 thyroid cancer deaths are estimated to occur annually (Green Brigade, 1994).

9. ROMANIA. Thyroid cancer morbidity increased in the most contaminated areas of eastern Romania. This increase started in 1990, and by 1997–1998 was much higher than during the pre-Chernobyl years (Davydescu, 2004). The maximum incidence rate for thyroid cancer in Cluj City was registered in 1996—10 years after the catastrophe (Salagean *et al.*, 1998; Figure 6.15).

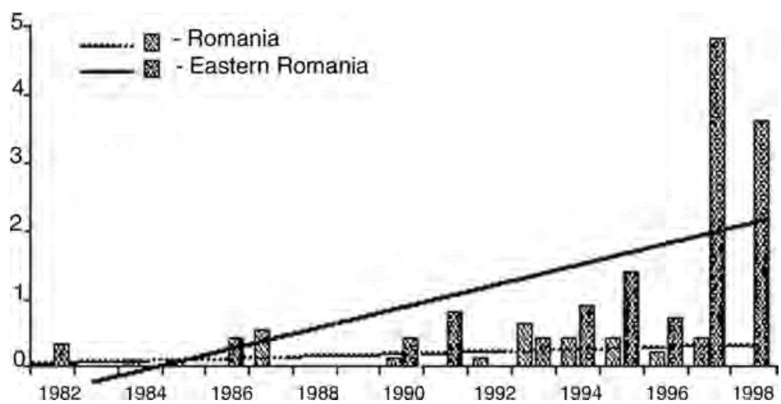

Figure 6.15. Thyroid cancer morbidity (cases per 10,000) in contaminated areas after the catastrophe in eastern Romania and the whole of Romania from 1982 to 1998 (Davydescu, 2004).

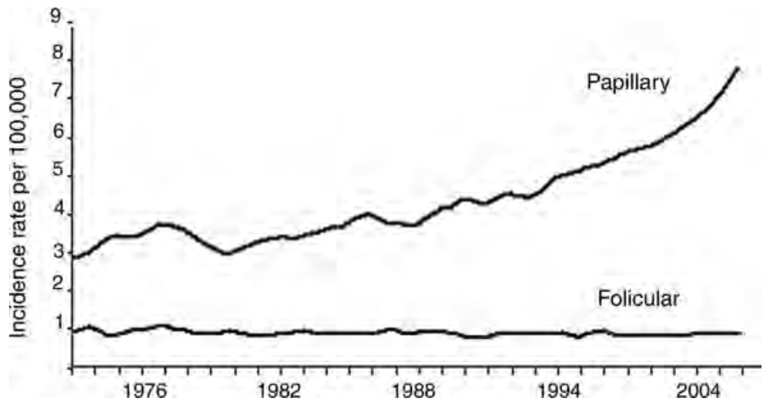

Figure 6.16. Papillary thyroid cancer incidence in women, United States from 1975 to 1997 (Wartofsky, 2006).

10. SWITZERLAND. Within-country geographical comparisons for current incidence rates by the Swiss Cancer Registries Network detected an increase over time for papillary cancers and a decrease for other types. Age-period-cohort analyses revealed that the youngest cohorts of men and women born after 1940 had an increased risk of all types of thyroid cancer, whereas the cohort of people born between 1920 and 1939 were at increased risk of the papillary subtype. As cautiously noted by F. Montanaro, "Assuming a higher sensitivity to ionizing radiation among the youngest people, a Chernobyl effect cannot be definitively excluded and continuous study of this topic should be encouraged" (Montanaro *et al.*, 2006).

11. UNITED STATES. From 1988 there was a marked increase in papillary thyroid cancer incidence in women (Figure 6.16), which may partly be explained by Chernobyl radiation. In Connecticut there were two separate fallouts of Chernobyl radionuclides (in the middle of May and the second half of June, 1986), resulting in a 7- to 28-fold increased level of I-131 in milk. The rate of thyroid cancer among Connecticut children under the age of 15 years rose sharply (from 0.16 to 0.31 per 100,000) from 1985–1989 to 1990–1992. During the same period rates of thyroid cancer for all age groups jumped to 23% (from 3.46 to 4.29 per 100,000), after 10 previous years without change (Figure 6.17).

6.2.2. How Many and When Will New Cases of Chernobyl Thyroid Cancer Occur?

In 1990, when the serious increase in the incidence of thyroid cancer in contaminated territories had already begun, official medical representatives from the Soviet Union indicated they expected 100 additional cases to be induced by the catastrophe's radiation (e.g., Ilyin *et al.*, 1990). The added risk of thyroid cancer after Hiroshima and Nagasaki radiation was highest 10 to 15 years later, with cases appearing 40 to 50 years afterward (Demidchik *et al.*, 1996). On this basis, it is predicted that the number of Chernobyl thyroid cancers will increase worldwide until 2011 (Tsyb, 1996; Goncharova, 2000). Various forecasts for future additional radiogenic thyroid cancers are shown in Table 6.8.

The calculations in Table 6.8 are based on the collective dose estimates and risk coefficients for I-131 by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and it is entirely possible that the determinations of collective doses were seriously underestimated (see, e.g., Fairlie and Sumner, 2006) and that the risk factors that were used were not reliable (Busby, 2004). One also has to consider that the thyroid cancers were caused not only by I-131, but also by other isotopes of iodine including I-129 and by Te-132, Ru-103, and Ru-106, as

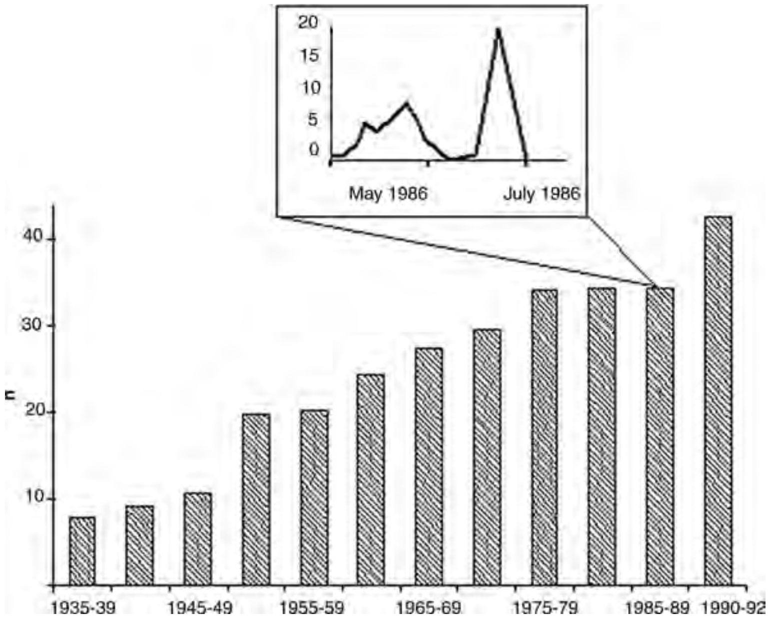

Figure 6.17. Thyroid cancer incidence in children (per 1,000,000), age adjusted rate 1935–1992, and I-131 concentration in milk for Connecticut (Reid and Mangano, 1995).

TABLE 6.8. Future Predicted Chernobyl-Induced Thyroid Cancers According to Various Sources

Number of cases	Period	Author	Comments
Belarus			
1,100 in boys, 2,300 in girls (whole country); 730 in boys, 1,500 in girls (Gomel Province)	Up to 2056	Demidchik *et al.*, 1999	In persons aged 0–17 years at the time of the meltdown
12,500 (whole country)	All time	Ostapenko, 2002; Fedorov, 2002	In persons aged 0–17 years at the time of the meltdown
15,000 (whole country)	Up to 2053	National Belarussian Report, 2003	
14,000–31,400 (whole country)	Up to 2056	Malko, 2007	
50,200 (Gomel province), "from above 5,000" (Mogilev Province)	All time	Brown, 2000	Data from the International Agency for Research on Cancer (IARC)
"Up to 50,000" (whole country)	All time	Krysenko, 2002; Fedorov, 2002	In today's adolescents and young people
Russia			
3,700 (Kaluga, Tula, and Oryol provinces)	All time	Brown, 2000	Data from the International Agency for Research on Cancer (IARC)
659 (Bryansk, Tula, Kaluga, Oryol, Kursk, Ryazan, and Leningrad provinces)	All time	Demidchik *et al.*, 1996	
Belarus, Ukraine, Russia			
50,330	All time	Malko, 1998	Including 5,230 fatalities
93,00–131,000	All time	Gofman, 1994b	

well as being a result of the adverse effects of Cs-134 and Cs-137. Therefore, the forecasts in Table 6.8 should be considered minimal estimates.

Based on real numbers of radiogenic cancers recorded for 1986–2000 in the contaminated territories of Belarus and Ukraine, V. Malko (2007) calculated a parity between the level of radiation and the number of additional cases due to the influence of that radiation (i.e., number of cancers vs. dose of radiation). This can also be done by comparing spontaneous, pre-Chernobyl and post-Chernobyl instances of cancer. The post-Chernobyl number is 5.5-fold higher than was predicted by most known international forecasts (Cardis *et al.*, 2006).

Malko also recalculated the relative number of cases of cancer per dose of Chernobyl radionuclide fallout on populations of European countries. The results of these calculations (as future instances of cancer and the related death toll) for the total lifetime of the "Chernobyl generation" (1986–2056) are presented in Table 6.9.

The confidence interval for all of Europe is 46,313–138,936 cases of thyroid cancer and 13,292–39,875 deaths (Malko, 2007: table 3). These calculations do not include the liquidators, of which a significant number (830,000) do not live in the contaminated territories. Malko's numbers could be lower owing to severe restrictions on the consumption of vegetables and milk in many European countries on the second and third days after the catastrophe. Conversely the number of cases may increase owing to exposure of several new generations to continuing Cs-137 radiation.

The prevalence and appearance of Chernobyl thyroid cancers differ widely from the Hiroshima and Nagasaki reference data. The Chernobyl thyroid cancers: (1) appear much earlier (not in 10, but in 3–4 years after irradiation); (2) develop in a much more aggressive form; and (3) affect not only children, but also adults at the time of irradiation.

It is mistaken to think that this cancer is easily treated surgically (Chernobyl Forum, 2006).

TABLE 6.9. Predicted Radiogenic Thyroid Cancer Cases and the Resultant Death Toll in Europe from 1986 to 2056 (Malko, 2007)

Country	Number of cases, *n*	Included fatalities
Belarus	31,400	9,012
Ukraine	18,805	5,397
Russia	8,626	2,476
Yugoslavia	7,137	2,048
Italy	5,162	1,481
Romania	3,976	1,141
Poland	3,221	924
Greece	2,879	826
Germany	2,514	721
Czech and Slovakia	2,347	674
Bulgaria	1,619	465
France	1,153	331
Switzerland	898	258
Austria	812	233
Great Britain	418	120
Finland	334	96
The Netherlands	328	94
Hungary	270	78
Belgium	239	69
Sweden	165	47
Norway	136	39
Ireland	100	29
Spain	54	15
Denmark	19	5
Luxembourg	13	4
Portugal	2	1
European Total	92,627	26,584
Included figures for Belarus, Ukraine, and Russia	58,831	16,885

In spite of the fact that the majority of victims undergo surgery, cancer continues to develop in approximately one-third of the cases (Demidchik and Demidchik, 1999). Moreover, without exception, despite surgical treatment, the person remains impaired for the rest of his/her life, completely dependent upon pharmacological supplements.

Lastly, thyroid cancer is only the tip of the iceberg for radiogenic thyroid gland disorders (see Section 5.3.2): for each case of cancer, one finds hundreds of cases of other organic thyroid gland diseases.

TABLE 6.10. Acute and Chronic Leukosis (Leukemia) Morbidity in Adults (per 100,000) in Gomel Province, 1993–2003 (National Belarussian Report, 2006)

	Whole province		Heavily contaminated districts	
Leukosis	Before	After	Before	After
Acute lymphoblastic	0.28 ± 0.07	0.78 ± 0.11**	0.35 ± 0.08	0.96 ± 0.28*
Acute nonlymphoblastic	1.23 ± 0.14	1.83 ± 0.11**	1.07 ± 0.132	2.30 ± 0.31**
Red cell leukemia	0.59 ± 0.11	0.93 ± 0.12	0.36 ± 0.13	1.25 ± 0.14***
All chronic leukoses	5.72 ± 0.32	8.83 ± 0.42***	5.91 ± 0.21	9.94 ± 0.75***
All leukoses	9.05 ± 0.22	11.79 ± 0.42***	9.45 ± 0.40	13.44 ± 0.69***

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

6.3. Cancer of the Blood—Leukemia

Radiogenic leukemia was detected in Hiroshima and Nagasaki a few months after the bombing and morbidity peaked in 5 years. The latency period for radiogenic leukemia is several months to years with the highest incidence occurring between 6 and 8 years after exposure (Sinclair, 1996). Owing to the secrecy and the official falsification of data that continued for 3 years after the catastrophe (see Chapter 3 for details), unknown numbers of leukemia cases in Ukraine, Belarus, and Russia were not included in any registry. These distortions should be kept in mind when analyzing the following data.

6.3.1. Belarus

1. There were 1,117 cases of leukemia in children 0 to 14 years old from 1990 to 2004 (National Belarussian Report, 2006).

2. Since 1992 (7 years after the catastrophe) there has been a significant increase in all forms of leukemia in the adult population. The higher rate of morbidity compared with the pre-Chernobyl data was observed in 1992–1994 (Ivanov *et al.*, 1996).

3. Primary lymphatic and blood-forming cancers significantly increased among male evacuees from 1993 to 2003 (National Belarussian Report, 2006).

4. Leukemia morbidity in Gomel Province adults increased significantly after the catastrophe (Table 6.10).

5. Since 1996 the number of preleukemia cases has increased. For the 1986–1987 liquidators there was a statistically significant additional number of instances of acute leukemia in 1990–1991 (Ivanov *et al.*, 1997).

6. There was a noticeable increase in lymphoid and blood-forming cancers in men and women across Belarus in the first 5 years after the catastrophe (Figure 6.18).

7. The highest incidence rate for acute and chronic leukemia and Hodgkin's disease occurred in the first 5 years after the catastrophe. The maximum increase in red cell leukemias, non-Hodgkin's lymphoma, and, especially, myelodysplastic syndrome occurred 10 years after the catastrophe. Incidence of all forms of leukemic disease was significantly higher after the catastrophe (Table 6.11).

8. There were nearly 2,300 cases of leukemia between 1986 and 2004 (Malko, 2007).

Figure 6.18. Lymphoid and blood-forming tumors in Belarus, 1985–1998: (upper curve) men, (middle) both sexes, (lower) women (Okeanov *et al.*, 2004).

TABLE 6.11. Leukemia Morbidity (per 100,000) among the Adult Population of Belarus, 1979–1997 (Gapanovich *et al.*, 2001)

Leukemia types	Number of cases, *n*	1979–1985	1986–1992	1993–1997
Acute leukemia	4,405	2.82 ± 0.10	3.17 ± 0.11*	2.92 ± 0.10
Chronic leukemia	11,052	6.09 ± 0.18	8.14 ± 0.31*	8.11 ± 0.26*
Erythremia	n/a	0.61 ± 0.05	0.8 ± 0.05*	0.98 ± 0.05*
Multiple myeloma	2,662	1.45 ± 0.06	1.86 ± 0.06*	2.19 ± 0.14*
Hodgkin's disease	4,870	3.13 ± 0.10	3.48 ± 0.12*	3.18 ± 0.06
Non-Hodgkin's lymphoma	5,719	2.85 ± 0.08	4.09 ± 0.16*	4.87 ± 0.15*
Myelodysplastic syndrome	1,543**	0.03 ± 0.01	0.12 ± 0.05*	0.82 ± 0.16*

*$P < 0.05$ from pre-Chernobyl status; **all cases of bone marrow depression.

9. There was a significant increase in leukemia morbidity for the elderly 15 years after the catastrophe (Medical Consequences, 2003).

10. After the catastrophe many forms of leukemic disease in adults significantly increased in Mogilev and Gomel provinces (Tables 6.12 and 6.13).

6.3.2. Ukraine

1. There was an increase in acute leukemia in children from the contaminated regions compared with clean areas 10 to 14 years after the catastrophe (Moroz, 1998; Moroz *et al.*, 1999; Moroz and Drozdova, 2000).

2. For children, leukemia morbidity began to increase in 1987 and peaked in 1996 (Horishna, 2005).

3. Leukemia incidence in 1986–1996 among Ukrainian children born in 1986 and thus exposed *in utero* in the contaminated areas of Zhytomir Province was compared with children born in the less contaminated Poltava Province. Risk ratios based on cumulative incidence show significant increases for all leukemia (rate ratio: 2.7, 95% CI: 1.9–3.8) and for acute lymphoblastic leukemia (rate ratio: 3.4, 95% CI: 1.1–10.4; Noshchenko *et al.*, 2001, 2002).

4. From 1993 to 1997 there were 652 cases of acute leukemia (AL) in Kiev City and Kiev Province, including 247 cases in children (Gluzman *et al.*, 1998).

5. Morbidity from leukemia in the heavily contaminated provinces was significantly elevated among children born in 1986 and the high morbidity continued for 10 years postexposure. Rates of acute lymphoblastic leukemia (ALL) were dramatically elevated for males and to a lesser extent for females. For both genders combined, the morbidity for ALL was

TABLE 6.12. Leukosis (Leukemia) (per 100,000) among the Adult Population in Mogilev and Gomel Provinces before and after the Catastrophe* (National Belarussian Report, 2006: tables 4.2 and 4.3)

	Mogilev Province		Gomel Province	
	1979–1985	1993–2003	1979–1985	1993–2003
Acute lymphoblastic leukosis	0.5 ± 0.1	0.8 ± 0.1	0.2 ± 0.07	0.8 ± 0.1
Acute nonlymphoblastic leukosis	0.3 ± 0.1	1.7 ± 0.2	1.2 ± 0.1	1.8 ± 0.1
Erythremia	0.4 ± 0.1	0.8 ± 0.1	0.6 ± 0.1	0.9 ± 0.1
Others chronic leukoses	0.2 ± 0.1	0.7 ± 0.1	0.2 ± 0.05	1.0 ± 0.1
All leukoses	9.8 ± 0.6	12.1 ± 0.4	9.1 ± 0.2	11.8 ± 0.4

*All differences are significant.

TABLE 6.13. Multiple Myeloma, Non-Hodgkin's Lymphoma, and Hodgkin's Disease Morbidity in Adults in Gomel and Mogilev Provinces before and after the Catastrophe (National Belarussian Report, 2006: table 4.4.)

	Mogilev Province		Gomel Province	
	1979–1985	1993–2003	1979–1985	1993–2003
Multiple myeloma	1.68 ± 0.15	2.39 ± 0.20*	1.24 ± 0.12	2.22 ± 0.14**
Hodgkin's disease	3.90 ± 0.14	3.06 ± 0.11**	2.95 ± 0.19	3.21 ± 0.23
Non-Hodgkin's lymphoma	2.99 ± 0.21	5.73 ± 0.25**	2.83 ± 0.20	5.57 ± 0.30**

*P <0.05; **P < 001.

more than threefold higher in the heavily contaminated provinces compared to those less contaminated (Noshchenko *et al.*, 2001).

6. In the children born in 1986–1987 who developed acute leukemia, an increasing relative number of acute myeloid leukemia (AML) cases were reported (21.2 and 25.3% in 1986 and 1987, respectively; Gluzman *et al.*, 2006).

7. During the first 4 years after the catastrophe, malignant blood diseases were significantly higher in the four most contaminated districts of Zhytomir and Kiev provinces compared with the pre-Chernobyl period and 1999–2000 (Figure 6.19).

8. Blood neoplasms were especially high in children during the first 5 years after the catastrophe, and among liquidators who worked in 1986–1987, the maximum incidence occurred 4 to 11 years after the catastrophe (Table 6.14).

9. During the first 4 years after the catastrophe there was an increase in myeloid leukemia in the first and third years; during the second 4 years there was a significant increase in lymphosarcoma and reticulosarcoma (Table 6.15).

10. There was a significant increase in the number of leukemia cases in liquidators 15 years after the catastrophe (National Ukrainian Report, 2006; Law of Ukraine, 2006).

11. The incidence of multiple myeloma among liquidators was twice as high as in the general population (7.8 vs. 4.0%). Five 1986–1987 liquidators were diagnosed with an unusual chronic lymphoproliferative disorder—large granular lymphocytic leukemia (Gluzman *et al.*, 2006).

6.3.3. Russia

1. Childhood leukemia morbidity increased in the Tula Province after the catastrophe (Table 6.16) and significantly exceeded the Russian average. Acute leukemia in children was especially high (Ushakova *et al.*, 2001).

2. In Bryansk Province all forms of leukemia and non-Hodgkin's lymphoma were

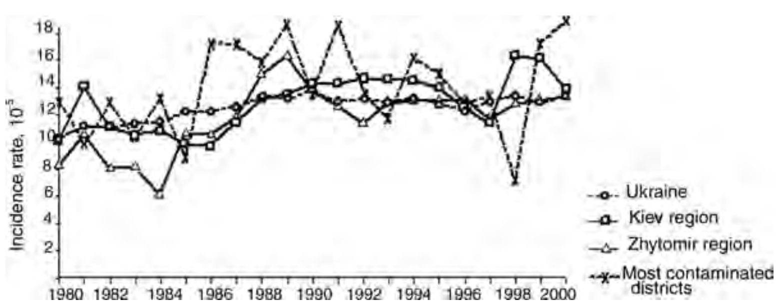

Figure 6.19. Leukemia and lymphoma morbidity (age adjusted, per 100,000, men and women) in Ukraine, 1980–2000 (Prysyazhnyuk *et al.*, 2002).

TABLE 6.14. Leukemia Morbidity (Standardized Data, per 100,000) in Ukraine (Prysyazhnyuk *et al.*, 2002)

Years	Person/ years	Number of cases Observed	Expected	SIR (%)
Leukemia, children, contaminated districts of the Kiev and Zhytomir provinces				
1980–1985	337,076	19	10.88	174.7
1986–1991	209,337	22	6.78	324.4
1992–1997	150,170	7	4.87	143.7
1998–2000	80,656	0	2.59	0.0
Leukemia and lymphoma, evacuees, men and women				
1990–1993	208,805	43	30.0	143.4
1994–1997	200,077	31	29.6	104.7
Leukemia and lymphoma, liquidators (1986–1987), men				
1990–1993	263,084	81	31.8	255.0
1994–1997	314,452	102	49.9	204.6

significantly higher 7 years after the catastrophe compared to the 6 years prior to the catastrophe (UNSCEAR, 2000).

3. A marked increase in acute lymphocyte leukemia occurred in the six most contaminated districts of Bryansk Province from 1986 to 1993 (Ivanov and Tsyb, 2002).

4. Since 1995 blood-related and lymphatic cancer morbidity in the southwest districts (contaminated by ≥ 5 Ci/km^2) was significantly higher than the province's average (Kukishev *et al.*, 2001).

5. From 1990 to 1994, children in Tula Province became ill significantly more often with tumors of the bone, soft tissue, and the central nervous system (Ushakova *et al.*, 2001).

6. In the city of Lipetsk, leukemia morbidity increased 4.5-fold from 1989 to 1995 (Krapyvin, 1997).

7. In 10 to 15 years after the catastrophe, lymphatic and blood-forming cancer morbidity doubled (Parshkov *et al.*, 2006).

8. Among liquidators, the first case of leukemia was officially registered in 1986; by 1991 there were already 11 such cases (Ivanov *et al.*, 2004: table 6.6).

9. In 10 to 12 years after the catastrophe the number of leukemia cases among 1986–1987 liquidators was double the average for the country (Tsyb, 1996; Zubovsky and Smirnova, 2000).

10. By 2004, lymphatic and blood-forming cancer morbidity in liquidators was twice as high as the country average (Zubovsky and Tararukhyna, 2007).

6.3.4. Other Countries

1. Germany. There was 1.5-fold increase in the incidence of leukemia among infants born in West Germany between July 1, 1986, and December 31, 1987 (Pflugbeil *et al.*, 2006).

2. Great Britain. In 1987 in Scotland leukemia in children under the age of 4 years rose by 37% (Gibson *et al.*, 1988; Busby and Scot Cato, 2000; Busby, 2006).

3. Greece. Infants born between July 1, 1986, and December 31, 1987, and exposed to Chernobyl fallout *in utero* had 2.6 times the incidence of leukemia compared to children

TABLE 6.15. Leukemia and Lymphoma Morbidity (per 10,000) in Five of the Most Contaminated Districts of Zhytomir and Kiev Provinces (Prysyazhnyuk *et al.*, 2002)

	Occurrence 1980–1985	1986–1991	1992–1997	1998–2000
Leukemia and lymphoma	10.12 ± 0.75	15.63 ± 1.06	13.41 ± 1.10	13.82 ± 1.52
Lympho- and reticulosarcoma	1.84 ± 0.33	2.70 ± 0.41	3.70 ± 0.58	3.36 ± 0.90
Hodgkin's disease	1.82 ± 0.34	2.47 ± 0.48	2.10 ± 0.48	1.23 ± 0.50
Multiple myeloma	0.54 ± 0.16	1.03 ± 0.25	0.78 ± 0.22	1.38 ± 0.40
Lymphoid leukemia	3.08 ± 0.40	4.93 ± 0.59	2.97 ± 0.49	4.11 ± 0.75
Myeloid leukemia	0.49 ± 0.17	1.99 ± 0.41	1.06 ± 0.30	2.32 ± 0.62

TABLE 6.16. Leukemia Morbidity (per 10,000) in Children of Tula Province, 1979–1985 and 1986–1997 (Ushakova *et al.*, 2001)

Years	Number of cases, *n*	95% CI
1979–1985	3.4	2.6–4.4
1986–1997	4.1	3.4–4.9

born between January 1, 1980, and December 31, 1985, and between January 1, 1988, and December 31, 1990. Elevated rates were also reported for children born in regions of Greece with higher levels of radioactive fallout (Petridou *et al.*, 1996).

4. ROMANIA. The incidence of leukemia in children born between July 1986 and March 1987 was significantly higher than for those born between April 1987 and December 1987 (386 vs. 173, $P = 0.03$). The most noticeable effect is in the newborn to 1-year-old age group (Davydescu *et al.*, 2004).

5. EUROPE. Realistic prognosis of blood cancer (all leukemias) morbidity and mortality is shown in Table 6.17.

TABLE 6.17. Predicted Incidence of Radiogenic Blood Cancer (Leukemia) and the Resultant Death Toll in Europe for the "Chernobyl Generation," 1986–2056 (Malko, 2007)

Country	Number of cases, *n*	Including fatalities
Ukraine	2,801	1,989
Belarus	2,800	1,988
Russia	2,512	1,784
Germany	918	652
Romania	517	367
Austria	500	355
Great Britain	423	300
Czech Republic	140	99
Italy	373	265
Bulgaria	289	205
Sweden	196	139
Greece	186	132
Poland	174	124
Finland	158	112
Switzerland	151	107
Moldova	131	93
France	121	86
Slovenia	95	67
Norway	91	65
Slovakia	71	50
Hungary	62	44
Croatia	62	44
Lithuania	42	30
Ireland	37	26
The Netherlands	13	9
Belgium	11	8
Spain	8	6
Latvia	7	5
Denmark	7	5
Estonia	6	4
Luxembourg	2	1
European total	12,904	9,161
Included figures for Belarus, Ukraine, and Russia	8,113	5,761

6.4. Other Cancers

There are many fragmentary reports about the increased occurrence of breast, lung, and other tumors after the Chernobyl catastrophe.

6.4.1. Belarus

1. Malignant and nonmalignant neoplasms in girls (0–14 years old) born to irradiated parents increased significantly from 1993 to 2003 (National Belarussian Report, 2006).

2. From 1987 to 1990 (3 years after the catastrophe) there was a doubling of admissions to the Minsk Eye Microsurgery Center to treat retinal glioma (retinoblastoma; Byrich *et al.*, 1994).

3. Lung cancer morbidity among the evacuees (about 32,000 examined) was fourfold higher than the country average (Marples, 1996).

4. From 1987 to 1999, approximately 26,000 cases of radiation-induced malignant neoplasms (including leukemia) were registered in the country, of which skin cancer accounted for 18.7% of the cases, lung cancer 10.5%, and stomach cancer 9.5%. Approximately 11,000 people died, 20.3% because of lung cancer and 18.4% from stomach cancer (Okeanov *et al.*, 1996; Goncharova, 2000).

5. From 1990 to 2003, breast cancer morbidity rates in the districts of Gomel Province

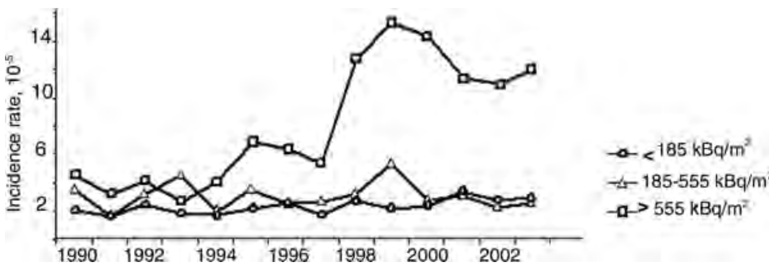

Figure 6.20. Breast cancer morbidity (women, per 100,000) in Gomel Province with various levels of Cs-137 contamination (National Belarussian Report, 2006).

contaminated by Cs-137 at a level of 185–555 kBq/m^2 and above were significantly higher compared with districts contaminated at levels lower than 185 kBq/m^2 (respectively, 30.2 ± 2.6; 76 ± 12; and 23.2 ± 1.4 per 100,000; Figure 6.20).

6. The incidence of breast cancer increased significantly from 1986 to 1999 for the entire country (1,745 to 2,322 cases; Putyrsky, 2002). By 2002 breast cancer morbidity in women 45 to 49 years of age increased 2.6-fold for the whole country compared with 1982. In the more contaminated Mogilev Province breast cancer increased fourfold from 1993 to 1996 compared with the period from 1989 to 1992 (Putyrsky and Putyrsky, 2006).

7. In the heavily contaminated Gomel Province there was a marked increase in the number of cases of intestinal, colon, breast, bladder, kidney, and lung cancers, and the occurrences correlated with the level of Chernobyl contamination (Okeanov *et al.*, 1996; Okeanov and Yakymovich, 1999).

8. For the second quinquennium after the catastrophe there was a 10-fold increase in the number of cases of pancreatic cancer compared with the first quinquennium (UNCSEAR, 2000, point 258, p. 52).

9. Primary malignant intestinal neoplasms significantly increased among woman evacuees from 1993 to 2003 (National Belarussian Report, 2006).

10. From 1993 to 2003 general cancer morbidity increased significantly among men and women from heavily contaminated territories, with the annual rate of increase being higher for women (18%) than for men (4.4%; National Belarussian Report, 2006).

11. The makeup of cancer morbidity changed markedly after the catastrophe: the proportion of stomach tumors decreased, whereas thyroid, lung, breast, urogenital system, colon, and rectal cancers increased (Malko, 2002).

12. From 1993 to 2003 there was a significant increase in morbidity due to malignancies of the intestines, respiratory organs, and urinary tracts in men and woman liquidators (National Belarussian Report, 2006).

6.4.2. Ukraine

1. The number of children with central nervous system neoplasms (including malignant forms) increased from 1987 to 1994. The number of children admitted to the Ukrainian Institute of Neurosurgery in Kiev with brain tumors (data on 1,699 children, aged 0 to 6 years) from 1987 to 1991 increased 63.7% compared with the period from 1981 to 1985 (Orlov, 1993, 1995; Orlov and Sharevsky, 2003; Figure 6.21).

2. After the catastrophe there were significant increases in bladder cancer in men in the contaminated territories (Romanenko *et al.*, 1999).

3. The incidence of breast cancer in the most radioactively contaminated territories was almost stable from 1980 to 1992 and lower than in the large comparison areas (the whole of Ukraine, Kiev area, and Zhytomir Province). Then, from 1992 to 2004, the rate increased

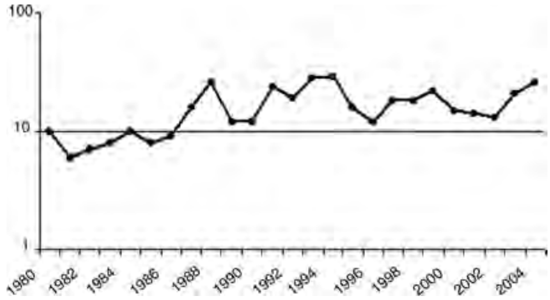

Figure 6.21. Central nervous system tumor cases (per 10,000) in children under 3 years of age, Ukrainian Institute of Neurosurgery data for the period 1980–2005 (Orlov *et al.*, 2006).

in the contaminated territories (Prysyazhnyuk *et al.*, 2007). Morbidity due to breast cancer in women living in the contaminated areas and among those evacuated increased 1.5-fold from 1993 to 1997 (Moskalenko, 2003; Prysyazhnyuk *et al.*, 2002).

4. There is an increase in breast cancer in premenopausal women from contaminated areas of Ukraine close to Chernobyl, compared with the general Ukrainian female population (standardized incidence ratio: 1.50, 95% CI: 1.27–1.73; Prysyazhnyuk *et al.*, 2002, cited by Hatch *et al.*, 2005).

5. Breast cancer morbidity in women in the contaminated territories and among liquidators and evacuees increased significantly from 1990 to 2004 (Moskalenko, 2003; National Ukrainian Report, 2006; Prysyazhnyuk *et al.*, 2007).

6. Prostate cancer mortality increased in the contaminated territories up to 2.2-fold and across all of Ukraine 1.3-fold (Omelyanets *et al.*, 2001).

7. The Kiev Interdepartmental Expert Commission revealed that for liquidators, digestive system tumors were the most common type of cancer (33.7%), followed by tumors of the respiratory system (25.3%), and tumors of the urogenital tract (13.1%). The fastest increase in cancer pathology was for the urogenital tract, for which an almost threefold increase (from 11.2 to 39.5%) was observed from 1993 to 1996 (Barylyak and Diomyna, 2003).

8. The rate of oncological illnesses in liquidators' mortality increased from 9.6 to 25.2% during the period from 1987 to 2004. For Ukrainian adults in 2004 the rate was 9.9% (Horishna, 2005).

9. A significant increase in urinary tract and bladder cancers was found in the contaminated territories of Ukraine (Romanenko *et al.*, 1999). In the period from 1987 to 1994, an increase in the number of children suffering from tumors of the nervous system was observed (Orlov, 1995).

10. From 1999 to 2004 cancer mortality in liquidators exceeded similar parameters among the rest of the population (Law of Ukraine, 2006).

6.4.3. Russia

1. There was a noticeable increase in respiratory tract tumors in women in the most contaminated areas of Kaluga Province (Ivanov *et al.*, 1997).

2. Since 1995 in southwest districts contaminated at levels higher than 5 Ci/km^2, there has been a significantly larger incidence of some cancers of the stomach, lung, breast, rectum, and colon than the province average (Kukyshev *et al.*, 2001).

3. The incidence of oral cavity, pharyngeal, and adrenal cancers in Tula Province children increased more than twofold from 1986 to 1997 compared to the period from 1979 to 1985 (Table 6.18).

4. Since 1990–1994 the incidence of tissue, bone, and central nervous system cancers in Tula Province children has been significantly higher (Ushakova *et al.*, 2001).

5. Melanoma of the skin increased fivefold and the incidence of brain cancer tripled in the first 10 to 15 years after the catastrophe (Parshkov *et al.*, 2006).

6. Infant mortality in the contaminated provinces differs from the country as a whole, with an increase in leukemia and brain tumors in both boys and girls (Fedorenko *et al.*, 2006).

TABLE 6.18. Increase in Morbidity owing to Various Cancers in Children of Tula Province after the Catastrophe (Ushakova *et al.*, 2001)

Cancer site	Oral cavity and pharynx	Adrenal glands	Skin	Kidneys	Genitalia (male)	Bones and soft tissues	Bladder	All cancers
1986–1997 compared with 1979–1985, %	225%	225%	188%	164%	163%	154%	150%	113%

7. As of 2004, kidney and bladder cancers were the most prevalent malignancies among liquidators, accounting for 17.6% of all malignant neoplasms, double the country average of 7.5%. Brain and laryngeal tumors also were widespread (Khrysanfov and Meskikh, 2001; Zubovsky and Tararukhyna, 2007).

6.5. Conclusions

UNSCEAR, along with other international organizations loyal to the nuclear industry, estimated the future number of fatal cancers owing to Chernobyl irradiation to be between 22,000 and 28,000, or even as few as 9,000 (Chernobyl Forum, 2006). At the time that report was issued, the number of deaths had already risen, but UNSCEAR unequivocally underestimated the number of deaths by basing its figures on false risk factors and understated collective doses (for details see Busby *et al.*, 2003; Fairlie and Sumner, 2006). Tables 6.19 and 6.20 present the results of more realistic mortality and morbidity calculations for Europe and the world.

Using the methodology described above for analyses of thyroid cancers (see Section 6.2), M. Malko has made the most detailed prognosis of Chernobyl-related cancers in Europe and the consequent mortality over the lifespan of the "Chernobyl generation" (1986–2056). Prognoses for the solid cancers are given in Table 6.21 and those for leukemia were shown earlier in Table 6.17.

Table 6.21 presents the average data. The confidence limits for the incidence of cancer are between 62,206 and 196,611, and the death toll is between 40,427 and 121,277 (Malko, 2007). These numbers could increase for many future generations because of continued radiation from the further release of Cs-137, Sr-90, Pu-241, Am-241, Cl-36, and Tc-99.

Undoubtedly, the above forecasts are incomplete. The fact is that for some years after the catastrophe, there was a marked increase,

TABLE 6.19. Predicted Cancer Morbidity and Mortality (Excluding Leukemia**) Caused by the Chernobyl Cs-137 for Future Generations* (Gofman, 1994b: vol. 2, ch. 24, p. 5)

Region	Number of cases: Lethal	Nonlethal
Belarus, Ukraine, Moldova	212,150	212,150
Europe (without CIS)	244,786	244,786
Other countries	18,512	18,512
Total	475,368	475,368

*On the basis of an expected collective dose "indefinitely" of 127.4 million person/rad; **Global death rate from Chernobyl leukemia by J. Gofman calculation as of 1994: 19,500 persons.

TABLE 6.20. Predicted Additional Chernobyl Cancer Morbidity and Mortality in Belarus, Ukraine, and European Russia* (Malko, 1998)

Cancer	Belarus	Russia	Ukraine
Thyroid—morbidity	20,300	8,000	24,000
Thyroid—mortality	2,030	800	2,400
Leukemia—mortality	1,300	760	1,550
Malignant tumors, other than thyroid—mortality	12,700	7,400	15,100
Total mortality	16,030	8,960 44,040	19,050

*Entire world: 90,000 lethal cancers.

TABLE 6.21. Predicted Incidence of Cancer Caused by Chernobyl and the Resultant Death Toll in Europe from 1986 to 2056 (Malko, 2007)

	Number of cases	
Country	All	Fatalities
Belarus	28,300	17,546
Ukraine	28,300	17,546
Russia	25,400	15,748
Germany	9,280	5,754
Romania	5,220	3,236
Austria	5,050	3,131
Great Britain	4,280	2,654
Italy	3,770	2,337
Bulgaria	2,920	1,810
Sweden	1,980	1,228
Greece	1,880	1,166
Poland	1,755	1,088
Finland	1,600	992
Switzerland	1,530	949
Czech Republic	1,410	874
Moldova	1,320	818
France	1,220	756
Slovenia	960	595
Norway	920	570
Slovakia	715	443
Croatia	630	391
Hungary	625	388
Lithuania	420	260
Ireland	375	233
The Netherlands	135	84
Belgium	110	68
Spain	80	50
Latvia	75	47
Denmark	70	43
Estonia	60	37
Luxembourg	15	9
European total	130,405	89,851
Included figures for Belarus, Ukraine, and European Russia	82,000	50,840

which is still in evidence, in the incidence of various malignant neoplasms in all of the territories subjected to Chernobyl fallout—that is, where adequate studies have been carried out.

Even the incomplete data now available indicate the specific character of cancers caused by Chernobyl. The onset of many cancers began not after 20 years, as in Hiroshima and Nagasaki, but in only a few years after the explosion. The assumption (e.g., Pryasyaznjuk *et al.*, 2007) that Chernobyl's radioactive influence on the incidence of malignant neoplasms will be much weaker than that of the Hiroshima and Nagasaki radiation is very doubtful. In Chernobyl's contaminated territories the radioactive impact may be even greater because of its duration and character, especially because of irradiation from internally absorbed radioisotopes.

The number of illnesses and deaths determined by Malko's (2007) calculations cannot be dismissed as grossly overestimated: 10,000–40,000 additional deaths from thyroid cancer, 40,000–120,000 deaths from the other malignant tumors, and 5,000–14,000 deaths from leukemia, for a total of 55,000 to 174,000 deaths for the "Chernobyl generation" from 1986 to 2056.

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7. Mortality after the Chernobyl Catastrophe

Alexey V. Yablokov

A detailed study reveals that 3.8–4.0% of all deaths in the contaminated territories of Ukraine and Russia from 1990 to 2004 were caused by the Chernobyl catastrophe. The lack of evidence of increased mortality in other affected countries is not proof of the absence of effects from the radioactive fallout. Since 1990, mortality among liquidators has exceeded the mortality rate in corresponding population groups. From 112,000 to 125,000 liquidators died before 2005—that is, some 15% of the 830,000 members of the Chernobyl cleanup teams. The calculations suggest that the Chernobyl catastrophe has already killed several hundred thousand human beings in a population of several hundred million that was unfortunate enough to live in territories affected by the fallout. The number of Chernobyl victims will continue to grow over many future generations.

Twenty years after the Chernobyl catastrophe, apart from several limited studies among specific groups and in isolated territories dealing primarily with the incidence of cancer (see Chapter 6), there are no official publications on mortality in areas affected by the nuclear fallout. There is strong evidence of radiation effects on cancer and noncancer mortality based on the Hiroshima data (Preston *et al.*, 2003). The analysis in this chapter is based on studies of territories with comparable ethnic, social, and economic factors but with different levels of radioactive contamination. Since the breakup of the Soviet Union, but even as early as 1987, life expectancy there has decreased significantly (Figure 7.1), whereas the decline in infant mortality has leveled off.

7.1. Increase in Antenatal Mortality

Irradiation has an adverse effect on the ovum and the sperm, as well as on the embryo. The major observable components of antenatal mortality are spontaneous abortions or miscarriages (spontaneous interruption of pregnancy until the 27th week) and stillbirths (after 27 weeks). Increased numbers of stillbirths and miscarriages are among the first effects of irradiation, with a delay of only some weeks or months after exposure. These effects can occur after exposure to very low doses, that is, at whole body doses as low as 5 mSv (Loganovsky, 2005), but the reasons are not yet understood. As a rule, spontaneous abortions are not registered, so a change in that rate can only be determined indirectly from a reduction in the birth rate. Long before the Chernobyl catastrophe, increases in antenatal mortality were found in the wake of the nuclear fallout from atmospheric weapons tests (Sternglass, 1972; Whyte, 1992; Playford *et al.*, 1992; Tchasnikov, 1996; Tkachev *et al.*, 1996; and many others; for reviews see C. Busby, 1995; A. Yablokov, 2002; A. Durakovič, 2003; and A. Körblein, 2004b).

7.1.1. Belarus

1. The incidence of stillbirths in highly contaminated territories increased (Golovko and Izhevsky, 1996; Figure 7.2).

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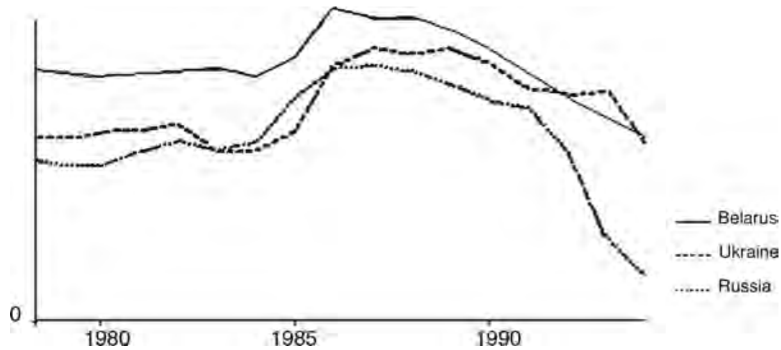

Figure 7.1. Average life expectancy for newborn males, 1961–2000, in Belarus, Ukraine, and Russia (//www.demoscope.ru/weekly/ssp/geO.php?c2).

2. In 1987, a significant reduction in the birth rate was observed in Gomel Province, the most contaminated region of Belarus (Kulakov *et al.*, 1993).

7.1.2. Ukraine

1. In the Ukrainian districts of Polessk and Cherkassk, there was a significant increase in the incidence of stillbirths, which was associated with the level of Cs-137 ground contamination. The study was based on more than 7,000 pregnancies 3 years before and 5 years after Chernobyl (Kulakov *et al.*, 1993).

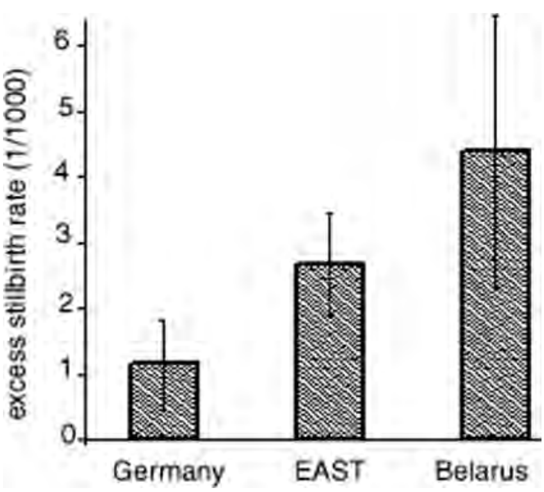

Figure 7.2. Excess stillbirth rate in 1987 in Sweden, Poland, Hungary, and Greece combined (EAST); Germany; and Belarus (Körblein, 2000, 2003). The error bars show one standard deviation.

2. In Kiev Province, a significant increase in spontaneous abortions was found in the more highly contaminated areas. The study was based on 66,379 pregnancies from 1999 to 2003 (Timchenko *et al.*, 2006).

3. After 1986, the prevalence of ovarian hypofunction (one of the main causes of spontaneous abortion) increased by a factor of 2.9 (Auvinen *et al.*, 2001).

4. After Chernobyl, the number of spontaneous abortions increased significantly in the Narodychy District (Buzhievskaya *et al.*, 1995).

5. Until 2004, the estimated total number of miscarriages and stillbirths in Ukraine as a result of Chernobyl was about 50,000 (Lypic, 2004).

7.1.3. Russia

1. The number of spontaneous abortions in the contaminated territories increased significantly after Chernobyl (Buldakov *et al.*, 1996).

2. In Kaluga Province, the rate of spontaneous abortions increased significantly 5 years after Chernobyl in the three most contaminated districts (Medvedeva *et al.*, 2001).

3. In the three most contaminated districts of Kaluga Province the stillbirth rate increased significantly from 1986 to 1990 relative to the rate before Chernobyl, and it continued to be higher than in less contaminated districts for the whole 15-year study period (Figure 7.3).

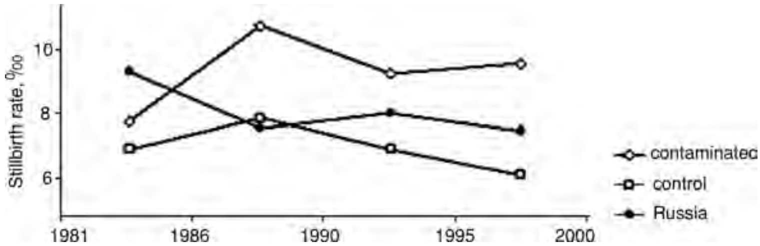

Figure 7.3. Stillbirth rate (per 1,000 live births plus stillbirths) with higher and lower contamination in districts of the Kaluga Province, and in Russia, during 1981–1986, 1986–1990, 1991–1995, and 1996–2000 (Tsyb *et al.*, 2006).

7.1.4. Other Countries

1. CROATIA. Stillbirth rates from 1985 to 1990 show significant peaks observed at the end of 1986 and the beginning of 1987 and around September 1988 (Figure 7.4). The second peak in 1988 may have resulted from the consumption of contaminated beef.

2. CZECH REPUBLIC. In the sex ratio of newborns the percentage of males was higher than 50% each month between 1950 and 1999, except in November 1986, when it was significantly reduced (Figure 7.5). The hypothesis is that there is a negative effect of the Chernobyl catastrophe on male fetuses during the third month of prenatal development (Peterka *et al.*, 2004).

3. GERMANY. In the former Federal Republic of Germany (excluding Bavaria and West Berlin), the area of the former German Democratic Republic (including West Berlin), and Bavaria alone, the excess perinatal mortality in 1987 was 2.4, 7.2, and 8.5%, respectively. In 1988 in the German Democratic Republic plus West Berlin, the perinatal mortality rate exceeded the expected figure by 7.4% (Figure 7.6.), which was presumably a consequence of the consumption of contaminated canned beef imported from the Soviet Union (Scherb *et al.*, 2000).

In 1987 in the 10 most affected districts of Bavaria (average Cs-137 ground level, 37.2 kBq/m^2), there was a 45% increase in the proportion of stillbirths ($P = 0.016$); in the three most contaminated Bavarian districts combined (Augsburg City, Berchtesgaden, and Garmisch Partenkirchen), the stillbirth proportion in that year was more than double relative

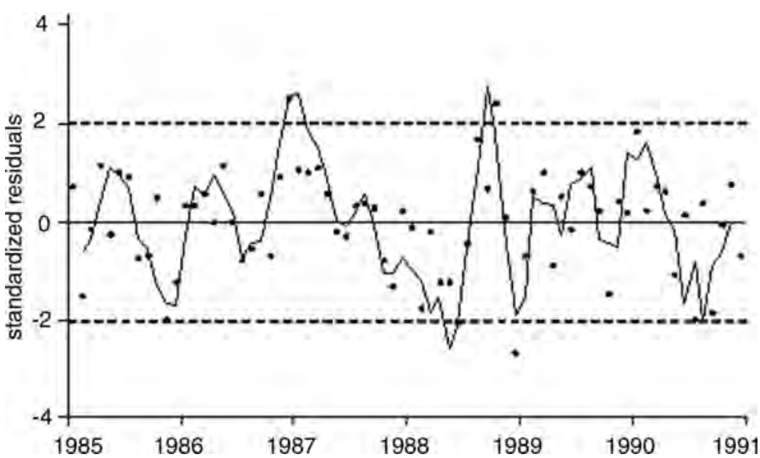

Figure 7.4. Deviation of stillbirth rates in Croatia 1985 to 1991 from the long-term trend in units of standard deviation (standardized residuals; Körblein, 2008).

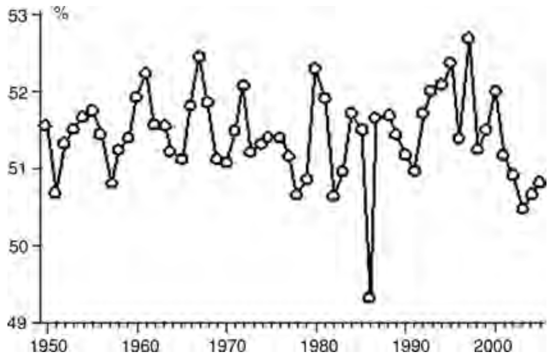

Figure 7.5. The percentage of infant boys born in the Czech Republic each November from 1950 to 2005. Only in November 1986 is the figure less than 50% (Peterka *et al.*, 2007).

to the expected figure ($P = 0.0004$; Scherb *et al.*, 2000).

4. GREAT BRITAIN. A significant increase in perinatal mortality occurred in March 1987, some 10 months after the catastrophe in the three most contaminated counties of England and Wales: Cumbria, Clwyd, and Gwynedd (Figure 7.7).

5. GREECE. A 10% reduction in the birth rate was observed from January to March 1987, which was attributed to the Chernobyl fallout. In May 1986, some 23% of early pregnancies were aborted for fear of an adverse pregnancy outcome (Trichopoulos *et al.*, 1987).

6. FINLAND. There was an increase in stillbirth rates from December 1986 through January 1987, which, however, was not significant (Auvinen *et al.*, 2001). There was a significant rise in preterm deliveries among infants who were exposed to radiation *in utero* during the first trimester of pregnancy (Harjulehto *et al.*, 1989).

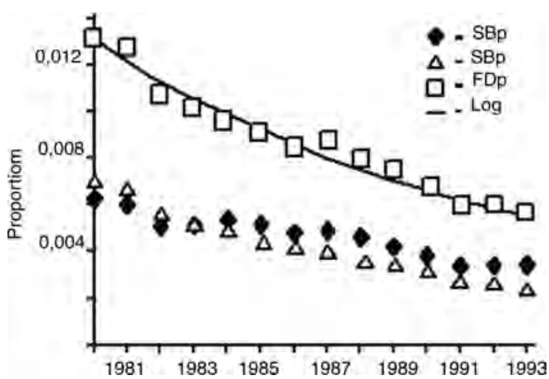

Figure 7.6. Perinatal mortality in Germany, the Federal Republic of Germany, and Bavaria (Scherb *et al.*, 2000).

7. HUNGARY. Birth rates were reduced in February and March 1987 (Czeizel *et al.*, 1991).

8. ITALY. In Lombardia there was a 20% increase in first-trimester spontaneous abortions among fetuses conceived during the main fallout period (Semisa, 1988).

9. NORWAY. A higher incidence of spontaneous abortions was observed for pregnancies conceived during the first 3 months after the catastrophe (Ulstein *et al.*, 1990). The observed increase for 36 months after Chernobyl is statistically significant, "but a causal relationship with the radiation exposure cannot be proved." Pregnancies temporarily decreased in the second half of 1986, during a period in which pregnancies usually increase, whereas there was no increase in induced abortions (Irgens *et al.*, 1991).

10. It should be noted that the reduction in birth rate in Sweden, Italy, Switzerland, Greece, and Finland in the first year after Chernobyl might not have been caused by radiation, but rather was due to family planning (Auvinen *et al.*, 2001).

11. A change point analysis of stillbirth odds ratios for gender, that is, the ratio of stillbirth odds of males to the stillbirth odds for females, found a change in 1986 or 1987 ($P = 0.01$) in several European countries (Figure 7.8).

12. Changes in the sex ratio and the stillbirth odds ratio for gender were significant for Denmark, Germany, Hungary, Norway, Poland, Latvia, and Sweden and visible but not statistically significant for Iceland (Figure 7.9).

13. Findings of increased rates of spontaneous abortions after the Chernobyl catastrophe in several European countries are summarized in Table 7.1.

14. Literature on increased stillbirth rates after Chernobyl in several European countries is listed in Table 7.2.

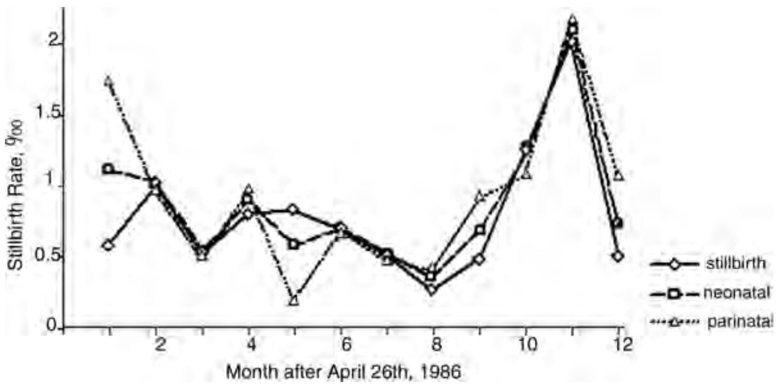

Figure 7.7. Trends of stillbirth rate and neonatal and perinatal mortality in England and Wales (Busby, 1995, based on Bentham, 1991).

Over an 18-year period after Chernobyl, if the number of miscarriages and stillbirths resulting from the Chernobyl fallout was 50,000 in Ukraine alone (Lypik, 2004), it is likely that the total antenatal death toll from Chernobyl in Russia, Belarus, and Ukraine up to 2003 is more than 100,000. As these three countries received only about 43% of the radioactive fallout from Chernobyl (see Chapter 1 for details) one can expect another 100,000 additional antenatal deaths in other European countries and in the rest of the world. Thus the total antenatal death toll from Chernobyl adds up to 200,000 cases (Rosen, 2006).

7.2. Increased Perinatal, Infant, and Childhood Mortality

Reports about the most probable adverse impacts of the Chernobyl contamination on childhood mortality include: perinatal mortality (stillbirths plus early neonatal deaths, 0–6 days), neonatal mortality (0–27 days), infant mortality (0–364 days), and childhood mortality (0–14 years). In a number of European countries the definition of stillbirth changed around 1994, which presents a problem in time-trend analyses. In the Former Soviet Union, the data for neonatal and infant mortality were

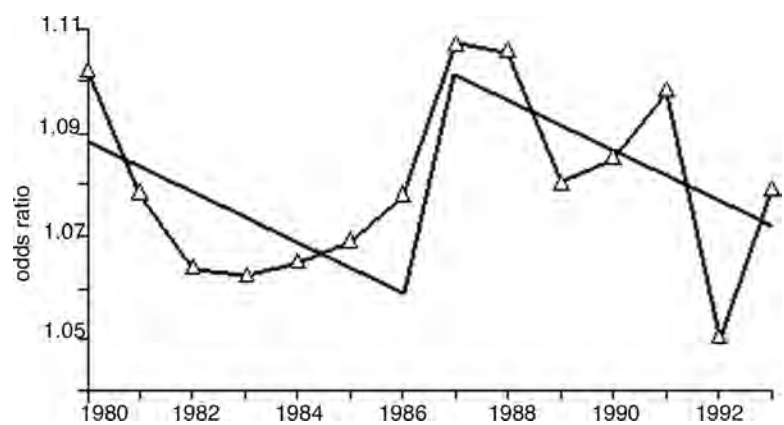

Figure 7.8. Sex ratio and stillbirth odds ratio by gender in several European countries (male stillbirths/male live births)/(female stillbirths/female live births; Scherb *et al.*, 1999).

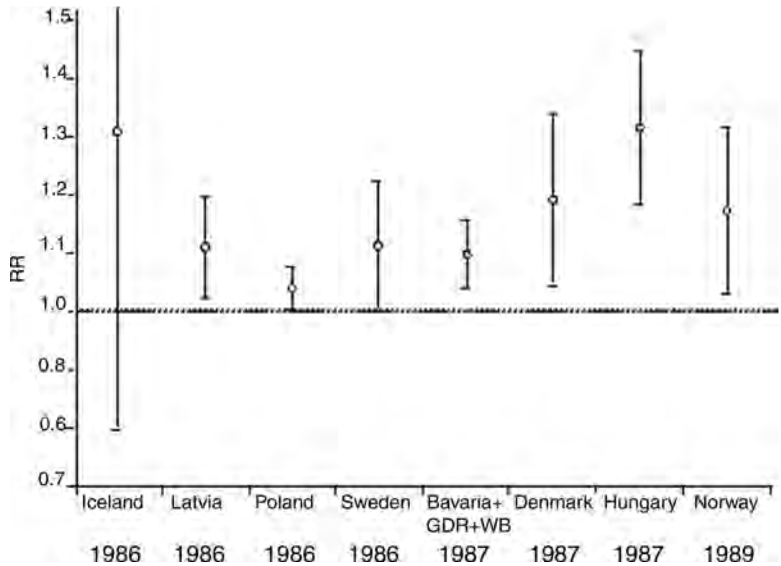

Figure 7.9. Relative risks (RR with 95% confidence limits) for change points for the stillbirth odds ratio in 1986 (Iceland, Latvia, Poland, and Sweden), in 1987 (Germany, Denmark, and Hungary), and 1989 (Norway), determined with a spatial–temporal trend model by Scherb and Weigelt (2000).

habitually underreported to "improve" health statistics, which makes the figures unreliable (Losoto, 2004).

7.2.1. Perinatal Mortality

7.2.1.1. Belarus

1. Perinatal mortality in Gomel Province increased after 1988. During the 1990s there is a rise and fall relative to the expected trend with a maximum number from 1993 to 1994 (Körblein, 2002). The additional mortality is associated with the average calculated Sr-90 burden on pregnant women (Figure 7.10).

2. An analysis of pregnancy outcomes before and after the catastrophe (1982 to 1990) revealed that neonatal mortality increased in Gomel and Mogilev, the two most highly contaminated regions of Belarus (Petrova *et al.*, 1997).

7.2.1.2. Ukraine

1. Perinatal mortality, stillbirth rate, and early neonatal mortality in Zhytomir and Kiev provinces were noticeably higher in the first year after the catastrophe and again 3 years later (Figure 7.11). The latter increase may be connected to consumption of locally contaminated food.

2. Comparison of perinatal mortality in the most contaminated regions of Ukraine (Zhytomir and Kiev provinces and Kiev City) with the mortality in the rest of Ukraine shows significantly higher figures 1991–1999 (Figure 7.12).

3. The increases in perinatal mortality in Ukraine and Belarus are associated with the Sr-90 burden on pregnant women (Körblein, 2003).

7.2.1.3. Russia

1. In the three most contaminated districts of Kaluga Province, infant mortality rates in 1986–1990 and 1991–1995 were higher than in less contaminated districts and in the Kaluga Province as a whole: 25.2, 21.5, and 17.0 per 1,000 live births, respectively (Tsyb *et al.*, 2006).

TABLE 7.1. Increase of the Rate of Spontaneous Abortions after Chernobyl (from Reviews by Auvinen *et al.*, 2001 and Körblein, 2006a)

Country	Period	Comments	Author
Finland	July to Dec., 1986	Increased in the territories with high level of Cs-137 ground contamination	Auvinen *et al.*, 2001
	From 1986	Up to 20%	Frentzel-Beyme and Scherb, 2007
Norway	1986–1988	In 1986 for conceptions during the first 3 months after Chernobyl in the contaminated territories	Ulstein *et al.*, 1990
	1986	Rate of spontaneous abortions increased from 7.2% before Chernobyl to 8.3% the year after in six contaminated counties	Irgens *et al.*, 1991
Sweden	1986	Increased for fetuses under 17 weeks at the time of the Chernobyl catastrophe	Ericson and Kallen, 1994
Italy	July 1986	Lombardy, increased 3%	Bertollini *et al.*, 1990
	June, July, Sept., 1986	Increased for whole country	Spinelli and Osborn, 1991; Parazzini *et al.*, 1988
	1986	20% increase in first-trimester spontaneous abortions	Semisa, 1988
Greece, Hungary, Poland, Sweden	1986	Increased compared to 1985	Scherb *et al.*, 1999
Poland	From 1986	Up to 5%	Frentzel-Beyme and Scherb, 2007
Sweden		Up to 10%, in some parts of the country	
Denmark		Up to 20%	
Hungary		Up to 30%	
Iceland		Up to 30%	
Germany	1987	Increased in Bavaria. Associated with the Cs-137 ground contamination	Scherb *et al.*, 2000
	Feb. 1987	13% decrease in birth rate in southern Bavaria	Körblein, 2006
Switzerland	June 1986	Birth rate decreased by 50% in Ticino Canton	Perucchi and Domenighetti, 1990

7.2.1.4. Other Countries

1. Germany. Perinatal mortality increased significantly in 1987 relative to the long-term trend of the data, 1980–1993. The 1987 increase was 4.8% ($P < 0.005$) of the expected proportion of perinatal deaths. Even more pronounced levels of 8.2% ($P < 0.05$) and 8.5% ($P = 0.0702$) can be found in the more heavily contaminated areas of the former German Democratic Republic, including West Berlin, and Bavaria, respectively (Scherb and Weigelt, 2000). A highly significant association of perinatal mortality with the Cs-137 burden during pregnancy is found in the combined data from West and East Germany (Körblein and Kuchenhoff, 1997). Spatial-temporal analyses of the proportion of stillbirths and perinatal deaths with Cs-137 deposition after the Chernobyl catastrophe in Bavaria on a district level reveal significant exposure–response relationships (Scherb *et al.*, 2000).

2. Poland. Perinatal mortality was significantly increased in 1987 relative to the

TABLE 7.2. Increased Stillbirth Rates, Infant Mortality Rates, and Low Birth Weight Associated with *In Utero* Exposure from Chernobyl (mostly by I. Schmitz-Feuerhake, 2006)

Country	Comments	References
Greece		Scherb and Weigelt, 2003
Sweden	Increased, in some parts up ca. 10%	Scherb and Weigelt, 2003; Frentzel-Beyme and Scherb, 2007
Poland	Stillbirth rate increased ca. 5%	Körblein, 2003; Scherb and Weigelt, 2003; Frentzel-Beyme and Scherb, 2007;
Norway		Ulstein *et al.*, 1990
Hungary		Czeizel and Billege, 1988; Scherb and Weigelt, 2003
Finland	Increased ca. 20%	Harjulehto *et al.*, 1989, 1991; Scherb and Weigelt, 2003; Frentzel-Beyme and Scherb, 2007
Germany		Körblein and Küchenhoff, 1997; Scherb and Weigelt, 2003; Lüning *et al.*, 1989; Grosche *et al.*, 1997; Scherb *et al.*, 1999; Körblein, 2003a; Frentzel-Beyme and Scherb, 2007
England and Wales	Increased twofold in February 1987	Bentham, 1991; Busby, 1995
Denmark	Increased 20%	Frentzel-Beyme and Scherb, 2007
Iceland	Increased 30%	Frentzel-Beyme and Scherb, 2007
Hungary	Increased 30%	Frentzel-Beyme and Scherb, 2007

long-term trend. Infant mortality monthly data, 1985–1991, show a significant correlation with the Cs-137 burden during pregnancy (Körblein, 2003, 2006).

3. Great Britain. Ten months after the catastrophe, a significant increase in perinatal mortality was found in the two most contaminated areas of the country—England and Wales (Bentham, 1991; Busby, 1995; see Figure 7.7).

7.2.2. Infant Mortality

7.2.2.1. Ukraine

1. A significant increase in infant mortality was found in 1987–1988 in highly contaminated territories (Grodzinsky, 1999; Omelyanets and Klement'ev, 2001). The main causes of infant death were antenatal pathologies and congenital malformations (Table 7.3).

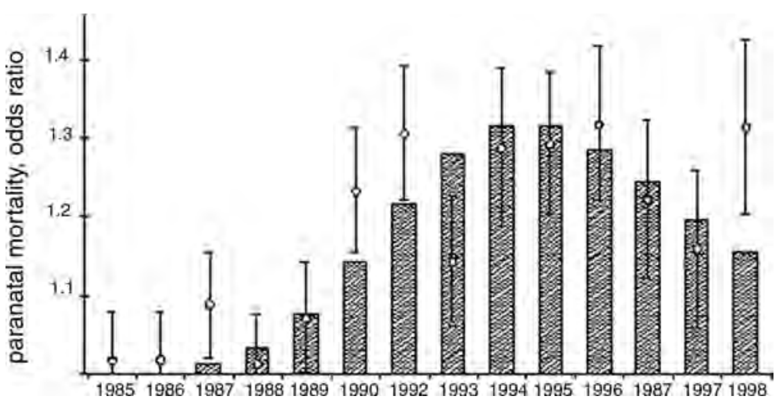

Figure 7.10. Deviation of perinatal mortality from the long-term trend in Gomel Province from 1985 to 1998. The columns show the average calculated Sr-90 burden in pregnant women (Körblein, 2006).

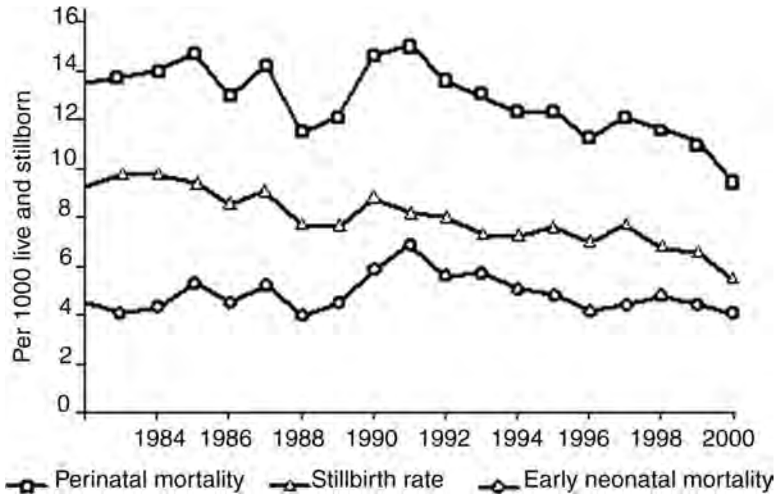

Figure 7.11. Perinatal mortality, stillbirth rate, and early neonatal mortality (per 1,000 live births and stillborns) in Zhytomir and Kiev provinces noticeably increased the first year and again after 3 years after the catastrophe (Dzykovich *et al.,* 2004).

7.2.2.2. Russia

1. In 1996 neonatal mortality in more highly contaminated districts of Bryansk Province was greater than in the province as a whole: 7.4 and 6.3 per 1,000, respectively (Baleva *et al.*, 2001).

2. In the southwest districts of Bryansk Province with higher contamination, infant mortality increased after 1986 (see Table 7.4), whereas in other districts it declined (Utka *et al.*, 2005).

Figure 7.13 shows the deviation of infant mortality in 1987–1989 from a declining long-term trend in Ukraine, Russia, and Belarus.

7.2.2.3. Other Countries

1. FINLAND. Infant mortality increased significantly immediately after the catastrophe and continued to rise until 1993 (Figure 7.14).

2. GERMANY. Infant mortality monthly data, 1980–1994, show two significant post-Chernobyl peaks, at the beginning and at the end of 1987 (Figure 7.15).

3. POLAND. Infant mortality monthly data, 1985–1991, show peaks at the beginning and at the end of 1987 (Figure 7.16).

3. SWEDEN. Infant mortality increased immediately after the catastrophe and

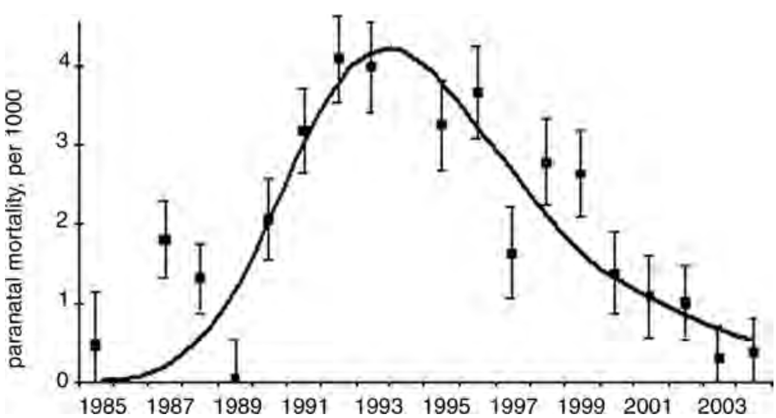

Figure 7.12. Deviation of perinatal mortality from the expected long-term trend in the combined Zhytomir and Kiev provinces and Kiev City, 1985–2004 (Körblein and Omelyanets, 2008).

TABLE 7.3. Main Causes of Infant Death (per 1,000 Live Births) in Ukraine, 1990–1995 (Grodzinsky, 1999)

Cause	Rate per 1,000	%
Antenatal pathologies	4.84	33.0
Congenital malformations	4.26	29.0
Respiratory diseases	1.45	9.9
Infections	1.12	7.6

increased significantly in 1989–1992 (Figure 7.17).

4. SWITZERLAND. Infant mortality rose to some extent in 1988 and increased significantly in 1989 and 1990 (Figure 7.18).

As noted above (Section 7.2.2), a total number of several thousand additional infant deaths might be expected following the Chernobyl catastrophe in Europe and other parts of the world. However, no study will be able to determine the exact number of added deaths because the putative trend without the Chernobyl catastrophe is unknown.

7.2.3. Childhood Mortality (0–14 Years of Age)

7.2.3.1. Belarus

1. In Gomel Province, childhood cancers are registered twice as often in the mortality statistics as in Belarus as a whole and 20-fold more often than in the least contaminated Vitebsk Province (Bogdanovich, 1997).

7.2.3.2. Ukraine

1. Childhood mortality increased from 0.5% (per 1,000 live born) in 1987 up to 1.2% in 1994. Death from diseases of the nervous system and the sense organs increased by a factor of five and congenital malformations by more than a factor of two (Grodzinsky, 1999).

2. According to official data, childhood mortality in highly contaminated territories was 4.7% in 1997 and 9.6% among children born to parents who had been irradiated (TASS, 1998).

TABLE 7.4. Infant Mortality (per 1,000 Live Births) in Highly Contaminated Districts of Bryansk Province, Russia, 1995–1998 (Fetysov, 1999; Komogortseva, 2006)

	Highly contaminated districts				Province
Years	1995	1996	1997	1998	1998
Infant mortality	17.2	17.6	17.7	20.0	15.7

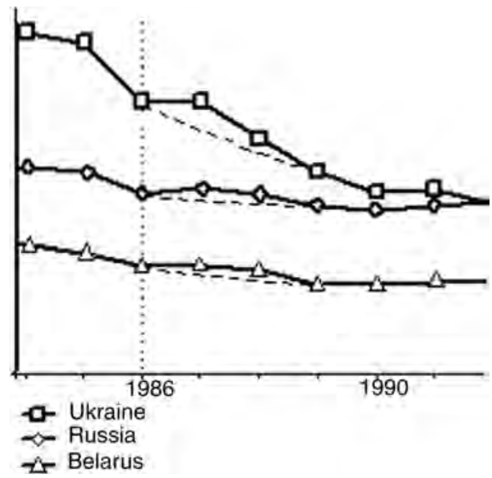

Figure 7.13. Trend of infant mortality (from top down) in Ukraine, Russia, and Belarus (//www.demoscope.ru/weekly/vote/fig_imr11png).

7.2.3.3. Russia

1. In districts of Tula Province with higher levels of contamination, childhood mortality was higher than in less contaminated districts (Khvorostenko, 1999).

The childhood death toll from the Chernobyl catastrophe will never be determined precisely. However, based on the existing fragmentary data, some 10,000 additional childhood deaths can be expected in Belarus, Ukraine, and Russia.

7.3. Mortality among Liquidators

The registration of deaths among liquidators in Ukraine, Russia, and Belarus was not complete in the first years after the Chernobyl catastrophe (see Chapter 1, Section 1.8 for details). As a rule, the liquidators were healthy young adults (average age 33 years) so a lower than

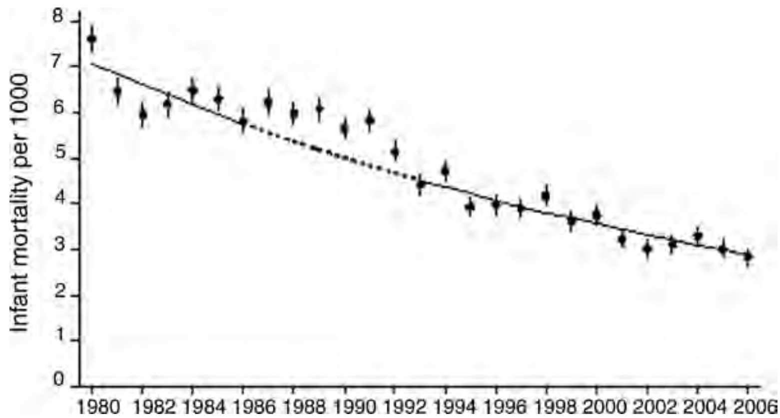

Figure 7.14. Trend of infant mortality rates in Finland, 1980–2006, and undisturbed trend line. Based on official statistical data (Körblein, 2008).

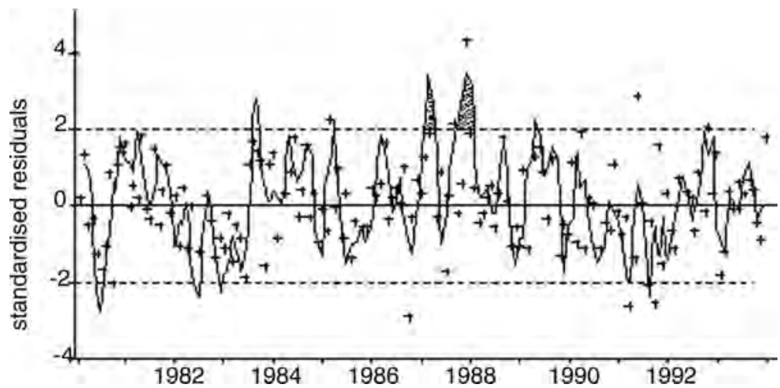

Figure 7.15. Deviation of infant mortality from the long-term trend in Germany, 1980–1994. The peaks of mortality follow peaks of the Cs-137 burden with a time lag of 7 months (Körblein, 2006).

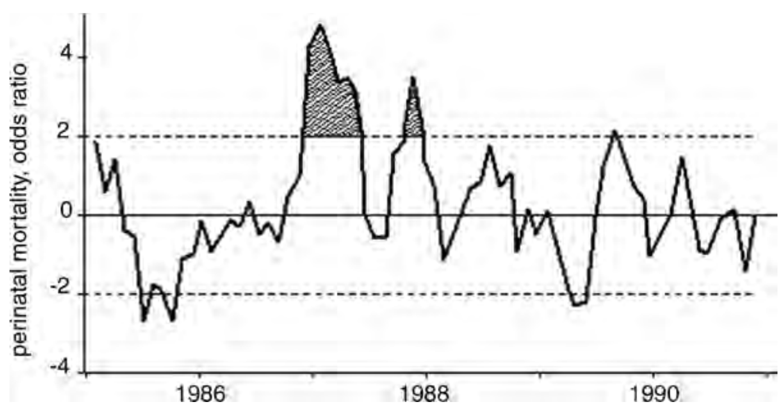

Figure 7.16. Deviation of infant mortality from the long-term trend in Poland, 1985–1991. The peaks of mortality follow peaks of the Cs-137 burden with a time lag of 7 months (Körblein, 2006).

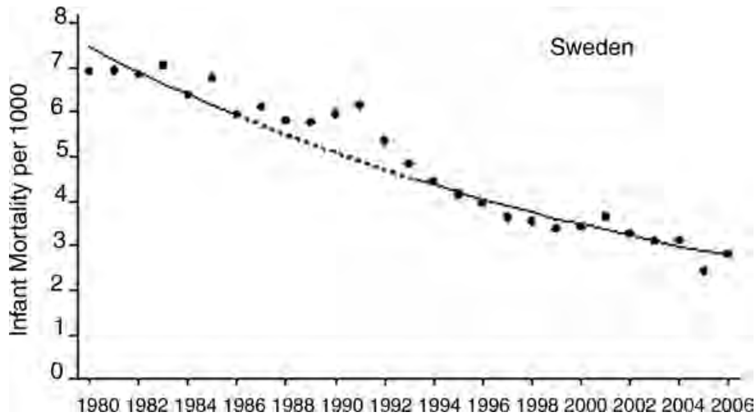

Figure 7.17. Trend in infant mortality rates in Sweden, 1980–2006, and undisturbed trend line. Based on official statistical data (Körblein, 2008).

average mortality rate among them should be expected.

7.3.1. Belarus

1. Mortality of male liquidators who worked in 1986 is higher than liquidators who worked in 1987 (Borysevich and Poplyko, 2002).

7.3.2. Ukraine

1. The mortality rate of the Ukrainian liquidators from nonmalignant diseases increased steadily from 1988 to 2003 (Figure 7.19).

2. Total mortality in contaminated territories and among liquidators increased significantly from 1987 to 2005 (Figure 7.20).

3. The mortality among male Ukrainian liquidators increased more than fivefold from 1989 to 2004, from 3.0 to 16.6 per 1,000, as compared to mortality rates of 4.1 to 6.0 per 1,000 among other men of working age (Horishna, 2005).

4. After 1995, the mortality of liquidators exceeded the mortality of the corresponding population group (Law of Ukraine, 2006).

7.3.3. Russia

1. Ten years after the Chernobyl catastrophe, the mortality rate among liquidators employed in 1986 was significantly increased (Ecological Security, 2002).

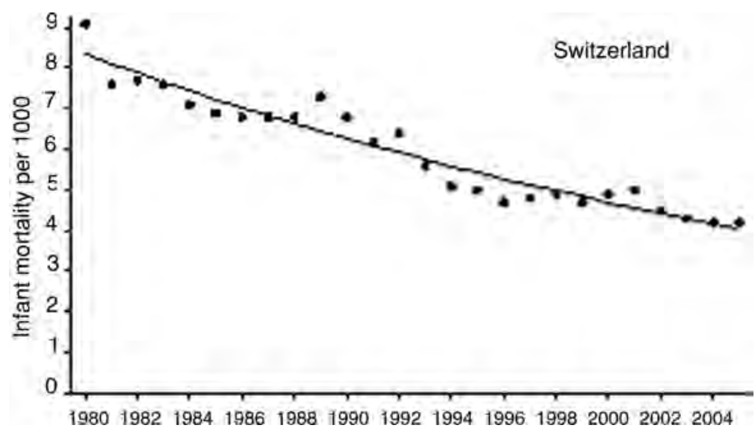

Figure 7.18. Trend of infant mortality rates in Switzerland, 1980–2006, and undisturbed trend line. Based on official statistical data (Körblein, 2008).

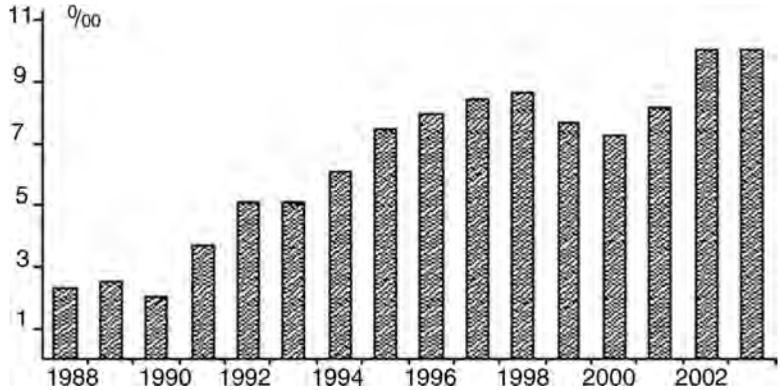

Figure 7.19. Trend of mortality (per 1,000) of Ukrainian liquidators employed in 1986–1987, from nonmalignant diseases from1988 to 2003 (National Ukrainian Report, 2006).

2. In the Russian National Register, 4,136 deaths were registered from 1991 to 1998 in a cohort of 52,714 liquidators. Only 216 cases (not counting 24 deaths from leukemia from 1986 to 1998) are officially accepted as radiation induced (Ivanov *et al.*, 2004).

3. According to official data, already "more than 10,000 liquidators" had died up until 2001 (National Russian Report, 2001). The standardized mortality ratio (SMR) among this cohort ranges between 0.78 and 0.88 for the categories "all causes," malignant neoplasm, "all causes except malignant neoplasm," and "traumas and poisonings" and does not differ from corresponding groups of the general population. Similar results are reported for employees of the Kurchatov Institute (Shykalov *et al.*, 2002).

4. A significant increase in cancer mortality was found in 1991–1998 in a cohort of 66,000 liquidators who were exposed (according to official data) to radiation doses of about 100 mSv (Maksyutov, 2002).

5. Figure 7.21 shows data obtained from the National Register on mortality of liquidators from nonmalignant causes.

6. According to the nongovernmental organization Chernobyl Union, by 2005 more than 31,700 out of 244,700 Russian liquidators, or 13%, had died (V. V. Grishin, Chernobyl Union Chairman, pers. comm.).

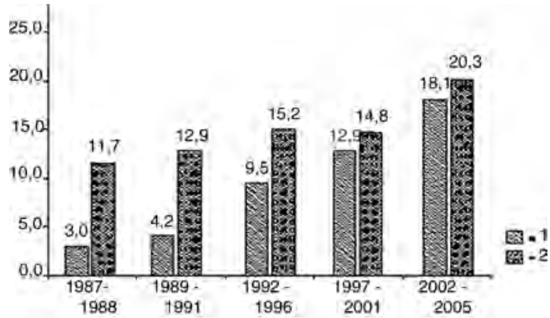

Figure 7.20. Total mortality (from all causes, per 1,000) in contaminated territories of Ukraine and among liquidators, 1986 to 2006 (Petruk, 2006).

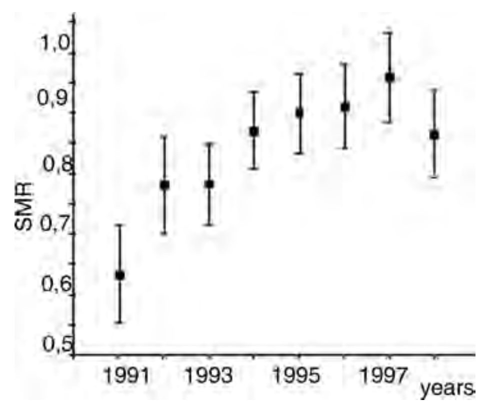

Figure 7.21. Trend of standardized mortality ratios (SMR) from nonmalignant diseases in liquidators, 1990–1999 (Ivanov *et al.*, 2004: fig. 8.7).

TABLE 7.5. Average Age of Deceased Liquidators

Group	Number of deaths	Average age at death, years	Comments
Tolyatti City, Samara Province	163	46.3	1995–2005, A.Y. calculations from Tymonin data (2005)
Workers in the nuclear industry	169	45.5	1986–1990 (Tukov, 2000)
Karelian Republic	644	43	1986–2008 (*Stolitsa on Onego*, 2008)

7. In the Voronezh Province, of 3,208 liquidators 1,113 (34.7%) have died (source: letter from regional branch of the Chernobyl Union).

8. In the Karelian Republic, of 1,204 liquidators 644 had died (53%) by the year 2008 (*Stolitsa on Onego*, 2008).

9. In Angarsk City (Irkutsk Province, Siberia) up to the year 2007 only about 300 out of 1,300 liquidators were still alive (Rikhvanova, 2007).

10. In Kaluga Province 87% of all liquidators who died in the first 12 years after the catastrophe were 30 to 39 years old (Lushnykov and Lantsov, 1999).

11. In 2001, mortality in male liquidators was 1.4 to 2.3 times higher than in corresponding age groups of the general population (Gil'manov *et al.*, 2001).

12. According to data from the National Register, from 1987 to 1996 mortality from malignant neoplasm of the urogenital tract was significantly higher in liquidators under the age of 50 years than in the corresponding age group in the general population (Kochergyna *et al.*, 2001).

13. The increased mortality results in a comparatively low life expectancy for liquidators (Table 7.5).

14. In 1993, according to the National Register, the three main causes of death among liquidators were trauma and poisonings (46%), circulatory diseases (29%), and malignant neoplasm (13%; Ecological Security, 2002).

15. According to the 1999 Registry, among the Russian liquidators who were employees of the nuclear industrial complex (14,827 men and 2,825 women) a significantly increased mortality rate was only found in the groups with circulatory and vegetovascular (autonomic nervous system) diseases (Tukov, 2000).

16. The decline in life expectancy among the Chernobyl liquidators who were employees of the nuclear industrial complex (NPPs, other nuclear installations, and atomic scientific institutes) was 16.3% from malignant neoplasms, 25.9% from blood diseases, and 39.6% from trauma and poisonings (Ignatov *et al.*, 2001).

17. The data from various sources for causes of liquidator mortality differ considerably, which indicates that they are of questionable quality (Table 7.6).

The data presented above show that, since 1990, mortality among liquidators exceeded the rate in corresponding population groups. By 2005 some 112,000 to 125,000 liquidators had died, or about 15% of a total cadre of 830,000.

7.4. Overall Mortality

The Chernobyl contamination undoubtedly caused an increase in overall mortality in the contaminated areas.

7.4.1. Belarus

1. In 1998, the mortality from malignant neoplasms for inhabitants of the territories contaminated by Cs-137 at levels higher than 555 kBq/m^2 (15 Ci/km^2) as well as for those who left such territories after the catastrophe started to exceed the mortality in the country as a whole (Antypova and Babichevskaya, 2001).

TABLE 7.6. Causes of Death (%) of Russian Liquidators in 2000 According to Various Sources

	Percentage of the total deaths		
Causes of death	Khrysanfov and Meskikh, 2001[a]	Loskutova, 2002[b]	Gil'manov *et al.*, 2001[c]
Blood and circulatory system pathology	63	45	50.9
Malignant neoplasm	31	32	5.3
Gastrointestinal tract pathology	7	–	5.3
Lung pathology	5	–	–
Trauma and suicide	5	14	26.3
Tuberculosis	3	–	–
Radiation sickness	–	1	–
Other	–	8	12.5

[a]Data of the official Russian Interdepartmental Advisory Council on the Establishment of a Causal Relationship of Diseases, Physical Disability and Death of Irradiated Persons.

[b]Data of the Moscow branch of the nongovernmental organization "Widows of Chernobyl" (559 cases).

[c]Data of the official Russian National Registry of Liquidators.

2. The average life expectancy of populations living in territories with Cs-137 ground contamination above 555 kBq/m^2 (15 Ci/km^2) was 8 years less than the national average (Antypova and Babichevskaya, 2001).

3. The concentration of radionuclides in the bodies of most (98%) of the 285 persons who died suddenly in Gomel Province was significantly increased in the heart, the kidneys, and the liver (Bandazhevsky, 1999).

4. In highly contaminated districts of Gomel Province, mortality is significantly higher than in less contaminated areas and higher than in the rest of Belarus; the mortality rate started to rise in 1989 (Figure 7.22).

5. The general mortality rate in Belarus increased from 6.5 to 9.3 per 1,000, that is, by 43%, from 1990 to 2004 (Malko, 2007).

7.4.2. Ukraine

1. After 1986, the general mortality increased significantly in the contaminated territories (IPHECA, 1996; Omelyanets and Klement'ev, 2001; Grodzinsky, 1999; Kashyryna, 2005; Sergeeva *et al.*, 2005).

2. According to official data, the general mortality rate in the heavily contaminated territories was 18.3 per 1,000 in 1999, some 28% higher than the national average of 14.8 per 1,000 (Reuters, 2000).

3. In contaminated territories and among evacuees, cancer mortality increased by 18 to 22% from 1986 to 1998 as compared to 12% in Ukraine as a whole (Omelyanets and Klement'ev, 2001; Golubchykov *et al.*, 2002). Mortality from prostate cancer increased by a factor

Figure 7.22. Trends in mortality rates (per 1,000) in several regions of Belarus. The highest mortality rates are found in the most contaminated districts of Gomel Province, and the increase after 1989 was greatest in Gomel Province (Rubanova, 2003).

TABLE 7.7. Causes of Death in Contaminated Territories of Ukraine, 1996 (Grodzinsky, 1999)

Cause of death	Percentage
Blood diseases	61.2
Oncological diseases	13.2
Traumas	9.3
Respiratory diseases	6.7
Diseases of the digestive tract	2.2

of 2.2 in contaminated territories and by a factor of 1.3 in Ukraine as a whole (Omelyanets and Klement'ev, 2001).

4. In 1996, the primary causes of death among inhabitants of contaminated territories were circulatory and oncological diseases (Table 7.7).

7.4.3. Russia

1. From 1994 to 2004, the general mortality in highly contaminated districts of Bryansk Province increased by 22.5%, primarily in the age group 45–49 years, where it increased by 87%. The general mortality in highly contaminated districts was 23 to 34% higher than the province average (Kashyryna, 2005; Sergeeva *et al.*, 2005; Table 7.8).

2. The general mortality in Lipetsk City, where Cs-137 ground contamination is less than 5 Ci/km^2, increased by 67% from 1986 to 1995 (from 7.5 to 12.6 per 1,000; Krapyvin, 1997).

3. General mortality in the Klintsy district of the Bryansk Province, 1997 to 1999, was correlated with Cs-137 ground contamination. Principal causes of the increased mortality were cardiovascular diseases (60%) and cancers (10.6%; Sukal'skaya *et al.*, 2004).

TABLE 7.8. General Mortality (per 1,000) in the Three Most Contaminated Districts of the Bryansk Province, and in Russia, 1995–1998 (Fetysov, 1999)

	Highly contaminated districts				Province	Russia
Year	1995	1996	1997	1998	1998	1997
General mortality	16.7	17.0	18.2	17.7	16.3	13.8

7.5. Calculations of General Mortality Based on the Carcinogenic Risks

Based on different risk factors (excess risk per unit dose), various authors have estimated the number of additional cancer deaths due to Chernobyl (Table 7.9). The estimates presented in Table 7.9 cover a range that spans two orders of magnitude. This wide range far exceeds the usual scientific uncertainty. Therefore, estimates of the damage to health from exposure to radiation should be interpreted with due caution given the existing state of knowledge (see Chapter 2 for details).

7.6. Calculations of General Mortality

An estimate of the additional mortality from Chernobyl is possible on the basis of a comparison of mortality rates in highly contaminated territories and in less contaminated ones—so called "clean" areas (Rubanova, 2003; Sergeeva *et al.*, 2005; Khudoley *et al.*, 2006; and others).

From 1985 to 2001, the standardized mortality ratio increased in the less contaminated Grodno and Vitebsk provinces of Belarus by 37.4 to 43.1%, and in the heavily contaminated Gomel Province by 59.6%. The socioeconomic and ethnic conditions in these areas are similar; the only difference is in the level of contamination. Therefore, the observed differences in mortality increase (16 to 22%) can be attributed to the Chernobyl radiation (Rubanova, 2003).

There are essentially six Russian provinces with considerable contamination from the Chernobyl fallout (Tula, Bryansk, Oryol,

TABLE 7.9. Estimates of the Number of Cancer Deaths Resulting from the Radionuclides Cs-134, Cs-137, and Sr-90 Released from the Chernobyl Reactor

Number of deaths	Author	Comments
4,000	Press release to the Chernobyl Forum (2005)	90 years, Belarus, Ukraine, European part of Russia
8,930	Chernobyl Forum (2006)	90 years, Belarus, Ukraine, European part of Russia
14,000*	Nuclear Regulatory Commission, USA	For all time, entire world
17,400	Anspaugh *et al.* (1988)	50 years, entire world
28,000	U.S. Department of Energy (Goldman, 1987)	50 years, entire world
30,000*	UNSCEAR (Bennett, 1996)	For all time, entire world
30,000–60,000	Fairlie and Sumner (2006)	For all time, entire world
93,080	Malko (2007)	70 years, entire world
180,000	Malko (2007)	70 years, all Chernobyl causes
495,000	Gofman (1994a,b)	For all time, entire world
899,310–1,786,657	Bertell (2006)	For all time, all radionuclides, entire world

*From J. Fairlie and D. Sumner (2006: table 6.2).

Ryazan, Kursk, and Kaluga), which had a total population of 7,418,000 in 2002 (study region). In 1999, more than 5% of this population lived in highly contaminated districts. The mortality rates in these regions were compared with the Russian average and with the rate in six neighboring (officially) less contaminated provinces with similar geographical and socioeconomic status (Smolensk, Belgorod, Lipetsk, Tambov, and Vladimir provinces and the Republic of Mordova) with a total population of 7,832,000 in 2002 (control region; Khudoley *et al.*, 2006).

In the region under study the general mortality, as well as the increased rate in mortality, exceeded the Russian average. Table 7.10 shows the raw and the age-standardized mortality rates in the six contaminated provinces. Both the observed and the age standardized mortality rates exceed the Russian average (Table 7.10). In Figure 7.23 the standardized mortality rates in the six contaminated provinces combined are compared with the mortality rates in the control region. The total number of additional deaths from Chernobyl in the area under study, calculated on the basis of the standardized mortality rates, is estimated at 60,400 (95% CI: 54,880 to 65,920).

A similar result is obtained when highly and less contaminated regions are compared. Figure 7.24 shows the standardized mortality rates for the neighboring Tula and Lipetsk provinces. The resulting number of about 60,400 additional deaths from 1990 to 2004 in the area under study, corresponding to 34 persons per 1,000, reveals the true dimension of the death toll from the Chernobyl catastrophe. From 1990 to 2004 the number of additional deaths represents 3.75% of the entire population of the contaminated territories. This finding agrees well with the figure of 4.2% for Ukraine given in the National Ukrainian Report for 2006.

TABLE 7.10. Observed (Raw) and Age-Standardized Mortality Rates (per 1,000) in the Six Most Contaminated Regions of Russia, 2002 (Khudoley *et al.*, 2006)

	Mortality	
Region	Observed	Standardized
Tula	21.9	19.6
Bryansk	19.3	18.0
Oryol	18.6	18.1
Ryazan	20.6	19.3
Kursk	19.3	18.5
Kaluga	18.8	17.7
Total	16.2	

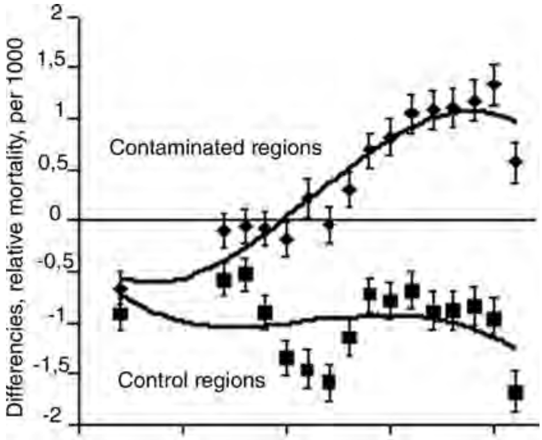

Figure 7.23. Difference in standardized mortality rates in the combined six most contaminated provinces and in the control region. "Zero" is the Russian average (Khudoley *et al.*, 2006).

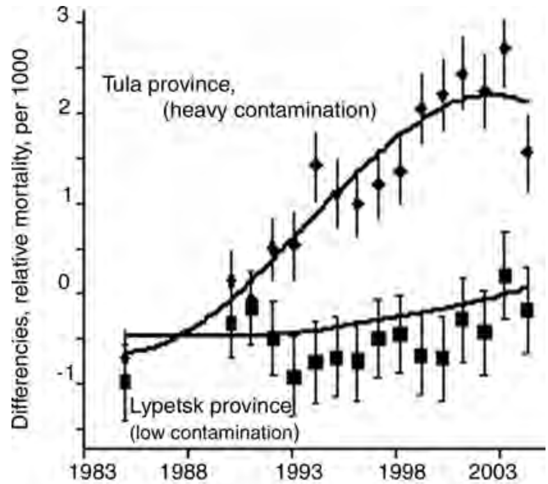

Figure 7.24. Standardized mortality rates, 1983–2003, in the more contaminated Tula Province, the less contaminated Lipetsk Province, and in Russia as a whole (Khudoley *et al.*, 2006).

For the populations in all the contaminated territories together (in European Russia 1,789,000 (1999), in Belarus 1,571,000 (2001), and in Ukraine 2,290,000 (2002; Khudoley *et al.*, 2006)), and based on the additional rate in Russia, the total number of extra deaths from Chernobyl in Belarus, Ukraine, and the European part of Russia is estimated to be 212,000 for the first 15 years after the catastrophe (Table 7.11).

This calculation seems straightforward, but it might underestimate the real figures for several reasons:

- Official data about the radioactive contamination for Belgorod and Lipetsk provinces do not correlate with corresponding changes in health statistics after Chernobyl. It means that the differences in mortality between contaminated and noncontaminated populations that were found by Khudoley *et al.* (2006) might actually be more pronounced. If so, the Ukrainian figure of 4.2% for the mortality rate may be more realistic than the 3.75% determined in Russia.
- It is well known (see Chapter 1 for details) that there was considerable contamination (sometimes more than 1 Ci/km^2) not only in the six regions mentioned above but also in 16 regions of the European part of Russia. This means that the total death toll for Russia is higher than estimated by Khudoley *et al.* (2006).
- All the calculations by Khudoley *et al.* (2006) cover a 15-year period (1990–2004). However, the radioactive contamination from Chernobyl had adverse health effects before 1990 and will continue for many years into the future.

7.7. What Is the Total Number of Chernobyl Victims?

The Chernobyl Forum (WHO, 2006) calculated a total number of 9,000 cancer deaths in Belarus, Ukraine, and Russia that can be attributed to the Chernobyl catastrophe for a period of 90 years after the meltdown.

Table 7.9 showed forecasts of the expected number of additional instances of cancer owing to the Chernobyl catastrophe. All projections are based on risk factors for cancer. It is well known, however, that cancer is not the only and not even the most frequent lethal effect of radiation (see, e.g., Table 7.7).

TABLE 7.11. Number of Additional Deaths in Belarus, Ukraine, and the European Part of Russia, 1990–2004, that Can Be Attributed to the Chernobyl Catastrophe (Khudoley *et al.*, 2006)

	Region/Country			
	European Russia	Belarus	Ukraine	Total
Population living in highly contaminated territories	1,789,000	1,571,000	2,290,000	5,650,000
Number of additional deaths	67,000	59,000	86,000	212,000

The assumptions concerning nonmalignant radiation risks differ even more than for radiation-induced cancers. Risk projections based on observed increases in the general mortality are more meaningful, and they are likely to be more realistic than calculations that only use individual and/or collective doses together with risk factors for fatal cancers.

Based on data presented in Section 7.6, it is possible to estimate the total death toll from the Chernobyl catastrophe:

- When we apply the additional mortality of 34 extra deaths per 1,000 population within 15 years (1990–2004), which was derived above, to the cohort of liquidators not living in contaminated zones (400,000), to the evacuees and to people who moved away from contaminated areas (350,000), then we expect another 25,500 deaths in this period. The overall number of Chernobyl-related deaths up until 2004 in Belarus, Ukraine, and Russia was estimated to be 237,500.
- Assuming that 10 million people in Europe, outside the Former Soviet Union, live in territories with a Cs-137 ground contamination higher than 40 kBq/m^2 (>1.08 Ci/km^2) and that the mortality risk is only half that determined in the Chernobyl region, that is, 17 deaths per 1,000 inhabitants (better food and better medical and socioeconomic situations), up until 2004, we can expect an additional 170,000 deaths in Europe outside the Former Soviet Union owing to Chernobyl.
- Let us further assume that for the other 150 million Europeans living in territories with a Cs-137 ground contamination below 40 kBq/m^2 (see Chapter 1 for details) the additional mortality will be 10-fold less (i.e., 1.7 deaths per 1,000 in 1990–2004). Then we can expect 150,000 × 1.7 or 255,000 more deaths in the rest of Europe.
- Assuming that 20% of the radionuclides released from the Chernobyl reactor were deposited outside Europe (see Chapter 1) and that the exposed population was 190 million, with a risk factor of 1.7 per 1,000 as before, we could have expected an additional 323,000 cancer deaths outside Europe until 2004.

Thus the overall mortality for the period from April 1986 to the end of 2004 from the Chernobyl catastrophe was estimated at 985,000 additional deaths. This estimate of the number of additional deaths is similar to those of Gofman (1994a) and Bertell (2006). A projection for a much longer period—for many future generations—is very difficult. Some counter-directed aspects of such prognoses are as follows:

- Given the half-life of the two main radionuclides (Cs-137 and Sr-90) of approximately 30 years each, the radionuclide load in the contaminated territories will decrease about 50% for each human generation. The concentrations of Pu, Cl-36, and Tc-99 will remain practically the same virtually forever (half-lives consequently more than 20,000 and 200,000 years), and the concentration of Am-241, which is a decay product of Pu-241, will increase over several generations.

- The genetic damage among descendants of irradiated parents will propagate in the population and will carry through many (at least seven) generations.
- Fertility is known to decrease after exposure to radiation (Radzikhovsky and Keisevich, 2002).
- A radiation adaptation process may occur (the effect is known from experiments with mammals) (Yablokov, 2002).

7.8. Conclusion

There are many findings of increased antenatal, childhood, and general mortality in the highly contaminated territories that are most probably associated with irradiation from the Chernobyl fallout. Significant increases in cancer mortality were observed for all irradiated groups.

A detailed study reveals that some 4% of all deaths from 1990 to 2004 in the contaminated territories of Ukraine and Russia were caused by the Chernobyl catastrophe. The lack of evidence of increased mortality in other affected countries is not proof of the absence of adverse effects of radiation.

The calculations in this chapter suggest that the Chernobyl catastrophe has already killed several hundred thousand human beings in a population of several hundred million that was unfortunate enough to live in territories affected by the Chernobyl fallout. The number of Chernobyl victims will continue to grow in the next several generations.

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Conclusion to Chapter II

Morbidity and prevalence of the separate specific illnesses as documented in Chapter II, parts 4, 5, 6, and 7 still do not give a complete picture of the state of public health in the territories affected by Chernobyl. The box below documents the health of the population in the small Ukrainian district of Lugini 10 years after the catastrophe. Lugini is located about 110 km southwest of the Chernobyl Nuclear Power Plant in Zhytomir Province and has radioactive contamination at a level above 5 Ci/km^2.

There are tens of similarly contaminated territories in Belarus, Ukraine, European Russia, Sweden, Norway, Turkey, Austria, South Germany, Finland, and other European countries. However, Lugini is unique not only because the same medical staff used the same medical equipment and followed the same protocols that were used before and after the catastrophe, but also because the doctors collected and published these facts (Godlevsky and Nasvit, 1999).

DETERIORATION IN PUBLIC HEALTH IN ONE UKRAINIAN DISTRICT 10 YEARS AFTER THE CATASTROPHE

District Lugini (Ukraine). The population in 1986: 29,276 persons, in 1996: 22,552 (including 4,227 children). Out of 50 villages 22 were contaminated in 1986 at a level 1–5 Ci/km^2 and 26 villages at a level under 1 Ci/km^2.

Lifespan from the time of diagnosis of lung or stomach cancer:
Years 1984–1985: 38–62 months
Years 1995–1996: 2–7.2 months

Initial diagnosis of active tuberculosis (percentage of primary diagnosed tuberculosis):
Years 1985–1986: 17.2–28.7 per 100,000
Years 1995–1996: 41.7–50.0 per 100,000

Endocrine system diseases in children:
Years 1985–1990: 10 per 1,000
Years 1994–1995: 90–97 per 1,000

Cases of goiter, children:
Up to 1988: not found
Years 1994–1995: 12–13 per 1,000

Neonatal mortality (0–6 days after birth):
Years 1984–1987: 25–75 per 1,000 live births
Years 1995–1996: 330–340 per 1,000 live births

General mortality:
Year 1985: 10.9 per 1,000
Year 1991: 15.5 per 1,000

Life expectancy:
Years 1984–1985: 75 years
Years 1990–1996: 65 years

Figure 1 presents data on the annual number of newborns with congenital malformations in Lugini districts. There was an increase in the number of such cases seen despite a 25% decrease in the total of Lugini population from 1986 to 1996.

In the radioactive-contaminated territories there is a noticeable increase in the incidence of a number of illnesses and in signs and symptoms that are not in official medical statistics. Among them there are abnormally poor increase in children's weight, delayed recovery after illnesses, frequent fevers, etc. (see Chapter II.5, Section 5.2).

The Chernobyl catastrophe has endowed world medicine with new terms, among them:

- The syndrome known as "vegetovascular dystonia" (autonomic nervous system dysfunction): functional disturbance of nervous regulation of the cardiovascular system with various clinical findings arising on a background of stress.
- The syndrome known as "incorporated long-living radionuclides" (Bandazhevsky, 1999) that includes pathology of the cardiovascular, nervous, endocrine, reproductive, and other systems as the result of the

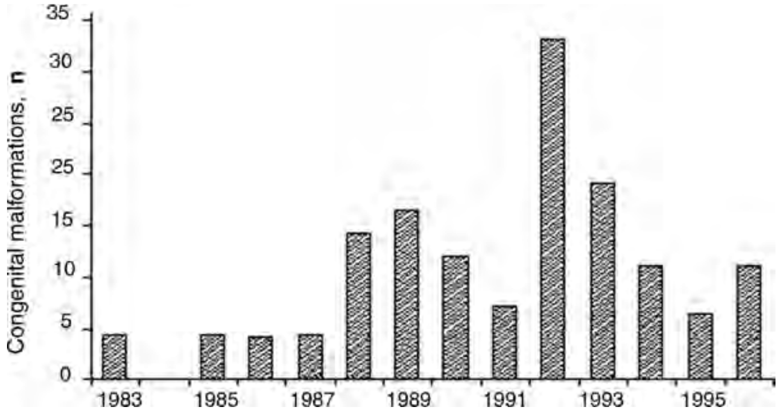

Figure 1. Absolute number of the congenital developmental anomalies in newborns in Lugini District, Zhytomir Province, Ukraine, from 1983 to 1996 (Godlevsky and Nasvit, 1999).

accumulation of more than 50 Bq/kg of Cs-137 and Sr-90 in a person.

- The syndrome known as "sharp inhalation effect of the upper respiratory path" (Chuchalin, 2002): a combination of a rhinitis, scratchy throat, dry cough, and shortness of breath with physical activity connected to the impact of inhaled radionuclides, including "hot particles."

Some of the earlier known syndromes have an unprecedented wide incidence of occurrence. Among them is the syndrome known as "chronic fatigue" (Lloyd *et al.*, 1988), which manifests as tiredness, disturbed dreams, periodic depression and dysphoria, fatigue without cause, impaired memory, diffuse muscular pains, pains in large joints, shivering, frequent mood changes, cervical lymph node sensitivity, and decreased body mass. It is postulated that these symptoms are a result of impaired immune system function in combination with disorders of the temporal–limbic parts of the central nervous system. These include: (a) the syndrome called "lingering radiating illness" (Furitsu *et al.*, 1992; Pshenichnykov, 1996), a combination of unusual weariness, dizziness, trembling, pains in the back, and a humeral belt, originally described in the hibakusha (survivors of Hiroshima and Nagasaki) and (b) the syndromes comprising choreoretinopathy, changes in retinal vessels, called "incipient chestnut syndrome" and "diffraction grating syndrome" (Fedirko, 1999, 2002).

Among conditions awaiting full medical description are other constellations of diseases, including "irradiation *in utero*," "Chernobyl AIDs," "Chernobyl heart," "Chernobyl dementia," and "Chernobyl legs."

Chernobyl's radioactive contamination at levels in excess of 1 Ci/km^2 (as of 1986–1987) is responsible for 3.8–4.4% of the overall mortality in areas of Russia, Ukraine, and Belarus. In several other European countries with contamination levels around 0.5 Ci/km^2 (as of 1986–1987), the mortality is about 0.3–0.7% (see Chapter II.7). Reasonable extrapolation for additional mortality in the heavily contaminated territories of Russia, Ukraine, and Belarus brings the estimated death toll to about 900,000, and that is only for the first 15 years after the Chernobyl catastrophe.

Chernobyl's contribution to the general morbidity is the determining factor in practically all territories with a level of contamination higher than 1 Ci/km^2. Chronic diseases of various etiologies became typical not only for liquidators but also for the affected populations and appear to be exacerbated by the radioactive contamination. Polymorbidity, the presence of multiple diseases in the same individual, has become a common feature in the contaminated territories. It appears that the Chernobyl cancer toll is one of the soundest reasons for the "cancer epidemic" that has been afflicting humankind since the end of the 20th century.

Despite the enormous quantity of data concerning the deterioration of public health in the affected territories, the full picture of the catastrophe's health impact is still far from complete. To ascertain the total complex picture of the health consequences of the Chernobyl catastrophe we must, first of all:

- Expand, not reduce, as was recently done in Russia, Ukraine, and Belarus, medical, biological, and radiological studies.
- Obtain correct reconstruction of individual doses, differentiated by the contribution of various radionuclides from both internal and external irradiation levels, ascertain personal behavior and habits, and have a mandatory requirement to determine correct doses based on chromosome and tooth enamel analysis.
- Perform comparative analyses of monthly medical statistics before and after the catastrophe (especially for the first years after the catastrophe) for the administrative units (local and regional) that were contaminated with various levels of particular radionuclides.

The constantly growing volume of objective scientific data about the negative consequences of the Chernobyl catastrophe for public health, not only for the Former Soviet Union but also in Sweden, Switzerland, France, Germany, Italy, Turkey, Finland, Moldova, Romania, The Czech Republic, and other countries are not a cause for optimism (details in Chapter II, parts 4–7). Without special large-scale programs of mitigation and prevention of morbidity and consequent mortality, the Chernobyl-related diseases linked to contamination that began some 23 years ago will continue to increase.

There are several signals to alert public health personnel in territories that have been contaminated by the Chernobyl fallout in Belarus, Ukraine, and Russia:

- An absence of a correlation between current average annual doses with doses received in 1986–1987.
- A noticeable growing contribution to a collective dose for individuals in zones with a low level of contamination.
- Increasing (instead of decreasing as was logically supposed) levels of individual irradiation for many people in the affected territories.
- A need to end the demand for a 20-year latency period for the development of cancer (skin, breast, lung, etc.). Different cancers have different latencies following exposure to various and differing carcinogenic exposures. Juvenile victims are an obvious example.

As a result of prolonged immune system suppression there will be an increase in many illnesses. As a result of radiation damage to the central nervous system in general and to temporal–limbic structures in the brain there will be more and more people with problems of intellectual development that threatens to cause loss of intellect across the population. As a result of radio-induced chromosomal mutations a spectrum of congenital illnesses will become widespread, not only in the contaminated territories but also with migration over many areas and over several generations.

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Chapter III. Consequences of the Chernobyl Catastrophe for the Environment

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Key words: **Chernobyl; radionuclides; radiolysis; soil; water ecosystems; bioaccumulation; transition ratio; radiomorphosis**

The level of radioactivity in the atmosphere, water, and soil in the contaminated territories will determine the eventual level of radiation of all living things, both directly and via the food chain. Patterns of radioactive contamination essentially change when the radionuclides are transferred by water, wind, and migrating animals. Land and bodies of water that were exposed to little or no contamination can become much more contaminated owing to secondary transfer. Many Russian-language publications have documented such radionuclide transfers, as well as changes in concentration and bioaccumulation in soil and water affecting various animals and plants (see, e.g., the reviews by Konoplya and Rolevich, 1996; Kutlachmedov and Polykarpov 1998; Sokolov and Kryvolutsky, 1998; Kozubov and Taskaev, 2002). The influence of Chernobyl radionuclide fallout on ecosystems and populations of animals, plants, and microorganisms is well documented.

In Chapters I and II we repeatedly emphasize that we do not present all of the available data on the consequences of Chernobyl, but only selected parts to reflect the many problems and to show the enormous scale of the contamination. In Chapter III as well we have included only part of the material concerning the impact of the catastrophe on the biosphere—on fauna and flora, on water, air, and soil. We emphasize that like the consequences for public health, which are not declining but rather increasing in scope and severity, the consequences for nature are neither fully documented nor completely understood and may also not decline.

Cs-137 is removed from ecological food chains a hundred times more slowly than was predicted right after the catastrophe (Smith *et al.*, 2000; and others). "Hot" particles have disintegrated much more rapidly than expected, leading to unpredictable secondary emissions from some radionuclides. Sr-90 and Am-241 are moving through the food chains much faster than predicted because they are so water soluble (Konoplya, 2006; Konoplya *et al.*, 2006; and many others). Chernobyl radioactive contamination has adversely affected all biological as well as nonliving components of the environment: the atmosphere, surface and ground waters, and soil.

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8. Atmospheric, Water, and Soil Contamination after Chernobyl

Alexey V. Yablokov, Vassily B. Nesterenko, and Alexey V. Nesterenko

Air particulate activity over all of the Northern Hemisphere reached its highest levels since the termination of nuclear weapons testing—sometimes up to 1 million times higher than before the Chernobyl contamination. There were essential changes in the ionic, aerosol, and gas structure of the surface air in the heavily contaminated territories, as measured by electroconductivity and air radiolysis. Many years after the catastrophe aerosols from forest fires have dispersed hundreds of kilometers away. The Chernobyl radionuclides concentrate in sediments, water, plants, and animals, sometimes 100,000 times more than the local background level. The consequences of such a shock on aquatic ecosystems is largely unclear. Secondary contamination of freshwater ecosystems occurs as a result of Cs-137 and Sr-90 washout by the high waters of spring. The speed of vertical migration of different radionuclides in floodplains, lowland moors, peat bogs, etc., is about 2–4 cm/year. As a result of this vertical migration of radionuclides in soil, plants with deep root systems absorb them and carry the ones that are buried to the surface again. This transfer is one of the important mechanisms, observed in recent years, that leads to increased doses of internal irradiation among people in the contaminated territories.

8.1. Chernobyl's Contamination of Surface Air

Data below show the detection of surface air contamination practically over the entire Northern Hemisphere (see Chapter I for relevant maps).

8.1.1. Belarus, Ukraine, and Russia

There are many hundreds of publications about specific radionuclide levels in the Former Soviet Union territories—of which the data below are only examples.

1. Immediately after the first explosion in the Chernobyl Nuclear Power Plant (NPP) on April 26, 1986, the concentrations of the primary radionuclides changed drastically from place to place and from day to day (Table 8.1).

2. Table 8.2 indicates the dynamics of the average annual concentration of some radionuclides in the atmosphere near the Chernobyl NPP.

3. There were essential changes in the ionic, aerosol, and gas structure of the surface air in the catastrophe zone. A year later, within a 7-km zone of the Chernobyl NPP, the electroconductivity of the air at ground level was 240–570 times higher than in the less contaminated territories several hundred kilometers away (Smirnov, 1992). Outside of the 30-km zone air radiolysis depressed the ecosystems. Concentrations of ionized surface air in the contaminated territories near the Chernobyl NPP repeatedly exceeded this level in Kaluga Province, Russia, and Zhytomir Province, Ukraine, by 130- to 200-fold (Kryshev and Ryazantsev, 2000).

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TABLE 8.1. Concentration (Bq/m^3) of Some Radionuclides on April 29–May 1, 1986, in Belarus (Minsk City) and Ukraine, Kiev Province (Kryshev and Ryazantsev, 2000)

Radionuclide	Minsk City, April 28–29	Baryshevka, Kiev Province, April 30–May 1
Te-132	74	3,300
I-131	320	300
Ba-140	27	230
Cs-137	93	78
Cs-134	48	52
Se-141	–	26
Se-144	–	26
Zr-95	3	24
Ru-103	16	24

TABLE 8.2. Dynamics of the Concentration of Some Radionuclides (Bq/m^3) in the Chernobyl City Atmosphere, 1986–1991 (Kryshev *et al.*, 1994)

Year	Sr-90	Ru-106	Cs-137	Se-144
1986, July–December	n/a	13,000	5,000	34,000
1987	n/a	4,000	2,000	12,000
1988	430	400	600	1,400
1989	130	–	90	160
1990	52	–	80	–
1991	52	–	100	–

4. From April to May 1986 surface air radioactivity in Belarus increased up to 1 million times. There was a subsequent gradual decrease until the end of 1986 and then the rate fell sharply. In the Berezinsk Nature Reserve (400 km from Chernobyl) on April 27–28, 1986, the concentrations of I-131 and Cs-137 in the air reached 150–200 Bq/m^3 and 9.9 Bq/m^3, respectively. In 1986 in Khoinyki, the midyear concentration of Cs-137 in the surface air was 3.2×10^{-2} Bq/m^3 and in Minsk it was 3.8×10^{-3}Bq/m^3, levels that are 1,000 to 10,000 times higher than precatastrophe concentrations, which were below 10^{-6} Bq/m^3. Midyear concentration of Pu-239 and Pu-240 in surface air in 1986 for Khoinyki was 8.3×10^{-6} Bq/m^3 and for Minsk it was 1.1×10^{-6} Bq/m^3, levels that were 1,000 times higher than the precatastrophe concentrations, which were measured at less than 10^{-9} Bq/m^3 (Gres', 1997). The half-life period to cleanse the surface air of Pu-239 and Pu-240 was 14.2 months, and for Cs-137 it took up to 40 months (Nesterenko, 2005). Noticeably high levels of radionuclides in surface air were detected many years after the catastrophe (Figure 8.1).

5. Surface atmospheric radioactivity rises markedly after some agricultural work (tilling, harrowing, etc.) and other dust-creating activities. There is a tendency for radionuclide levels in surface air to increase during the spring and summer months, especially during dry weather.

6. Levels of radioactive contamination of the surface air in Belarus has three dynamic components: (1) the general radioecological situation; (2) cyclical, connected with seasonal changes (e.g., agricultural activities); and (3) incidental, as a consequence of numerous anthropogenic and natural factors. The incidental component was strongly demonstrated in 1992, when there were raging forest fires over all of Belarus. Their impact on the radioactive level in the atmosphere was so great that it led to a significant increase in the midyear concentration of radionuclides in surface air and most probably in human contamination via inhalation. In territories with a high density of ground-level radioactive contamination (in soil, water, vegetation) the hot air resulting from the fires caused radionuclides to be carried up to a height of 3 km and transported over hundreds of kilometers (Konoplia *et al.*, 2006).

7. In Russia beta-activity originating from Chernobyl was detected several days after April 26, 1986, in Bryansk, Tula, Kaluga, Oryol, Voronezh, Smolensk, and Nizhni Novgorod (Gor'ky); also in Rostov, Tambov, and Penza provinces in the Karelia Republic in the European part of the county; in Ural (Sverdlovsk Province); and in the far eastern sector (Khabarovsk and Vladivostok), and in

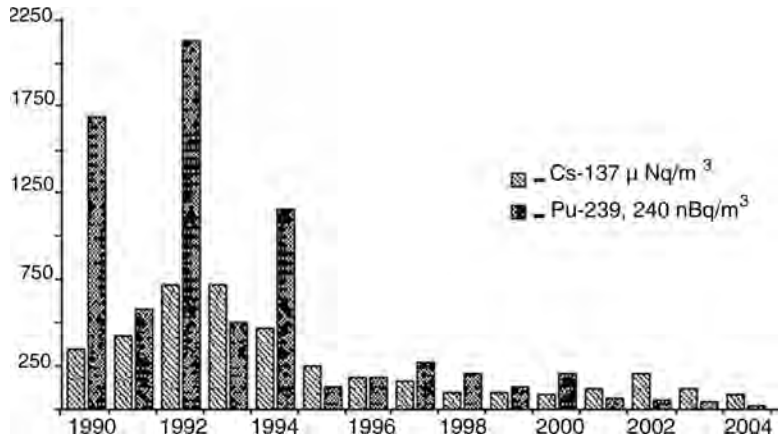

Figure 8.1. Dynamics of the radionuclides Pu-239, Pu-240, and Cs-137 in the surface air in Khoiniky, Belarus, 1990–2004 (Konoplya *et al.*, 2006).

some places was more than 10,000 times higher than the precatastrophe levels (Kryshev and Ryazantsev, 2000).

8. Several years after the catastrophe, secondary radioactive contamination from dust and aerosols became the important factor. On September 6, 1992, radioactive aerosols lifted by a strong wind from the 30-km Chernobyl zone reached the vicinity of Vilnius, Lithuania (about 300 km away) in 5–7 h, where the Cs-137 concentration increased 100-fold (Ogorodnykov, 2002). The same scale of radionuclide dispersion occurs in the wake of forest fires that at times rage over large areas of the contaminated territories of Belarus, Russia, and Ukraine.

8.1.2. Other Countries

Below are some examples of Chernobyl's radioactive contamination of the atmosphere in the Northern Hemisphere.

1. CANADA. Three Chernobyl clouds entered eastern Canada: the first on May 6, 1986; the second around May 14; the third on May 25–26. The fallout included: Be-7, Fe-59, Nb-95, Zr-95, Ru-103, Ru-106, Cs-137, I-131, La-141, Ce-141, Ce-144, Mn-54, Co-60, Zn-65, and Ba-140 (Roy *et al.*, 1988).

2. DENMARK. From April 27 to 28 the mean air concentration of Cs-137 was 0.24 Bq/m^3; Sr-90, 5.7 mBq/m^3; Pu-239 + Pu-240, 51 Bq/m^3; and Am-241, 5.2 μBq/m^3 (Aarkrog, 1988).

3. FINLAND. The most detailed accounting of the Chernobyl radionuclide fallout during the first days after the catastrophe was in Sweden and Finland (Table 8.3).

4. JAPAN. Two Chernobyl radioactive clouds were detected over Japan: one at a height of about 1,500 m in the first days of May 1986 and the other at a height of more than 6,000 m at the end of May (Higuchi *et al.*, 1988). Up to 20 radionuclides were detected in the surface air, including Cs-137, I-131, and Ru-103.

TABLE 8.3. Airborne Radioactivity (mBq/m^3) of 19 Radionuclides in Finland, Nurmijarvi, April 28, 1986 (Sinkko *et al.*, 1987)

Nuclide	Activity	Nuclide	Activity
I-131	223,000	Te-131m	1,700
I-133	48,000	Sb-127	1,650
Te-132	33,000	Ru-106	630
Cs-137	11,900	Ce-141	570
Cs-134	7,200	Cd-115	400
Ba-140	7,000	Zr-95	380
Te-129m	4,000	Sb-125	253
Ru-103	2,880	Ce-143	240
Mo-99	2,440	Nd-147	150
Cs-136	2,740	Ag-110m	130
Np-239	1,900		

Concentrations of Cs-131/Cs-134/Cs-137 in the surface air northwest of Japan increased more than 1,000 times (Aoyama *et al.*, 1986; Ooe *et al.*, 1988). Noticeable atmospheric Cs-137 fallout was marked in Japan up through the end of 1988 (Aoyama *et al.*, 1991).

5. YUGOSLAVIA. The increase in Pu-238/P239-240 ratios in surface air at the Vinca-Belgrade site for May 1–15, 1986, confirms that Chernobyl was the source (Mani-Kudra *et al.*, 1995).

6. SCOTLAND. The Chernobyl fallout on the evening of May 3 included Te-132, I-132, I-131, Ru-103, Cs-137, Cs-134, and Ba-140/La-140 (Martin *et al.*, 1988).

7. UNITED STATES. Chernobyl's radioactive clouds were noted in the Bering Sea area of the north Pacific (Kusakabe and Ku, 1988), and reached North America. The pathways of the Chernobyl plumes crossed the Arctic within the lower troposphere and the Pacific Ocean within the mid-troposphere. The first measured radiation arrived in the United States on May 10, and there was a second peak on May 20–23. The second phase yielded much higher Ru-103 and Ba-140 activity relative to Cs-137 (Bondietti *et al.*, 1988; Bondietti and Brantley, 1986). The air particulate activity in the United States reached its highest level since the termination of nuclear weapons testing (US EPA, 1986). Examples of Chernobyl's atmospheric contamination are presented in Table 8.4.

Table 8.5 summarizes some examples of surface air contamination in several countries resulting from the Chernobyl catastrophe.

Modern science is far from understanding or even being able to register all of the specific radiogenic effects for each of the Chernobyl radionuclides. However, the effects of the products of radiolysis from such huge atmospheric radiation fallout demands close attention. The term "atmospheric radiotoxins" appeared after the catastrophe (Gagarinsky *et al.*, 1994). As noted earlier, radionuclide air dispersion may occur secondarily as a result of forest fires.

TABLE 8.4. Examples of Surface Air Concentrations of I-131, Cs-131, Cs-137, and Cs-134 over the United States after the Chernobyl Catastrophe, May 1986 (Larsen and Juzdan, 1986; Larsen *et al.*, 1986; US EPA, 1986; Toppan, 1986; Feely *et al.*, 1988; Gebbie and Paris, 1986; Vermont, 1986)

Radionuclide	Location	Activity
I-131	New York, NY	20,720 $\mu Bq/m^3$
	Rexburg, ID	11,390 $\mu Bq/m^3$
	Portland, ME	2.9 pCi/m^3
	Augusta, ME	0.80 pCi/m^3
	Barrow, AL	218.7 fCi/m^3
	Mauna Loa, HI	28.5 fCi/m^3
Cs-137	New York, NY	9,720 $\mu Bq/m^3$
	Barrow, AL	27.6 fCi/m^3
	Mauna Loa, HI	22.9 fCi/m^3
Cs-134	Mauna Loa, HI	11.2 fCi/m^3
	Barrow, AL	18.6 fCi/m^3
Gross beta	Portland, ME	1.031 pCi/m^3
	Lincoln, NE	14.3 pCi/m^3
	Vermont	0.113 pCi/m^3

8.2. Chernobyl's Contamination of Aquatic Ecosystems

Chernobyl contamination traveled across the Northern Hemisphere for hours, days, and weeks after the catastrophe, was deposited via rain and snow, and soon ended up in bodies of water—rivers, lakes, and seas. Many Belarussian, Ukrainian, Russian, Latvian, and Lithuanian rivers were shown to be contaminated after the catastrophe, including the water basins of the Dnepr, Sozha, Pripyat, Neman, Volga, Don, and the Zapadnaya/Dvina-Daugava.

8.2.1. Belarus, Ukraine, and Russia

1. In the first days after the catastrophe (the period of primary aerosol contamination), the total activity in Pripyat River water near the Chernobyl NPP exceeded 3,000 Bq/liter. Only by the end of May 1986 had it decreased to 200 Bq/liter. The maximum concentration of Pu-239 in the Pripyat River was 0.37 Bq/liter.

TABLE 8.5. Examples of Surface Air Concentrations of Some Radionuclides in the Northern Hemisphere after the Catastrophe, 1986

Radionuclide	Concentration	Location	Date	Reference
I-131	223 Bq/m^3	Nurmijarvi	Apr. 28	RADNET, 2008
	251 Bq/m^3	Revelstoke, B.C., Canada	May 13	
	176 Bq/m^3	Quebec, Canada	May 5–6	
	20.7 Bq/m^3	New York, NY	May	
	0.8 Bq/m^3	Japan	May 5	Imanaka and Koide, 1986
Cs-137	9.7 Bq/m^3	Vienna	Apr. 30	Irlweck *et al.*, 1993
Ru-103	62.5 Bq/m^3			
Gross beta	160 Bq/m^3	Bulgaria	May 1	Pourchet *et al.*, 1997
	100 Bq/m^3	Munich	Apr. 30	Hotzl *et al.*, 1987
Pu-239 + Pu-240	89 $\mu Bq/m^3$	Vienna	May	Irlweck *et al.*, 1993
	0.4 $\mu Bq/m^{3,*}$	Paris	Apr. 29–30	Thomas and Martin, 1986

*During 1984, total Pu-239 + Pu-240 activity was 1,000-fold less (10–40 nBq/m^3).

2. From May to July 1986 the level of radiation in the northern part of the Kiev water reservoir was 100,000 times higher than the precatastrophe level (Ryabov, 2004).

3. Concentration of I-131 in surface water in Leningrad Province (Sosnovy Bor City) on May 2, 1986, was 1,300 Bq/liter and on May 4, 1986, it was 740 Bq/liter (Kryshev and Ryazantsev, 2000; Blynova, 1998).

4. During the first period after the catastrophe the littoral zone was heavily contaminated with radioactivity. In the years that followed bodies of water became secondarily contaminated as a result of the washout of Cs-137 and Sr-90 by spring high waters and from woodland fire fallout (Ryabov, 2004).

5. In July 1986, the primary dose-forming radionuclides in clay in the bodies of water near the Chernobyl NPP were Ni-98 (27 kBq/kg), Ce-144 (20.1 kBq/kg), and Zr-96 (19.3 kBq/kg). In March–April 1987 the concentration of Ni-95 in aquatic plants there reached 29 kBq/kg and Zr-95 levels in fowl were up to 146 kBq/kg (Kryshev *et al.*, 1992).

6. The Sr-90 contamination in the Dnepr River floodplain–lake ecosystem was concentrated primarily in bivalve mollusks, 10–40% concentrated in aquatic plants, about 2% in fish, 1–10% in gastropod mollusks, and less than 1% in plankton (Gudkov *et al.*, 2006).

7. The Cs-137 in the Dnepr River floodplain–lake ecosystem was distributed as follows: 85–97% in aquatic plants, 1–8% in zoobenthos, 1–8% in fish, and about 1% in gastropod mollusks (Gudkov *et al.*, 2006).

8. Owing to bioaccumulation, the amount of radionuclides can be thousands of times higher in plants, invertebrate, and fishes compared with concentrations in water (Table 8.6).

9. In contaminated territories with Cs-137 levels of 0.2 Ci/km^2 the rate of transfer from water into turf plants can vary 15- to 60-fold from year to year (Borysevich and Poplyko, 2002).

10. More than 90% of the Pu + Am in aquatic ecosystems is in the sediment (Borysevich and Poplyko, 2002).

11. The Cs-137 and Sr-90 concentrations increased in underground water and correlated with the density of land contamination and zones of aeration. The highest level of Sr-90 (up to 2.7 Bq/liter) was observed in rivers that ran through the heavily contaminated territories. In the Pripyat River floodplains in the territories with land contamination greater than 1,480 kBq/km^2 ground water activity reached 3.0 Bq/liter of Cs-137 and

TABLE 8.6. Coefficients of Accumulation for Some Live Organisms* of Chernobyl Radionuclides in the Dnepr River and the Kiev Reservoir, 1986–1989 (Kryshev and Ryazantsev, 2000: tables 9.12, 9.13, 9.14; Gudkov *et al.*, 2004)

Radionuclide	Mollusks	Water plants	Fishes (bream, sander, roach, silver bream)
Ce-141, Ce-144	3,000–4,600	20,000–24,000	500–900
Ru-103, Ru-106	750–1,000	11,000–17,000	120–130
Cs-134, Cs-137	178–500	2,700–3,000	100–1,100
Zr-95	2,900	20,000	190
Ni-95	3,700	22,000	220
Sr-90	440–3,000	240	50–3,000
Pu	—	4,175	98
Am	—	7,458	1,667
I-131	120	60	2–40

*Concentration in aquatic flora and fauna as compared with concentration in water.

0.7 Bq/liter of S-90 (Konoplia and Rolevich, 1996).

12. During spring high waters Cs-137 that has accumulated in bottom sediments becomes suspended and leads to noticeably increased radioactivity in water. Up to 99% of Sr-90 migrates in a dissolved state (Konoplia and Rolevich, 1996).

13. Owing to its higher solubility, Sr-90 leaves river ecosystems much faster than Cs-137. At the same time Cs-137 can accumulate up to 93 × 10^{-9} Ci/kg in grass and sod on flooded land (Borysevich and Poplyko, 2002).

14. The amount of Cs-137 and Sr-90 in water has decreased over time, but it has increased in aquatic plants and sediments (Konoplia and Rolevich, 1996).

15. More intensive radionuclide accumulation occurs in lake sediments owing to annual die-off of vegetation and the absence of drainage. In the 5 to 9 years after the catastrophe, in heavily weeded bodies of water there was a decrease in Cs-137 and Sr-90 in the water itself but a simultaneous increase in radioactivity in the sediment (Konoplia and Rolevich, 1996).

16. In the Svjetsko Lake (Vetka District, Belarus), total radionuclide concentration in water measured 8.7 Bq/liter, in aquatic plants upto 3,700 Bq/kg, and in fish up to 39,000 Bq/kg (Konoplia and Rolevich, 1996).

8.2.2. Other Countries

1. Finland, France, and Canada. Data on some radionuclide concentrations in rainfall and surface water in Finland, France, and Canada are presented in Table 8.7.

2. Great Britain (Scotland). On the evening of May 3, one of the Chernobyl clouds contaminated the sea with Te-132/I-132, I-131, Ru-103, Cs-137, Cs-134, and Ba-140/La-140 totaling 7,000 Bq/liter (Martin *et al.*, 1988).

3. Greece. Composition of dose-forming radionuclides and their activity in Greece in May 1986 are presented in Table 8.8.

4. North Sea. In a North Sea sediment trap, the highest Chernobyl activity reached 670,000 Bq/kg, with Ru-103 being the most prevalent isotope (Kempe and Nies, 1987). Radionuclide levels in sea spume were several thousand times higher than in seawater in June of 1986. Cs-137 and Cs-134 quickly migrated to the sediments, whereas Ru-106 and Ag-110 lingered in the spume (Martin *et al.*, 1988).

5. The Netherlands. I-131, Te-132, I-132, La-140, Cs-134, Cs-137, and Ru-103 were measured in rainwater in the Nijmegen area during May 1–21, 1986. The total activity on the first rainy day was of 9 kBq/liter

TABLE 8.7. Rainfall and Surface Water Radionuclide Concentrations in Several Countries, 1986–1987

Radionuclide	Maximum concentration	Location	Date	Reference
Cs-137	5,300 Bq/m^3*	Finland	1986	Saxen and Aaltonen, 1987
	325 mBq/liter	Canada, Ontario	May 1986	Joshi, 1988
	700 Bq/liter	France, Paris	Apr. 29–30, 1986	Thomas and Martin, 1986
Sr-89	11,000 Bq/m^3	Finland	1986	Saxen and Aaltonen, 1987
Te-132	7,400 Bq/liter	France, Paris	Apr. 29–30, 1986	Thomas and Martin, 1986

*About 1,000 times higher than the precatastrophe concentration, and up to 80 times higher than the highest values after the nuclear weapons test period in the 1960s.

(2.7 kBq/liter for I-131 and 2.3 kBq/liter each for Te-132 and I-132). The total activity precipitated per square kilometer in this period was about 55 GBq (Beentjes and Duijsings, 1987).

6. POLAND. Average values of Pu-239 + Pu-240 in the Polish economic zone of the Baltic Sea ranged from 30 to 98 Bq/m^2 in three sampling locations. The highest concentration of Pu in sediment probably came from the Vistula River, which delivered 192 MBq of Chernobyl's Pu-239 + Pu-240 to the Baltic Sea in 1989 (Skwarzec and Bojanowski, 1992). The total Cs-137 loading of Lake Sniardwy was estimated to average 6,100 Bq/m^2 (Robbins and Jasinski, 1995).

7. SWEDEN. The annual mean concentration of Cs-137 (in Bq/kg) in surface water near Gotland Island from 1984 to 2004 is shown in Figure 8.2.

TABLE 8.8. Composition and Activity of the Chernobyl Radioactive Fallout in Thessaloniki, Greece, (Total Wet Deposition, Bq/m^2), May 5–6, 1986 (Papastefanou *et al.*, 1988)

Radionuclide	Maximum concentration
I-131	117,278
Te-132	70,700
I-132	64,686
Ru-103	48,256
Ba-140	35,580
Cs-137	23,900
La-140	15,470
Cs-134	12,276

8. TYRRHENIAN SEA. Concentration of Cs-137 in surface water of the Tyrrhenian Sea rose significantly immediately after the catastrophe (Figure 8.3).

8.3. Chernobyl's Contamination of the Soil Mantle

The soil mantle will accumulate Chernobyl's radionuclides with long half-lives for centuries. As in the previous review, this material is only a representative selection from the very large body of existing data.

8.3.1. Belarus, Ukraine, and Russia

1. Radionuclides on sod-podzol and heavily podzolized sandy clay soils move from the surface to the bottom soil layer during the course of time, resulting in the concentration of radionuclides in the root zone. It is in this way that soils with low surface contamination transfer radioactivity to the vegetative (and edible) parts of plants (Borysevich and Poplyko, 2002).

2. Plowed and natural pastures located 50 to 650 km from the Chernobyl site have levels of Cs-137 activity in the 1,000 to 25 kBq/m^2 range in the upper soil layers (0–5 cm). Levels of contamination are higher in natural pastures as compared with plowed pastures, with the Sr-90 activity ranging from 1.4 to 40 kBq/m^2 (Salbu *et al.*, 1994).

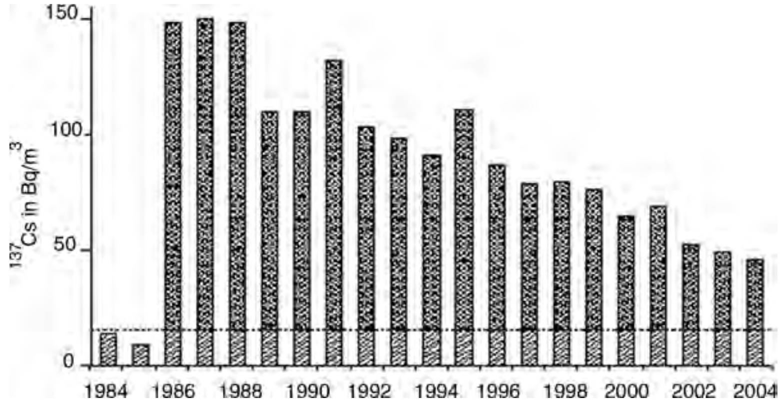

Figure 8.2. The annual mean Cs-137 concentrations (in Bq/liter) in surface waters of East and West Gotland (sampling depth $\leq$10 m) from 1984 to 2004. Straight line—average pre-Chernobyl (1984–1985) level (HELCOM, 2006).

3. The soils most highly contaminated by I-131 are in northern Ukraine, eastern Belarus, and nearby provinces of Russia, but some "spots" of radioiodine soil contamination have been detected in many areas, including Kaliningrad Province on the Baltic shore (Makhon'ko, 1992).

4. In many areas up to hundreds of kilometers to the west, northwest, and northeast of the Chernobyl NPP the levels of Cs-137 soil contamination exceed 1,489 kBq/m^2 (Kryshev and Ryazantsev, 2000).

5. In humid environments such as flood planes, lowland moors, and peat bogs vertical migration is activated at different speeds for different radionuclides (Table 8.9).

6. Self-cleansing of soils by vertical migration of radionuclides can reach 2 to 4 cm/year (Bakhur *et al.*, 2005).

7. The granular composition of soil and agrichemical soil characteristics modifies the transfer coefficient for Cs-137 (see Chapter 9). There is roughly a 10-fold variation (from 0.01 to 0.11 Bq/kg) in the degree of Cs-137 transition from soil to beetroots depending on whether the soil is sod-podzol, loamy, sandy-clay, or sandy (Borysevich and Poplyko, 2002).

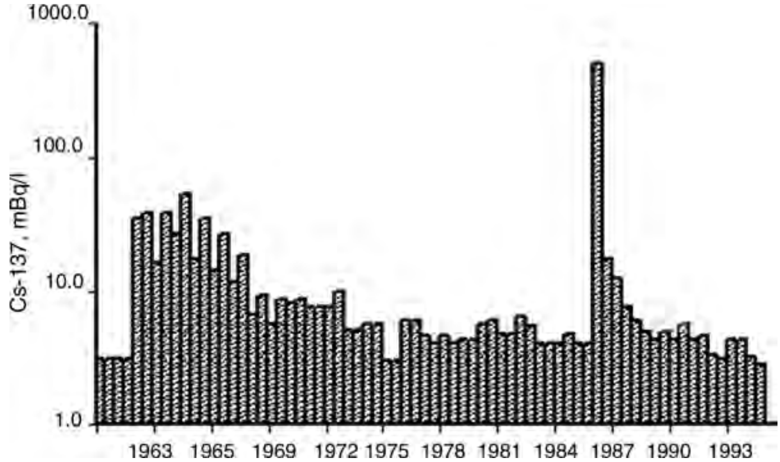

Figure 8.3. Concentration of Cs-137 (mBq/liter) in surface waters of the Tyrrhenian Sea, 1960–1995 (Europe Environmental Agency, 1999).

TABLE 8.9. The Years Needed to Achieve a 50% Reduction in the Amount of Each Radionuclide in the Top (0–5 cm) Soil Layer in Areas 50 and 200 km from the Chernobyl NPP (National Belarussian Report, 2006)

	Years	
Radionuclide	Up to 50 km	Up to 200 km
Pu-239, Pu-240	6–7	>50
Am-241	6–7	>50
Sr-90	7–12	7–12
Cs-137	10–17	24–27

8.3.2. Other Countries

1. AUSTRIA. The alpine regions were among the most heavily contaminated territories outside of the Former Soviet Union. In May 1986 in Salzburg Province the median Cs-137 surface deposition was about 31 kBq/m^2 with maximum values exceeding 90 kBq/m^2 (Lettner *et al.*, 2007) or even 200 kBq/m^2 (Energy, 2008). Ten years after the catastrophe 54% of Chernobyl-derived Cs-137 was 2 cm deeper into the soil layer in a spruce forest stand, with less than 3% having reached layers deeper than 20 cm. The average retention half-life of Cs-137 was 5.3 years in the 0–5 cm layer, 9.9 years in the 5–10 cm layer, and 1.78 years in layers deeper than 10 cm (Strebl *et al.*, 1996).

2. BULGARIA. Surface soil Cs-137 activity was up to 81.8 kBq/m^2 in the most contaminated territories, which is eight times higher than the cumulative amount deposited during the peak period of weapons testing (Pourchet *et al.*, 1997).

3. CROATIA. In 1986 Cs-137 fallout deposit reached 6.3 kBq/m^2 (Franić *et al.*, 2006).

4. DENMARK. The total mean Cs-137 and Sr-90 deposits over Denmark reached 1.3 and 38 Bq/m^2, respectively, as a result of Chernobyl. Most of the debris was deposited in the first half of May. In the Faeroe Islands the mean deposition of Cs-137 was 2 kBq/m^2 and in Greenland it was up to 188 Bq/m^2 (Aarkrog, 1988).

5. ESTONIA. The ground deposition from Chernobyl for Cs-137 was 40 kBq/m^2 (Realo *et al.*, 1995).

6. FRANCE. The maximal Cs-137 Chernobyl soil contamination reached up to 545 kBq/kg (CRII-RAD, 1988) and radioactivity from Chernobyl fallout in the French Alps reached 400 Bq/m^2 (Pinglot *et al.*, 1994).

7. GERMANY. Average ground deposition for total Cs was 6 kBq/m^2 (Energy, 2008), and concentration of radionuclides in the southern part of the country was much higher (Table 8.10).

8. IRELAND. The initial Chernobyl fallout owing to Cs-137/Cs-134 reached a concentration of 14,200 Bq/m^2, some 20-fold higher than the pre-catastrophe level (McAuley and Moran,1989).

9. ITALY. In the mountain area of Friuli-Venezia Giulia deposition of Cs-137 from Chernobyl ranged from 20 to 40 kBq/m^{-2}. Concentration of Cs-137 in soil 0–5 cm deep declined only 20% in the first 5 years after the catastrophe (Velasko *et al.*, 1997).

10. JAPAN. Up to 20 radionuclides were detected on the ground, including Cs-137, I-131, and Ru-103, with resulting levels of 414, 19, and 1 Bq/m^2, respectively (Aoyama *et al.*, 1987).

11. NORWAY. Many places in Norway were heavy contaminated after the catastrophe (Table 8.11).

12. POLAND. Soil in central Poland was contaminated by a wide spectrum of the Chernobyl radionuclides (Table 8.12). In the northeastern part of the country Cs-134 + Cs-137 ground deposition levels were up to 30 kBq/m^2 and I-131 and I-132 deposition was up to 1 MBq/m^2 (Energy, 2008).

13. SWEDEN. The mean deposition of Chernobyl Cs-137 in the forest soils was above 50 kBq/m^2 (McGee *et al.*, 2000), and maximum Cs-134 + Cs-137 ground deposition was up to 200 kBq/m^2 (Energy, 2008).

14. UNITED KINGDOM. Examples of radioactive contamination in soil are presented in Table 8.13. Floodplain loading of Cs-137 in soil was up to 100 times greater than in soils above the floodplain (Walling and Bradley, 1988). On May 3, one of the Chernobyl clouds

TABLE 8.10. Ground Deposition (kBq/m²) of Some Chernobyl Radionuclides in Germany, 1986

Radionuclide	Location	Concentration, max	Reference
Cs-137	Upper Swabia	43	Bilo *et al.*, 1993
	Bonn	1.38	Clooth and Aumann, 1990
Cs-134 + Cs-137	South Germany	60	Energy, 2008
Te-132	Munich*	120	Gogolak *et al.*, 1986

*June 3, 1986; cumulative dry and wet deposition.

TABLE 8.11. Examples of Cs-137 Ground Contamination after the Chernobyl Catastrophe in Norway, 1986

Maximum radioactivity	Location	Reference
22 kBq/kg*	Stream gravel	Hongve *et al.*, 1995
500 kBq/m²*	Average in sediment	Hongve *et al.*, 1995
22 Bq/kg	Svalbard glaciers	Pinglot *et al.*, 1994
80 kBq/m²	Dovrefjell	Solem and Gaare, 1992
54 kBq/m² (mean)	Southern Norway, grazing areas	Staaland *et al.*, 1995
200 kBq/m²*	Soils in affected areas	Blakar *et al.*, 1992

*Cs-134 + Cs-137

contaminated the Scottish landscape with Te-132/I-132, I-131, Ru-103, Cs-137, Cs-134, and Ba-140/La-140 totaling 41 kBq/m² (Martin *et al.*, 1988).

15. United States. Observations of radionuclide contamination of U.S. soils from Chernobyl are listed in Table 8.14. Ground deposition for Cs-137 comes close to or exceeds the total weapons' testing fallout (Dibb and Rice, 1988). The spectrum of Chernobyl's soil contamination in the United States included Ru-103, Ru-106, Cs-134, Cs-136, Cs-137, Ba-140, La-140, I-132, Zr-95, Mo-95, Ce-141, and Ce-144 (Larsen *et al.*, 1986).

16. Table 8.15 presents data on Cs-137 + Cs-134 contamination in several European countries.

TABLE 8.12. Spectrum and Activity of Chernobyl Radionuclides in Soil Samples (kBq/m² in 0–5 cm Layer) in the Krakov Area, May 1, 1986 (Broda, 1987)

Radionuclide	Activity	Radionuclide	Activity
Te-132	29.3	Ba-140	2.5
I-132	25.7	La-140	2.4
I-131	23.6	Mo-99	1.7
Te-129m	8.0	Ru-106	1.3
Ru-103	6.1	Sb-127	0.8
Cs-137	5.2	Cs-136	0.7
Cs-134	2.7	Total	Up to 360

8.4. Conclusion

Chernobyl's radioactive contamination has adversely affected all biological as well as nonliving components of the environment: the atmosphere, surface and ground waters, the surface and the bottom soil layers, especially in the heavily contaminated areas of Belarus, Ukraine, and European Russia. Levels of Chernobyl's radioactive contamination even in North America and eastern Asia are above the maximum levels that were found in the wake of weapons testing in the 1960s.

Modern science is far from understanding or even being able to register all of the radiological effects on the air, water, and soil ecosystems due to anthropogenic radioactive contamination.

TABLE 8.13. I-131 and Cs-134/Cs-137 Soil Contamination (kBq/m²) from Chernobyl Radionuclides in Some Parts of the United Kingdom, 1986

Radionuclide	Activity	Location	Date	Reference
I-131	26	Lerwick, Shetland	May 1–6	Cambray *et al.*, 1987
	41	Holmrook, Cumbria		
Cs-137	7.4	Sellafield, Cumbria	May	Fulker, 1987
	15	Ireland	1986	Rafferty *et al.*, 1993
	0.6	Berkeley, Gloucestershire	May	Nair and Darley, 1986
Cs-134/Cs-137	100	Scotland	May	Wynne, 1989
Gross beta	88.4	Strathclyde, Scotland	May 6	RADNET, 2008

TABLE 8.14. Examples of Ground Deposition of Chernobyl Radionuclides (Dibb and Rice, 1988; Dreicer *et al.*, 1986; Miller and Gedulig, 1986; Gebbie and Paris, 1986)

Radionuclide	Location	Date, 1986	Activity
Cs-137	Solomons Island, MD	May 8–June 20	4,250 Bq/m^2
	Chester, NJ	May 17	9.40 Bq/m^{2*}
Cs-134	Solomons Island, MD	May 8–June 20	2,000 Bq/m^2
Ru-103	Solomons Island, MD	May 8–June 20	22,000 Bq/m^2
	Chester, NJ	June 3	18.46 Bq/m^2
	Chester, NJ	May 23	15 Bq/m^2
I-131	Chester, NJ	May 23	47.2 Bq/m^2
	Portland, OR	May 11	9,157 pCi/m^2

*Deposition on grass.

Undoubtedly there are such changes and, owing to the amount of Chernobyl radionuclides that were added to the biosphere, the changes will continue for many decades.

Contrary to the common view that the Chernobyl plumes contained mostly light and gaseous radionuclides, which would disappear without a trace into the Earth's atmosphere, the available facts indicate that even Pu concentrations increased thousands of times at distances as far as many thousands of kilometers away from Chernobyl.

TABLE 8.15. Level of Ground Radioactive Contamination after the Chernobyl Catastrophe on British Embassy Territory in Some European Countries (http://members.tripod.com/~BRuslan/win/energe1.htm)

Location	Cs-134, kBq/m^2	Cs-137, kBq/m^2
Czech (Prague)	4.9	2.9
Hungary (Budapest)	8.8	5.3
Yugoslavia (Belgrade)	7.3	4.4
Romania (Bucharest)	4.3	2.6
Poland (Warsaw)	2.8	1.7

Common estimates of the level of radioactivity per liter or cubic or square meter mask the phenomenon of radionuclides concentrating (sometimes many thousands of times) in sediments, in sea spume, in soil microfilms, etc., through bioconcentration (for details see Chapters 9 and 10). This means that harmless looking "average" levels of radionuclides inevitably have a powerful impact on living organisms in the contaminated ecosystems.

As a result of vertical migration of radionuclides through soil, they accumulate in plants with deep root systems. Absorbed by the roots, the buried radionuclides again rise to the surface and will be incorporated in the food chain. This transfer is one of the more important mechanisms observed in recent years that leads to increased internal irradiation for people in the all of the territories contaminated by nuclear fallout.

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9. Chernobyl's Radioactive Impact on Flora

Alexey V. Yablokov

Plants and mushrooms accumulate the Chernobyl radionuclides at a level that depends upon the soil, the climate, the particular biosphere, the season, spotty radioactive contamination, and the particular species and populations (subspecies, cultivars), etc. Each radionuclide has its own accumulation characteristics (e. g., levels of accumulation for Sr-90 are much higher than for Cs-137, and a thousand times less than that for Ce-144). Coefficients of accumulation and transition ratios vary so much in time and space that it is difficult, if not impossible, to predict the actual levels of Cs-137, Sr-90, Pu-238, Pu-239, Pu-240, and Am-241 at each place and time and for each individual plant or fungus. Chernobyl irradiation has caused structural anomalies and tumorlike changes in many plant species. Unique pathologic complexes are seen in the Chernobyl zone, such as a high percentage of anomalous pollen grains and spores. Chernobyl's irradiation has led to genetic disorders, sometimes continuing for many years, and it appears that it has awakened genes that have been silent over a long evolutionary time.

There are thousands of papers about agricultural, medicinal, and other plants and mushrooms contaminated after the Chernobyl catastrophe (Aleksakhin *et al.*, 1992; Aleksakhin, 2006; Grodzinsky *et al.*, 1991; Ipat'ev 1994, 1999; Parfenov and Yakushev, 1995; Krasnov, 1998; Orlov, 2001; and many others). There is also an extensive body of literature on genetic, morphological, and other changes in plants caused by Chernobyl radiation. In this chapter we present only a relatively small number of the many scientific papers that address Chernobyl's radioactive impact on flora.

The Chernobyl fallout has ruined the pine forests near the nuclear power plant, which were not able to withstand the powerful radioactive impact, where contamination in the first weeks and months after the catastrophe reached several thousand curies per square kilometer. With the catastrophe's initial atmospheric radiotoxins (see Chapter 8) and the powerful irradiation caused by "hot particles," the soil and plants surfaces became contaminated and a cycle of absorption and release of radioisotopes from soil to plants and back again was put into motion (Figure 9.1).

Soon after the catastrophe plants and fungi in the contaminated territories became concentrators of radionuclides, pulling them from the soil via their roots and sending them to other parts of the plant. Radionuclide levels in plants depend on the transfer ratio (TR, transition coefficient) and the coefficient of accumulation (CA)—the relationship of specific activity of a radionuclide in a plant's biomass to the specific activity of the same radionuclide in soil: [TR = (Bq/kg of plant biomass)/(kBq/m^2 for soil contamination); CA = (Bq/kg of plant biomass)/(Bq/kg of soil)].

9.1. Radioactive Contamination of Plants, Mushrooms, and Lichens

The level of radionuclide incorporation (accumulation) in a living organism is a simple and reliable mark of the potential for damage to the genetic, immunological, and life-support

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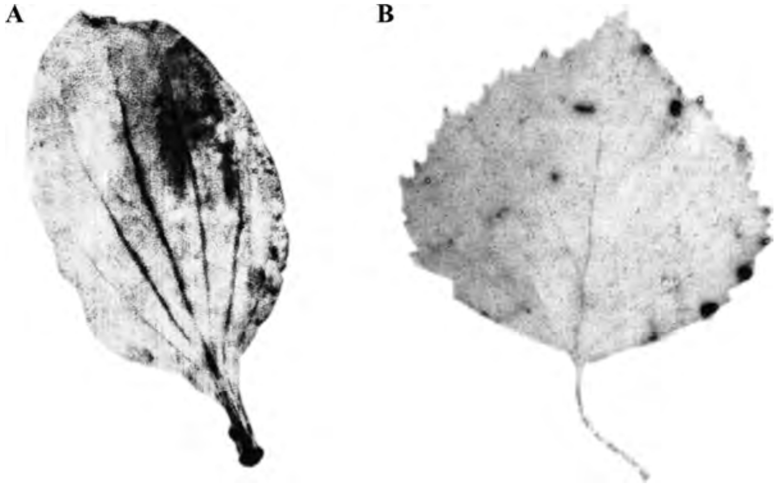

Figure 9.1. Radioautographs of plants with Chernobyl radionuclides: (**A**) leaf of common plantain (*Plantago major*); (**B**) aspen leaf (*Populus tremula*) Bryansk Province, Russia, 1991. Spots of the raised radioactivity are visible. (A. E. Bakhur photo, with permission.)

systems of that organism. The first part of this section presents data regarding radioactive contamination in plants and the second relates to the levels of contamination in mushrooms and lichens.

9.1.1. Plants

1. The levels of surface contamination of three species of plants in Kiev City reached 399 kBq/kg and varied by specific location and particular radionuclide (Table 9.1).

2. Table 9.2 presents data on radionuclide accumulation in the pine needles in Finland after the catastrophe.

3. Data in Table 9.3 indicate the level of plant radionuclide contamination that was reached worldwide after the catastrophe.

4. There were high levels of radionuclide accumulation in aquatic plants (Table 9.4).

5. After the catastrophe the levels of incorporated radionuclides jumped in all of the heavily contaminated territories. In annual plants such as absinthe (*Artemisia absinthium*), C-14

TABLE 9.1. Chernobyl Radioactivity (Bq/kg, dry weight) of Leafage in Three Species in Kiev City at the End of July 1986 (Grodzinsky, 1995b)

Nuclide	*Aesculus hippocastanum**	*Tilla cordata***	*Betula verrucosa***	*Pinus silvestris***
Pm-144	58,800	146,150	10,800	–
Ce-141	18,800	–	6,500	4,100
Ce-144	63,300	–	21,800	18,800
La-140	1,100	1,930	390	660
Cs-137	4,030	–	3,400	4,300
Cs-134	2,000	–	1,540	2,100
Ru-103, Rh-103	18,350	36,600	10,290	7,180
Ru-106	14,600	41,800	400	5,700
Zr-95	35,600	61,050	11,400	6,500
Nb-95	53,650	94,350	18,500	9,900
Zn-65	–	400	–	–
Total activity	312,000	399,600	101,400	70,300

*Near underground station "Darnitza"; ** near underground station "Lesnaya."

TABLE 9.2. Concentration of Three Radionuclides in Pine Needles in Central Finland, May–December 1986 (Lang *et al.*, 1988)

Radionuclide	Concentration, Bq/kg
Cs-137	30,000
Ce-141	40,000
Ru-103	35,000

concentrations increased as much as fivefold in 1986 (Grodzinsky *et al.*, 1995c). Figure 9.2 shows the concentration of C-14 in three rings (percent compared to the 1950 level) of pine (*Pinus silvestris*) from the 10-km zone.

6. There was a marked increase in the total amount of radionuclides in tree rings of pine (*Pinus silvestris*) in the Karelia Republic, Russian northwest (more than 1,200 km from Chernobyl) after the catastrophe (Figure 9.3). It is important to note that Karelia officially characterized the level of contamination as very moderate (<0.5 Ci/km^2; Cort and Tsaturov, 1998).

7. The Belarussian berries, semifrutex of the Vacciniaceae species, are characterized by a maximum intensity of Cs-137 accumulation (Mukhamedshin *et al.*, 1995; Kenigsberg *et al.*, 1996; Jacob and Likhtarev, 1996).

8. The coefficient of accumulation of Cs-137 in cranberries (*Oxycoccus palustris*) is up to 1,028 (Orlov and Krasnov, 1997; Krasnov and Orlov, 2006).

9. There are wide intraspecies variations in specific Sr-90 activity: from 2–3 up to 555 Bq/kg in fresh bilberries (*Vaccinium myrtillus*) in mertyllus-type pinewoods (Orlov *et al.*, 1996).

10. More radionuclides accumulated in the root system (up to sevenfold more than in above-ground parts of plants). In above-ground parts, the higher radionuclide concentration is in the leaves and lower levels in the flowers (Grodzinsky *et al.*, 1995a). The leaves of bilberry (*Vaccinium myrtillus*) during fruiting (July) contain 31% of the general Cs-137 activity, stalks have 26%, berries 25%, and rhizomes with roots 18% (Korotkova and Orlov, 1999).

11. Concentration of Cs-137 in the vegetative mass in different lupine (*Lupinus*) varieties was on average fivefold more than in maize (*Zea*), and clover (*Trifolium*) and vetch (*Vicia*) had intermediate levels. Cs-137 accumulation in the various grain crops varied to an even greater degree than that in vegetative masses, in dernopodzolic soils by a factor of 38 and in chernozem by a factor of 49 (Kuznetsov

TABLE 9.3. Examples of the Worldwide Contamination of Plants (Bq/kg) in 1986

Nuclide	Subject	Activity	Country	Reference
Cs-137	Moss	40,180*	Norway	Staaland *et al.*, 1995
	Hair moss	28,000	Finland	Ilus *et al.*, 1987
	Moss	20,290**	Norway	Staaland *et al.*, 1995
	Moss	12,370***	Germany	Elstner *et al.*, 1987
	Tea, *Thea sinensis*	44,000	Turkey	Gedikoglu and Sipahi, 1989
	Moss, *Hylocomium splendens*	40,000	Norway	Steinnes and Njastad, 1993
	Moss	30,000	Germany	Heinzl *et al.*, 1988
I-131	Plants	2,100	Japan	Ishida *et al.*, 1988
	Edible seaweed	1,300	Japan	Hisamatsu *et al.*, 1987
	Grass	15,000 Bq/m^2	UK	Clark, 1986
Ce-141	Pine needles	40,000	Finland	Lang *et al.*, 1988
Ru-103	Pine needles	35,000	Finland	Lang *et al.*, 1988
	Hair moss	18,000	Finland	Ilus *et al.*, 1987
Te-132	Herbs	730	Finland	Rantavaara, 1987
Sr-89	Hair moss	3,500	Finland	Ilus *et al.*, 1987

*1987; **1988; ***up to 139 times higher than in 1985.

TABLE 9.4. Levels of Radionuclide Accumulations (Bq/kg, Dry Weight) by Some Aquatic Plants, Ukraine, 1986–1993 (Bar'yakhtar, 1995)

Species	Ce-144	Ru-103, Rh-103	Ru-106, Rh-106	Cs-137	Cs-134	Nb-95, Zr-95	Sr-90
Shining pondweed (*Potamogeton natans*)	44,400	4,800	33,300	12,600	8,100	63,000	925
Common reed grass (*Phragmites communis*), above-water parts	26,000	3,700	8,900	12,900	4,800	3,700	5
Common reed grass (*Phragmites communis*), underwater parts	99,900	6,700	129,500	66,600	21,800	13,700	2,400
Narrow-leaved cat's-tail (*Typha angustifolia*)	20,350	7,000	24,800	3,700	1,370	1,330	270

et al., 2000). The most active transfer of radionuclides from soil to plants occurs on peat-bog soil. The transfer coefficient for Cs-137 from scrub forests is up to three times higher for half-submerged soil as compared with drier soil and up to twice that for mixed vegetation as compared with pinewoods (Borysevich and Poplyko, 2002).

12. The level of incorporated radionuclides tends to correlate with the density of radioactive contamination in the soil (Figure 9.4).

13. There are strong correlations between specific Cs-137 activity in a phytomass of *Convallaria majalis* and both the density of ground contamination ($r = 0.89$) and the specific activity of Cs-137 in the soil ($r = 0.84$; Elyashevich and Rubanova, 1993).

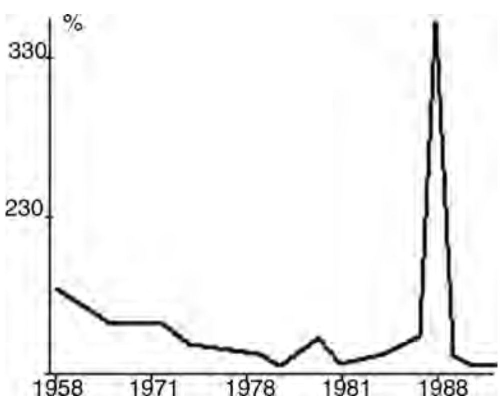

Figure 9.2. Concentration of C-14 in tree rings of pine (*Pinis silvestris*; percent difference from the level in the year 1950) from the 10-km Chernobyl zone (Grodzinsky *et al.*, 1995c).

14. The Cs-137 CA of 120 plant species increases in the following order of ecotopes: boggy forest (425) > oakwood (241) > depressions between hill-forest of flood plain (188) > pinewood (94) > undrained lowland swamp (78) > hill forest of flood plains (68) > upland meadows (21) > drained peat-bog soil (11) > long-term fallow soil (0.04; Elyashevich and Rubanova, 1993).

15. Transfer ratios from soil to plants are different for each species and also vary by season and habitat (Table 9.5).

16. The maximum transfer ratio (from soil to plant) of Sr-90 was measured in wild strawberries (TR 14–15), and the minimum was in bilberry (TR 0.6–0.9) in Belarus. The Cs-137 transfer ratio in bilberry (*Vaccinium myrtillus*) is threefold higher than that for wild strawberry (*Fragaria vesca*; Ipat'ev, 1994; Bulavik, 1998).

17. Plants growing on hydromorphic landscapes accumulate 10-fold more Cs-137 than those in automorphic soil. There is up to a 50-fold difference in the Cs-137 TR between an automorphic and a hydromorphic environment: intensity of accumulation of Cs-137 in berries is much lower on richer and dry soils as compared with poor and wet soils (Tsvetnova *et al.*, 1990; Wirth *et al.*, 1996; Korotkova, 2000; and others).

18. There are heavy accumulations of Cs-137 in a plant's above-ground biomass in the Ukrainian wet pine subor for the cowberry family species (Vacciniaceae): TR is about 74

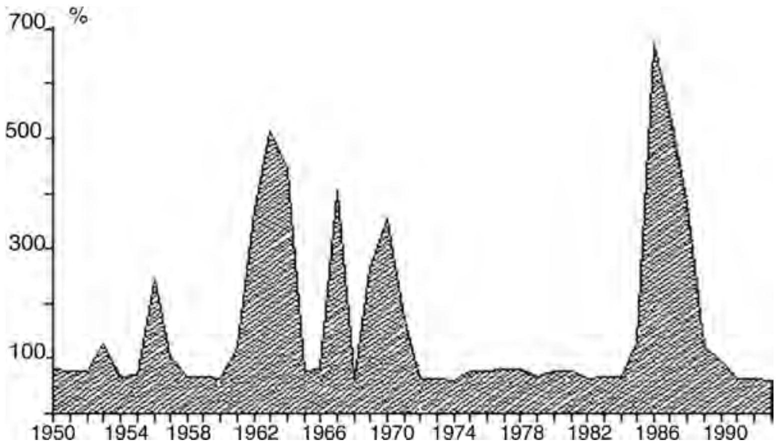

Figure 9.3. Total radioactivity in tree rings of pine (*Pinus silvestris*) near Petrozavodsk City, Karelia, for the period 1975–1994 (Rybakov, 2000).

in bilberry (*Vaccinium myrtillus*), 67 in cowberry (*Vaccinium vitis-idaea*), and 63 in blueberry (*Vaccinium uliginosum*; Krasnov, 1998).

19. For nonwood medicinal plants the decreasing order of Cs-137 incorporation is as follows: berries (*Vaccinium myrtillus*) > leaf (*Vaccinium myrtillus*) > grass (*Thymus serpyllum*) > grass (*Convallaria majalis*) > grass (*Fragaria vesca*) > flowers (*Helichrysum arenarium*) > grass (*Hypericum perforatum* and *Betonica officinalis*) > grass (*Origanum vulgare*; Orlov, 2001).

20. The maximum TR values are: wild plants (*Ledum palustre*) 451, grass (*Polygonum hydropiper*) 122, fruits (*Vaccinium myrtillus*) 159, leaves (*Fragaria vesca*) 73 and (*Vaccinium vitis-idaea*) 79, and buds (*Pinus sylvestris*) 61 and (*Betula pendula*) 47 (Elyashevich and Rubanova, 1993).

21. In the Ukrainian Poles'e, Cs-137 in fresh berries and air-dried bilberry offsets decreased fivefold in 1998 in comparison with 1991 (Korotkov, 2000). In other data, from 1991 to 1999 the amount of Cs-137 in bilberry fruit (*Vaccinium myrtillus*) fluctuated greatly (Orlov, 2001).

22. In mossy pine forests the concentration of Cs-137 in bilberry (*Vaccinium myrtillus*) fruit

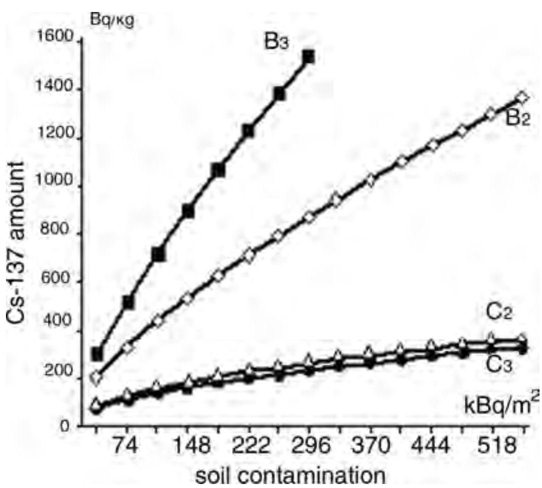

Figure 9.4. Correlation between the amount of Cs-137 in fresh bilberry (*Vaccinium myrtillus*) (Bq/kg) and the level of soil contamination (kBq/m^2) for four different biospheres in Central Poles'e, Ukraine (Orlov, 2001): (vertical axis) specific activity, Bq/kg; (horizontal axis) soil contamination, kBq/m^2 (B_2, fresh subor; B_3, dry subor; C_2, fresh sudubrava; C_3, dry sudubrava).

TABLE 9.5. Cs-137 TR from Soil to Fresh Fruits of the Principal Wild Ukrainian Berries (Orlov, 2001)

Species	TR	Species	TR
Vaccinium myrtillus	3.4–16.1	*Rubus nessensis*	6.6
V. vitis-idaea	8.3–12.9	*Rubus caesius*	1.0
V. uliginosum	9.4–11.7	*Fragaria vesca*	2.0–10.9
Oxycoccus palustris	13.0–16.6	*Sorbus aucuparia*	1.0
Rubus idaeus	0.8–8.4	*Viburnum opulus*	0.3

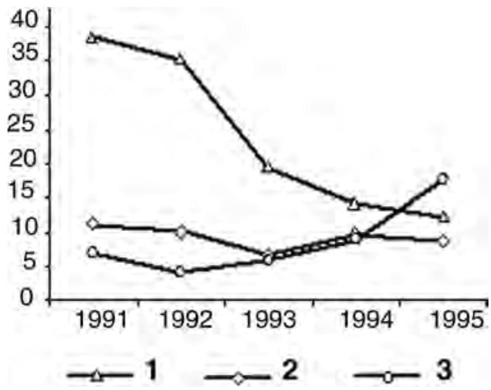

Figure 9.5. Variations of the transfer ratio for Cs-137 for three medicinal plants: the grasses *Convallaria majalis* and *Hypericum perforatum* and the bark *Frangula alnus* over several years (1991–1995). Average data for 28 stations in Ukrainian Poles'e (Krasnov, 1998).

from 1987 to 1990 was practically stable in some places, whereas in other areas there was a threefold decrease in the TR in 1989–1990 as compared with 1987–1988 (Parfenov and Yakushev, 1995).

23. Maximum Cs-137 activity in the vegetative parts of undershrubs and trees is observed in May and June (Korotkova and Orlov, 1999; Borysevich and Poplyko, 2002).

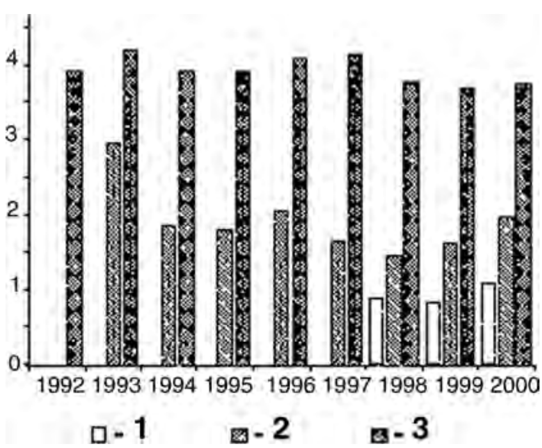

Figure 9.6. Variation of the transfer ratio for Cs-137 for three species of wild forest berries in Belarus: raspberry (*Rubus idaeus*), strawberry (*Fragaria vesca*), and blueberry (*Vaccinium myrtillus*) in the same area from 1990 to 1998 (Ipat'ev, 1999).

TABLE 9.6. Inter- and Intraspecific Variations of TR ($m^2/kg \times 10^{-3}$) from Soil to Fresh Wild Edible Berries in Belarussian, Ukrainian, and Russian Forest Zones Affected by Chernobyl Fallout (Based on Many References from Orlov, 2001)

Species	TR (Lim)	Max/min
Rubus idaeus	0.8–8.4	10.5
Fragaria vesca	2.0–10.9	5.5
Vaccinium myrtillus	3.4–16.1	5.3
Vaccinium vitis-idaea	8.1–12.9	1.6
Oxycoccus palustris	13–16.6	1.3
Vaccinium uliginosum	9.4–11.7	1.2
Rubus nessensis	6.6	
Rubus caesius	1.0	
Sorbus aucuparia	1.0	
Viburnum opulus	0.3	

24. Specific Sr-90 activity in the fresh fruits of bilberry (*Vaccinium myrtillus*) in the Ukrainian pine forests varied from 2 to 555 Bq/kg (Orlov, 2001).

25. Long-term dynamics of Cs-137 TR from soil to plants revealed all possible variations: for the grass *Convallaria majalis* there was a significant decrease over time; for the grass *Hypericum perforatum* there was a marked decrease from 1991 to 1992, but more than a twofold increase from 1993 to 1995; for the bark *Frangula alnus* there was a steady total threefold decrease in 1995 as compared with 1991 (Figure 9.5); for blueberries there was a slight decrease over 9 years; and for strawberries there was a sharp increase followed by a slower one (Figure 9.6).

26. The lognormal distribution of the TR in the same species in a similar ecological ambience makes it impossible to correctly estimate specific TR by sporadic observations (Jacob and Likhtarev, 1996).

27. There are wide inter- and intraspecies variations in TR for the edible wild berries (Table 9.6).

28. TR differs for the same species for different biotopes (Table 9.7).

29. Dynamics of Cs-137 contamination of various parts of pine (*Pinus silvestris*) are presented in Figure 9.7. The levels of contamination in the trunk, branches, and needles were nearly stable over 12 years.

TABLE 9.7. Average TR in Fresh Blueberries (*Vaccinium myrtillus*) in Three Different Types of Pine Forests in 1995 (Ipat'ev and Bulko, 2000)

Type of pine forest	TR
Bilberry	5.19
Polytric	14.00
Ledum	24.00

30. In automorphic landscapes the Cs-137 TR decreased in grass species from 1988 to 1995. In hydromorphic landscapes there was gradual increase in this coefficient beginning in 1992 (Tscheglov, 1999).

31. The intensities of Cs-137 accumulation in herbs that were studied are divided into five groups: very strong accumulation (average TR >100), strong accumulation (TR 50–100), moderate accumulation (TR 10–50), weak accumulation (TR 1–10), and very weak accumulation (TR <1; Table 9.8).

32. The highest intensity of Cs-137 accumulation according to species was found in the families Ericaceae and Fabaceae, somewhat less in the families Boraginaceae and Caryophyllaceae, still less in the species of the family Lamiaceae (*Origanum vulgare*, *Salvia officinalis*, *Thymus* sp.), and minimal in species of the families Asteraceae (*Achillea millefolium*, *Calendula officinalis*) and Hypericaceae (*Hypericum perforatum*; Aleksenyzer *et al.*, 1997).

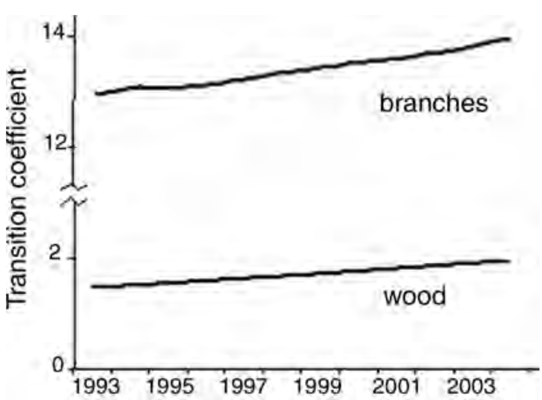

Figure 9.7. Dynamics of Cs-137 transfer ratio (TR × 10^{-3}) for branches and wood of pine (*Pinus silvestris*) from 1993 to 2004 (Averin *et al.*, 2006).

33. The TR for Sr-90 from soil to plants is 10 to 20 times higher than the TR of Cs-137 in the same habitat and the same species (Orlov *et al.*, 1999).

34. In the Ukrainian Poles'e intensity of accumulation of Sr-90 in berry species is as follows: *Fragaria vesca* > *Vaccinium myrtillus* > *Vaccinium vitis-idaea* > *Vaccinium uliginosum* > *Viburnum opulus*.

35. The following order of TR for medicinal undershrubs is: rhamn (*Rhamnus*) and mountain ash (*Sorbus aucuparia*), fresh hydrotops 3–4, quercus bark 7, branches of aglet (*Corylus avellana*) and buckthorn (*Frangula alnus*) 7–9, branch of raspberry (*Rubus idaeus*) 11, branch of European dewberry (*Rubus caesius*) 13, and branch of mountain ash (*Sorbus aucuparia*) in the wet biotopes 13–18 (Borysevich and Poplyko, 2002).

36. The TR for Sr-90 was 14.0–15.1 for wild strawberry (*Fragaria*), 0.6–0.9 for blueberry (*Vaccinium myrtillus*), and 0.9 for raspberry (*Rubus idaeus*; Ipat'ev, 1999).

37. The TR for Sr-90 in wild forest berries depends on the level of soil contamination: it appears that the TR is lower under conditions of higher contamination (Table 9.9).

38. In Belarus in increasing order for Cs-137 levels in cereal grains that were studied: spring wheat < barley < oats; among root vegetables: carrot < beetroot < radish. For Sr-90 levels the order was: wheat < oats < barley; radish and carrot < beetroot (Borysevich and Poplyko, 2002).

39. There are marked differences in the amount of incorporated radionuclides even for different cultivars of the same species among carrots, beetroots, and radishes (Borysevich and Poplyko, 2002).

40. Total incorporated gamma-activity in various populations of lupinus (*Lupinus luteus*) differed by as much as 20-fold (Grodzinsky *et al.*, 1995b).

41. The concentrations of Sr-90 and Pu-238, Pu-239, and Pu-240 were significantly higher in the surface phytomass of wild strawberry

TABLE 9.8. Intensity of Cs-137 Accumulation in Several Species of Herbs in Ukraine (Krasnov and Orlov, 1996)

Group	Species	Plant part	TR (M ± m)
Very strong accumulation	*Inonotus obliquus*	Fruit body	130 ± 30
	Vaccinium myrtillus	Berries	125 ± 18
	Lycopodium clavatum	Spores	120 ± 20
	Vaccinium vitis-idaea	Leaf	94 ± 14
Strong accumulation	*Ledum palustre*	Branches	82 ± 18
	Chelidonium majus	Grass	79 ± 14
	Vaccinium myrtillus	Leaf	78 ± 6
	Pinus sylvestris	Buds	77 ± 11
	Centaurium erythraea	Grass	61 ± 6
	Viola tricolour	Grass	27 ± 4
Moderate accumulation	*Potentilla alba*	Rhizomes	20 ± 3
	Hypericum perforatum	Grass	18 ± 2
	Sambucus nigra	Inflorescences	18 ± 2
	Convallaria majalis	Inflorescences	16 ± 2
	Frangula alnus	Bark	15.4 ±1.8
	Tanacetum vulgare	Inflorescences	15.0 ± 1.2
	Potentilla alba	Grass	12.5 ± 1.4
	Arctostaphylos uva-ursi	Leaves	12.1 ± 2.5
Weak accumulation	*Convallaria majalis*	Grass	9.8 ± 0.8
	Urtica dioica	Grass	8.6 ± 0.7
	Oryganum vulgare	Grass	7.4 ± 2.8
	Quercus robur	Bark	7.2 ± 1.2
	Helichrysum arenarium	Inflorescences	5.4 ± 0.6
	Thymus serpyllum	Grass	4.6 ± 0.5
	Digitalis grandiflora	Grass	4.4 ± 0.7
	Leonurus cardiaca	Grass	3.9 ± 0.5
	Achillea millefolium	Grass	2.9 ± 0.6
Very weak accumulation	*Juniperus communis*	Galberry	0.64 ± 0.05
	Valeriana officinalis	Rhizomes	0.36 ± 0.05
	Acorus calamus	Rhizomes	0.27 ± 0.03

(*Fragaria vesca*) as compared with bilberry (*Vaccinium myrtillus*) in the bilberry pine forests (Parfenov and Yakushev, 1995).

42. The main radioactive contaminants in most species of medicinal herbs in Belarus prior to 1990 was Cs-137, but with Ce-144 and Ru-106 being found in the bark (Tsvetnova *et al.*, 1990).

TABLE 9.9. TR for Sr-90 in Three Wild Berry Species under Various Levels of Soil Contamination (Ipat'ev, 1999)

Species	Level of soil contamination, kBq/m^2	
	1.9	28.1
Blueberry	0.8	1.0
Raspberry	14.6	9.1
Wild strawberry	22.7	10.0

43. Among annual plant species, those of the pea family (Leguminosae) tend to concentrate Pu and Am (Borysevich and Poplyko, 2002).

44. Concentrations of Cs-134 and Cs-137 in tree rings of French white fir (*Abies concolor*) from the French–German border near Nancy, France, reflect the Chernobyl fallout (Garrec *et al.*, 1995).

9.1.2. Mushrooms and Lichens

1. Table 9.10 presents data on radionuclide accumulation in lichens and mushrooms after the catastrophe.

TABLE 9.10. Examples of the Worldwide Contamination of Mushrooms and Lichens (Bq/kg) in 1986

Nuclide	Subject	Activity	Country	Reference
Cs-137	Lichen	40,040*	Norway	Staaland *et al.*, 1995
	Lichen	36,630	Poland	Seaward *et al.*, 1988
	Reindeer lichen	25,000**	Norway	Solem and Gaare, 1992
	Mushrooms	16,300	Japan	Yoshida *et al.*, 1994
	Lichen	14,560	Greece	Papastefanou *et al.*, 1988
	Mushrooms	8,300***	Germany	Elstner *et al.*,1987
	Mushrooms	6,680	Finland	Rantavaara, 1987
Cs-135/Cs-137	Lichen, *Cladonia stellaris*	60,000	Norway	Brittain *et al.*,1991; Steinnes *et al.*,1993
	Mushrooms	24,000	France	Coles, 1987
Ce-144	Lichen	18,500	Poland	Seaward *et al.*, 1988
Nb-95	Lichen	8,114	Poland	Seaward *et al.*, 1988
Ru-106/Rh-106	Lichen	16,570	Poland	Seaward *et al.*, 1988
Total activity	Lichen, *Cladonia silvatica*	400,000	Ukraine	Grodzinsky, 1995b

*1987; **up to 75-fold higher than in 1985; ***up to 93-fold more than in 1985.

2. Various species of mushrooms have different TR characteristics (Table 9.11).

3. There is correlation between the specific activity of Cs-137 in the fruit of the mushrooms and the radioactive density of soil contamination (Krasnov *et al.*, 1998; Kubert, 1998).

4. The concentration of Cs-137 in mushrooms of the same species differs more than 500-fold depending on the levels of radionuclide concentration in the soil (Shatrova *et al.*, 2002).

TABLE 9.11. TR of Cs-137 in Mushrooms in the Ukrainian Poles'e Ecosystems (Orlov *et al.*, 1998; Krasnov *et al.*, 1997; Kubert, 1998)

TR	Species
1–10	Honey mushroom (*Armialliela mellea*), chanterelle (*Cantharellus cibarius*), edible boletus (*Boletus edulis*), aspen mushroom (*Boletus versipellis*)
1–50	Black milk mushroom (*Lactarius* sp.), green boletus (*Xerocomus subtomentosus*)
50–100	Birch mushroom *(Leccinum scabrum*), russula marsh (*Russula*), Polish mushroom (*Xerocomus badius*), blue boletus (*Gyroporus cyanescens*)
>100	Paxill (*Paxilus* sp.), yellow boletus *(Suillus luteus*)

5. The specific Cs-137 activity in the fruit of mushrooms *Lactarius necator*, *Armillariella mellea*, and *Xerocomus badius* increased exponentially with increased density of radioactive soil contamination (Krasnov *et al.*, 1998).

6. The Cs-137 accumulation in the fruit of mushrooms is lower in richer environmental conditions: in russulas (*Russula* sp.) a difference between Cs-137 accumulation in sudubravas (mixed oak forests), pine forests, and subors are up to fourfold, and in lurid boletus (*Boletus luridus*) about threefold.

7. The Cs-137 accumulations in the fruit bodies of the edible boletus (*Boletus edulus*) were noticeably low in pine forests and for the Polish mushroom (*Xerocomus badius*) in subors (Krasnov *et al.*, 1998).

The level of radionuclide accumulation in plants and mushrooms depends upon the soil, the climate, the particular biosphere, the season, spotty radioactive contamination, the species, and the population (subspecies, cultivars), etc. Each radionuclide has its own accumulation characteristics. Coefficients of accumulation and transition ratios vary so much in time and space that it is difficult, if not impossible, to predict the actual levels of the Cs-137, Sr-90, Pu-238, Pu-239, Pu-240, and Am-241 in each place and time for each individual plant or mushroom.

9.2. Radioinduced Morphology, Anomalies, and Tumors

Changes from the normal morphological structure of plants under the impact of irradiation (radiomorphosis) are typical manifestations in the heavily contaminated territories (Grodzinsky *et al.*, 1991; Grodzinsky, 1999c; Gudkov and Vinichuk, 2006; and others). Radiomorphosis arises primarily because of the impaired duplication process in live cells under the influence of external and/or internal irradiation.

1. Radiation-induced changes that have been observed in plants in the Chernobyl-contaminated territories include alterations in shape, intercepts, twists, wrinkling, bifurcations, abnormal flattening of stems, etc. (Table 9.12).

2. When top buds, which contain the actively dividing cells die, there is a loss of apical domination and transfer of activity to axial buds, which under normal conditions are in a resting state and are more radioresistant. The newly active buds produce extra shoots, leaves, and flowers (Gudkov and Vinichuk, 2006).

3. Radiation-induced death of the main root meristem in plants with pivotal root systems results in more active development of lateral roots, which in turn provokes growth of some above-ground organs. Swelling-like excrescents on leaves, stems, roots, flowers, and other organs also appeared as the result of irradiation in the 30-km zone in 1986. In 1987 and the years following, the number of such abnormalities increased and were observed mainly in coniferous trees, on which needles are replaced once every few years and on perennial shoots and branches (Figure 9.8).

4. Table 9.13 presents examples of radiation-induced morphologic changes in pine (*Pinus silvestris*) and spruce (*Picea abies*).

TABLE 9.12. Some Radiation-Induced Morphological Changes in Plants in Heavily Contaminated Territories after the Catastrophe (Grodzinsky, 1999; Gudkov and Vinichuk, 2006)

Part	Morphological changes
Leaves	Increase or decrease in size and quantity
	Shape change
	Twists
	Wrinkles
	Nervation break
	Asymmetry
	Thickening
	Leaf plates inosculation
	Fasciations and swellings
	Appearance of necrotic spots
	Loss of leaf plate
	Premature defoliation
Shoots	Additional vegetative lateral and apex shoots
	Impairment of geotopical orientation of the shoots
	“Bald” shoots
Stems	Speedup or inhibition of growth
	Phyllotaxis failure (order of leaf placing)
	Color change
	Loss of apical dominance
	Dichotomy and fasciations
	Change of intercepts
	Swellings
Roots	Speedup or inhibition of growth
	Splitting of main root
	Death of main root
	Trimming of meristem zone
	Absence of lateral roots
	Swellings and twists
	Appearance of aerial roots
	Heliotropism break
Flowers	Speedup or inhibition of flowering
	Color change
	Increase or decrease of quantity
	Shape change
	Defoliation of flowers and floscules
	Swellings
	Sterility

5. The number of pollen structural anomalies in winter wheat increased in the heavily contaminated territories (Kovalchuk *et al.*, 2000).

6. Several years after the catastrophe there was a significant rise in the incidence

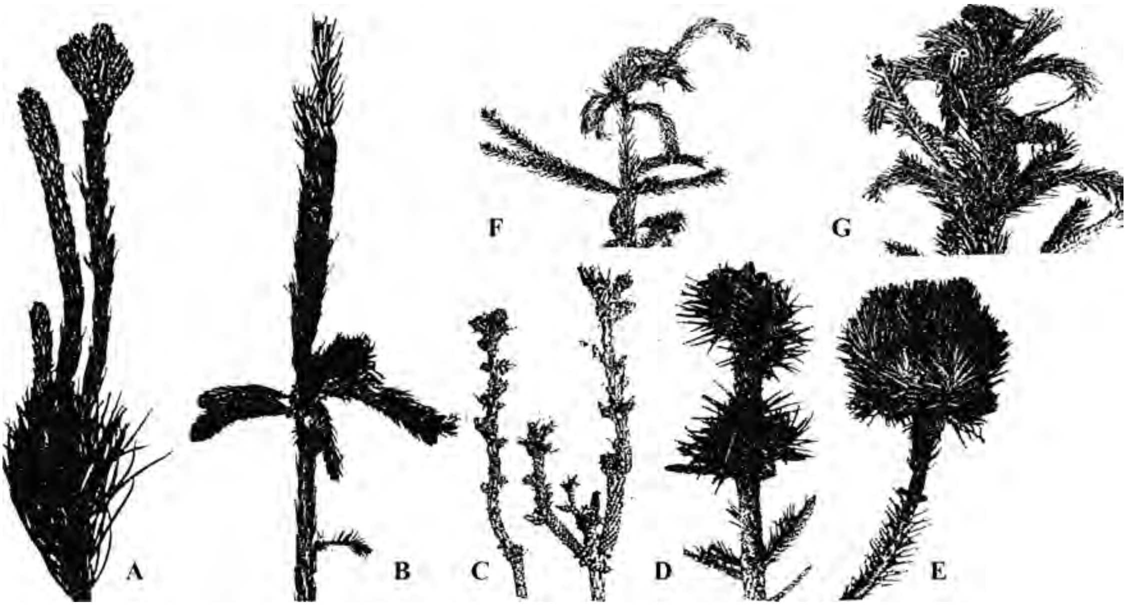

Figure 9.8. Anomalies in the shoots of pine (*Pinus silvestris*: **A, B**) and spruce (*Picea excelsa*: **C–G**) in the 30-km zone in 1986–1987 (Kozubov and Taskaev, 2002; Grodzinsky *et al.*, 1991).

of various teratological characteristics in plantain seedlings (*Plantago lanceolata*) growing within the 30-km zone (Frolova *et al.*, 1993).

7. The incidence of two morphologic characteristics in winter wheat (*Triticum aestivum*) increased after the catastrophe and decreased in the next two generations (Group 1); the frequency of nine other morphologic characteristics (Group 2) increased in subsequent generations (Table 9.14).

8. Irradiation in the contaminated territories caused a noticeably stronger influence on barley pollen than did experimental gamma-irradiation done under controlled conditions (Table 9.15).

9. Chernobyl radiation, causing morphogenetic breaks, provokes the development of tumors caused by the bacterium *Agrobacterium tumefaciens*. Active development of such tumors is seen in some plants, including *Hieracium murorum*, *Hieracium umbellatum*, *Rubus idaeus*, and *Rubus caesius*, in the heavily contaminated territories (Grodzinsky *et al.*, 1991).

10. Tumorlike tissue is found in 80% of individual milk thistle (*Sonchus arvensis*) plants growing in heavily contaminated soil (Grodzinsky *et al.*, 1991).

TABLE 9.13. Chernobyl's Irradiation Impact on Pine (*Pinus silvestris*) and Spruce (*Picea abies*) Morphometrics (Sorochinsky, 1998)*

	Characters	Low contamination	Heavy contamination
Pine	Length of needles, mm	60 ± 4	19 ± 3
	Weight of needles, mg	80 ± 3	14 ± 2
Spruce	Length of needles, mm	16 ± 2	40 ± 3
	Weight of needles, mg	5 ± 1	95 ± 5

*All differences are significant.

TABLE 9.14. Frequency of Some Morphologic Changes in Three Generations of a Species of Winter Wheat *(Triticum aestivum)* in the Chernobyl-Contaminated Territories (Grodzinsky *et al.*, 1999; Grodzinsky, 2006)

Characters	Year 1986	1987	1988
Group 1			
Infertile zones in spike	49.0	29.8	1.9
Truncated spike	10.0	9.4	0.8
Lengthened stem	4.4	4.7	5.4
Scabrous beard	1.4	3.4	2.9
Group 2			
Split spike	4.5	11.1	9.4
Lengthened beard	2.8	2.8	4.7
Angular forms	4.9	14.0	24.7
Change of stalk color	0.9	1.7	1.9
Spike gigantism	1.4	1.8	2.9
Stem plate	4.5	5.7	4.9
Additional spikelets	14.0	14.8	29.7

11. In the heavily contaminated territories there was a significant increase in gall formation on oak (*Quercus*) leaves (Grodzinsky *et al.*, 1991).

12. Formation of tumoral tissue (callus) in plants under the influence of soil contaminated with radioactivity has been confirmed experimentally (Table 9.16).

TABLE 9.15. Frequency of Abnormal Barley (*Hordeum vulgare*) Pollen Grains (per 1,000,000) after 55 Days of Irradiation around Chernobyl's NPP and in the Experimental Gamma-Field (Bubryak *et al.*, 1991)

	Dose rate, μSv/h	Dose, mSv	Abnormal grains, %
30-km zone	Control (0.96)	1.3	0
	59	75	23
	320	422	79
	400	528	86
	515	680	90
Experimental gamma-field	Background (0.11)	0.1	0
	5	3.0	43
	50	29.6	45
	500	296	59
	5,000	2,960	57
	50,000	29,600	72

TABLE 9.16. Influence of a Chernobyl Soil Extract (Cs-137 and Ce-144 with Total Activity of 3.1 × 10^4 Bq/kg) on Growth and Cell Division of a Stramonium (*Datura stramonium*; Grodzinsky, 2006)

	Cells, per 1 g tissue,		Cells, per callus	
	$n \times 10^5$	%	$n \times 10^5$	%
Normal tissue	39.7	100	78.6	100
With an extract	38.9	98	100.4	127.6
Tumorous tissue	23.0	100	74.5	100
With an extract	32.4	140.7	91.5	122.8

13. There is some tendency toward normalization of the number of gametogenetic anomalies in soft wheat (*Triticum aestivum*) in four to six generations after the Chernobyl irradiation, but there was an accumulation of mutations in some wheat populations (Grodzinsky *et al.*, 1995a).

9.3. Genetic Changes

1. Immediately after the catastrophe, the frequency of plant mutations in the contaminated territories increased sharply, and the increase was maintained at a high level for several years (Tables 9.17 and 9.18).

2. In the first 2–3 years after the catastrophe, the number of lethal and chlorophyll

TABLE 9.17. Frequency (%) of Chlorophyll Mutations in Barley (*Hordeum vulgare*), and Rye (*Secale seriale*) in the 30-km Zone with Cs-134, Cs-137, Ce-144, and Ru-106 Ground Contamination (Grodzinsky *et al.*, 1991)

	Control	Contamination Years 1986	1987	1988	1989
Rye, var. "Kiev-80"	0.01	0.14	0.40	0.91	0.71
Rye, var. "Kharkov-03"	0.02	0.80	0.99	1.20	1.14
Barley, var. # 2	0.35	0.81	0.63	0.70	0.71

TABLE 9.18. Frequency of Chromosomal Aberrations (%) in Root Meristems of Some Cultivated Plants in the Chernobyl-Contaminated Territories, 1986–1989 (Grodzinsky, 2006)*

		Years			
	Control	1986	1987	1988	1989
Lupinus alba	0.9	19.4	20.9	14.0	15.9
Pisum sativum	0.2	12.9	14.1	9.1	7.9
Secale cereale	0.7	14.9	18.7	17.1	17.4
Triticum aestivum	0.9	16.7	19.3	17.7	14.2
Hordeum vulgare	0.8	9.9	11.7	14.5	9.8

*All differences from controls are significant.

mutations in all studied populations of *Arabidopsis thaliana* in the 30-km zone increased significantly. The original spontaneous level of mutation was reached in 6 years in areas with gamma-radiation levels up to 10 mR/h. In areas with gamma-radiation levels up to 130 mR/h the level of mutations was up to eightfold higher than the spontaneous level for 8 years after the catastrophe (Abramov *et al.*, 1995).

3. The frequency of mutations in wheat (*Triticum aestivum*) was sixfold higher in the contaminated territories (Kovalchuk *et al.*, 2000). Some 13 years after the catastrophe the frequency of chromosome aberrations in two wheat cultivars in the 30-km zone was significantly higher than the spontaneous frequency (Yakimchuk *et al.*, 2001).

4. In acorns of the oak *Quercus robur* and the pine *Pinus silvestris* in Voronez City areas contaminated by Chernobyl fallout there was significantly increased mitotic activity, demonstrated by increased frequency of cells with a residual karyo nucleus at metaphase, anaphase, and telophase and with multinucleated cells persisting "many years" after the catastrophe (Butoryna *et al.*, 2000; Artyukhov *et al.*, 2004).

5. The level of chromosomal aberrations in onions was correlated with the density of radioactive contamination of the territory (Table 9.19).

6. The average frequency of mutations in pine (*Pinus silvestris*) correlated with the density of radiation contamination in an area, and in the 30-km zone was 10-fold higher than in control locations (Shevchenko *et al.*, 1996).

7. Progeny tests of plantain (*Plantago lanceolata*), gosmore (*Hypochoeris radicata*), autumnal hawkbit (*Leontodon autumnalis*), wall lettuce (*Mycelis muralis*), bloodwort (*Achillea millefolium)*, gold birch (*Solidago virgaurea*), and field wormwood (*Artemisia camprestris*) collected in the 30-km zone (gamma-activity at ground level 130–3,188 Ci/km^2) and after additional intense irradiation developed significantly more mutations than in controls (i.e., the number of chromosomal aberrations is correlated with the density of contamination). Only devil's-bit (*Succisa pratensis*) showed increased resistance to radioactivity (Dmitryeva, 1996).

8. The significantly increased mutation level in pine (*Pinus sylvestris*) seeds from the 30-km zone persisted for 8 years after the catastrophe (Kal'chenko *et al.*, 1995).

9. In the 6 to 8 years after the catastrophe, the number of meiosis anomalies in microspore formation (the number of anomalies in a root meristem) and the number of pollen grain anomalies documented in 8–10% of

TABLE 9.19. Damage of Apical Root Meristem (Growing Tip) of Onions (*Allium cepa*) under Different Levels of the Chernobyl Soil Contamination (Grodzinsky, 2006)

			Percent of control		
Soil activity, kBq/kg	Number of cells, *n*	Mitotic index,%	Aberrant cells	Cells with micronucleus	Degenerate cells
Control	15,005	4.1	100	100	100
37	33,275	4.4	240	171	250
185	29,290	4.4	216	129	500
370	23,325	117	150	229	900

TABLE 9.20. Change in Anthocyanin Concentration in Irradiated Plants (Grodzinsky, 2006)

	Levels of irradiation	Anthocyanin (% of control)
Corn (*Zea mays*), sprouts	Soil 975 Bq/kg	119
Mung (*Phaseolus aureus*)	Chronic irradiation, 0.5 Gy	157
Arabidopsis thaliana	Chronic irradiation, 0.5 Gy	173

94 plant species correlate with the level of gamma-irradiation (Kordyum and Sydorenko, 1997).

10. In natural populations of *Crepis tectorum* from the 30-km zone, the sprouting of seeds did not exceed 50%. The number of a growing root cells with chromosome disorders (inversions, translocations, change in number of chromosomes, etc.) is significantly higher than in controls (Shevchenko *et al.*, 1995).

11. The number of sterile pollen grains in violets (*Viola matutina*) correlates with the level of radioactive soil contamination (Popova *et al.*, 1991).

12. More than a 10-fold lower frequency of extrachromosomal homologous recombinations are found in native *Arabidopsis thaliana* plants from radioactively contaminated territories (Kovalchuk *et al.*, 2004).

13. Unique polynoteratogenic complexes are seen in the 30-km Chernobyl zone: a high percentage of pollen grains and spores with different genetic anomalies (underdeveloped pollen grains/spores, dwarf and ultradwarf forms, and polynomorphs that diverge from the norm in several morphological characters). This indicates that the Chernobyl catastrophe caused a "geobotanical catastrophe" (Levkovskaya, 2005).

9.4. Other Changes in Plants and Mushrooms in the Contaminated Territories

1. Coniferous forests have suffered most strongly from irradiation (so-called "Red forest") as compared with mixed and deciduous forests (Kryshev and Ryazantsev, 2000).

2. Some metabolic processes in plants are disturbed in the contaminated territories (Sorochin'sky, 1998). Table 9.20 lists examples of such impairments, expressed in changes of anthocyanin (purple color) concentration.

3. Radiosensitivity of some plant species increases under chronic low-rate irradiation in the 30-km zone owing to a gradual loss of the ability to repair DNA (Grodzinsky, 1999).

4. Some phenolic compounds with altered qualitative structure accumulated in all winter wheat, winter rye, and corn cultivars in the 30-km zone during the 6 years after the catastrophe (Fedenko and Struzhko, 1996).

5. The radial growth in trees in the heavily contaminated territories was slowed (Kozubov and Taskaev, 1994; Shmatov *et al.*, 2000).

6. A new form of stem rust fungus (*Puccinia graminis*) is present in the Chernobyl zone, and its virulence is greater than in the control form (Dmitryev *et al.*, 2006).

It is clear that plants and mushrooms became natural accumulators of Chernobyl radionuclides. The levels of such uptake and the transition of radionuclides from soil to plants and mushrooms are specific for each radionuclide and vary from species to species, by season, by year, and by landscape, etc.

Chernobyl irradiation has caused many structural anomalies and tumorlike changes in many plant species and has led to genetic disorders, sometimes continuing for many years. It appears that the Chernobyl irradiation awakened genes that had been quiescent for long evolutionary periods.

Twenty-three years after the catastrophe it is still too early to know if the whole spectrum of plant radiogenic changes has been discerned. We are far from knowing all of the consequences for flora resulting from the catastrophe.

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10. Chernobyl's Radioactive Impact on Fauna

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The radioactive shock when the Chernobyl reactor exploded in 1986 combined with chronic low-dose contamination has resulted in morphologic, physiologic, and genetic disorders in every animal species that has been studied—mammals, birds, amphibians, fish, and invertebrates. These populations exhibit a wide variety of morphological deformities not found in other populations. Despite reports of a "healthy" environment in proximity to Chernobyl for rare species of birds and mammals, the presence of such wildlife is likely the result of immigration and not from locally sustained populations. Twenty-three years after the catastrophe levels of incorporated radionuclides remain dangerously high for mammals, birds, amphibians, and fish in some areas of Europe. Mutation rates in animal populations in contaminated territories are significantly higher and there is transgenerational genomic instability in animal populations, manifested in adverse cellular and systemic effects. Long-term observations of both wild and experimental animal populations in the heavily contaminated areas show significant increases in morbidity and mortality that bear a striking resemblance to changes in the health of humans—increased occurrence of tumor and immunodeficiencies, decreased life expectancy, early aging, changes in blood and the circulatory system, malformations, and other factors that compromise health.

The Chernobyl catastrophe has impacted on fauna and will continue to have an impact for many decades to come, with effects ranging from changes in population vitality to abnormal reproductive and genetic disorders. It is well to remember that *Homo sapiens* are a part of the animal kingdom and suffer the same kinds of health consequences that are observed in animals.

As in the earlier chapters, only a small part of the available scientific literature is presented here, but several monographic reviews have been included: Frantsevich *et al.*, 1991; Sutshenya *et al.*, 1995; Zakharov and Krysanov, 1996; Sokolov and Kryvolutsky, 1998; Ryabov, 2002; Goncharova, 2000; and others.

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Apart from zoological studies, there are many hundreds of studies published by veterinarians in Ukraine, Belarus, and Russia that show deterioration in the health of cows, boars, sheep, and chickens in the areas contaminated by Chernobyl.

The first section of this chapter is devoted to levels of Chernobyl radionuclide accumulations in various species. The second section addresses reproductive impairment in animals in the contaminated territories and the resultant genetic changes. The order of presentation is mammals, birds, amphibians, fish, and invertebrates.

10.1. Incorporation of Radionuclides

The level of radionuclides maintained in an animal's body depends on the transfer ratio (TR, transition coefficient) and the coefficient

TABLE 10.1. Maximum Concentration (Bq/kg, Fresh Weight) of Some Radionuclides after the Catastrophe

Nuclide	Bq/kg	Species	Country	Reference
Sr-90	1,870	Bank vole (*Clethrionomys glareolus*)	Belarus	Ryabokon' *et al.*, 2005*
Cs-137	400,000	Bank vole (*Clethrionomys glareolus*)	Belarus	Ryabokon' *et al.*, 2005*
	187,000	Wild swine (*Sus scrofa*)	Russia	Pel'gunov *et al.*, 2006
	74,750	Roe deer (*Capreolus capreolus*)	Russia	Pel'gunov *et al.*, 2006
	48,355	Common shrew (*Sorex araneus*)	Russia	Ushakov *et al.*, 1996
	42,000	Little shrew (*Sorex minutus*)	Russia	Ushakov *et al.*, 1996
	24,630	Yellow neck mouse (*Apodemus flavicollis*)	Russia	Ushakov *et al.*, 1996
	7,500	Brown hare (*Lepus europaeus*)	Russia	Pel'gunov *et al.*, 2006
	3,320	Moose (*Alces alces*)	Russia	Pel'gunov *et al.*, 2006
	1,954	White tailed deer	Finland	Rantavaara, 1987
	1,888	Arctic hare (*Lepus timidus*)	Finland	Rantavaara *et al.*, 1987
	1,610	Moose (*Alces alces*)	Finland	Rantavaara *et al.*, 1987
	760[1]	Moose (*Alces alces*)	Sweden	Johanson and Bergström, 1989
	720	Reindeer (*Rangifer tarandus*)	Finland	Rissanen *et al.*, 1987
Cs-134	60,000	Bank vole (*Clethrionomys glareolus*)	Belarus	Ryabokon' *et al.*, 2005*
Cs134/Cs-137	100,000	Reindeer (*Rangifer tarandus*)	Norway	Strand, 1987
	15,000	Sheep (*Ovis ammon*)	Norway	Strand, 1987
	3,898	Sheep (*Ovis ammon*)	Great Britain (Cumbria)	Sherlock *et al.*, 1988
	3,200	Roe deer (*Capreolus capreolus*)	Germany	Heinzl *et al.*, 1988
Pu-239 + Pu-240	1.3	Bank vole (*Clethrionomys glareolus*)	Belarus	Ryabokon' *et al.*, 2005*
Pu-238	0.6	Bank vole (*Clethrionomys glareolus*)	Belarus	Ryabokon' *et al.*, 2005*
Am-241	12	Bank vole (*Clethrionomys glareolus*)	Belarus	Ryabokon' *et al.*, 2005*
	<0.01	Wild boar (*Sus scrofa*)	Belarus	Borysevich and Poplyko, 2002
Ag-110m	74	Cow (*Bos taurus*)	Great Britain, 1986	Jones *et al.*, 1986
Total gamma	58,000	Roe deer (*Capreolus capreolus*)	Western Europe	Eriksson *et al.*, 1996
	113,000	Wild boar (*Sus scrofa*)	France	Tchykin, 1997
	79,500 d.w.[2]	Otter scats	Scotland, July 1986	Mason and MacDonald, 1988

*Calculation from figure (A.Y.).
[1]Up to 33 times higher than pre-Chernobyl level (Danell *et al.*, 1989).
[2]10.7 times higher than the pre-Chernobyl peak concentration.

of accumulation (CA), that is, on the relationship between the specific activity of a radionuclide in a body and the specific activity of the same radionuclide in the environment [TR = (Bq/kg of animal biomass)/(kBq/m^2 for background contamination); CA = (Bq/kg of animal biomass)/(Bq/kg of air, soil, or water)]. Animals, from mammals to birds, fish, worms, and insects, depend upon whatever food they can catch or forage. The health and survival of the animals provide a view into environmental radiation levels and effects.

1. Table 10.1 presents the maximum concentrations of some radionuclides in mammals after the catastrophe.

2. Indicator species such as the bank vole (*Clethrionomys glareolus*) and the yellow-necked mouse (*Apodemus flavicollus*) that inhabit the natural forest ecosystems of Belarus showed maximum levels of Cs-134 and Cs-137 for 1 to

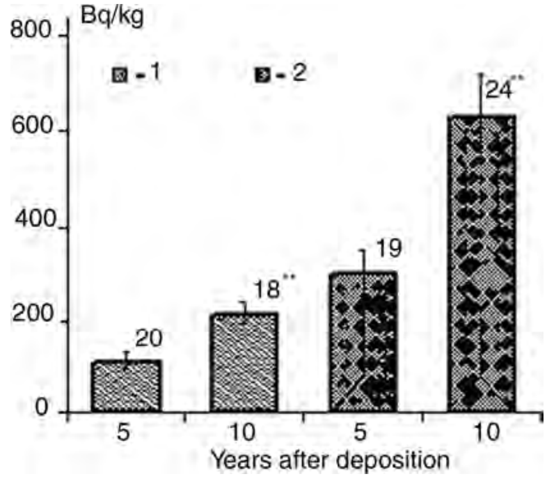

Figure 10.1. Time course of Sr-90 activity concentration (Bq/kg) in two Belarussian populations of bank voles (*Clethrionomys glareolus*) in 1991 and 1996 (5 and 10 years after the catastrophe). Standard deviations of mean values are indicated: $p <$ 0.01 in comparison with previous year (Ryabokon' *et al.*, 2005).

2 years after the catastrophe, followed by an exponential decrease. However, incorporated Sr-90 concentrations increased up to 10 years after the catastrophe (Figure 10.1).

3. Five years after the meltdown, significant Am-241 activity was detected in bank voles (*Clethrionomys glareolus*) from areas with high levels of contamination. Levels increased up to the 10th year and are expected to increase further (Ryabokon' *et al.*, 2005).

4. There is marked individual variability in the incorporation of Cs-134, Cs-137, Sr-90, Pu, and Am-241 in the bank vole (*Clethrionomys glareolus*) populations living in contaminated territories of Belarus (Figure 10.2) (Ryabokon' *et al.*, 2005).

5. Radionuclide level accumulation for roe deer (*Capreolus capreolus*) can vary from 10- to 30-fold according to seasons (McGee *et al.*, 2000).

6. During the autumn in Ukraine, the level of Cs-137 accumulation in mice species (Muridae) and the internal organs of fawns increased 11-fold (Krasnov *et al.*, 1997). The greatest contamination in fawns was due to grazing on aspen, oak, bilberry, and heather (Krasnov *et al.*, 1998).

7. Ten years after the catastrophe, in contaminated areas of Western Europe, radioactivity in the meat of roe deer (*Capreolus capreolus*) reached an average of 58,000 Bq/kg and that in wild boar (*Sus scrofa*) was up to 113,000 Bq/kg (Eriksson and Petrov, 1995; Eriksson *et al.*, 1996; Tchykin, 1997).

8. Decrease in Cs-137 concentration in cattle (*Bos taurus*) in the contaminated territories is occurring more slowly than was predicted by all of the International Atomic Energy Agency (IAEA) models (Thiessen *et al.*, 1997).

9. The level of Cs-137 incorporation is significantly different in cattle (*Bos taurus*) in the heavily and less contaminated areas in Ukraine (Table 10.2).

10. Accumulation of Cs-137 shows significant individual variation in wild boar (*Sus scrofa*) and roe deer (*Capreolus capreolus*) and is more homogeneous in moose (*Alces alces*), depending not only upon species-specific food chains, but also upon spotty radioactive contamination (see Chapter 1 for details) and on activity in a specific area (Table 10.3).

11. The concentration of Cs-137 in wild ungulates in the contaminated territories increased for 7 to 20 years after the catastrophe, and the increased uptake occurred despite lower levels of ambient radioactive contamination in some areas (Figure 10.3).

12. Study of 44 bird species in the Chernobyl 5-km zone from 2003 to 2005 revealed that the greatest contamination was present during nesting and hatching. Females accumulate more Sr-90 than males, and nestlings and juveniles accumulate more than females. Cs-137 accumulation did not differ between young and adult birds or between the sexes. Maximum levels of Sr-90 and Cs-137 accumulation are shown in Table 10.4.

13. In Belarus, 10 years after the catastrophe, levels of total gamma-radionuclides in the bodies of teals (*Querquedula querquedula* and *Q. crecca*) exceeded 13,000 Bq/kg; in mallard ducks (*Anas platyrhynchos*) it was about 10,000 Bq/kg; and in coots (*Fulica atra*) it was more than 4,000 Bq/kg (Sutchenya *et al.*, 1995).

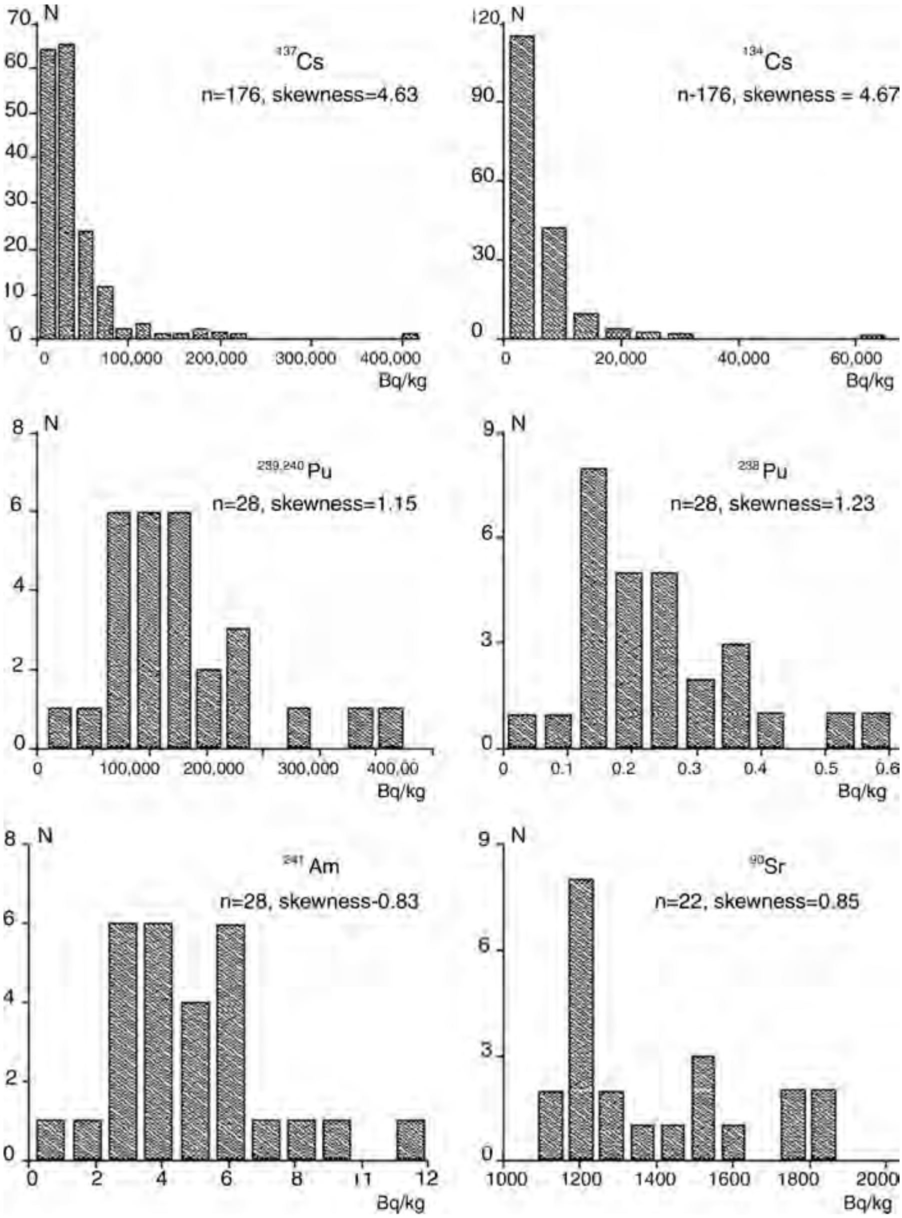

Figure 10.2. Individual variability in the level of incorporated radionuclides in the bank vole (*Clethrionomys glareolus*) population in Belarus: Cs-137 and Cs-134 (3 years after the catastrophe) and Pu-238, Pu-239, Pu-240, Am–241, and Sr-90 (10 years after) (Ryabokon' *et al.*, 2005).

14. Intraspecies (individual) variations of Cs-137 concentrations are greater than interspecies ones (Table 10.5).

15. In the 30-km zone, accumulations of Cs-137 and Sr-90 reached 5.3 kBq/kg in some amphibians. The transfer rate (TR) from substrate to animal measured in Bq/kg demonstrated that the TR is higher for Sr-90 and less for Cs-137 in all the amphibians studied. The TRs for Sr-90 in decreasing order were: red-bellied toad (*Bombina bombina*), spade-footed toad (*Pelobates fuscus*), tree frog (*Hyla* sp.), and true frogs (*Rana* sp.), respectively, 44.1, 34.4, 20.6, and 20.4 (Bondar'kov *et al.*, 2002).

TABLE 10.2. Cs-137 Incorporation (Bq/kg, Bq/liter) in Amniotic Membranes, Placentas, and Colostral Milk of Cows from More Heavily and Less Contaminated Areas, Zhytomir Province, Ukraine, 1997–1999 (Karpuk, 2001)[1]

	Level of contamination	
	5–15 Ci/km^2	< 0.1 Ci/km^2
Afterbirth and amniotic membranes	24.3 ± 2.1*	3.1 ± 0.1
Placentas (cotyledons)	36.3 ± 4.2*	4.9 ± 0.4
Colostral milk	17.3 ± 1.4*	4.4 ± 0.5

[1]Data for Ci/km^2 – summarized for two farms by A. Y.
*$p < 0.001$.

16. The highest TR for Cs-137 was found in the European common toad (*Bufo bufo*), 12.9 and the moor frog (*Rana arvalis*), 10.0 (Bondar'kov *et al.*, 2002).

17. Levels of contamination after the catastrophe in some fishes are listed in Table 10.6.

18. Initial forecasts of a rapid Cs-137 elimination from fishes (in 7 to 8 years) appear to be inaccurate: after 3 to 4 years of fast decline, lowering of contamination levels slowed drastically (Figure 10.4).

19. Up until 1994 the level of Cs-137 in perch (*Perca fluviatilis*) in Swedish and Finnish lakes exceeded the official safe level (Kryshev and Ryazantsev, 2000).

TABLE 10.3. Cs-137 Accumulation (Bq/kg of Wet Weight) in the Muscles of Several Species of Game Mammals from Bryansk Province Areas Contaminated at a Level of 8–28 Ci/km^2, 1992–2006 (Pel'gunov *et al.*, 2006)

Species	$M \pm m$	Min–max
Wild boar (*Sus scrofa*), $n = 59$	13,120 ± 3,410	250–187,900*
Roe deer (*Capreolus capreolus*), $n = 97$	12,660 ± 1,340	800–74,750
Moose (*Alces alces*), $n = 30$	1,860 ± 160	240–3,320
Brown hare (*Lepus europaeus*), $n = 8$	2,560	504–7,500

*Russian permissible level = 320 Bq/kg.

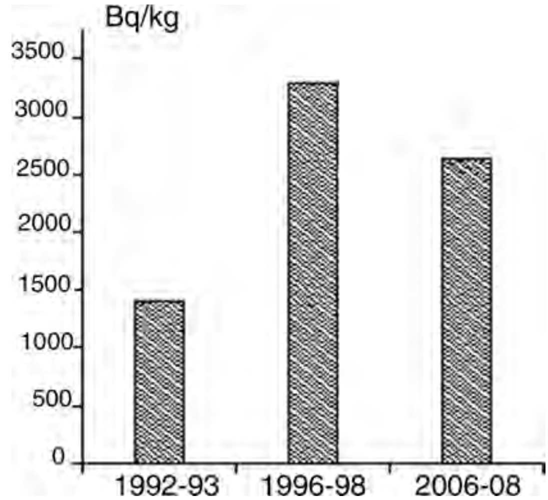

Figure 10.3. Average concentration of Cs-137 (Bq/kg fresh weight) in moose (*Alces alces*) in contaminated territories of Bryansk Province, Russia, for three periods after the catastrophe (Pel'gunov *et al.*, 2006).

20. From 1987 to 2002 the amount of Cs-137 in catfish (*Silurus glanis*) muscle in the Chernobyl Nuclear Power Plant (NPP) cooler reservoir increased from 1,140 to 6,500 Bq/kg (Zarubin, 2004).

21. In landlocked bodies of water in the contaminated areas, radionuclide concentration in raptorial fish reached 300 × 10^3 Bq/kg (Gudkov *et al.*, 2004).

22. Several hours after the catastrophe, honey in Germany was heavily contaminated with I-131 (>14 × 10^3 Bq/kg) and by Ru-193 (>750 Bq/kg; Bunzl and Kracke, 1988).

23. Table 10.7 provides data on Chernobyl radionuclide concentrations in zooplankton that reflect both high levels of bioaccumulation and the wide range of contaminated waters.

24. Radioactive contamination of Baltic plankton in 1986 reached 2,600 Bq/kg (gross-beta) and 3,900 Bq/kg of Np-239 (Ikaheimonen *et al.*, 1988).

10.2. Reproductive Abnormalities

Regular biological observations in the heavily contaminated territories of Ukraine, Belarus, and European Russia were not begun

TABLE 10.4. Concentration of Some Radionuclides (Bq/kg, Fresh Weight) in Several Bird Species after the Catastrophe

Radionuclide	Bq/kg	Species	Country	Reference
Sr-90	1,635,000	Great tit (*Parus major*)	Ukraine	Gaschak *et al.*, 2008
	556,000	Long-tailed tit (*Aegithalos caudatus*)	Ukraine	Gaschak *et al.*, 2008
	226,000	Nightingale (*Luscinia luscinia*)	Ukraine	Gaschak *et al.*, 2008
Cs-137	367,000	Great tit (*Parus major*)	Ukraine	Gaschak *et al.*, 2008
	305,000	Blackbird (*Turdus merula*)	Ukraine	Gaschak *et al.*, 2008
	85,000	Song thrush(*Turdus philomelos*)	Ukraine	Gaschak *et al.*, 2008
	1,930	Mallard duck (*Anas platyrynchus*)	Russia	Pel'gunov *et al.*, 2006
	450	Gray partridge (*Perdix perdix*)	Russia	Pel'gunov *et al.*, 2006
	470	Woodcock (*Scopolas rusticola*)	Russia	Pel'gunov *et al.*, 2006
	350	Robin (*Erithacus rubecola*)	Netherlands	De Knijff and Van Swelm, 2008
Cs-134	112	Robin (*Erithacus rubecola*)	Netherlands	De Knijff and Van Swelm, 2008
Cs-134, Cs-137	10,469	Waterfowl (*Anas* sp.)	Finland	Rantavaara *et al.*, 1987
	6,666	Goldeneye (*Bucephala clangula*)	Finland	Rantavaara *et al*., 1987
Zr-95	467	Robin (*Erithacus rubecola*)	Netherlands	De Knijff and Van Swelm, 2008
Nb-95	1,292	Robin (*Erithacus rubecola*)	Netherlands	De Knijff and Van Swelm, 2008
Total gamma	>13,000	Teal (*Quercuedula quercuedula* and *Q. crecca*)	Belarus	Sutchenya *et al.*, 1995
	10,000	Mallard ducks (*Anas platyrhyncha*)	Belarus	Sutchenya *et al.*, 1995
	>4,000	Coots (*Fulica atra*)	Belarus	Sutchenya *et al.*, 1995

until 2 months after the explosion. Fortunately, during that time, data concerning the harmful effects of the Chernobyl contamination on cattle and other farm animals were collected from many veterinarians (Il'yazov, 2002; Konyukhov *et al.*, 1994; Novykov *et al.*, 2006; and many others).

1. By September 1986, the population of murine species in the heavily contaminated Ukrainian territories had decreased up to fivefold (Bar'yakhtar, 1995).

TABLE 10.5. Cs-137 Accumulation (Bq/kg of Wet Weight) in Three Game Bird Species from Bryansk Province Areas Contaminated at a Level of 8–28 Ci/km^2, 1992–2006 (Pel'gunov *et al.*, 2006)

Species	Average	Min–max*
Mallard duck (*Anas platyrynchus*), $n = 28$	920	314–1,930
Gray partridge (*Perdix perdix*), $n = 14$	350	280–450
Woodcock (*Scopolas rusticola*), $n = 11$	370	270–470

*Russian permissible level—180 Bq/kg.

2. The mortality of laboratory mice (*Mus musculus*) that remained in the 10-km zone from 1 to 14 days increased significantly and is associated with additional radiation (Nazarov *et al.*, 2007).

3. There was an increasing incidence of embryo deaths over 22 generations of bank voles (*Clethrionomys glareolus*) from the contaminated territories that correlated with the radionuclide levels in monitored areas. A significantly high prenatal mortality has persisted despite a decrease in the level of ground contamination (Goncharova and Ryabokon', 1998a,b; Smolich and Ryabokon', 1997).

4. For 1.5 months sexually active male rats (*Rattus norvegicus*) within the 30-km zone demonstrated suppressed sexual motivation and erections, which resulted in a reduction in the number of inseminated females, reduced fertility, and an increase in preimplantation deaths (Karpenko, 2000).

5. Observations in farm hog sires (*Sus scrofa*) with Cs-137 contamination levels of 1–5 Ci/km^2 plus Sr-90 at a level of 0.04–0.08 Ci/km^2 demonstrated significantly fewer

TABLE 10.6. Concentration (Bq/kg) of Some Radionuclides in Fishes after the Catastrophe

Nuclide	Concentration	Species	Country	Reference
Cs-137	16,000	Perch (*Perca fluviatilis*)	Finland	Saxen and Rantavaara, 1987
	10,000	Pike (*Esox luceus*)	Finland	Saxen and Rantavaara, 1987
	7,100	Whitefish (*Coregonus* sp.)	Finland	Saxen and Rantavaara, 1987
	6,500	Catfish (*Silurus glanis*)	Ukraine	Zarubin, 2006
	4,500	Bream (*Abramis brama*)	Finland	Saxen and Rantavaara, 1987
	2,000	Vendace (*Coregonus albula*)	Finland	Saxen and Rantavaara, 1987
	708	Crucian carp (*Carassius carassius*)	Russia	Ushakov *et al.*, 1996
	493	Bream (*Abramis brama*)*	Poland	Robbins and Jasinski, 1995
	190	"Fish"	Baltic	Ilus *et al.*, 1987
	15–30	"Pike and cod"**	Baltic	Ikaheimonen *et al.*, 1988
Cs-134/137	55,000	"Freshwater fish"	Norway	Strand, 1987
	12,500	Brown trout (*Salmo trutta*)	Norway	Brittain *et al.*, 1991
Sr-90	157	Crucian carp (*Carassius carassius*)	Russia	Ushakov *et al.*, 1996
Total gamma	300,000	Raptorial fish	Ukraine	Gudkov *et al.*, 2004

*120 times that of pre-Chernobyl level.
**About five times the pre-Chernobyl level.

semen channels (especially for hogs 2 to 4 years old), as well as widening, necrosis, and unusual positions of sex cells within the channels (Table 10.8).

6. There was a marked decrease in insemination and 1.8 to 2.5% of the piglets were born dead or with congenital malformations involving the mouth, anus, legs, and gigantic heads, etc. (Oleinik, 2005).

7. Pregnancy outcomes and some health characteristics of calves (*Bos taurus*) (a Poles'e breed) in the heavily contaminated Korosten and Narodnitsky districts, Zhytomir Province, Ukraine (Cs-137 levels of 5–15 Ci/km^2) were significantly different from the same species bred in the less contaminated (<0.1 Ci/km^2) Baranovka District. More calves had abnormal weights, and morbidity and mortality were higher in the heavily contaminated areas (Table 10.9).

8. Calving problems included delayed delivery of the placenta and amniotic membranes. The weight of the amniotic tissues and placental lobule characteristics were significantly lower in cows (*Bos taurus*) in contaminated areas (Table 10.10).

9. House mice (*Mus musculus*) populations in the heavily contaminated areas decreased

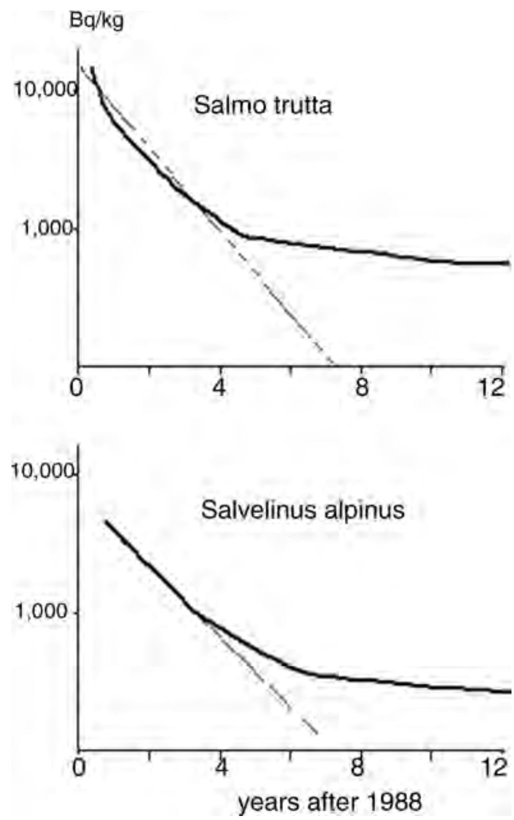

Figure 10.4. Dynamics of concentration of Chernobyl Cs-137 in lake trout (*Salmo trutta*) and charr (*Salvelinus alpinus*) in lakes in northern Norway from 1986 to 1998. Dotted line, forecast; solid line, actual concentration (Jonsson *et al.*, 1999).

TABLE 10.7. Some Recorded Chernobyl Radionuclides in Zooplankton (after J. Turner, 2002)

Sea	Date	Notes	Reference
North Sea off Norway	May–June	At depth of 222 m. Fecal pellets in sediment traps	Kempe and Nies, 1987
Mediterranean off Corsica	May 8–15 (rainfall on May 4–5), 1986	Ce-141 and Ce-144, 200 m depth. >70% composed of copepod fecal pellets	Fowler *et al.*, 1987
Black Sea	May–June, 1986	At a depth of 1,071 m (*Emiliania huxleyi*)	Buesseler *et al.*, 1987; Kempe *et al.*, 1987
North Pacific and Bering Sea	June–July, 1986	From 110 to 780 m	Kusakabe and Ku, 1988

owing to sterility, as well as to abnormal spermatozoa (Pomerantseva *et al.*, 1990, 1996).

10. Higher antenatal mortality was observed in field mice (*Clethrionomys* and *Microtus* sp.) in the first years after the catastrophe in the heavily contaminated areas owing to pathologic changes in the urogenital tract and embryo resorption in the early stages of development (Medvedev, 1991; Sokolov and Krivolutsky, 1998).

11. In October 1986 in Chernobyl City, a special animal facility was established for laboratory rats (*Rattus norvegicus*) from the breeding group that originated in the Kiev laboratory colony. After the catastrophe there was a significant decrease in the average life span of laboratory rats (*Rattus norvegicus*) in animal facilities in both Chernobyl and Kiev (Table 10.11).

12. The sex ratio of bank voles (*Clethrionomys* sp.) as a percent of the current year of breeding young deviated significantly in the heavily contaminated territories (Kudryashova *et al.*, 2004).

13. Irradiation caused increased prenatal and postnatal mortality and reduced breeding success for bank vole populations (*Clethrionomys* sp.) in contaminated areas (Kudryashova *et al.*, 2004).

14. Radiation contamination caused bank vole populations *(Clethrionomys* sp.) to mature early and intensified reproduction, both of which are associated with premature aging and reduced life expectancy (Kudryashova *et al.*, 2004).

15. The reproductive rate (number of litters during the reproductive period and number of newborns in each litter) of laboratory mice (*Mus musculus*) line CC57W of a Chernobyl experimental population steadily decreased over seven generations. At the same time the number that died in the first month postnatal period and preimplantation period significantly increased (Stolyna and Solomko, 1996).

16. Long-term studies of small-rodent populations (*Clethrionomys glareolus* and others) in

TABLE 10.8. Histological Characteristics of Hog Testes Associated with Sr-90 and Cs-137 Contamination (Oleinik, 2005)

	Specific numbers of semen channels		Thickness of white envelopes, mkm	
Age	Contaminated	Control	Contaminated	Control
5 months	39.0 ± 0.7	63.7 ± 2.8*	178.0 ± 8.5*	465.2 ± 11.7
8 months	20.5 ± 0.9	21.4 ± 0.9*	231.0 ± 12.7*	572.0 ± 18.1
2 years	13.4 ± 0.4	21.2 ± 0.8	335.0 ± 8.81*	428.0 ± 17.3
4 years	12.9 ± 0.6	19.2 ± 0.9*	380.3 ± 22.2	349.5 ± 26.0

*$p < 0.05$.

TABLE 10.9. Weight, Total Morbidity, and Mortality (%) of Calves from Heavily (5–15 Ci/m²) and Lower (<1 Ci/km²) Contaminated Districts of Zhytomir Province, Ukraine, 1997–1999 (Karpuk, 2001)

	Weight			Total morbidity	Mortality
	Less than 26 kg	More than 35 kg	Normal		
Heavy contamination	13.3	10	76.7	34	7
Low contamination	20	15	65	50.5*	12*

*$p < 0.01$.

the Kanev Natural Reserve pre- and postcatastrophe revealed disturbances in ecological balance, delay in the "population clock" run, and biotic turnover (Mezhzherin and Myakushko, 1998).

17. The litter size of wolves (*Lupus lupus*) in Russian contaminated territories correlates with the level of radioactive contamination and specific activity of Cs-137 in their fur (Adamovich, 1998).

18. Observations from 1978 to 1999, covering 5,427 horse-breeding years, indicated that the success of breeding free-range horses (*Equus caballus*) correlated with the level of farm radioactive contamination: the greatest number of abortions, stillbirths, and sick foals occurred in a horse-breeding center in the Gomel area (Belarus) from 1993 to 1999 when contamination levels were up to 40 Ci/km². An intermediate level of problems was in a horse-breeding center in the Bryansk area, Russia, with background radiation levels of 1–5 Ci/km², and the fewest problems occurred in a horse-breeding center in the Smolensk area, Russia, with contamination levels less than 1 Ci/km² (Yakovleva, 2005).

TABLE 10.10. Some Characters of Afterbirth Membranes in Cows (*Bos taurus*) from Greater and Lesser Contaminated Areas, Zhytomir Province, Ukraine, 1997–1999 (Karpuk, 2001)[1]

	Contamination level	
	5–15 Ci/km²	<0.1 Ci/km²
Weight amniotic membranes, kg	4.6 ± 0.3	5.6 ± 0.3*
Placental lobules		
Number	76.9 ± 4.0	88.0 ± 2.7*
cm²	4,043 ± 118	4,853 ± 206*

[1]Data for Ci/km²—summarized for two farms by A. Y.
*$p < 0.05$.

19. Decreased clutch size of some bird species was found in the United States in California, Washington, and Oregon in June–July 1986, most probably connected with the Chernobyl fallout (DeSante and Geupel, 1987; Millpointer, 1991).

20. Survival rates of barn swallows (*Hirundo rustica*) in the most contaminated sites near the Chernobyl NPP are close to zero. In areas of moderate contamination, annual survival is less than 25% (vs. about 40% in control populations in Ukraine, Spain, Italy, and Denmark). Overall, Chernobyl bird populations show dramatically reduced reproductive rates and lower offspring survival rates (Møller *et al.*, 2005).

21. Abnormal spermatozoa (head deviations, two heads, two tails, etc.) in barn swallows (*Hirundo rustica*) occurred at significantly higher frequencies in heavily contaminated areas (Møller *et al.*, 2005).

22. The Chernobyl barn swallow populations are only sustained via immigration from adjacent, uncontaminated populations. Stable

TABLE 10.11. Average Life Span of Laboratory Rats (*Rattus norvegicus*) under Heavy Irradiation in Chernobyl City, and Less Irradiation in Kiev (Serkiz, 1995)

	October 1986 to 1989		Kiev before April 1986
	Chernobyl City	Kiev	
Life span months	20.3 ± 0.8	21.6 ± 0.5	28.2 ± 0.6

isotope analyses on current and past specimens (from museums) have indicated that current Chernobyl populations are composed of a more diverse group of individuals (i.e., immigrants) than is observed in control populations or in populations collected from the Chernobyl region prior to the disaster (Møller *et al.*, 2006).

23. Detailed surveys of birds indicate that many species are either absent or present in very low numbers in the Chernobyl region. Brightly colored and migratory bird species appear to be particularly sensitive to radioactive contaminants (Møller and Moussaeu, 2007a).

24. Concentrations of total carotenoids and vitamins A and E in the yolks of the great tit (*Parus major*) were depressed in the 10-km zone as compared to concentrations in a less contaminated Ukrainian area or in France. Egg-laying dates were advanced and clutch sizes increased in nest boxes with high dose rates. There was reduced hatching in boxes with high levels of radiation, which eventually eliminated and even reversed the differences in reproductive success associated with early reproduction and large clutch size. These findings are consistent with the hypothesis that radioactive contamination reduces levels of dietary antioxidants in yolks, resulting in negative consequences for hatching and reproductive success (Møller *et al.*, 2008b).

25. Species richness and abundance of forest birds declined by more than 50% as contamination levels increased. Abundance of birds decreased by about 66% in the most contaminated areas as compared to sites with typical (control) background radiation levels (Møller and Mousseau, 2007a).

26. Great tit (*Parus major*) and pied flycatcher (*Ficedula hypoleuca*) species avoided nest boxes in the heavily contaminated areas to a marked degree. Where it interacted with habitat for the great tit and with the laying date for the pied flycatcher, hatching success was depressed as radioactive contamination increased (Møller and Mousseau, 2007b).

27. A significant decrease in volume and concentration of seminal fluids and destructive changes in the testes were observed in several generations of white silver carp (*Hypophthalmichthys molitrix*) from the breeding stock at a Chernobyl NPP reservoir-cooler (Verygin *et al.*, 1996).

28. Abnormal growth of testicular connective tissue, decreased sperm concentration, and increased numbers of abnormal spermatozoa were found in motley silver carp (*Aristichthys nobilis*) that were radiated in 1986 at the age of 1–2 years and then lived under conditions of chronic low-dose radiation (Makeeva *et al.*, 1996).

29. Reproductive characteristics of carp (*Cyprinus carpio*) correlated with levels of incorporated radionuclides in sperm and eggs (Figure 10.5).

30. Degenerative morphological changes were seen in oocytes of pike (*Esox lucius*) during vitellogenesis in heavily contaminated waters. In gonads of fish from two lakes within the 30-km zone (Smerzhov Lake with Cs-134 and Cs-137 levels of 5,800 Bq/kg in 1991, and Perstok Lake, with levels up to 199,900 Bq/kg in 1995) the thickness of the radial membrane in egg cells reached 25 – 30 μm, compared with a thickness of about 10 μm for egg cells from the Pripyat River (875 Bq/kg in 1992; Kokhnenko, 2000).

31. Deviation in gametogenesis (i.e., changes in normal oocytes and nucleus size, developmental abnormalities of oocytes, thickening of the follicular wall, decomposition of the nucleus, etc.) was found in bream (*Abramis brama*) and small fry (*Rutilus rutilus*) from the Pripyat River and Smerzhov Lake (Gomel Province, Belarus). Changes were correlated with the level of radiation contamination of the reservoirs (Petukhov and Kokhnenko, 1998).

32. Adult earthworms dominated in heavily contaminated sites during the first period after the catastrophe, whereas in control areas there was parity between adult and young individuals (Victorov, 1993; Krivolutsky and Pokarzhevsky, 1992).

33. Nine years after the catastrophe in bodies of water with heavy radioactivity, 20% of

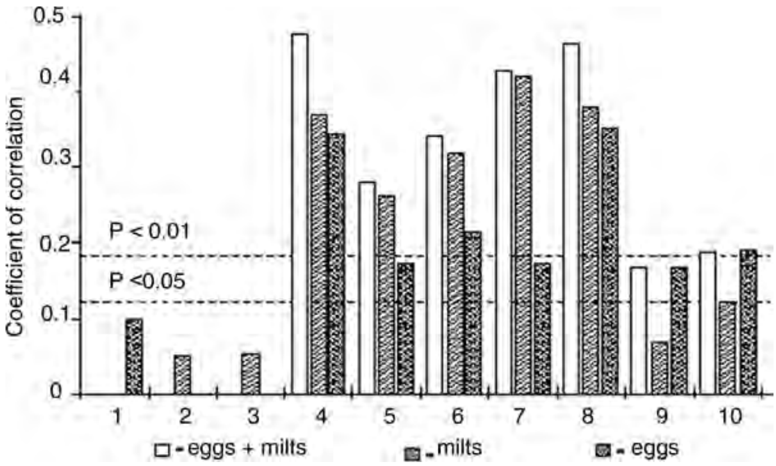

Figure 10.5. Coefficients of correlation between reproductive characteristics of carp (*Cyprinus carpio*) and radionuclide concentration in their eggs and sperm (milt; coefficients of correlation are given in absolute values): (1) number of eggs (thousands per female); (2) amount of milt (ml per male); (3) quality of milt; (4) fertilization, %; (5) number of prelarvae (thousands per female); (6) number of larvae (thousands per female); (7) larva survival, %; (8) frequency of morphological abnormalities, %; (9) mitotic index, %; (10) frequency of chromosome aberrations at late blastula stage, % (Goncharova, 1997).

oligochaete (*Stylaria lacustris*) specimens have sex cells, whereas normally this species reproduces asexually (Tsytsugyna *et al.*, 2005).

10.3. Genetic Changes

1. In 1989 there was a significantly higher frequency of cytogenetic disorders in somatic and germinal cells (number of chromosomes and aberrations in marrow cells) in bank voles (*Clethrionomys glareolus*) and yellow-necked mice (*Apodemus flavicollis*) in territories with Cs-137 levels of 8–1,526 kBq/m^2 and in laboratory mice (*Mus musculus*) lines CBA × C57Bl/6j (F1) in the heavily contaminated areas. These abnormalities were maintained at high levels for no fewer than 22 generations, which increased from 1986 until 1991/1992 in all the populations studied, despite a decrease in contamination (Goncharova and Ryabokon', 1998a,b; Smolitch and Ryabokon', 1997; Ryabokon', 1999a).

2. In all the studied populations of bank voles (*Clethrionomys glareolus*) in heavily contaminated Belarussian territories, polyploidy cells occurred in an excess of up to three orders of incidence as compared with precatastrophe frequencies (Ryabokon', 1999).

3. The number of polyploidy cells in all studied populations of bank voles (*Clethrionomys glareolus*) in heavily contaminated Belarussian territories correlates with the level of incorporated radionuclides (Ryabokon', 1999).

4. The number of genomic mutations in a population of bank voles (*Clethrionomys glareolus*) increased to the 12th generation after the catastrophe (from 1986 to 1991) despite a decrease in background radioactivity (Ryabokon', 1999).

5. The offspring of female bank voles (*Clethrionomys glareolus*) captured in the contaminated territories and raised under contamination-free conditions showed the same enhanced level of chromosomal aberrations as the contaminated mothers (Ryabokon' and Goncharova, 2006).

6. Wild populations of house mice (*Mus musculus*) living in the contaminated territories have a significantly increased level of dominant lethal mutations and chromosome translocations. The frequency of reciprocal translocations in spermatocytes was higher in areas with more intensive contamination during the

TABLE 10.12. Abnormalities in Laboratory Mice (*Mus musculus*) Fibroblast Cell Cultures after 5 Days of Exposure in the 10-km Zone (Pelevyna *et al.*, 2006)

	Chromosomal aberrations	
	Percent of cells	Types
Controls	Up to 3	Deletions
After exposure	Up to 24.5	Deletions, fragments, and translocations

TABLE 10.13. Number of Micronuclei in Polychromatic Erythrocytes of Bone Marrow in Laboratory Mice (*Mus musculus*) after 12 Weeks in 30-km Chernobyl Zone (Sushko *et al.*, 2006)*

	Sex	Studied cells, *n*	Cells with micronucleus
Controls	♂	5,000	0.34 ± 0.11
	♀	5,000	0.29 ± 0.09
30-km zone	♂	5,000	4.1 ± 0.45
	♀	5,000	4.06 ± 0.53

*All significantly different from controls.

period from 1986 to 1994 (Pomerantseva *et al.*, 1990, 1996).

7. The frequency of mutations through several generations in both somatic and germinal cells of house mice (*Mus musculus*) remained significantly higher after irradiation as compared to nonradiated descendants (Dubrova *et al.*, 2000).

8. Laboratory mice (*Mus musculus*) lines C57BL/6, BALB/C, CC57W/Mv contained within the 30-km zone and other rodents caught in 1995 in the 10-km zone, were found to have a wide spectrum of cytogenetic anomalies (Glazko *et al.*, 1996).

9. The frequency of mitochondrial DNA mutations in voles in the 30-km zone was significantly increased in the first years after the catastrophe (Freemantle, 1996; Baker, 1996; Hillis, 1996).

10. The number of aberrant alveolar macrophage cells in bank voles (*Clethrionomys glareolus*) was significantly higher in the populations living in heavily contaminated territories (Yelyseeva *et al.*, 1996).

11. The micronuclear frequencies in laboratory mice (*Mus musculus*) increased significantly after a 10-day stay in the "Red Forest" (10-km zone) for the BALB/c line and after 30 days for the C57BL/6 line (Wickliffe *et al.*, 2002).

12. The rate of chromosome aberrations and embryonic lethality noticeably increased for more than 22 generations of bank voles (*Clethrionomys glareolus*), whereas the whole-body absorbed dose rates decreased exponentially after 1986 (Goncharova *et al.*, 2005).

13. In laboratory mice (*Mus musculus*), cell fibroblast cultures originating from embryos conceived in the 10-km zone demonstrate significantly increased numbers of cells with chromosomal aberrations, including cells with multiple aberrations (Nazarov *et al.*, 2007; Table 10.12).

14. Keeping laboratory mice (*Mus musculus*) for 4 months in the 30-km zone resulted in a sharp and significantly increased incidence of micronuclei in polychromatic cells of the bone marrow (Table 10.13).

15. The number of chromosome aberrations in the bank vole (*Clethrionomys glareolus*) was higher in a more radioactively contaminated environment (Table 10.14).

16. The level of both somatic and genomic mutations in a population of barn swallows (*Hirundo rustica*) in the Chernobyl zone was two to ten times greater than in other populations in Ukraine or in Italy (Ellegren *et al.*, 1997).

TABLE 10.14. Frequency of Aberrant Cells in Bank Voles (*Clethrionomys glareolus*) under Various Levels of Radioactive Contamination, 1993, Bryansk Province, Russia (Krysanov *et al.*, 1996)

Contamination level	Cells studied *n*	Aberrant cell frequencies
20 μR/h	229	0.04 ± 0.008
60 μR/h	593	0.06 ± 0.006
180 μR/h	325	0.13 ± 0.02
220 μR/h	864	0.11 ± 0.02

Figure 10.6. Normal barn swallow (left) and partial albino (right; photo by T. Mousseau).

17. Barn swallow populations (*Hirundo rustica*) that originated in the Ukrainian Chernobyl zone after the catastrophe have significantly more (up to 15%) albino mutations (Figure 10.6). Mutation rates seen in Chernobyl populations have significantly higher numbers of morphological defects as compared to control populations in Ukraine, Italy, Spain, and Denmark (Møller and Mousseau, 2001; Møller *et al.*, 2007).

18. There are positive correlations between the number of abnormalities in black redstart (*Phoenicurus ochruros*) and house sparrows (*Passer domestica*) and the level of background radiation in Ukraine (Møller *et al.*, 2007).

19. From 2005 to 2006 there were significant differences in motility and morphology of live sperm of barn swallows (*Hirundo rustica*) breeding in heavily radioactively contaminated areas (390 mR/h) around Chernobyl as compared to sperm from swallows in two less contaminated (0.25 and 0.006 mR/h) areas in Ukraine. The incidence of sperm with low motility, high linearity, small amplitude, lateral head displacement, and low track velocity increased with increasing background radiation levels (Møller *et al.*, 2008b).

20. Brown frogs (*Rana temporaria*, *R. arvalis*) from the heavily contaminated territories showed a significantly higher number of aberrant bone marrow and intestinal epithelial cells and an increased number of micronuclei in peripheral blood (Yelyseeva *et al.*, 1996).

21. The incidence of erythrocytes with micronuclei was higher in the hybrid frog complex (*Rana esculenta*) in the more contaminated areas in Bryansk Province (Table 10.15).

22. The frequency of morphological anomalies (congenital malformations) in carp (*Cyprinus carpio*) embryos, larvae, and fingerlings was significantly higher in more contaminated ponds in Belarus (Slukvin and Goncharova, 1998).

23. The frequency of chromosome aberrations and genomic mutations in carp (*Cyprinus carpio*) populations was significantly higher in more contaminated ponds in Belarus (Goncharova *et al.*, 1996).

24. Colorado beetle (*Leptinotarsa decemlineata*) wing color pattern mutations occurred with greater frequency in the more contaminated territories in Belarus (Makeeva *et al.*, 1995).

TABLE 10.15. The Frequency of Micronuclei in Erythrocytes in Frog Hybrid Complex (*Rana esculenta*) in Three Populations in Bryansk Province, 1993 (Chubanishvyli, 1996)

Contamination, dose		
15 μ R/h	60 μR/h	220 μR/h
0.22%	1.33%	1.55*

*$p < 0.05$.

TABLE 10.16. The Frequency of Dominant Lethal Mutations (DLM) and Recessive Sex-Linked Lethal Mutations (RLM) in Natural Drosophila (*Drosophila melanogaster*) Populations from the Vetka District in Gomel Province as Compared with the Population from the Less Contaminated Berezinsk Reserve, Belarus (Glushkova *et al.*, 1999)

	Vetka District	Berezinsky Reserve
DLM	42.76 ± 0.88	$63.09 \pm 0.91^{*}$
RLM	6.65 ± 0.66	$12.64 \pm 1.15^{**}$

$^{*}p < 0.05$; $^{**}p < 0.001$.

25. The frequency of lethal and semilethal mutations in drosophila (*Drosophila melanogaster*) populations is significantly higher in the Belarussian contaminated territories (Makeeva *et al.*, 1995).

26. In natural drosophila (*Drosophila melanogaster*) populations from the Vetka District, Gomel Province (radiation level of 24 Ci/km^2), the incidence of dominant lethal and recessive sex-linked lethal mutations is significantly lower than in the less contaminated Berezinsky Reserve, as a result of increased radioresistance in the irradiated population (Table 10.16).

27. The highest level of mutations was observed in aquatic crustaceans Amphipoda and Platyhelminth worm populations in the Chernobyl 10-km zone as compared with populations from the Black and Aegean seas and the Danube and Dnieper rivers (Tsytsugyna and Polycarpov, 2007).

28. Table 10.17 presents some additional data on genetic changes in animals associated with the Chernobyl contamination.

10.4. Changes in Other Biological Characteristics

1. Voles (*Clethrionomys* sp. and *Microtus* sp.) from the contaminated areas showed impaired brain development and deformed limbs (Sokolov and Kryvolutsky, 1998).

2. Neutrophilic phagocytic activity to *Staphylococcus aureus* in the blood serum and the B-lymphocytic system was significantly lower in

TABLE 10.17. Examples of Genetic Changes in Animals as a Consequence of the Chernobyl Catastrophe (Based on Møller and Mousseau, 2006)

Species	Genetic marker	Effect, comments	Reference
Apodemus flavicollis	Chromosome aberrations	Increase by a factor of 3–7	Savchenko, 1995
Mus musculus	Reciprocal translocations	Increase by a factor of 15	Pomerantseva *et al.*, 1990, 1996
Clethryonomys glareolus	Somatic mutation	Increased*	Matson, 2000
	Multiple substitutions in Cytochrome-b and transversions	Only from Chernobyl samples	Baker *et al.*, 1999
	Mutation and heteroplasmy**	Increased*	Wickliffe *et al.*, 2002
	Point mutations	Increased*	Dubrova, 2003; Wickliffe *et al.*, 2002
Hirundo rustica	Microsatellites	Increased by a factor of 2–10	Ellegren *et al.*, 1997
Icterus punctatus	DNA breakage I	Increased rate	Snugg, 1996
Carassius carassius	DNA content	Changes	Lingerfelser, 1997
Four fish species	Frequency of aneuploidy	Increased	Dallas, 1998
Drosophila melanogaster	Sex-linked lethal mutations	Increased	Zainullin, 1992
Three Oligochaete species	Chromosomal aberrations	Increased by a factor of ~ 2	Tsytsugyna and Polycarpov, 2003

*Not statistically significant.

**Heteroplasmy—mixed mitochondria in a single cell.

TABLE 10.18. Some Hematological Characteristics of Calf-Bearing Cows from Heavily and Less Contaminated Areas, Zhytomir Province, Ukraine, 1997–1999 (Karpuk, 2001)[1]

	5–15 Ci/km^2	<0.1 Ci/km^2
Erythrocytes (thousands/liter)	4.8 ± 0.1	5.8 ± 0.2*
Leucocytes (g/liter)	6.2 ± 0.4	6.9 ± 0.3
Hemoglobin (g/liter)	78.6 ± 2.0	91.4 ± 2.8*
Basophiles, %	0.3 ± 0.2	1.3 ± 0.2*
Eosinophils, %	10.0 ± 1.0	4.6 ± 0.3
Segmented neutrophiles, %	24.7 ± 1.5	32 ± 0.9*
Lymphocytes, %	57.7 ± 1.5	60.9 ± 0.8*
Monocytes, %	3.8 ± 0.3	4.5 ± 0.3

[1]Data for Ci/km^2—summarized for two farms by A. Y.

* $p < 0.01$.

cows from more contaminated areas ($p < 0.05$ and $p < 0.001$; Karpuk, 2001).

3. Hematological characteristics differ significantly in cattle (*Bos taurus*) from areas with different levels of contamination (Table 10.18).

4. Hypoplasia and degenerative-dystrophic changes developed in the thymus glands of 20-day-old laboratory albino rats (*Rattus norvegicus*) whose pregnant mothers lived for 25 days in an area with a Cs-137 level of 116 Ci/km^2 and an Sr-90 level of 26 Ci/km^2. Changes included accelerated cytolysis and lowered mitotic activity. Such thymus gland changes led to immune disorders (Amvros'ev *et al.*, 1998).

5. Endogenous activity changed significantly in spinal cord nerve cells and in the cerebrum of laboratory mice (*Mus musculus*) lines C57BI/6 after they were in the Chernobyl zone for 40 days with background radiation of 100–120 mR/h (Mustafin *et al.*, 1996).

6. Dairy cows (*Bos taurus*) from areas contaminated at levels of 15–40 Ci/km^2 developed inflammatory and atrophic changes in lymphoid tissue accompanied by decreased T-lymphocyte functional activity, and they demonstrated abnormal connective tissue growth 4 years after the catastrophe (Velykanov and Molev, 2004).

TABLE 10.19. Frequency of Lung Neoplasms in Laboratory Mice (*Mus musculus*) after 20 Weeks Exposure in the 30-km Zone (Sushko *et al.*, 2006)

	Neoplasms per mouse
Control	0.26 ± 0.06
30-km zone	0.77 ± 0.17

7. Dairy cows (*Bos taurus*) in areas with contamination levels of 15–40 Ci/km^2 developed indurated spleens with reduced volume and sharply reduced white pulp area. There was coarsening of reticular fibrous structures and dispersed and reduced lymph nodes in the cortex (Velykanov and Molev, 2004).

8. Asymmetry of yellow-neck mouse (*Apodemus flavicollis*) skulls was significantly higher in populations from more contaminated territories (Smith *et al.*, 2002).

9. After 20 weeks of exposure in the 30-km zone the incidence of lung neoplasms in laboratory mice (*Mus musculus*) was significantly greater (Table 10.19).

10. There was a decreased density of endotheliocytes in various parts of the brain in laboratory mice (*Mus musculus*) after they had lived in the 10-km zone for 1 month (Pelevyna *et al.*, 2006; Nazarov *et al.*, 2007).

11. Large horned livestock (*Bos taurus*) in contaminated areas had lowered lysozymic activity in whey and lowered resistance to skin infections, which indicated the development of immunodeficiency (Il'yazov, 1993, 2002).

12. Resistance to skin infections is lowered in wild murine rodents in heavily contaminated territories (Kozynenko and Zavodnykova, 1993).

13. There was increased sensitivity to viral infections in laboratory mice (*Mus musculus*) after they had been in the 10-km zone (Savtsova *et al.*, 1991).

14. There was a significantly increased frequency of tumors in laboratory mice (*Mus musculus*) experimentally inoculated with tumor cells after they had been in the 10-km zone (Savtsova *et al.*, 1991).

15. Animals in the Chernobyl zone had accelerated aging of the immune system (Savtsova, 1995).

16. Laboratory rats (*Rattus norvegicus*) kept in the 10-km zone from 1986 to 1993 were found to have (Pinchuk and Rodionova, 1995; Serkiz *et al.*, 2003):

- Decreased numbers of bone marrow cells, peripheral blood leukocytes, and myelokaryocytes.
- Hypochromatic anemia, leukocytopenia (onset during the third month of being in the radioactive zone), granulocytopenia with very high levels of eosinophils, and eosinophilia.
- Increased numbers of abnormal cells (huge hypersegmented neutrophilic leukocytes, cells with fragmented nuclei, cells with shaggy chromatin structure, cytoplasm nuclear inclusions, and multinucleated lymphocytes.

17. After being in the 10-km zone for 3 to 6 months, laboratory rats (*Rattus norvegicus*) developed significant mitotic growth activity (sometimes accompanied by an increase in the number of bone marrow cells) and then had a subsequent decrease in mitotic activity. Similar processes were observed in wild murines living in the 10-km zone (Serkiz *et al.*, 2003).

18. Low red cell counts, decreased hemoglobin levels, and decreased percentage of neutrophils and monocytes were seen in cattle (*Bos taurus*) that remained in the 12-km zone for 2 months after the catastrophe (Il'yazov, 1993; Il'yazov *et al.*, 1990).

19. Until October 1986 free-range cattle (*Bos taurus*) living 3–6 km from the Chernobyl NPP had high eosinophil and low lymphocyte counts, as well as undifferentiated cells, broken cell forms, and hyperchromic anemia (Glazko *et al.*, 1996).

20. In farm-raised hog sires (*Sus scrofa*) in Mlinivs'sk and Sarnens'k districts of Rivne Province, Ukraine, from 1997 to 2001, where Cs-137 contamination levels were 1–5 Ci/km^2 and Sr-90 levels were 0.04–0.08 Ci/km^2, erythrocyte counts were significantly lower (up to 15.0%), hemoglobin was lower (up to 45.0%), the percentage of young and stick hearted leukocytes increased 1.3 to 2.8 times, and blood levels of alpha- and gammaglobulins decreased up to 44.4% (Oleinik, 2005).

TABLE 10.20. Cause of Death (%) in Laboratory Rats (*Rattus norvegicus*) from the Experimental Animal Facilities in Chernobyl City (Heavy Background Radiation) and Kiev (Less Background Radiation), October 1986–December 1989 (Serkiz, 1995)

Cause of death	Kiev	Chernobyl City
Pneumonia, lung hemorrhage	10.3	35.5
Pulmonitis	8.4	11.1
Colitis	19.1	31.1
Lymph node hyperplasia	10.3	13.2
Thymus gland/spleen hyperplasia	2.4	4.4

21. Laboratory rats (*Rattus norvegicus*) kept in the 30-km zone for 1 month had significantly increased leukocytes and have a tendency toward increased numbers of marrow cells (Izmozherov *et al.*, 1990).

22. Laboratory mice (*Mus musculus*) kept in the 30-km zone for 1 month had significantly increased numbers of lymphocytes and leukocytes (Pelevyna *et al.*, 1993).

23. The most common immediate causes of death for laboratory rats (*Rattus norvegicus*) in the animal facilities in Chernobyl City and Kiev after the catastrophe were inflammatory processes of the lungs and intestines (Serkiz, 1995). Table 10.20 presents data on their mortality from 1986 to 1989.

24. Mammary adenofibromas and malignant lung and intestinal tumors appeared at earlier ages in laboratory rats (*Rattus norvegicus*) in the Chernobyl animal facility from 1987 to 1989 and included lymphoid and connective tissue tumors, including lymphatic sarcoma (Table 10.21).

25. Tumors developed in 74% of laboratory rats (*Rattus norvegicus*) in the Chernobyl and Kiev experimental breeding colonies

TABLE 10.21. Average Age of Occurrence and Probability of Occurrence (%) of Malignant Tumors in Laboratory Rats (*Rattus norvegicus*) under Different Levels of Contamination before and after the Catastrophe (Pinchuk, 1995)

	After 1986		
	Chernobyl	Kiev	1985
Average age for malignant tumors, months	10	14	16
Probability of occurrence of tumors, months	35	17	5

from 1989 to 1992. Endocrine gland tumors (Table 10.22) in combination with mammary tumors (Table 10.23) were typical for rats from Chernobyl. Adenocarcinoma and epithelial tumors in Chernobyl rats were not observed in rats in the Kiev group and were not seen as spontaneous tumors in this breeding line before the catastrophe (Pinchuk, 1995).

26. Female rats (*Rattus norvegicus*) age 4–5 months with hyperthyroidism kept in the 30-km zone for 30 days had significantly reduced basal activity of myocardial adenyl cyclase (ACS; 14.48 ± 0.78 nMol/mg protein/min as compared with 20.78 ± 0.57 in the controls). A test of F-dependent enzyme activation revealed a significant reduction in the stimulative effect of ACS activity on myocardium in animals kept under irradiation. The data point to the possibility of modulating hyperthyroid effects at

TABLE 10.22. Occurrence (% of Total Tumors) in Laboratory Rats (*Rattus norvegicus*) from 1986 to 1992 in Chernobyl City and Kiev Experimental Animal Facilities (Pinchuk, 1995)

	Chernobyl City	Kiev
Thymus gland tumor*	15.9	2.7
Adrenal cortex adenoma	43.2	6.8
Thyroid gland tumor	43.2	15.7
Cellular adenoma of islet of Langerhans	34.1	1

*Between 1986 and 1989 the animals in Kiev had no such tumors, but such tumors did develop in 4.8% of all the animals in the Chernobyl facility.

TABLE 10.23. Occurrence and Features of Breast Neoplasms in Laboratory Rats (*Rattus norbegicus*) from 1989 to 1992 in Chernobyl City and Kiev Experimental Animal Facilities (Pinchuk, 1995)

	Chernobyl City	Kiev
Breast adenofibroma with malignancy, %*	14.7	9.5
Animals with multiple mammary tumors, %**	29	27
Animals with a breast tumors combined with other tumors**	58.8	20.3

*From the total number of animals.

**From number of animals with mammary gland tumors.

the β-adrenergic link level of ACS in cardiomyocytes in animals exposed to radiation (Komar *et al.*, 2000).

27. The level of fluctuating asymmetry in populations of the common shrew (*Sorex araneus*) was higher in the more radioactively contaminated environment in Bryansk Province, Russia (Table 10.24).

28. The level of developmental stability (by fluctuating asymmetry of many morphological characters) in barn swallows (*Hirundo rustica*) was significantly higher in the contaminated areas (Møller, 1993).

29. Carbohydrate metabolism and lipid balance were noticeably abnormal in some birds from the Chernobyl zone, reflecting endocrine system impairment (Mykytyuk and Ermakov, 1990).

30. The percentage of dead cells in the spleen and bone marrow of moor frogs (*Rana arvalis*)

TABLE 10.24. Level of Fluctuating Asymmetry (Asymmetric Cases per Character) in Three Populations of Common Shrew (*Sorex araneus*) with Different Levels of Radioactive Contamination, Bryansk Province, 1992 (Zakharov *et al.*, 1996b)

Contamination, dose		
60 μR/h	180 μR/h	220 μR/h
0.016 ± 0.03	0.24 ± 0.03	0.26 ± 0.03

TABLE 10.25. Immune Status of the Frog Hybrid Complex *Rana esculenta* in Two Populations with Different Contamination Levels, Bryansk Province, 1994 (Isaeva and Vyazov, 1996)

	Contamination, μR/h	
Index	60	220
Leukocytes, 10^6/liter	15.32 ± 0.99	21.7 ± 1.83
Lymphocytes, 10^6/liter	6.16 ± 0.41	11.08 ± 1.0
Neutrophils, %	47.2 ± 1.11	28.9 ± 1.55
T lymphocytes, %	47.1 ± 1.45	26.6 ± 1.03
B lymphocytes, %	20.9 ± 0.56	12.5 ± 0.67
Zero-cells, %	32.0 ± 1.59	61.9 ± 1.38
Rosette-forming neutrophiles, %	22.8 ± 1.22	17.7 ± 0.49

from populations living under heavy radiation for 7–8 years differed significantly from controls after exposure to additional experimental radiation (Afonin and Voitovich, 1998; Afonin *et al.*, 1999).

31. The number of micronucleated erythrocytes in all the populations of brown frogs (*Rana temporaria*) from heavily contaminated areas caught before 1991 was significantly higher ($p < 0.001$) than from less contaminated areas (in some cases by a factor of 30). Both brown (*R. temporaria*) and narrow-muzzled (*R. arvalis*) frogs inhabiting radiation-contaminated areas have increased cytogenetic damage in bone marrow cells and erythrocytes and a change in the ratio of erythrocytes in peripheral blood (Voitovich, 2000).

32. Additional gamma-irradiation-induced apoptosis of bone marrow cells was discovered in narrow-muzzled frogs (*Rana arvalis*) inhabiting the 30-km zone. The initial level of cells with chromatin changes was significantly higher ($p < 0.05$) in animals from the 30-km zone (Afonin *et al.*, 1999).

33. Changes were demonstrated in the functional immune status activity in the frog hybrid (*Rana esculenta*) in the more contaminated areas (Table 10.25).

34. The level of developmental stability (by number of asymmetric cases per character) in three populations of frogs (*Rana esculenta*) was lower in less contaminated environments (Table 10.26).

TABLE 10.26. The Level of Developmental Stability (Asymmetric Cases Per Character) in Populations of Frog Hybrid Complex *Rana esculenta* with Different Levels of Radioactive Contamination, Bryansk Province, 1992–1993 (Chubanishvyli *et al.*, 1996)

	Contamination, dose		
Year	15 μR/h	60 μR/h	220 μR/h
1994	0.45 ± 0.03	0.46 ± 0.03	0.54 ± 0.03
1993	—	0.54 ± 0.03	0.64 ± 0.03

35. The level of fluctuating asymmetry and the number of phenodeviations in populations of crucian carp (*Carassius carassius*) and wild goldfish (*Carassius auratus*) were higher in those living in water with more radioactive contamination in Bryansk Province, Russia (Table 10.27).

36. After the catastrophe, there were many malformed specimens of true insect (*Heteroptera*) species collected in areas with the most radioactive contamination in eastern Sweden (Gysinge, Osterfarnebo, and Galve) and southern Switzerland (Melano near Ticino). In 1990 up to 22% of all insects collected in the Polessk District, near the 30-km zone, were malformed (Hesse-Honegger, 2001; Hesse-Honegger and Wallimann, 2008).

37. The number of oribatid mite species, inhabitants on pine bark and the lichen *Hypogymnia physodes* significantly declined on radioactively contaminated trees 2–3 km from the Chernobyl NPP. Before the catastrophe, there were 16 species; afterward the numbers were: 1986, 0; 1987, 2; 1988, 2; 1991, 4; 1999, 6; and 2002, 8 (Kryvolutsky, 2004).

38. In the 5 to 6 years after the catastrophe the species diversity of large soil invertebrates was significantly lowered, and even 13 to 15 years after there were also fewer small-sized species (Pokarzhevsky *et al.*, 2006).

39. The intensity of nematode and cestode invasions was higher in more radioactively contaminated environments (Table 10.28).

TABLE 10.27. Level of Fluctuating Asymmetry and Number of Phenodeviation in Populations of Crucian Carp (*Carassius carassius*) and Wild Goldfish (*Carassius auratus*) with Different Levels of Radioactive Contamination of the Water, Bryansk Province, 1992 (Zakharov *et al.*, 1996a)

Species	Character	60 μR/h	80 μR/h	180 μR/h
C. carassius	Asymmetric cases per character	0.31 ± 0.07	0.37 ± 0.04	0.42 ± 0.06
	Phenodeviation per specimen	1.57 ± 0.61	2.93 ± 0.26	4.88 ± 0.30
C. auratus	Asymmetric cases per character	0.26 ± 0.03	0.45 ± 0.04	-
	Phenodeviation per specimen	2.0 ± 0.29	4.10 ± 0.27	-

40. In the 10 years after the catastrophe the biodiversity of soil protozoa did not exceed 50% of the precatastrophe level (Pokarzhevsky *et al.*, 2006).

10.5. Conclusion

In 1986 in the contaminated territories, an enormous amount of many different radionuclides was absorbed by animals through food, water, and air. Levels of incorporated radionuclides were sometimes hundreds of times higher than precatastrophe ones. Now, 23 years after the catastrophe, the levels of incorporated radionuclides in some areas of Europe remain dangerous for mammals, birds, amphibians, and fish. This first radioactive shock together with chronic low-dose contamination has resulted in morphologic, physiologic, and genetic disorders in all of the animals studied—mammals, birds, amphibians, fish, and invertebrates. "Chernobyl" populations exhibit a wide variety of morphological deformities that are not found in normal populations of domestic animals, even beetles, living in the contaminated territories.

TABLE 10.28. Intensity of the Invasion of Bank Voles (*Clethrionomys glareolus*) by Nematodes and Cestodes, Bryansk Province, Russia, 1992–1995 (Pel'gunov, 1996)

	60 μR/h	180 μR/h	220 μR/h
Nematodes*			
Intensity, %	3.5	5.0	48.1
Index of abundance	3.0	3.9	40.0
Cestodes**			
Intensity, %	1.6	1.1	3.4
Index of abundance	0.53	0.71	2.1

*Predominant species: *Heligmosomum mixtum*, *Heligmosomoides glareoli*, and *Syphacia obvelata*.

**Predominant species: *Catenotaenia cricetorum* and *Paranoplocephala omphalodes*.

Some bird species may persist in the 30-km Chernobyl zone only via immigration from uncontaminated areas. Despite reports of a "healthy" Chernobyl environment for rare species of birds and mammals, their existence there is likely the result of immigration and not from locally sustained populations.

Mutation rates in animal populations in contaminated territories are significantly higher. There is transgenerational accumulation of genomic instability in animal populations, manifested as adverse cellular and systemic effects. These long-term effects may be even more detrimental because the genomes of animals in subsequent generations are more sensitive to the impact of very low doses of radiation (Goncharova, 2005).

Since the catastrophe, long-term observations of both wild and experimental animal populations in the heavily contaminated areas show serious increases in morbidity and mortality that bear striking resemblance to changes in the public health of humans—increasing tumor rates, immunodeficiencies, decreasing life expectancy, early aging, changes in blood formation, malformations, and other compromises to health.

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11. Chernobyl's Radioactive Impact on Microbial Biota

Alexey V. Yablokov

Of the few microorganisms that have been studied, all underwent rapid changes in the areas heavily contaminated by Chernobyl. Organisms such as tuberculosis bacilli; hepatitis, herpes, and tobacco mosaic viruses; cytomegalovirus; and soil micromycetes and bacteria were activated in various ways. The ultimate long-term consequences for the Chernobyl microbiologic biota may be worse than what we know today. Compared to humans and other mammals, the profound changes that take place among these small live organisms with rapid reproductive turnover do not bode well for the health and survival of other species.

One gram of soil contains some 2,500,000,000 microorganisms (bacteria, microfungi, and protozoa). Up to 3 kg of the mass of an adult human body is made up of bacteria, viruses, and microfungi. In spite of the fact that these represent such important and fundamentally live ecosystems there are only scarce data on the various microbiological consequences of the Chernobyl catastrophe.

Several incidences of increased morbidity owing to certain infectious diseases may be due to increased virulence of microbial populations as a result of Chernobyl irradiation.

1. Soon after the catastrophe studies observed activation of retroviruses (Kavsan *et al.*, 1992).
2. There is evidence of increased susceptibility to *Pneumocystis carinii* and cytomegalovirus in children whose immune systems were suppressed in the contaminated territories of Novozybkov District, Bryansk Province (Lysenko *et al.*, 1996).
3. Tuberculosis became more virulent in the more contaminated areas of Belarus (Chernetsky and Osynovsky, 1993; Belookaya, 1993; Borschevsky *et al.*, 1996).
4. In some heavily contaminated areas of Belarus and Russia there was a markedly higher level of cryptosporidium infestation (Lavdovskaya *et al.*, 1996).
5. From 1993 to 1997 the hepatitis viruses B, C, D, and G became noticeably activated in the heavily contaminated areas of Belarus (Zhavoronok *et al.*, 1998a,b).
6. Herpes viruses were activated in the heavily contaminated territories of Belarus 6 to 7 years after the catastrophe (Matveev, 1993; Matveev *et al.*, 1995; Voropaev *et al.*, 1996).
7. Activation of cytomegalovirus was found in the heavily contaminated districts of Gomel and Mogilev provinces, Belarus (Matveev, 1993).
8. Prevalence of *Pneumocystis* was noticeably higher in the heavily contaminated territories of Bryansk Province (Lavdovskaya *et al.*, 1996).
9. The prevalence and severity of Gruby's disease (ringworm), caused by the fungus microsporia *Microsporum* sp., was significantly higher in the heavily contaminated areas of Bryansk Province (Rudnitsky *et al.*, 2003).
10. The number of saprophytic bacteria in Belarussian sod-podzolic soils is at maximum in areas with radioactivity levels of 15 Ci/km^2 or less and minimal in areas

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with up to 40 Ci/km^2 (Zymenko *et al.*, 1995).

11. There is a wide range of radionuclide bioaccumulations in soil micromycetes. The accumulation factor of Cs-137 in *Stemphylium* (family Dematiaceae) is 348 and in *Verticillium* (family Muctdinaceae) 28 (Zymenko *et al.*, 1995).
12. Since the catastrophe, the prevalence of black microfungi has dramatically increased in contaminated soil surrounding Chernobyl (Zhdanova *et al.*, 1991, 1994).
13. Among soil bacteria that most actively accumulate Cs-137 are *Agrobacterium* sp. (accumulation factor 587), *Enterobacter* sp. (60–288), and *Klebsiella* sp. (256; Zymenko *et al.*, 1995).
14. In all soil samples from the 10-km Chernobyl zone the abundance of soil bacteria (nitrifying, sulfate-reducing, nitrogen-fixing, and cellulose-fermenting bacteria, and heterotrophic iron-oxidizing bacteria) was reduced by up to two orders of magnitude as compared to control areas (Romanovskaya *et al.*, 1998).
15. In contaminated areas several new variants of tobacco mosaic virus appeared that affect plants other than Solanaceous species, and their virulence is most likely correlated with the level of radioactive contamination in the areas. Infection of tobacco plants with tobacco mosaic virus and oilseed rape mosaic virus was shown to induce a threefold increase in homologous DNA recombination in noninfected tissues (Boyko *et al.*, 2007; Kovalchuk *et al.*, 2003).
16. All the strains of microfungi species that were studied (*Alternaria alternata*, *Mucorhiemalis*, and *Paecilomyces lilacinus*) from the heavily contaminated Chernobyl areas have aggregated growth of threadlike hyphae, whereas the same species from soil with low radionuclide contamination show normal growth. Only slowly growing *Cladosporium cladosporioides* has aggregated growth both in contaminated and lightly contaminated soils (Ivanova *et al.*, 2006).
17. Sharp reduction in the abundance of bifidus bacteria and the prevalence of microbes of the class *Escherichia*; in particular, a sharp increase in *E. coli* has been noted in the intestines of evacuee children living in Ukraine (Luk'yanova *et al.*, 1995).
18. In a long-term study (1954 to 1994—before and after the catastrophe) in Belarus, Ukraine, and Russia it was revealed that in areas with a high level of radioactive contamination (740–1,480 kBq/m^2 and higher) in Bryansk, Mogilev, Gomel, Chernygov, Sumy, Kaluga, Oryol, Smolensk, and Kursk provinces, practically no cases of rabies in wild animals have been reported since the catastrophe (Adamovich, 1998). This suggests that the rabies virus has either disappeared or become inactivate.
19. Rodents in the heavily contaminated territories of Belarus have been extensively invaded by coccids (obligate intracellular protozoan parasites from the phylum Apicomplexa; Sutchenya *et al.*, 1995).
20. There are fewer than normal, more anomalous, and no sporulated oocysts of coccidia *Eimeria cerna* in voles (*Clethrionomys glareolus*) in Bryansk Province (Table 11.1).
21. Six years after the catastrophe a population of *Eimeria cernae* from *Clethrionomys glareolus* living in heavily contaminated soil (up to 7.3 kBq/kg of Cs-134, Cs-137, Sr-90, and Pu-106) in Kiev Province

TABLE 11.1. Characteristics of Oocysts of Coccidia (*Eimeria cerna*) in Voles (*Clethrionomys glareolus*) from Two Differently Contaminated Sites, Bryansk Province (Pel'gunov, 1996)

	Level of contamination	
	20 μR/h	180–220 μR/h
Normal	94.5	76.6
Anomalous	0	6.3
Nonsporulated	5.2	12.2

had anomalous oocysts (Soshkin and Pel'gunov, 1994).

22. There was a significant decline in the Shannon diversity index of infusoria species and a concomitant increase in their abundance in the Pripyat River mouth from 1986 to 1988 (Nebrat, 1992).

All microorganisms (viruses, bacteria, fungi, and protozoa) and microbiological communities as a whole undergo rapid changes after any additional irradiation. The mechanism of such changes is well known: inclusion and increase in the frequency of mutations by natural selection and preservation of beneficial novel genes that for whatever reason appear more viable under the new conditions. This microevolutionary mechanism has been activated in all radioactively contaminated areas and leads to activation of old and the occurrence of new forms of viruses and bacteria. All but a few microorganisms that have been studied in Chernobyl-affected territories underwent rapid changes in heavily contaminated areas.

Our contemporary knowledge is too limited to understand even the main consequences of the inevitable radioactive-induced genetic changes among the myriad of viruses, bacteria, protozoa, and fungi that inhabit the intestines, lungs, blood, organs, and cells of human beings. The strong association between carcinogenesis and viruses (papilloma virus, hepatitis virus, *Helicobacter pylori*, Epstein–Barr virus, Kaposi's sarcoma, and herpes virus) provides another reason why the cancer rate increased in areas contaminated by Chernobyl irradiation (for a review, see Sreelekha *et al.*, 2003).

Not only cancer, but also many other illnesses are connected with viruses and bacteria. Radiologically induced pathologic changes in the microflora in humans can increase susceptibility to infections, inflammatory diseases of bacterial and viral origin (influenza, chronic intestinal diseases, pyelonephritis, cystitis, vaginitis, endocolitis, asthma, dermatitis, and ischemia), and various pathologies of pregnancy.

The long-term consequences for microbial biota may be worse than what we understand today.

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Conclusion to Chapter III

The 1986 radioactive fallout from Chernobyl impacted fauna and flora over the entire Northern Hemisphere. Elevated radiation levels were documented in plants and animals (including microorganisms) in Western Europe, North America, the Arctic, and east Asia, and the levels were often hundreds of times higher than previous background levels that were considered "normal." This huge outpouring of high-level radioactivity together with the ensuing low-level chronic irradiation resulted in morphologic, physiologic, and genetic disorders in all living organisms: plants, mammals, birds, amphibians, fish, invertebrates, and bacteria, as well as viruses. Without exception, adverse effects were evident in all the plants and animals that were studied.

Affected populations exhibited a wide variety of morphological deformities that were extremely rare or not known before the catastrophe. Twenty-plus years later, game animals and livestock in some Chernobyl-contaminated areas far from Ukraine continue to have dangerous levels of absorbed radionuclides.

Chernobyl's overall radioactive effect on water, atmosphere, and soil is dynamic from both the radionuclide decay transformations as well as from biologic, geologic, chemical, and other ecological processes such as migration and accumulation of radionuclides throughout the ecosystems, including introduction into multiple food chains. The active migration of Sr-90, Cs-137, Pu, Am, and other isotopes results in bioaccumulation that will present unforeseen surprises for decades to centuries to come.

The data presented in Chapter III, however varied, show that the Chernobyl catastrophe has had and will continue to have multiple impacts upon flora and fauna.

As soon as industrial, agricultural, and other anthropogenic pressures on wildlife in the heavily contaminated areas eased, wildlife began to be restored and even appeared to flourish. Large mammals—wolves, elk, wild boars, deer, and birds, including eagles—are living in the Chernobyl zone of contamination, but the prosperity of this wildlife is deceptive. Studies of birds indicate that some species may be found in the contaminated regions only because of migration from uncontaminated areas (Møller and Moussaeu, 2007). Morphologic, cytogenic, and immunological studies of plant, fish, amphibian, and mammalian populations reveal deterioration in all the organisms that were studied in detail (For review see Grodzinsky, 2006 and Zakharov and Krysanov, 1996).

Mutation loads and mutation rates in plants, animals, and microorganisms in the Chernobyl-contaminated territories are much higher than elsewhere. Chronic low-dose exposure to Chernobyl irradiation has resulted in transgenerational accumulation of genomic instability, manifested by abnormal cellular and systemic effects. These transgenerational long-term effects are detrimental because the genomes of animals in more distant generations are more sensitive to very low radiation doses, as compared to the genomes of animals that were exposed in the first few generations (Goncharova, 2000; Pelevyna *et al.*, 2006).

Conversely, in the contaminated territories there are also active processes of natural selection for the survival of less radiosensitive individuals—the processes of a radioadaptation. Radioadaptation in a population under conditions of chronic contamination will lead to diminish radiosensitivity over many generations, and evolutionary theory predicts that this will result because of special adaptation accompanied by elimination of sensitive genotypes and pauperization of the gene pool. Some plants and animals in the Chernobyl zone demonstrate a return to historically atavistic, primitive types of genetic systems (Glazko *et al.*, 1996). These facts predict increased numbers and kinds of insects harmful to agriculture in areas that have increased radiation backgrounds (Mosse, 2002). Considering the short life span of a generation of microorganisms, this rapid microevolutionary process can lead to activation of more primitive life forms as well as to the occurrence of new forms of viruses, bacteria, and fungi.

The material presented in Chapter III testifies to the fact that it is dangerous and shortsighted to consider the Chernobyl radioactive zone as a natural reserve where plants and animals can develop and thrive. For deeper understanding of the many processes currently continuing in the Chernobyl-contaminated zone, biological research should not be curtailed and stopped (as is happening in Belarus, Ukraine, and Russia), but must be supported, expanded, and intensified to understand, predict, and avoid unexpected and dangerous successions of events.

There is another more critical dimension to the study of animals in the contaminated territories. We, human beings, belong to the animal kingdom and have the same organs and biological systems as other animals such as mice and rats. The material in Chapter III demonstrates a sharply increasing mutational load, increasing morbidity, and cancer. More than 70% of all experimental rats raised under conditions of Chernobyl contamination developed cancer within the next few years and suffered multiple other diseases and impaired immunological competence. All of these processes that occurred in the first 5 to 7 years around Chernobyl definitely foreshadowed what happened later to the exposed human populations.

Chernobyl is, on the one hand, a microevolutionary incubator, actively transforming the gene pool with unpredictable consequences, and on the other hand, a black hole into which there is accelerated genetic degeneration of large animals. We ignore these findings at our peril.

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Chapter IV. Radiation Protection after the Chernobyl Catastrophe

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Key words: **Chernobyl; dose burden; radionuclide decorporation**

Since the Chernobyl catastrophe more than 5 million people in Belarus, Ukraine, and European Russia continue to live in the contaminated territories. Many thousands more live in other European countries contaminated with radiation, including Sweden, Finland, Norway, Scotland, Britain, and Wales (see Chapter I for details). Radiation protection is necessary for all of these people.

After the catastrophe there were enormous efforts to introduce countermeasures in Belarus, Ukraine, and Russia—to relocate hundreds of thousands of people and to try to lessen exposure to radioactive contamination. Steps that were taken included restricted food consumption and changes in food preparation, as well as changes in agricultural, fishery, and forestry practices under the guidance of qualified scientists (Bar'yachtar, 1995; Aleksakhin *et al.*, 2006).

The situation in regard to radiation protection in the contaminated territories places public health advocates in what is described in Russian as between an "upper and nether millstone," and in the West, as between a rock and a hard place. Authorities allocate as little as possible to provide financial resources for rehabilitation and disaster management and at the same time are reluctant to accept data about dangerous levels of contamination of populations, food, and the environment. These attitudes hold for officials practically everywhere.

The reluctance on the part of officialdom to acknowledge the truth about Chernobyl's consequences has led to concerned citizens organizing to find additional sources of information and devising ways to help those who are suffering. Hundreds of such public local, national, and international organizations have been created, such as "Children of Chernobyl," "Physicians of Chernobyl," "Widows of Chernobyl," and Liquidator's Unions in Belarus, Ukraine, Russia, and many other countries including Germany, Austria, France, Switzerland, Canada, the United States, and Israel.

In 1987, initiated by physicist and humanist Andrei Sakharov, famous Belarussian writer Ales' Adamovich, and world chess champion Anatoly Karpov, the Belarussian Institute of Radiation Safety–BELRAD was established as an independent public organization devoted to helping Belarussian children—those who suffered most after the catastrophic contamination from Chernobyl. For 21 years the BELRAD Institute has collected an extensive database in the field of radiation protection and has become unique as a nongovernmental Chernobyl center for both scientific and practical information.

Chapter IV is based primarily on the BELRAD materials. Chapter IV.12 presents data on the Chernobyl contamination of food and humans in many countries, Chapter IV.13 reports on the Belarussian experience with effective countermeasures to lower levels of incorporated radionuclides such as the use of

†Deceased.

enterosorbents, and Chapter IV.14 outlines common countermeasures against radioactive contamination in agriculture and forestry.

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12. Chernobyl's Radioactive Contamination of Food and People

Alexey V. Nesterenko, Vassily B. Nesterenko, and Alexey V. Yablokov

In many European countries levels of I-131, Cs-134/137, Sr-90, and other radionuclides in milk, dairy products, vegetables, grains, meat, and fish increased drastically (sometimes as much as 1,000-fold) immediately after the catastrophe. Up until 1991 the United States imported food products with measurable amounts of Chernobyl radioactive contamination, mostly from Turkey, Italy, Austria, West Germany, Greece, Yugoslavia, Hungary, Sweden, and Denmark. These products included juices, cheeses, pasta, mushrooms, hazelnuts, sage, figs, tea, thyme, juniper, caraway seeds, and apricots. In Gomel, Mogilev, and Brest provinces in Belarus 7–8% of milk and 13–16% of other food products from small farms exceeded permissible levels of Cs-137, even as recently as 2005–2007. As of 2000, up to 90% of the wild berries and mushrooms exceeded permissible levels of Cs-137 in Rovno and Zhytomir provinces, Ukraine. Owing to weight and metabolic differences, a child's radiation exposure is 3–5 times higher than that of an adult on the same diet. From 1995 to 2007, up to 90% of the children from heavily contaminated territories of Belarus had levels of Cs-137 accumulation higher than 15–20 Bq/kg, with maximum levels of up to 7,300 Bq/kg in Narovlya District, Gomel Province. Average levels of incorporated Cs-137 and Sr-90 in the heavily contaminated territories of Belarus, Ukraine, and European Russia did not decline, but rather increased from 1991 to 2005. Given that more than 90% of the current radiation fallout is due to Cs-137, with a half-life of about 30 years, we know that the contaminated areas will be dangerously radioactive for roughly the next three centuries.

However much money is allocated by any government for radiation protection (e.g., in Belarus in 2006 nearly $300 million was allocated to reduce radioactive contamination in agricultural production), no nation has the ability to provide total protection from radiation for populations living in contaminated areas and eating locally produced vegetables, forest products, and fish and game that are contaminated with radionuclides.

Thus it is of prime importance that radiation-monitoring capability be established on the local level so that citizens have access to the information and the ability to monitor their own locally produced food and to actively participate in organizing and carrying out radiation protection. Too often, central data monitoring repositories have little incentive to ensure that people around the country get the information that they should have.

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12.1. Radiation Monitoring of Food

12.1.1. Belarus

At the end of 1993, in order to monitor food radiation, the BELRAD Institute with support from the State Belarus Committee of Chernobyl Affairs ("Comchernobyl") created 370 public local centers for radiation control (LCRC) to monitor foodstuffs in the contaminated areas. The general database on contaminated foodstuffs available from BELRAD today has more than 340,000 measurements, including some 111,000 tests of milk.

1. According to the BELRAD database up to 15% of milk from small farms and up to 80% of other food produce in three Belarus provinces was contaminated with Cs-137 above the permissible levels (Table 12.1).

2. The percentage of food products with radioactive contamination in excess of official permissible levels did not decrease for 14 years after the catastrophe; on the contrary, in 1997 in the Gomel and Brest areas this percentage began to increase (Table 12.2).

3. Up to 34.3% of all milk tested from Brest Province in 1996 had radiation levels higher than the permissible ones. The number of milk tests showing dangerous levels was significantly higher in Gomel and Brest than in Mogilev province. From 1993 to 2006, there was some reduction in the number of milk tests that exceeded the permissible level (Table 12.3).

4. The portion of dangerous milk tests noticeably increased year by year: for example, from 19.3% in 1994 to 32.7% in 1995 in Brest Province; from 9.9% in 2003 to 15.8% in 2004 in Gomel Province; and from 0.7% in 2004 to 7.2% in 2005 in Mogilev Province.

5. In some places the percent of milk tests that showed dangerous levels of Cs-137 was significantly above the average. For example, in 2006 in Luga Village, Luninetsk District, Gomel Province, results in 90.7% of the tests exceeded the permissible level and levels were more than 16-fold higher than the province average.

TABLE 12.1. Cs-137 Concentration in Some Foodstuffs in Brest, Gomel, and Mogilev Provinces, Belarus, 1993 (BELRAD data)

Foodstuff	Number of samples	Above official permissible level for 1992	Official permissible level (1992), Bq/kg
Mushrooms (starry agaric)	133	80.5	370
Cranberry	429	62.7	185
Blackberry	1,383	61.0	185
Meat (game)	125	58.4	600
Mushrooms (dried)	459	57.7	3,700
Rough boletus	160	57.5	370
Edible boletus	561	54.4	370
Mushrooms (boiled)	87	52.9	370
Chanterelle	125	52.8	370
Blackberry (preserves)	150	42.0	185
Kefir	71	25.4	111
Honey fungus	57	22.8	370
Milk	19,111	14.9	111
Lard	234	14.1	185
Sour cream	242	12.8	111
Raspberry	154	11.7	185
Pot cheese	344	11.6	111
Carp	152	11.2	370
Strawberry	73	9.6	185
Water	2,141	8.8	185
Beetroot	1,628	8.2	185
Cream	51	7.8	111
Garden strawberries	389	6.4	185
Carrots	1,439	5.8	185
Cabbage	590	4.4	185
Meat (beef)	297	3.7	600
Cucumber	433	3.2	185
Tomatoes	141	2.8	185
Pears	208	2.4	185
Apples	1,547	2.3	185
Onion	435	2.1	185
Cherry	196	2.0	185
Meat (pork)	969	2.0	600
Butter	51	2.0	185
Potatoes	4,996	1.6	370

12.1.2. Ukraine

1. Even up to the year 2000, Cs-137 levels remained in excess of admissible levels: 80% in berries and mushrooms in Rovno Province, 90% in Zhytomir Province, 24% in forest-steppe Vinnitsa and Cherkassk provinces, and 15% in the Volyn' Province (Orlov, 2002).

2. According to data from the Ukrainian Ministry of Health, in 2000, from 1.1 up to

TABLE 12.2. Percent of Food Products with Excess of Permissible Levels of Cs-137 in Gomel, Mogilev, and Brest Provinces, Belarus, 1993–2007 (BELRAD Database)

	Years							
Province	1993–1994	1995–1996	1997–1998	1999–2000	2001–2002	2003–2004	2005–2006	2007
Gomel	12.1	9.6	12.0*	12.7	14.8	19.9	14.8	16.3
Mogilev	9.2	4.0	4.2	5.3	4.8	5.4	15.2	n/a
Brest	15.5	16.6	14.2	17.8	18.0	19.2	13.0	12.5

*Data on the Gomel Province since 1995 may be underestimated (24 LCRC from the heavily contaminated Lel'chitsy District were withdrawn from BELRAD and transferred to the official Institute of Radiology—Comchernobyl).

70.8% of milk and meat in the private sector in Volyn', Zhytomir, Kiev, Rovno, and Chernygov provinces had levels of Cs-137 in excess of allowable limits (Omelyanets, 2001).

12.1.3. Other Countries and Areas

There are considerable data in other countries concerning the contamination of food as a result of Chernobyl.

1. FINLAND. The level of Cs-137 in milk, beef, and pork in Finland drastically increased immediately after the catastrophe (Figure 12.1). Beginning in 1995, some 7.7 tons of mushrooms (mostly *Lactarium* genus) that were collected annually contained 1,600 MBq of Cs-137, or about 300 Bq of Cs-137 per person (Rantavaara and Markkula, 1999).

2. BALTIC SEA AREA. A significantly increased Cs-137 contamination occurred in Baltic fish (Figure 12.2) and there was an even greater increase in freshwater fish (Table 12.4). All game species were heavily contaminated; for example, Cs-137 and Cs-134 levels reached about 6,700 Bq/kg in the golden-eye duck and about 10,500 Bq/kg in other waterfowl (Rantavaara *et al.*, 1987).

3. CROATIA. After the catastrophe the concentration of Cs-137 in wheat increased more than 100-fold (Figure 12.3).

4. FRANCE. In 1997 in Vosges Cs-137 contamination in wild hogs and mushrooms exceeded the norms by up to 40-fold (Chykin, 1997).

5. GREAT BRITAIN. The peak Chernobyl contamination of milk was reached in May 1986 and was up to 1,000-fold as compared with the mean values reported in 1985 for I-131 and Cs-137 and up to four times higher for Sr-90 (Jackson *et al.*, 1987). Twenty-three years after the catastrophe, according to Great Britain's Ministry of Health, 369 farms in Great Britain, accounting for more than 190,000 sheep, continued to be dangerously contaminated with Chernobyl's Cs-137 (Macalister and Carter, 2009).

TABLE 12.3. Percent of a Milk Tests Exceeding the Permissible Level of Cs-137 in Gomel, Mogilev, and Brest Provinces, Belarus, 1993–2007 (BELRAD Database)

	Years							
Province	1993–1994	1995–1996	1997–1998	1999–2000	2001–2002	2003–2004	2005–2006	2007
Gomel	16.6	8.6*	8.7	9.6	8.6	12.9	6.8	6.7
Mogilev	12.0	2.8	1.2	0.5	0.2	0.6	7.2	n/a
Brest	21.7	33.5	18.5	21.4	22.8	17.8	7.9	8.0

*See the footnote to Table 12.2.

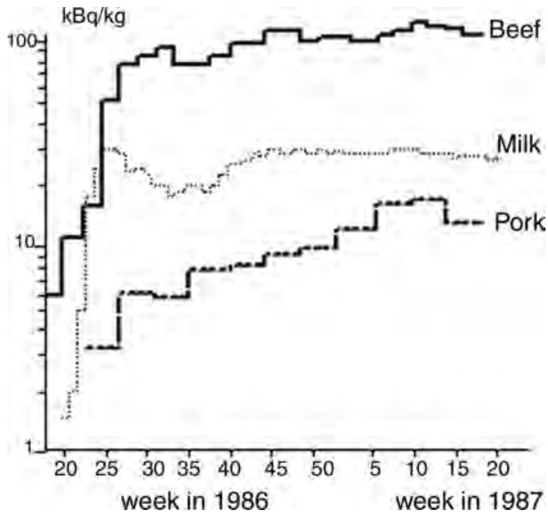

Figure 12.1. Countrywide mean concentration of Cs-137 in meat and milk in Finland (UNSCEAR, 1988).

6. ITALY. According to radiation measurements from the Directorate of Nuclear Safety Health Protection obtained in June 1988, meat, noodles, bread, milk, and cheese were still markedly contaminated by Chernobyl radionuclides (WISE, 1988a).

7. MEXICO. In 1988 Mexico returned 3,000 tons of milk powder to Northern Ireland because of radioactive contamination from Chernobyl (WISE, 1988b).

8. POLAND. In June 1987, a 1,600-ton shipment of powdered milk from Poland to Bangladesh showed unacceptably high levels of radioactivity (Mydans, 1987).

9. SWEDEN. Average Cs-137 concentration in moose (*Alces alces*) meat was 9–14 times higher after Chernobyl. Levels were 470 Bq/kg for calves and 300 Bq/kg for older animals, compared with the precatastrophe average level of 33 Bq/kg (Danell *et al.*, 1989).

10. TURKEY. Some 45,000 tons of tea was contaminated with Chernobyl radioactivity in 1986–1987, and more than a third of the 1986 harvest could not be used (WISE, 1988c).

11. UNITED STATES. Food contaminated in the United States as a result of Chernobyl is especially interesting because of the wide geographical scale of contamination and the broad range of contaminated foods. In spite of official secrecy (see Chapter II.3 for details) the full picture of Chernobyl food contamination

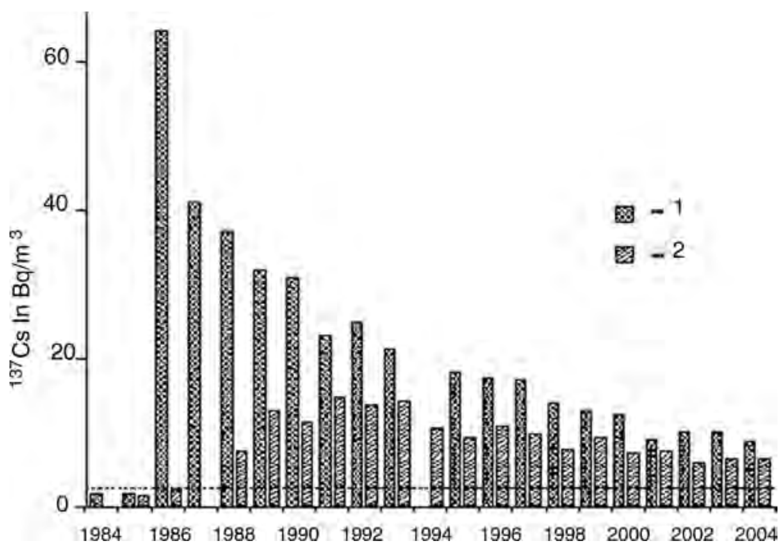

Figure 12.2. Cs-137 concentrations (Bq/kg) in: (1) plaice (*Platichthys flesus*) and (2) flounder (*Pleuronectes platessa*) from 1984 to 2004, as annual mean values in the Bornholm and southern Baltic seas. Pre-Chernobyl (1984–1985) concentrations were 2.9 for plaice and flounder (HELCOM Indicator Fact Sheets. 2006. Online 22.04.2008;//www.helcom.fi/environment2/ifs/en_GB/cover/).

TABLE 12.4. Fish Cs-137 Contamination in Finland, 1986 (Saxen and Rantavaara, 1987)

Species	Concentration, Bq/kg*
Perch	16,000
Pike	10,000
Whitefish	7,100
Bream	4,500
Vendace	2,000

*EU limit of Cs-137 for consumption of wild freshwater fish is 3,000 Bq/kg.

in the United States continues to become more visible. The peak of Chernobyl-derived I-131 in imported foods was observed in May–June 1986, and for Cs-134 and Cs-137, some 10 to 16 months after the catastrophe (RADNET, 2008, Section 9, Part 4).

Between May 5, 1986, and December 22, 1988, the FDA tested 1,749 samples of imported foods for I-131, Cs-134, and Cs-137 contamination. The survey had been classified and was only obtained after a recent freedom of information request (RADNET, 2008). The first food imported into the United States that was contaminated from Chernobyl radioactivity was fish from Norway with a detectable level of Cs-137. The contamination was revealed on May 5, 1986, that is, 11 days after the catastrophe. In May–June 1986, it was found that 15 samples of imported foods (mostly mushrooms and cheese from Italy, but also cheese from West Germany and Denmark) exceeded the I-131 level of 1,000 pCi/kg. Some 44% of such samples from February 1 to October 4, 1987, had Cs-137 levels higher than 100 pCi/kg, and 5% exceeded 5,000 pCi/kg. More than 50% of samples from February 5 to January 25, 1987, had Cs-137 levels higher than 1,000 pCi/kg, and about 7% of samples had more than 5,000 pCi/kg.

According to other data (Cunningham and Anderson, 1994), up to 24% of the imported food sampled in 1989 was noticeably contaminated. By 1990, 25% of samples were contaminated; in 1991, 8% of samples; and in 1992, 2%. "In spite of the general decline, contaminated foods were still occasionally found during FY91 and FY92; indeed, elk meat collected in FY91 contained the highest Cs-137 contamination found since the Chernobyl accident occurred": 81,000 pCi/kg (Cunningham and Anderson, 1994, p. 1426; cit. by RADNET, 2008). According to U.S. federal regulations, imported foods containing more than 10,000 pCi of Cs-134 + Cs-137 must be seized and destroyed (U.S. FDA guidelines on May 16, 1986, by RADNET, 2008). The official documents obtained through the RADNET request (Section 9) shows that between 1986 and 1988 there were 12 such occasions.

The food products contaminated by Chernobyl radioactivity imported into the United States from 1986 to 1988 originated from (in order of the number of cases): Turkey, Italy,

Figure 12.3. Cs-137 concentration in wheat in Croatia from 1965 to 2004 (Franic *et al.*, 2006).

TABLE 12.5. Concentration (pCi/l) of Chernobyl Radionuclides in Milk in the United States, 1986 (Various Authors from RADNET, 2008)

Radionuclide	Concentration	Location	Date
I-131	560	Redland	May 5
	167	Willamette Valley	May 12
	88	Vermont	May
	82	New York area	May 28
	52.5	Maine	May 16
	40	New York area	May 12
Cs-137	20.3	Maine	June
	39.7	Chester, New Jersey	May 17
	40.5	New York City	May
	66	Seattle	June 4
	80	New York area	May 12
	97	Willamette Valley	May 19
Cs-134	9.7	Maine	June
Cs-134 + Cs-137	1,250*	East Washington	May 5

*Food, pCi/kg.

Austria, West Germany, Greece, Yugoslavia, Hungary, Sweden, Denmark, Egypt, France, The Netherlands, Spain, and Switzerland. The contaminated foodstuffs, in order of prevalence, were: apple juice, cheese, pasta, oregano, berry juices, mushrooms, hazelnuts, filberts (*Corylus* sp.), sage (*Salvia* sp.), figs, laurel leaves, tea, thyme, red lentils (*Lens* sp.), juniper, caraway seeds (*Carum* sp.), endive (*Cychorium* sp.), apricots, and even Swiss chocolate.

Table 12.5 shows the level of radioactive contamination in local milk after the catastrophe all over of the United States. In spite of all the measurements, according to the official derived intervention level (DIL), it is a fact that Chernobyl fallout has deposited harmful radioisotopes across the entire extent of North America.

Concentration of Chernobyl Cs-134 + Cs-137 in elk meat was up to 3,000 Bq/kg (RADNET, 2008); the concentration of Ru-106 and Cs-137 in fiddleheads was 261 and 328 pCi/kg, respectively; in mushrooms the C-137 concentration was 3,750 pCi/kg (RADNET, 2008).

12. Some examples of radioactive contamination of food products in other countries are listed in Table 12.6. Although Cs-137, Sr-90, Pu, and Am concentrate in the root zone of plants, they will be mobilized for decades to hundreds of years into the future, and agricultural products will continue to contain radioactivity in all of the Northern Hemisphere countries contaminated by Chernobyl.

12.2. Monitoring of Incorporated Radionuclides

For effective radiation protection, especially for children, it is necessary to monitor not only food, but also to directly monitor radionuclides incorporated into the body. Such monitoring can determine the level of contamination for each particular location in a contaminated territory and for every group of people with high levels of incorporated radionuclides in order to adequately implement radiation protection.

12.2.1. Belarus

To determine the correlation between radioactive contamination of food and incorporated radionuclides in children (as children are the most subject to radiation risk) the BELRAD Institute chose the most intensely contaminated territories from the point of view of size of the mid-annual effective radiation dose and the level of local food contamination.

From 1995 to 2007 BELRAD conducted measurements of absorbed radionuclides in about 300,000 Belarussian children. Measurement of the Cs-137 contamination is carried out by automated complex spectrometry of internal radiation, utilizing an individual radiation counter (IRC) "SCANNER-3." The Institute of Ecological and Medical Systems, Kiev, Ukraine, makes the equipment. The BELRAD Institute has eight such IRC SCANNER-3M instruments, which measure the activity of incorporated gamma-radionuclides (Cs-137, Cs-134, Ca-40, Ra-226,

TABLE 12.6. Chernobyl Radioactive Contamination of Food in Several Countries, 1986–1987

Radionuclide	Food	Maximum concentration	Country	Reference
Cs-137*	Reindeer meat	44,800 Bq/kg	Sweden	Ahman and Ahman, 1994
	Mushrooms	> 20,000 Bq/kg	Germany	UNSCEAR, 1988
	Sheep's milk	18,000 Bq/liter	Greece	Assikmakopoulos *et al.*, 1987
	Mushrooms	16,300 Bq/kg**	Japan	Yoshida *et al.*, 1994
	Reindeer	>10,000 Bq/kg	Sweden	UNSCEAR, 1988
	Potatoes	1.100 ± 0.650 Bq/kg	Croatia	Franic *et al.*, 2006
	Lamb	1,087 Bq/kg	Sweden	Rosen *et al.*, 1995
	Milk	500 Bq/liter	United Kingdom	Clark, 1986
	Meat	395 Bq/kg	Italy	Capra *et al.*, 1989
	Milk	254 Bq/dm^3	Italy	Capra *et al.*, 1989
	Perch	6,042 (mean) Bq/kg	Sweden	Hakanson *et al.*, 1989
	Perch	3,585 (mean) Bq/kg	Sweden	Hakanson *et al.*, 1989
	Farm milk	2,900 Bq/liter	Sweden	Reizenstein, 1987
	Milk	400 Bq/liter	Bulgaria	Energy, 2008
I-131	Milk	135,000	Italy	Orlando *et al.*, 1986
	Yogurt	6,000 Bq/kg	Greece	Assikmakopoulos *et al.*, 1987
	Edible seaweed	1,300 Bq/kg	Japan	Hisamatsu *et al.*, 1987
	Milk	500 Bq/liter	United Kingdom	Clark, 1986
	Breast milk	110 Bq/liter (mean)	Czechoslovakia	Kliment and Bucina, 1990
	Breast milk	55 Bq/l (mean	Czechoslovakia	Kliment and Bucina, 1990
	Pork	45 Bq/kg (mean)	Czechoslovakia	Kliment and Bucina, 1990
	Milk	21.8 Bq/liter	Japan	Nishizawa *et al.*, 1986
	Milk	20.7 Bq/liter	United States	RADNET, 2008
Total	Reindeer meat	15,000 Bq/kg	Sweden	Fox, 1988
	Mutton	10,000 Bq/kg	Yugoslavia	Energy, 2008
	Milk	3,000 Bq/liter	Yugoslavia	Energy, 2008
	Fruits	>1,000 Bq/kg	Italy	Energy, 2008

*Limits of Cs-137 for consumption in EU: 600 Bq/kg for food items; 370 Bq/kg for milk and baby food; 3,000 Bq/kg for game and reindeer meat.

**Year 1990.

Th-232, Mn-54, Co-60, I-131, etc.) in an individual's body as well as the specific dose. It is certified by the Belarus State Committee on Standardization and also registered by the State Registry of Belarus. Each IRC scanner undergoes an annual official inspection. All measurements are done according to protocols approved by that committee. For additional accuracy, the BELRAD IRC SCANNER-3M system was calibrated with the "Julich" Nuclear Center in Germany (see Table 12.7).

1. Measurements were taken in Valavsk Village, in the El'sk District, Gomel Province, where there were 800 inhabitants, including 159 children. The village is located in an area with Cs-137 contamination of 8.3 Ci/km^2 (307 kBq/m^2). According to the 2004 data, the total annual effective dose was 2.39 mSv/year, and an internal irradiation dose was 1.3 mSv/year.

2. There was a correlation between the levels of local food contamination (Figure 12.4) and the level of incorporated radionuclides in the children's bodies (Figure 12.5).

The pattern of curves in Figures 12.4 and 12.5 reflects the seasonal (within the year) variation of contaminated food consumption and thus the accumulation of Cs-137 in a child's body. As a rule, the level of contamination

TABLE 12.7. Cs-137 Body Burden in Children of Narovlya, Bragin, and Chechersk Districts as Measured by Individual Radiation Counters, 1999–2003 (BELRAD Data)

Date	Location	Measured by IRC children, *n* (% of total inhabitants)	% Children with exposure dose ≥ 1 mSv/year
June 1999	Grushevka	35 (18.6)	26
November 2001		44 (23.4)	11
April 2002		64 (34)	11
November 2001	Verbovichi	60 (20)	33
January 2002		65 (21.5)	9
April 2002		64 (21)	5
November 2002		41 (13.5)	20
December 2002		35 (11.6)	13
November 2003		51 (16.8)	20
November 2001	Golovchitsy	139 (33)	8
January 2002		56 (13.3)	4
November 2002		103 (24.5)	2
October 2003		130 (30.9)	2
January 1999	Demidov	109 (38.5)	10
November 2001		110 (38.8)	12
December 2001		91 (32.3)	9
April 2002		94 (33.2)	9
November 2002		75 (26.5)	12
January 2003		65 (23)	5
January 2000	Zavoit	51 (12.8)	4
November 2001		52 (13)	19
January 2002		49 (12.3)	2
October 2003		50 (12.5)	6
January 1999	Kyrov	94 (22.2)	16
March 1999		98 (23.1)	21
November 2001		92 (21.7)	22
January 2002		84 (19.8)	13
March 2002		91 (21.5)	22
April 2002		75 (17.7)	12
May 2002		90 (21.2)	12
June 2003		43 (10.1)	7
June 1999	Krasnovka	21 (11)	14
November 2001	Narovlya	34	5
January 2002		221	14
February 2002		170	8
November 2002		56	7
November 2003		140	6
December 2003		35	6
February 1999	Dublin	98 (28.3)	4
February 1999	Belyaevka	98 (23.8)	11
March 1999		96 (23.3)	
October 2001		81 (19.7)	
January 1999	Poles'e	132 (25.3)	14
October 1999		185 (35.4)	3
October 2001		95 (18.2)	25
November 2001		95 (18.2)	25
January 2002		148 (28.4)	11
April 2002		144 (27.6)	3

(Continued)

TABLE 12.7. *Continued*

Date	Location	Measured by IRC children, *n* (% of total inhabitants)	% Children with exposure dose ≥ 1 mSv/year
January 2003		148 (28.4)	5
September 2003		141 (27)	9
November 2003		140 (26.8)	10
December 2001	Sydorovychi	84 (30.3)	
January 2002		105 (37.9)	

increased in the autumn and winter (third and fourth quarters) because of increased consumption of especially heavily contaminated foods (mushrooms, berries, wild animal meat). Milk contamination reflects forage with high levels of Cs-137 prepared for the winter.

3. Of about 300,000 children from heavily contaminated territories of Belarus who were tested by BELRAD from 1995 to 2007, some 70–90% had levels of Cs-137 accumulation higher than 15–20 Bq/kg (leading to 0.1 mSv/year internal irradiation). In many villages levels of Cs-137 accumulation reached 200–400 Bq/kg, and some children in Gomel and Brest provinces had levels up to 2,000 Bq/kg (up to 100 mSv/year) (Table 12.7).

4. Belarus and Ukraine, with levels of incorporation of 50 Bq/kg, which is common for territories with Cs-137 contamination of 555 kBq/m^2, show an increase in various diseases and death rates and a decrease in the number of healthy children (Resolution, 2006; see also Chapter II).

5. High levels of the accumulation of Cs-137 have been found in a significant number of children in the Lel'chitsy District (Figure 12.6), the El'sk District (Figure 12.7), and the Chechersk District (Figure 12.8) of Gomel Province. Maximum levels of accumulation of Cs-137 (6,700–7,300 Bq/kg) have been found in a significant number of children in the Narovlya District of Gomel Province. In many villages in this district up to 33% of children have dose levels exceeding the officially permissible 1 mSv/year (Figure 12.9).

6. The level of radionuclide incorporation is significantly different for different organs (Table 12.8).

7. Average Sr-90 concentration in the bodies of inhabitants of Gomel Province noticeably

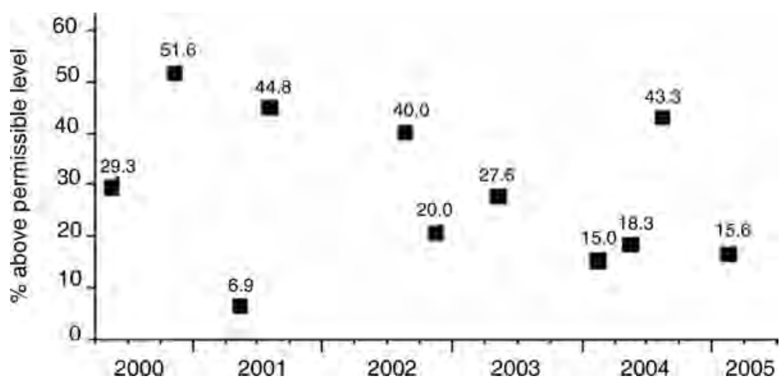

Figure 12.4. Percentage of foodstuffs exceeding permissible levels of Cs-137 for the years 2000 to 2005, Valavsk Village, Gomel Province, Belarus (BELRAD data). The horizontal axis shows the year divided into quarters; the vertical axis indicates the percentage of foodstuffs in which levels exceeded the norm.

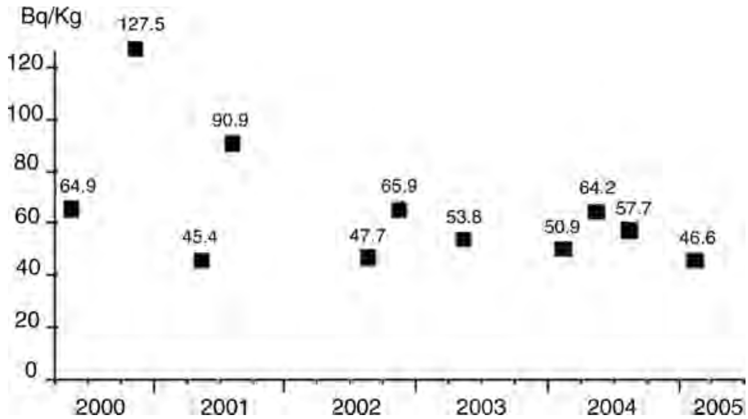

Figure 12.5. Average specific activity of Cs-137 (Bq/kg) in children from Valavsk Village, Gomel Province, Belarus, from 2000 to 2005 (BELRAD data).

increased from 1991 to 2000 (Borysevich and Poplyko, 2002).

8. The Pu body contamination of Gomel citizens 4–5 years after the Chernobyl accident is on average three to four times higher than global levels (Hohryakov *et al.*, 1994).

12.2.2. Other Countries

1. DENMARK. Sr-90 and Cs-137 contamination occurs in humans, with Sr accumulating along with Ca and Cs occurring in the same tissues as K. The Sr-90 mean content in adult human vertebral bone collected in 1992 was 18 Bq (kg Ca)$^{-1}$. Whole body measurements of Cs-137 were resumed after the Chernobyl accident. The measured mean level of Cs-137 in 1990 was 359 Bq (kg K)$^{-1}$ (Aarkrog *et al.*, 1995).

2. FINLAND. Peak body burdens in Finland in 1986 were 6,300 and 13,000 Bq for Cs-134 and for Cs-137, respectively (Rahola *et al.*, 1987). The average Cs-137 body burden 17 years after the catastrophe for the entire country was about 200 Bq; for inhabitants of Padasyoki

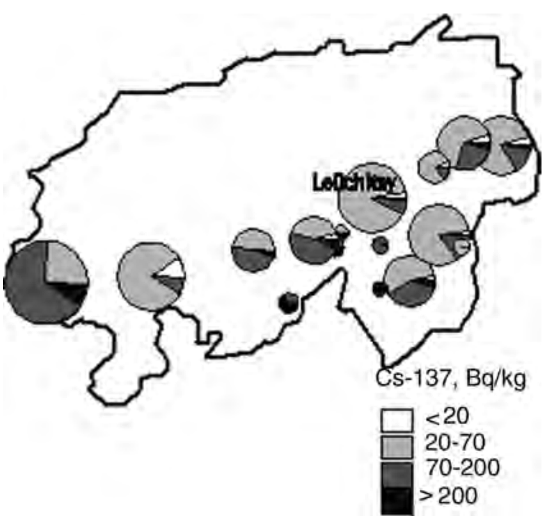

Figure 12.6. Cs-137 levels in children of Lel'chitsy District, Gomel Province, Belarus (Nesterenko, 2007).

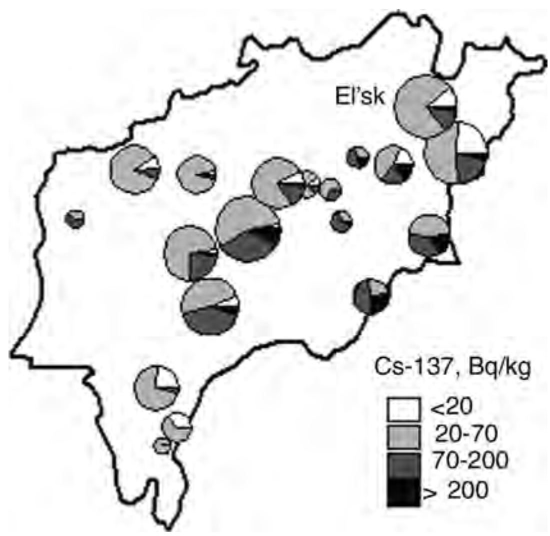

Figure 12.7. Cs-137 levels in children of El'sk District, Gomel Province, Belarus (Nesterenko, 2007).

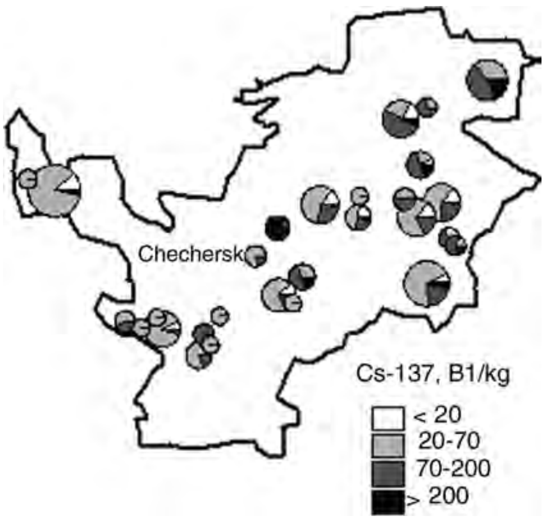

Figure 12.8. Cs-137 levels in children of Chechersk District, Gomel Province, Belarus (Nesterenko, 2007).

City it was 3,000 Bq (the maximum figure was 15,000 Bq). At the end of 1986 the mean Cs-134 body burden was 730 Bq. The Cs-137 mean body burden increased from 150 to 1,500 Bq in December 1986. The maximum levels of body burdens for Cs-134 and C-137 were

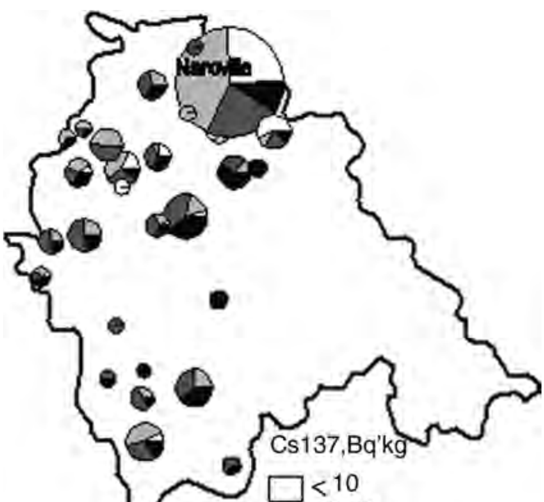

Figure 12.9. Cs-137 levels in children of Narovlya District, Gomel Province, Belarus (Nesterenko, 2007).

TABLE 12.8. Concentration (Bq/kg) of the Cs-137 in Autopsied Organs (56 Persons), Gomel Province, 1997 (Bandazhevsky, 2003)

Organ	Concentration
Thyroid	2,054 ± 288
Adrenal glands	1,576 ± 290
Pancreas	1,359 ± 350
Thymus	930 ± 278
Skeletal muscle	902 ± 234
Spleen	608 ± 109
Heart	478 ± 106
Liver	347 ± 61

6,300 and 13,000 Bq, respectively (Rahola *et al.*, 1987).

3. JAPAN. Before the Chernobyl accident Cs-137 body burdens were about 30 Bq, rising the year following 1986 to more than 50 Bq with values still increasing in May 1987. This compares to body burdens in England of 250–450 Bq (Uchiyama *et al.*, 1998). Peak concentrations of I-131 in urine increased to 3.3 Bq/ml in adult males (Kawamura *et al.*, 1988). Before the Chernobyl catastrophe Cs-137 body burdens were about 30 Bq, rising to more than 50 Bq in 1986 with values continuing to increase in May 1987 (Uchiyama and Kobayashi, 1988).

4. ITALY. Average I-131 thyroid incorporation for 51 adults was 6.5 Bq/g from May 3 to June 16, 1986 (Orlando *et al.*, 1986). Peak urinary excretion of Cs-137 occurred 300 to 425 days after the main fallout cloud had passed on May 5, 1986: pv 15–20 Bq/day (Capra *et al.*, 1989).

5. GERMANY AND FRANCE. There are data concerning human contamination by Chernobyl radionuclides outside of the Former Soviet Union. Figure 12.10 shows body burden levels of Cs-137 in Germany and France.

6. GREAT BRITAIN. Average Cs-134 + Cs-137 body burden levels for adults in Scotland in 1986 after the catastrophe were: Cs-134, 172 Bq; Cs-137, 363 Bq; and K-40, 4,430 Bq. Peak concentrations were: Cs-134, 285 Bq and Cs-137, 663 Bq (Watson, 1986). The Cs-137 body

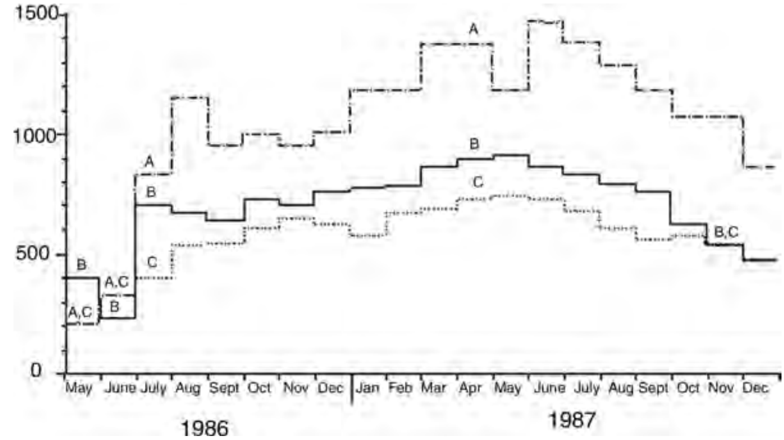

Figure 12.10. Body burden of Cs-137 (Bq) in humans in Munich, Germany: (A) males, (B) females); in Grenoble, France (C) adults (UNSCEAR, 1988).

burden in England in 1987 was 250–450 Bq (Uchiyama and Kobayashi, 1988). The thyroid I-131 burden measured in the neck region was up to 33 Bq in adults and up to 16 Bq in children in Britain (Hill *et al.*, 1986).

12.3. Conclusion

All people living in territories heavily contaminated by Chernobyl fallout continue to be exposed to low doses of chronic radiation. Human beings do not have sense organs to detect ionizing radiation because it cannot be perceived by sight, smell, taste, hearing, or touch. Therefore without special equipment to identify levels of environmental contamination, it is impossible to know what radionuclide levels are in our food and water or have been incorporated into our bodies.

The simplest way to ensure radiation safety in all areas contaminated by Chernobyl is to monitor food for incorporated radionuclides. Analysis of levels of incorporated gamma-radionuclides by individual spectrometry (IRC) and radioactive monitoring of local food in many Belarussian locations have demonstrated a high correlation between Cs-137 food contamination and the amount of radionuclides in humans and, most importantly, in children.

Chapter II of this volume detailed many cases of deterioration in public health associated with the Chernobyl radionuclide contamination. Many people suffer from continuing chronic low-dose radiation 23 years after the catastrophe, owing primarily to consumption of radioactively contaminated food. An important consideration is the fact that given an identical diet, a child's radiation exposure is three- to fivefold higher than that of an adult. Since more than 90% of the radiation burden nowadays is due to Cs-137, which has a half-life of about 30 years, contaminated areas will continue to be dangerously radioactive for roughly the next three centuries.

Experience has shown that existing official radioactive monitoring systems are inadequate (not only in the countries of the Former Soviet Union). Generally, the systems cover territories selectively, do not measure each person, and often conceal important facts when releasing information. The common factor among all governments is to minimize spending for which they are not directly responsible, such as the Chernobyl meltdown, which occurred 23 years ago. Thus officials are not eager to obtain objective data of radioactive contamination of communities, individuals, or food. Under such circumstances, which are common, an independent system of public monitoring is needed. Such an independent system is not a substitute for official responsibility or control, but is needed to provide regular voluntary monitoring of food for each family, which would determine the radionuclide level in each person.

We have to take responsibility not only for our own health, but for the health of future generations of humans, plants, and animals, which can be harmed by mutations resulting from exposure to even the smallest amount of radioactive contamination.

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13. Decorporation of Chernobyl Radionuclides

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Tens of thousands of Chernobyl children (mostly from Belarus) annually leave to receive treatment and health care in other countries. Doctors from many countries gratuitously work in the Chernobyl contaminated territories, helping to minimize the consequences of this most terrible technologic catastrophe in history. But the scale and spectrum of the consequences are so high, that no country in the world can cope alone with the long-term consequences of such a catastrophe as Chernobyl. The countries that have suffered the most, especially Ukraine and Belarus, extend gratitude for the help that has come through the United Nations and other international organizations, as well as from private funds and initiatives. Twenty-two years after the Chernobyl releases, the annual individual dose limit in heavily contaminated territories of Belarus, Ukraine, and European Russia exceed 1 mSv/year just because of the unavoidable consumption of locally contaminated products. The 11-year experience of the BELRAD Institute shows that for effective radiation protection it is necessary to establish the interference level for children at 30% of the official dangerous limit (i.e., 15–20 Bq/kg). The direct whole body counting measurements of Cs-137 accumulation in the bodies of inhabitants of the heavily contaminated Belarussian region shows that the official Dose Catalogue underestimates the annual dose burdens by three to eight times. For practical reasons the curative-like use of apple-pectin food additives might be especially helpful for effective decorporation of Cs-137. From 1996 to 2007 a total of more than 160,000 Belarussian children received pectin food additives during 18 to 25 days of treatment (5 g twice a day). As a result, levels of Cs-137 in children's organs decreased after each course of pectin additives by an average of 30 to 40%. Manufacture and application of various pectin-based food additives and drinks (using apples, currants, grapes, sea seaweed, etc.) is one of the most effective ways for individual radioprotection (through decorporation) under circumstances where consumption of radioactively contaminated food is unavoidable.

There are three basic ways to decrease the radionuclide levels in the bodies of people living in contaminated territories: reduce the amount of radionuclides in the food consumed, accelerate removal of radionuclides from the body, and stimulate the body's immune and other protective systems.

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13.1. Reducing Radionuclides in Food

Soaking in water, scalding, salting, and pickling foods such as mushrooms and vegetables and processing the fats in milk and cheeses can reduce the amount of radionuclides in some foods severalfold.

Stimulation of the body's natural defenses through the use of food additives that raise one's resistance to irradiation is also useful. Among such additives are the antioxidant vitamins A and C and the microelements I, Cu, Zn, Se, and Co, which interfere with free-radical formation. The additives prevent the oxidation of organic substances caused by irradiation (lipid peroxidation). Various food supplements can stimulate immunity: sprouts of plants, such as wheat, seaweed (e.g., *Spirulina*), pine needles, mycelium, and others.

Accelerating the removal of radionuclides is done in three ways (Rudnev *et al.*, 1995; Trakhtenberg, 1995; Leggett *et al.*, 2003; and many others):

- Increase the stable elements in food to impede the incorporation of radionuclides. For example, K and Rb interfere with the incorporation of Cs; Ca interferes with Sr; and trivalent Fe interferes with the uptake of Pu.
- Make use of the various food additives that can immobilize radionuclides.
- Increase consumption of liquids to "wash away" radionuclides—infusions, juices, and other liquids as well as enriched food with dietary fiber.

Decorporants (decontaminants) are preparations that promote the removal of incorporated radionuclides via excretion in feces and urine. Several effective decorporants specific for medical treatment of heavy radionuclide contamination are known (for Cs, Fe compounds; for Sr, alginates and barium sulfates; for Pu, ion-exchange resins, etc.). They are effective in cases of sudden contamination. In the heavily contaminated Belarussian, Ukrainian, and European Russian territories the situation is different. Daily exposure to small amounts of radionuclides (mostly Cs-137) is virtually unavoidable as they get into the body with food (up to 94%), with drinking water (up to 5%), and through the air (about 1%). Accumulation of radionuclides in the body is dangerous, primarily for children, and for those living in the contaminated territories where there are high levels of Cs-137 in local foodstuffs (see Chapter IV.12). The incorporation of radionuclides is now the primary cause of the deterioration of public health in the contaminated territories (see Chapter II for details), and all possible approaches should be employed to mitigate the consequences of that irradiation.

There is evidence that incorporation of 50 Bq/kg of Cs-137 into a child's body can produce pathological changes in vital organ systems (cardiovascular, nervous, endocrine, and immune), as well as in the kidneys, liver, eyes, and other organs (Bandazhevskaya *et al.*, 2004). Such levels of radioisotope incorporation are not unusual in the Chernobyl-contaminated areas of Belarus, Ukraine, and European Russia nowadays (see Chapter III.11 for details), which is why it is necessary to use any and all possible measures to decrease the level of radionuclide incorporation in people living in those territories. When children have the same menu as adults, they get up to five times higher dose burdens from locally produced foodstuffs because of their lower weight and more active processes of metabolism. Children living in rural villages have a dose burden five to six times higher than city children of the same age.

13.2. Results of Decontamination by the Pectin Enterosorbents

It is known that pectin chemically binds cations such as Cs in the gastrointestinal tract and thereby increases fecal excretion. Research and development by the Ukrainian Center of Radiation Medicine (Porokhnyak-Ganovska, 1998) and the Belarussian Institute of Radiation Medicine and Endocrinology (Gres' *et al.*, 1997) have led to the conclusion that adding pectin preparations to the food of inhabitants of the Chernobyl-contaminated regions promotes an effective excretion of incorporated radionuclides.

1. In 1981, based on 2-year clinical tests, the Joint Committee of the World Health Organization (WHO) and the U.N. Food and Agriculture Organization (FAO) on Food Additives declared the pectinaceous enterosorbents effective and harmless for everyday use (WHO, 1981).

2. In Ukraine and Belarus various pectin-based preparations have been studied as agents to promote the excretion of incorporated radionuclides (Gres', 1997; Ostapenko, 2002; Ukrainian Institute, 1997). The product based on the pectin from an aquatic plant (*Zostera*), known commercially as Zosterin-Ultra® is a mass prophylaxis agent used in the Russian nuclear industry. As it is a nonassimilated pectin, the injection of zosterine into the bloodstream does not harm nutrition, metabolism, or other functions. Zosterin-Ultra® in liquid form for oral administration was approved by the Ukrainian Ministry of Health (1998) and the Russian Ministry of Health (1999) as a biologically active (or therapeutic) food additive endowed with enterosorption and hemosorption properties.

3. In 1996, the BELRAD Institute initiated enterosorbent treatments based on pectin food additives (Medetopect®, France; Yablopect®, Ukraine) to accelerate the excretion of Cs-137. In 1999 BELRAD together with "Hermes" Hmbh (Munich, Germany) developed a composition of apple pectin additives known as Vitapect® powder, made up of pectin (concentration 18–20%) supplemented with vitamins B1, B2, B6, B12, C, E, beta-carotene, folic acid; the trace elements K, Zn, Fe, and Ca; and flavoring. BELRAD has been producing this food additive, which has been approved by the Belarussian Ministry of Health, since 2000.

4. In June–July 2001 BELRAD together with the association "Children of Chernobyl of Belarus" (France) in the Silver Springs sanatorium (Svetlogorsk City, Gomel Province) conducted a placebo-controlled double-blind study of 615 children with internal contamination who were treated with Vitapect (5 g twice a day) for a 3-week period. In children taking the Vitapect (together with clean food) Cs-137 levels were lowered much more effectively than in the control group, who had clean food combined with a placebo (Table 13.1 and Figure 13.1).

5. In another group of children the relative reduction in the specific activity of Cs-137 in the Vitapect-intake group was 32.4 ± 0.6%, and that of the placebo group was 14.2 ± 0.5% ($p > 0.001$), with a mean effective half-life for Cs-137 in a body of 27 days for the pectin group, as compared with 69 days without pectin. This was a reduction of the effective half-life by a factor of 2.4. These results mean that the pectin additive Vitapect with clean nutrition appears to be 50% more effective in decreasing the levels of Cs-137 than clean nutrition alone (Nesterenko *et al.*, 2004).

6. A clinical study of 94 children, 7 to 17 years of age, divided into two groups according to their initial level of Cs-137 contamination determined by whole body counting (WBC) and given Vitapect orally for 16 days (5 g twice a day) revealed both a significant decrease in incorporated Cs-137 and marked

TABLE 13.1. Decreased Cs-137 Concentration after Using Vitapect for 21 Days (Total 615 Children) in 2001 in the Silver Springs Belarussian Sanatorium (BELRAD Institute Data)

	Concentration of Cs-137, Bq/kg		
Group	Before	In 21 days	Decrease,%
Vitapect	30.1 ± 0.7	10.4 ± 1.0	63.6*
Placebo	30.0 ± 0.9	25.8 ± 0.8	13.9

*$p < 0.01$.

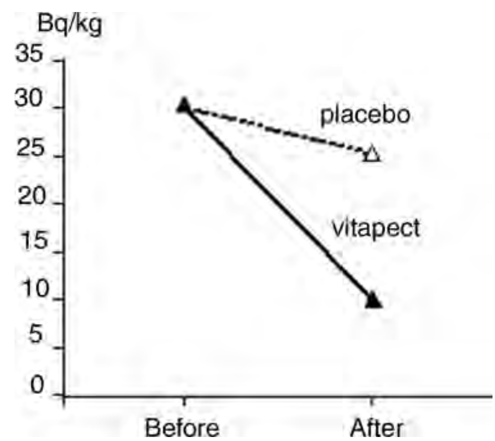

Figure 13.1. Decrease in levels of specific activity of Cs-137 in children's bodies after Vitapect intake (5 g twice a day) for 21 days (Nesterenko *et al.*, 2004).

TABLE 13.2. EKG Normalization Results in the Two Groups of Children Contaminated with Cs-137 Treated with Vitapect (Bandazevskaya *et al.*, 2004)

Group	Before		After 16 days	
	Normal EKG,%	Bq/kg	Normal EKG,%	Bq/kg
1	72	38 ± 2.4	87	23
2	79	122 ± 18.5	93	88

improvement in their electrocardiograms (EKG; Table 13.2).

7. From 2001 to 2003 the association "Children of Chernobyl in Belarus" (France), Mitterand's Fund (France), the Fund for Children of Chernobyl (Belgium), and the BELRAD Institute treated 1,400 children (10 schools serving 13 villages) in the Narovlyansky District, Gomel Province, in cycles in which the children received the pectin preparation Vitapect five times over the course of a year. The results demonstrated a three- to fivefold annual decrease in radioactive contamination in children who took the Vitapect. The results for one village can be seen in Figure 13.2.

8. There was concern that pectin enterosorbents remove not only Cs-137, but also vital microelements. Special studies were carried out in 2003 and 2004 within the framework of the project "Highly-Irradiated Belarus Children" with the support of the German Federal Office of Radiation Protection (BfS). Tests carried out in three Belarus sanatoriums (Timberland, Silver Springs, and Belarussian Girls) showed that Vitapect does not impair the positive balance of the K, Zn, Cu, and Fe in children's blood (Nesterenko *et al.*, 2004).

TABLE 13.3. Results of Treatment of 46 Children for 30 Days in France in 2004 (BELRAD Institute Data)

	Concentration, Bq/kg		Decrease, %
	Before	After	
Vitapect	39.0 ± 4.4	24.6 ± 3.4	37*
Placebo	29.6 ± 2.7	24.6 ± 2.1	17

*$p < 0.05$.

9. At the request of the "Chernobyl's Children" NGOs initiatives in Germany, France, England, and Ireland, the BELRAD Institute conducted measurements of Cs-137 in children before departure to and after their return from health programs in these countries. Children who only ate clean food during the 25–30 days showed a decrease in Cs-137 levels of some 20 to 22%, whereas children who also received a course of treatment with Vitapect showed an even further decrease in the level of Cs-137 incorporation (Tables 13.3 and 13.4).

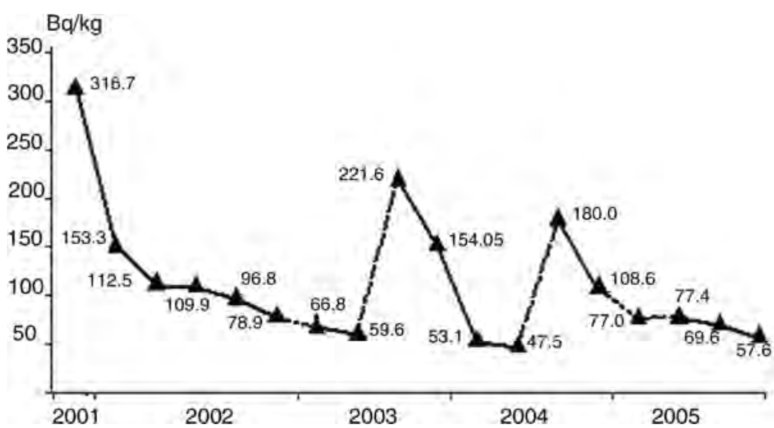

Figure 13.2. Changes in average specific activity of Cs-137 (Bq/kg) in the bodies of children of Verbovichi Village, Narovlyansky District, Gomel Province. Averages for these data are shown. Dotted line indicates the periods of Vitapect intake (Nesterenko *et al.*, 2004).

TABLE 13.4. Several Results of Vitapect Treatment of Belarussian Children (BELRAD Institute Data)

Concentration, Bq/kg		Decreasing,	
Before	After	%	Group data
30.0 ± 1.5	19.2 ± 1.4*	36	Germany, $n = 43$; Jul. 7 to Aug. 29, 2007
42.1 ± 5.1	19.6 ± 2.5*	53	Spain, $n = 30$; Jul. 2 to Aug. 30, 2007
26.4 ± 1.5	13.2 ± 0.8*	50	Canada, $n = 22$; Jun. 26 to Aug. 22, 2007
23.4 ± 2.0	11.8 ± 0.7*	49	Canada, $n = 15$; Jun. 24 to Aug. 22, 2007

*$p < 0.01$.

10. The frequency distribution of the activity reduction in one experiment is shown in Figure 13.3. The relative reduction of the specific activity for the pectin groups was 32.4% (arithmetic mean) and 33.6% (median), respectively, whereas the specific activity in the children who received placebos decreased only by 14.2% (arithmetic mean) and 13.1% (median), respectively. This corresponds to a reduction in the mean effective half-life of 27 days for the pectin groups, as compared with 69 days for the placebo groups.

11. The two calculated whole-body retention functions are shown in Figure 13.4 (for adults). The first curve represents the effect of replacing contaminated food by clean food effective from $t = 0$ and the second corresponds to clean food plus Vitapect, also effective from $t = 0$. The observed reduction of mean effective half-life (69→27 days) corresponds to a factor of 2.5.

12. From 1996 to 2007 a total of more than 160,000 Belarussian children received oral Vitapect (5 g twice a day) for an 18- to 25-day course of treatment. The results showed a decrease in Cs-137 levels after each course of treatment by an average of 30–40%.

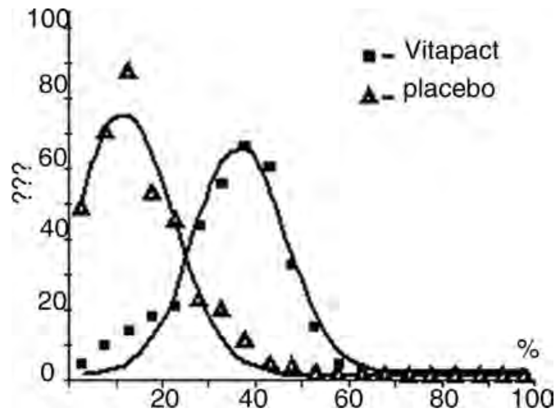

Figure 13.3. Frequency of occurrence of observed relative reduction of the Cs-137 body burden with Vitapect treatment in Belarussian children (Hill *et al.*, 2007).

Based on long-term experience, the BELRAD Institute recommends that all children living in radioactive contaminated territories receive a quadruple course of oral pectin food additives annually along with their conventional food ration. Eleven years of BELRAD's activities in controlling levels of incorporated Cs-137 in more than 327,000 children has not caused alarm in the population or radiophobia and has led to the spread of knowledge concerning radiation protection and an

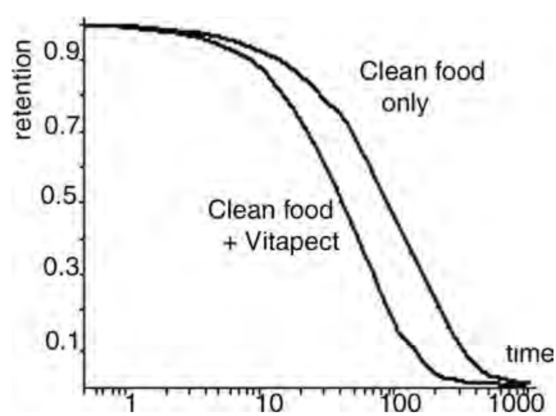

Figure 13.4. Theoretical retention functions for adults based on the model of Leggett *et al.* (2003). The upper curve shows the effect of clean food and the lower one illustrates the additional effect of blocking adsorption using Vitapect (Hill *et al.*, 2007).

increased sense of personal responsibility for one's health.

13.3. New Principles of Radiation Protection Based on Direct Measurements

The BELRAD Institute's 11 years of experience shows that for effective radiation protection in the contaminated territories, an intervention level—30% of the official dangerous limit (i.e., 15–20 Bq/kg)—must be established for children.

1. The direct whole body counting (WBC) measurements of Cs-137 accumulation in individuals in the heavily contaminated Belarussian regions showed that the official Dose Catalogue prepared on the basis of the Cs-137 concentrations in 10 milk samples and 10 potato samples underestimates the annual personal dose burden three- to eightfold and cannot be relied on for effective radiation protection.

2. It is obvious that a true dose catalogue of the contaminated population should be developed on the basis of the data obtained from the direct WBC measurements of Cs-137, which reflect the accumulated internal dose burden. This should be done via reliable sampling of inhabitants from each area of Belarus affected by Chernobyl.

3. Only by combining WBC measurements of Cs-137 accumulation in the body with medical evaluations can the causal relationship (dose dependence) between the increase in morbidity and incorporated radionuclides in the population be known. At this time, these data can only be obtained in the Chernobyl-contaminated regions of Belarus, Ukraine, and European Russia. This information can be an important factor in designing radiation protection and treating people, in persuading the world community of the need to help Belarus minimize radiation exposures, and in understanding the dimensions of the consequences of the Chernobyl catastrophe.

13.4. Where International Help for Chernobyl's Children Would Be Especially Effective

No country in the world is able to cope alone with the long-term consequences of a catastrophe of the magnitude of the meltdown in Chernobyl. The countries most severely affected, especially Ukraine and Belarus, which suffered greatly, are grateful for the help they get from the United Nations and other international organizations, as well as from private funds and initiatives.

Annually, tens of thousands of Chernobyl children go to other countries for treatment to improve their health. Doctors from many countries work pro bono in the Chernobyl-contaminated territories to help minimize the consequences of this most terrible technologic catastrophe in history. The scale and the range of the consequences are so great that there is always the question of how to make such help even more effective.

Experience from large-scale long-term programs to monitor foodstuffs and the levels of incorporated radionuclides in the bodies of those living in the contaminated territories is the basis for the following proposals to increase the efficacy of the international and national programs:

- Joint studies to determine the frequency and intensity of various diseases, especially in children, correlated with levels of incorporated radionuclides.
- Regular individual radiometric evaluation of the populations, especially children, in all contaminated territories. To accomplish this, Belarus will have to increase the number of mobile laboratories from eight to twelve or fifteen. Similar to the Belarussian system, independent, practical, science/clinical centers must be established in Ukraine and European Russia to use the results of such regular radiometric monitoring to identify critical groups with high radionuclide incorporation.

- Manufacture and administer various pectin-based food additives and drinks (based on apples, currants, grapes, seaweed, etc.) as one of the most effective ways of providing individual radiation protection (through decorporation) when circumstances make using contaminated food unavoidable.
- Independent radiation monitoring and radiation control of local foodstuffs, making use of the BELRAD Institute's experience in organizing local centers for radioactive control. This does not replace, but can add to the existing official system.
- Regular courses of oral pectin food additives for preventive maintenance.

Twenty-two years after the catastrophe the true situation in Chernobyl's heavily contaminated territories shows that the internationally accepted individual dose limit is in excess of 1 mSv/year because of the unavoidable consumption of local radioactively contaminated products. Thus the most advisable way to lower the levels of incorporated radionuclides is to consume only clean food. In those situations where clean food is not available, decorporant and sorbent additives should be used to remove as much as possible of the absorbed and incorporated radionuclides.

There are many more-or-less effective decorporants and sorbents: a wide spectrum of products with alginic acid-alginates (mostly from brown seaweed) promotes the reduction of Sr, iron and copper cyanides (e.g., ferrocyanide blue) promote the reduction of Cs. Activated charcoal, cellulose, and various pectins are also effective sorbents for incorporated radionuclides. For practical reasons the curative-like application of apple-pectin food additives may be especially helpful to effectively decorporate Cs-137.

What can be done:

- Reduce Cs-137 concentration in the main dose-forming product—milk—by feeding cows with mixed fodder containing sorbents and by separating the milk to produce cream and butter.
- Provide children and pregnant women with clean foodstuffs and with food additives to increase the elimination of radionuclides and heavy metals from their bodies.
- Inform the population about the levels of radionuclide contamination of the local foodstuffs and the radionuclide concentration in the bodies of the inhabitants (especially children), taking into consideration the existing available foods and the local way of life.
- Institute the practice of regular decorporation of radionuclides into the lifestyle as an effective measure of radiation protection for the population of the Chernobyl-contaminated regions.

The use of food additives, pectin preparations with a complex of vitamins and microelements, demonstrated a high efficiency in eliminating incorporated radionuclides.

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14. Protective Measures for Activities in Chernobyl's Radioactively Contaminated Territories

Alexey V. Nesterenko and Vassily B. Nesterenko

Owing to internally absorbed radionuclides, radiation levels for individuals living in the contaminated territories of Belarus, Ukraine, and Russia have been increasing steadily since 1994. Special protective measures in connection with agriculture, forestry, hunting, and fishing are necessary to protect the health of people in all the radioactively contaminated territories. Among the measures that have proven to be effective in reducing levels of incorporated radionuclides in meat production are food additives with ferrocyanides, zeolites, and mineral salts. Significant decreases in radionuclide levels in crops are achieved using lime/Ca as an antagonist of Sr-90, K fertilizers as antagonists of Cs-137, and phosphoric fertilizers that form a hard, soluble phosphate with Sr-90. Disk tillage and replowing of hayfields incorporating applications of organic and mineral fertilizers reduces the levels of Cs-137 and Sr-90 three- to fivefold in herbage grown in mineral soils. Among food technologies to reduce radionuclide content are cleaning cereal seeds, processing potatoes into starch, processing carbohydrate-containing products into sugars, and processing milk into cream and butter. There are several simple cooking techniques that decrease radionuclides in foodstuffs. Belarus has effectively used some forestry operations to create "a live partition wall," to regulate the redistribution of radionuclides into ecosystems. All such protective measures will be necessary in many European territories for many generations.

As a result of the Chernobyl catastrophe, millions of hectares of agricultural lands are dangerously contaminated with Cs-137 with concentrations higher than 37 kBq/m^2: in Belarus, 1.8 million hectares; in Russia, 1.6 million hectares; and in Ukraine, 1.2 million hectares. According to the Belarus Ministry of Agriculture, agricultural production now takes place on more than 1.1 million hectares of land contaminated with Cs-137 at a level from 37 to 1,480 kBq/m^2, and 0.38 million more hectares are similarly contaminated by Sr-90 at a level of more than 5.55 kBq/m^2. In Gomel Province 56% of all the agricultural land is contaminated, and in Mogilev Province that figure is 26%. Millions of hectares of Belarussian, Russian, and Ukrainian forests (more than 22% of all Belarussian woodlands) appear to be dangerously contaminated (National Belarussian Report, 2006). More than 5 million people live in the contaminated territories of Belarus, Ukraine, and Russia (see Chapter I for details). Moreover, some grasslands, forests, mountains, and lakes in Sweden, Norway, Scotland, Germany, Switzerland, Austria, Italy, France, and Turkey continue to show measurable contamination.

Over the 23 years since the catastrophe, owing to the devoted activities of many thousands of scientists and technical specialists, some methods and practical measures have been developed to decrease the risks from the contamination linked to the use of natural resources (agricultural, forestry, hunting, etc.). As a comprehensive review all these results would

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require a separate monograph. This short chapter simply outlines some basic techniques designed to achieve radiation protection for the resources utilized in the course of everyday living in the contaminated territories.

14.1. Measures for Radiation Protection in Agriculture

1. Where production with "permissible" amounts of radionuclides is impossible, agricultural lands have been taken out of use: in Belarus, 265,000 hectares; in Ukraine, 130,000 hectares; and in Russia, 17,000 hectares (Aleksakhin *et al.*, 2006).

2. Agricultural land with radioactive contamination is subject to obligatory monitoring of both soil and production processes for end-product control technology to ensure permissible levels of Cs-137 and Sr-90 in foodstuffs. This *permissible* level is established by calculating the combined individual average annual food intake so as to limit the effective equivalent radiation dose to less than 1 mSv/year. For beef and mutton the level of Cs-137 should be no higher than 500 Bq/kg in Belarus and 160 Bq/kg in Russia and Ukraine, flour and groats (buckwheat) should have no more than 90 Bq/kg, etc. (Bagdevich *et al.*, 2001). Each country has its own radioprotection policy.

3. Effective decreases in the levels of radionuclides in crops are achieved by applications of lime/Ca as antagonists of Sr-90, K fertilizers as antagonists of Cs-137, phosphoric fertilizers that form a hard soluble phosphate and precipitate Sr-90, plus zeolites, sapropel (gyttja), and other natural antagonists and absorbents (Aleksakhin *et al.*, 1992; and many others; Table 14.1).

4. Hayfields (meadows and pastures) used to support milk and meat production account for up to half of all contaminated agricultural land in Belarus. Disk tilling and replowing of hayfields incorporating an application of organic and mineral fertilizers reduces the levels of Cs-137 and Sr-90 accumulation three- to fivefold in herbage grown in mineral soils. Such radical treatment of hayfields on peat soils sharply reduces Cs-137, but is less effective for Sr-90. Owing to degradation of cultivated hayfields, repeated grassland renovation with an application of fertilizers is needed every 3 to 6 years.

TABLE 14.1. Efficiency of Agrochemical Measures to Reduce Cs-137 and Sr-90 Concentrations in Plant Production (Gudkov, 2006)

	Reduction factor	
Method	Cs-137	Sr-90
Lime	1.5–4	1.5–2.5
Higher level of:		
Phosphoric fertilizers	1.5–2	1.2–1.5
Potassium fertilizers	1.8	None
Organic fertilizers 40 tons/ha	1.5–3	1.5–2
Combined application of lime, mineral, and organic fertilizers	2–5	2–4
Mineral soil absorbents (zeolites, vermiculites, bentonites, etc.)*	1.5–2.5	1.5–2

*They were most effective during the first 5 years after the catastrophe (Kenik, 1998).

5. As noted above, radiation protection measures are effectively applied in large state-owned and collective farms. In small private-sector households and farms, which in Belarus account for more than 50% of agricultural production, these measures are incidental. Generally for each cow on a private Belarus farm there is about 1 hectare of hayfield and improved pasture. This is not sufficient to sustain the animal so the farmers have to get hay from grassy forest glades and unarable lands that are contaminated with higher levels of radioactivity than cultivated hayfields. Thus a significant number of settlements, even 23 years since the catastrophe, had inadequate radiation protection for agricultural production. There are more than 300 such settlements each in Belarus and Ukraine, and more than 150 in Russia (Kashparov *et al.*, 2005).

6. Twenty years after the catastrophe, some 10 to 15% of the milk on private Belarussian farms had a higher Cs-137 contamination than the permissible level. In 2006 there were

TABLE 14.2. Efficiency of Measures to Reduce Cs-137 and Sr-90 Concentrations in Animal-Breeding Production (Gudkov, 2006)

Measure	Reduction factor Cs-137	Reduction factor Sr-90
Improvement of meadows and pastures*	1.5–10	1.5–5
Food additives with ferrocyanide	2–8 (to 20)	None
Food additives with zeolites	2–4	None
Food additives with mineral salts	1.5–2	2–3
Month on clean fodder before slaughter	2–4	None

*Less effective on peat soils.

instances in which household milk contained Cs-137 at a value as high as 1,000 Bq/liter. In Gomel Province in 2004, some 12% of beef had Cs-137 levels above 160 Bq/kg (BELRAD Institute data).

7. There are some effective measures to reduce levels of incorporated radionuclides in meat production (Table 14.2) and food-processing technologies to reduce radionuclide content in foodstuffs (Table 14.3).

8. Table 14.4 presents the primary known antiradiation chemical and pharmacological measures to achieve clean animal breeding in the contaminated territories.

9. All the methods described to reduce radiation in agricultural production require additional material and labor; thus economic efficiency in the contaminated areas is compromised. In spite of measures taken and subsidies, agricultural production in radioactive contaminated areas continues to be difficult and the farmers often turn to specialized enterprises for cattle breeding for meat production, production of oils and industrial crops, etc.

TABLE 14.3. Efficiency of Measures to Reduce Cs-137 and Sr-90 Content in Foodstuffs (Gudkov, 2006)

Measure	Reduction factor Cs-137	Reduction factor Sr-90
Cleaning of cereals seeds	1.5–2	
Processing of potato to starch	15–50	
Processing carbohydrate-containing: Production to sugars	60–70	
Production to ethyl alcohol	Up to 1,000	
Processing of milk to cream	6–12	5–10
Processing of milk to butter	20–30	30–50
Culinary treatment of meat	2–4	None

TABLE 14.4. Chemical and Pharmacological Antiradiation Remedies (Based on Gudkov, 2006)

Radionuclide blockers and decontaminants	
Antagonists—competitors	Stable isotopes, chemical analogues
Enterosorbents	Activated charcoal, zeolite, Vitapect, Algisorb, etc.
Insoluble complexes	Ferrocyanides, alginates, pectins, phosphates
Soluble complexes	Natural (flavonoids: flavones, anthocyans, catechins) and synthetic (Zinkacyne, etc.)
Radioprotectants	
Antioxidants	Aminothiols; disulfides; thiosulfates; vitamins A, C, E
Stabilizers of DNA and membranes	Metal ions, chelates, flavonoids
Metabolism inhibitors	Cyanides, nitriles, azides, endotoxins
Adaptogenes	Immunostimulants, vitamins, microelements, etc.

14.2. Radiation Protection Measures for Forestry, Hunting, and Fisheries

Forestlands accumulated about 70% of the Chernobyl radionuclides that fell on Belarus. Shortly after the catastrophe most forest radionuclide contamination was on the surface of trees. Roots absorb Cs-137 and Sr-90 from the soil and transport them into the wood and other parts of the plant. Specific activity of Cs-137 can exceed 20 kBq/kg in forest berries and mushrooms, as much as 150 kBq/kg in dried mushrooms, and 250 kBq/kg in wild game meat. In predatory fish breeds in landlocked reservoirs the levels can reach 300 kBq/kg (see Chapter III for details).

1. In the exclusion zone, which in 1986–1987 was 30 km wide, as well as in the zone of involuntary resettlement, all forestry activities are forbidden where there is risk to an individual of a dose greater than 5.0 mSv. In this zone permanent housing is banned and economic activity is strictly limited. The zone of involuntary resettlement is an area outside the exclusion zone where the level of ground contamination from Cs-137 is above 15 Ci/km^2, that from Sr-90 is above 3 Ci/km^2, or that from Pu-239 and Pu-240 is above 0.1 Ci/km^2. The territories of involuntary resettlement also include some areas with low-level radioactivity where radionuclides migrate into plants from contaminated soil.

2. According to official Belarussian data, for several years after the catastrophe radiation levels in contaminated forest products (wild berries, mushrooms, firewood, etc.) exceeded those in domestic agricultural products (milk, bread, cereals, etc.).

3. Ten years after the catastrophe, the amount of radionuclides in underground parts of trees doubled and reached 15% of the total amount in forest ecosystems. Even now, in Belarus, owing to external radiation contamination, foresters are exposed to levels two to three times higher than agricultural workers.

4. Among the principal measures proposed to decrease radiation risk for forestry workers are: (a) shorten the length of stay in contaminated territory; (b) minimize manned technologies and maximize mechanization; (c) provide individual safety equipment and shielding for the driver's cabin on farm machines and devices for protection from gamma irradiation; (d) require special permission to enter the forests; and (e) impose seasonal regulations on forestry operations (Maradudin *et al.*, 1997).

5. Contamination is increasing and it appears that it will rise even more with the use of contaminated firewood as fuel and its radioactive ashes as fertilizer; all of these activities will increase individual radiation doses.

6. Among forest products, mushrooms, berries, and hazelnuts are the most contaminated. Up to 50% of all the mushrooms and berries that were measured exceeded the permissible level of Cs-137 (370 Bq/kg). Consumption of forest products accounts for up to 40% of the annual individual dose of internal radiation in Belarus. Persistence of Cs-137 in forest products exceeds the permissible level even in territories with soil contamination below 37 kBq/m^2 (<1 Ci/km^2).

7. The Belarus National Academy Forest Institute revealed that the forest can serve as "a live partition wall," by regulating redistribution of radionuclides in ecosystems. In test plots in sections of the Vetka and El'sk forests in Gomel Province the amounts of radionuclides in the roots of trees, in forest berries, and in mushrooms have been decreased up to sevenfold as a result of special forestry and reclamation measures (Ipat'ev, 2008).

8. To prevent dispersion of radionuclides from contaminated forest areas to adjoining territories as a result of water and wind erosion it is necessary to reforest eroded land. Universal efforts to prevent forest fires and improve fire-fighting efficiency are needed to stop radionuclide dispersion via wind currents several hundred or even thousands of kilometers away from contaminated territories. Unfortunately, this was not done during the fires that raged in 1992.

9. In zones with a Cs-137 level of more than 15 Ci/km^2 it is dangerous to consume wild game. Obligatory total control over all game production is needed in zones contaminated up to 15 Ci/km^2. In contaminated territories it is recommended to shoot wild boars and roe deer aged 2 years or older because they have lower levels of incorporated radionuclides than younger ones.

10. The situation with elk is the opposite. The level of radionuclide incorporation is significantly lower among young animals as compared to adults.

11. Radionuclide concentrations in the visceral organs of game mammals (heart, liver, kidneys, lungs, etc.) are significantly higher than in muscle tissue.

12. Decreasing levels of specific radioactive contamination of principal game species are as follows: wolf > fox > wild boar > roe deer > hare > duck > elk.

13. In contaminated territories the same species of fish taken from rivers and streams have significantly lower radionuclide levels than those from lakes and ponds. Phytophagous fish have three to four times lower radionuclide levels than predatory species (catfish, pike, etc.). Benthic fishes (crucian, tench, etc.) have several times more contamination than fish that live in the top water layers (small fry, chub, etc.).

14. There are some effective methods to significantly decrease radionuclide contamination in pond cultures by plowing from the pond bottom down to a depth up to 50 cm and washing with flowing water, applying potash fertilizers, and using vitamins and antioxidants (radioprotectants) as food additives for the fish (Slukvin and Goncharova, 1998).

14.3. Radiation Protection Measures in Everyday Life

Instructions for radiation protection and self-help countermeasures can be found in Ramzaev, 1992; Nesterenko, 1997; Beresdorf and Wright, 1999; Annenkov and Averin, 2003; Babenko, 2008; Parkhomenko *et al.*, 2008; and many others.

It is very important to avoid radionuclides in food and if they are consumed to try to eliminate them from the body as quickly as possible. In a baby, the biological half-life of Cs-137 is 14 days; for a 5-year old it is 21 days; for a 10-year old, 49 days; for teenagers, about 90 days; and for a young male, about 100 days (Nesterenko, 1997).

1. The most direct way of decreasing radionuclide intake is to avoid foods that are potentially heavily contaminated and to consume foodstuffs with lower levels. However, this is not easy to do because the average level of radionuclide bioaccumulation differs in each region owing to differences in soils, cultivars, agriculture techniques, etc.

Several examples of differing levels of contamination are presented below.

1.1. Vegetables: Order of decreasing Cs-137 in some areas of Belarus: sweet pepper > cabbage >potatoes > beetroot > sorrel > lettuce > radish > onion > garlic > carrots > cucumbers > tomatoes. Order of decreasing levels in Gomel Province: sorrel > beans > radish > carrots > been root > potatoes > garlic > sweet pepper > tomatoes > squash > cucumbers > cabbage (kohlrabi) > cauliflower > colewort (Radiology Institute, 2003).

1.2. Berries: Order of decreasing Cs-137 among some berries: blueberry (*Vaccinium myrtillus*), cowberry (*V. vitis-idaea*), red and black currants (*Ribes sp.*), and cranberry (*Oxycoccus*) usually accumulate more Cs-137 than strawberry (*Fragaria*), gooseberry (*Grossularia*), white currant, raspberry (*Rubus*), and mountainash (*Sorbus*).

1.3. Meat: Order of decreasing Cs-137 in some meats: poultry > beef > mutton > pork. Meats from older animals have more radionuclides that meat from younger ones owing to accumulation over time. Bones of young animals have more Sr-90. Among visceral organs the order of decreasing levels of Cs-137 is: lung > kidney > liver > fat.

1.4. Eggs: Order of decreasing levels: shell > egg-white > yolk.

1.5. Fish: Predatory and benthic fishes (pike, perch, carp, catfish, tench, etc.) are more contaminated, and fish living in rivers and streams are always less contaminated than those from lakes and ponds.

1.6. Mushrooms: The cap usually contains more Cs-137 than the pedicle. Agaric (Agaricales) mushrooms usually concentrate more radionuclides than boletuses (Boletus).

2. The biological properties of Cs-137 are similar to those of stable K and Rb, and Sr-90 and Pu are similar to Ca. These properties determine where they concentrate in the body so the use of stable elements may help to decrease the absorption of radionuclides.

Foods rich in K include potatoes, maize, beans, beets, raisins, dried apricots, tea, nuts, potatoes, lemons, and dried plums. Ca-rich foods include milk, eggs, legumes, horseradish, green onions, turnip, parsley, dill, and spinach. Green vegetables, apples, sunflower seeds, black chokeberries, and rye bread are rich in Fe; and Rb is found in red grapes.

3. A diet to protect against radioactive contamination should include uncontaminated fruits and vegetables, those rich in pectin, and those with high-fiber complexes to promote the rapid elimination of radionuclides.

4. High intake of fluids including fruit drinks helps promote excretion of contaminants in urine.

5. Daily addition of antioxidants (vitamins A, C, E, and the trace elements Zn, Co, Cu, and Se) is recommended.

6. Individuals exposed to radioactive contamination should consume special food additives such as Vitapect (see Chapter IV.13) and products made from apples, green algae (*Spirulinae*), fir-needles, etc.

7. There are several simple cooking techniques that decrease radionuclides: boil foods several times and discard the water, wash food thoroughly, soak some foods and discard the water, avoid the rinds of fruits and vegetables, salt and pickle some foods but throw away the pickling juice! Avoid eating strong bouillon, use rendered butter, etc.

Experiences from around the world after the catastrophe show that citizens of countries that did not provide information and methods to counter the effects of the radioactive fallout fared more poorly than those in countries that did provide such help. In 1986 the effective individual dose to the "average" person in Bulgaria, where there was no emergency protection was 0.7 to 0.8 mSv, or about threefold higher than the dose for the "average" Norwegian. The Norwegian government placed a prohibition against eating leafy vegetables and drinking fresh milk, destroyed contaminated meat, maintained cattle in stalls, deactivated pastures and reservoirs, and mandated that prior to slaughter the cattle be fed on clean forage, etc. This disparity in contamination doses occurred even though the level of contamination in Bulgaria was measurably lower than that in Norway (Energy, 2008).

Since 1994, radiation exposure of individuals living in the contaminated territories of Belarus, Ukraine, and Russia has continued to increase owing to internal absorption of radionuclides—the most dangerous form of radiation exposure despite natural radioactive decay.

Migration of Chernobyl radionuclides into soil root zones allows plants to absorb them, transport them to the surface, and incorporate them into edible portions of the plant. Agricultural and forest product radionuclides are introduced into food chains, significantly increasing the radiation danger for all who consume those foodstuffs. Today the most serious contaminating agents are Cs-137 and Sr-90. In coming years the situation will change and Am-241 will present a very serious problem (see Chapter I for details).

For at least six to seven generations, vast territories of Belarus, Russia, and Ukraine must take special measures to control radiation exposure in agriculture, forestry, hunting, and fishing. So too must other countries with areas of high radioactive contamination, including Sweden, Norway, Switzerland, Austria, France, and Germany. This means, that local economies will require external grants-in-aid and donations to minimize the level of radionuclides in all products because many areas simply do not have the funds to monitor, teach, and mandate protection. Thus the problem of contamination is dynamic and requires constant monitoring and control—for Cs-137 and Sr-90 pollution at least 150 to 300 years into the future. The contamination from the wider spectrum of radioisotopes is dynamic and will require constant monitoring and control essentially forever.

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15. Consequences of the Chernobyl Catastrophe for Public Health and the Environment 23 Years Later

Alexey V. Yablokov, Vassily B. Nesterenko, and Alexey V. Nesterenko

More than 50% of Chernobyl's radionuclides were dispersed outside of Belarus, Ukraine, and European Russia and caused fallout as far away as North America. In 1986 nearly 400 million people lived in areas radioactively contaminated at a level higher than 4 kBq/m^2 and nearly 5 million individuals are still being exposed to dangerous contamination. The increase in morbidity, premature aging, and mutations is seen in all the contaminated territories that have been studied. The increase in the rates of total mortality for the first 17 years in European Russia was up to 3.75% and in Ukraine it was up to 4.0%. Levels of internal irradiation are increasing owing to plants absorbing and recycling Cs-137, Sr-90, Pu, and Am. During recent years, where internal levels of Cs-137 have exceeded 1 mSv/year, which is considered "safe," it must be lowered to 50 Bq/kg in children and to 75 Bq/kg in adults. Useful practices to accomplish this include applying mineral fertilizers on agricultural lands, K and organosoluble lignin on forestlands, and regular individual consumption of natural pectin enterosorbents. Extensive international help is needed to provide radiation protection for children, especially in Belarus, where over the next 25 to 30 years radionuclides will continue to contaminate plants through the root layers in the soil. Irradiated populations of plants and animals exhibit a variety of morphological deformities and have significantly higher levels of mutations that were rare prior to 1986. The Chernobyl zone is a "black hole": some species may persist there only via immigration from uncontaminated areas.

The explosion of the fourth block of the Chernobyl nuclear power plant in Ukraine on April, 26, 1986 was the worst technogenic accident in history. The information presented in the first 14 parts of this volume was abstracted from the several thousand cited scientific papers and other materials. What follows here is a summary of the main results of this meta-analysis of the consequences of the Chernobyl catastrophe.

The principal methodological approach of this meta-review is to reveal the consequences of Chernobyl by comparing differences among populations, including territories or subgroups that had and have different levels of contamination but are comparable to one another in ethnic, biologic, social, and economic characteristics. This approach is clearly more valid than trying to find "statistically significant" correlations between population doses that are impossible to quantify after the fact and health outcomes that are defined precisely by morbidity and mortality data.

15.1. The Global Scale of the Catastrophe

1. As a result of the catastrophe, 40% of Europe was contaminated with dangerous

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radioactivity. Asia and North America were also exposed to significant amounts of radioactive fallout. Contaminated countries include Austria, Finland, Sweden, Norway, Switzerland, Romania, Great Britain, Germany, Italy, France, Greece, Iceland, and Slovenia, as well as wide territories in Asia, including Turkey, Georgia, Armenia, The Emirates, China, and northern Africa. Nearly 400 million people lived in areas with radioactivity at a level exceeding 4 kBq/m^2 ($\geq$0.1 Ci/km^2) during the period from April to July 1986.

2. Belarus was especially heavily contaminated. Twenty-three years after the catastrophe nearly 5 million people, including some 1 million children, live in vast areas of Belarus, Ukraine, and European Russia where dangerous levels of radioactive contamination persist (see Chapter 1).

3. The claim by the International Atomic Energy Agency (IAEA), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and several other groups that the Chernobyl radioactive fallout adds "only" 2% to the natural radioactive background ignores several facts:

- First, many territories continue to have dangerously high levels of radiation.
- Second, high levels of radiation were spread far and wide in the first weeks after the catastrophe.
- Third, there will be decades of chronic, low-level contamination after the catastrophe (Fig. 15.1).
- Fourth, every increase in nuclear radiation has an effect on both somatic and reproductive cells of all living things.

4. There is no scientific justification for the fact that specialists from IAEA and the World Health Organization (WHO) (Chernobyl Forum, 2005) completely neglected to cite the extensive data on the negative consequences of radioactive contamination in areas other than Belarus, Ukraine, and European Russia,

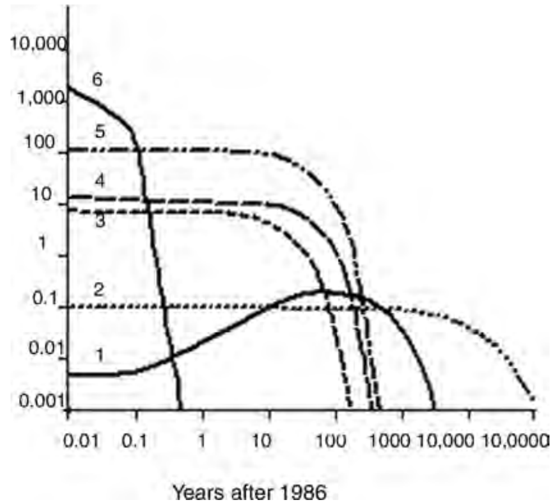

Figure 15.1. Total additional radioactivity (in petabequerels) in the global environment after the Chernobyl catastrophe: (1) Am-241, (2) Pu (239 + 240), (3) Pu-241, (4) Sr-90, (5) Cs-137, (6) I-131 (Mulev, 2008).

where about 57% of the Chernobyl radionuclides were deposited.

15.2. Obstacles to Analysis of the Chernobyl Consequences

1. Among the reasons complicating a full-scale estimation of the impact of the Chernobyl catastrophe on health are the following:

- Official secrecy and unrectifiable falsification of Soviet Union medical statistics for the first 3.5 years after the catastrophe.
- Lack of detailed and clearly reliable medical statistics in Ukraine, Belarus, and Russia.
- Difficulties in estimating true individual radioactive doses in view of: (a) reconstruction of doses in the first days, weeks, and months after the catastrophe; (b) uncertainty as to the influence of individual "hot particles"; (c) problems accounting for uneven and spotty contamination; and (d) inability to determine the influence of each of many radionuclides, singly and in combination.

- Inadequacy of modern knowledge as to: (a) the specific effect of each of the many radionuclides; (b) synergy of interactions of radionuclides among themselves and with other environmental factors; (c) population and individual variations in radiosensitivity; (d) impact of ultralow doses and dose rates; and (e) impact of internally absorbed radiation on various organs and biological systems.

2. The demand by IAEA and WHO experts to require "significant correlation" between the imprecisely calculated levels of individual radiation (and thus groups of individuals) and precisely diagnosed illnesses as the only iron clad proof to associate illness with Chernobyl radiation is not, in our view, scientifically valid.

3. We believe it is scientifically incorrect to reject data generated by many thousands of scientists, doctors, and other experts who directly observed the suffering of millions affected by radioactive fallout in Belarus, Ukraine, and Russia as "mismatching scientific protocols." It is scientifically valid to find ways to abstract the valuable information from these data.

4. The objective information concerning the impact of the Chernobyl catastrophe on health can be obtained in several ways:

- Compare morbidity and mortality of territories having identical physiographic, social, and economic backgrounds and that differ only in the levels and spectra of radioactive contamination to which they have been and are being exposed.
- Compare the health of the same group of individuals during specific periods after the catastrophe.
- Compare the health of the same individual in regard to disorders linked to radiation that are not a function of age or sex (e.g., stable chromosomal aberrations).
- Compare the health of individuals living in contaminated territories by measuring the level of incorporated Cs-137, Sr-90, Pu, and Am. This method is especially effective for evaluating children who were born after the catastrophe.
- Correlate pathological changes in particular organs by measuring their levels of incorporated radionuclides.

The objective documentation of the catastrophe's consequences requires the analysis of the health status of about 800,000 liquidators, hundreds of thousands of evacuees, and those who voluntary left the contaminated territories of Belarus, Ukraine, and Russia (and their children), who are now living outside of these territories, even in other countries.

5. It is necessary to determine territories in Asia (including Trans-Caucasus, Iran, China, Turkey, Emirates), northern Africa, and North America that were exposed to the Chernobyl fallout from April to July 1986 and to analyze detailed medical statistics for these and surrounding territories.

15.3. Health Consequences of Chernobyl

1. A significant increase in general morbidity is apparent in all the territories contaminated by Chernobyl that have been studied.

2. Among specific health disorders associated with Chernobyl radiation there are increased morbidity and prevalence of the following groups of diseases:

- Circulatory system (owing primarily to radioactive destruction of the endothelium, the internal lining of the blood vessels).
- Endocrine system (especially nonmalignant thyroid pathology).
- Immune system ("Chernobyl AIDS," increased incidence and seriousness of all illnesses).
- Respiratory system.
- Urogenital tract and reproductive disorders.
- Musculoskeletal system (including pathologic changes in the structure and

composition of bones: osteopenia and osteoporosis).
- Central nervous system (changes in frontal, temporal, and occipitoparietal lobes of the brain, leading to diminished intelligence and behaviorial and mental disorders).
- Eyes (cataracts, vitreous destruction, refraction anomalies, and conjunctive disorders).
- Digestive tract.
- Congenital malformations and anomalies (including previously rare multiple defects of limbs and head).
- Thyroid cancer (All forecasts concerning this cancer have been erroneous; Chernobyl-related thyroid cancers have rapid onset and aggressive development, striking both children and adults. After surgery the person becomes dependent on replacement hormone medication for life.)
- Leukemia (blood cancers) not only in children and liquidators, but in the general adult population of contaminated territories.
- Other malignant neoplasms.

3. Other health consequences of the catastrophe:

- Changes in the body's biological balance, leading to increased numbers of serious illnesses owing to intestinal toxicoses, bacterial infections, and sepsis.
- Intensified infectious and parasitic diseases (e.g., viral hepatitis and respiratory viruses).
- Increased incidence of health disorders in children born to radiated parents (both to liquidators and to individuals who left the contaminated territories), especially those radiated *in utero*. These disorders, involving practically all the body's organs and systems, also include genetic changes.
- Catastrophic state of health of liquidators (especially liquidators who worked in 1986–1987).
- Premature aging in both adults and children.
- Increased incidence of multiple somatic and genetic mutations.

4. Chronic diseases associated with radioactive contamination are pervasive in liquidators and in the population living in contaminated territories. Among these individuals polymorbidity is common; that is, people are often afflicted by multiple illnesses at the same time.

5. Chernobyl has "enriched" world medicine with such terms, as "cancer rejuvenescence," as well as three new syndromes:

- "Vegetovascular dystonia"—dysfunctional regulation of the nervous system involving cardiovascular and other organs (also called autonomic nervous system dysfunction), with clinical signs that present against a background of stress.
- "Incorporated long-life radionuclides"—functional and structural disorders of the cardiovascular, nervous, endocrine, reproductive, and other systems owing to absorbed radionuclides.
- "Acute inhalation lesions of the upper respiratory tract"—a combination of a rhinitis, throat tickling, dry cough, difficulty breathing, and shortness of breath owing to the effect of inhaled radionuclides, including "hot particles."

6. Several new syndromes, reflecting increased incidence of some illnesses, appeared after Chernobyl. Among them:

- "Chronic fatigue syndrome"—excessive and unrelieved fatigue, fatigue without obvious cause, periodic depression, memory loss, diffuse muscular and joint pains, chills and fever, frequent mood changes, cervical lymph node sensitivity, weight loss; it is also often associated with immune system dysfunction and CNS disorders.
- "Lingering radiating illness syndrome"—a combination of excessive fatigue, dizziness, trembling, and back pain.
- "Early aging syndrome"—a divergence between physical and chronological age

with illnesses characteristic of the elderly occurring at an early age.

7. Specific Chernobyl syndromes such as "radiation in utero," "Chernobyl AIDS," "Chernobyl heart," "Chernobyl limbs," and others await more detailed definitive medical descriptions.

8. The full picture of deteriorating health in the contaminated territories is still far from complete, despite a large quantity of data. Medical, biological, and radiological research must expand and be supported to provide the full picture of Chernobyl's consequences. Instead this research has been cut back in Russia, Ukraine, and Belarus.

9. Deterioration of public health (especially of children) in the Chernobyl-contaminated territories 23 years after the catastrophe is not due to psychological stress or radiophobia, or from resettlement, but is mostly and primarily due to Chernobyl irradiation. Superimposed upon the first powerful shock in 1986 is continuing chronic low-dose and low-dose-rate radionuclide exposure.

10. Psychological factors ("radiation phobia") simply cannot be the defining reason because morbidity continued to increase for some years after the catastrophe, whereas radiation concerns have decreased. And what is the level of radiation phobia among voles, swallows, frogs, and pine trees, which demonstrate similar health disorders, including increased mutation rates? There is no question but that social and economic factors are dire for those sick from radiation. Sickness, deformed and impaired children, death of family and friends, loss of home and treasured possessions, loss of work, and dislocation are serious financial and mental stresses.

15.4. Total Number of Victims

1. Early official forecasts by IAEA and WHO predicted few additional cases of cancer. In 2005, the Chernobyl Forum declared that the total death toll from the catastrophe would be about 9,000 and the number of sick about 200,000. These numbers cannot distinguish radiation-related deaths and illnesses from the natural mortality and morbidity of a huge population base.

2. Soon after the catastrophe average life expectancy noticeably decreased and morbidity and mortality increased in infants and the elderly in the Soviet Union.

3. Detailed statistical comparisons of heavily contaminated territories with less contaminated ones showed an increase in the mortality rate in contaminated European Russia and Ukraine of up to 3.75% and 4.0%, respectively, in the first 15 to 17 years after the catastrophe.

4. According to evaluations based on detailed analyses of official demographic statistics in the contaminated territories of Belarus, Ukraine, and European Russia, the additional Chernobyl death toll for the first 15 years after the catastrophe amounted to nearly 237,000 people. It is safe to assume that the total Chernobyl death toll for the period from 1987 to 2004 has reached nearly 417,000 in other parts of Europe, Asia, and Africa, and nearly 170,000 in North America, accounting for nearly 824,000 deaths worldwide.

5. The numbers of Chernobyl victims will continue to increase for several generations.

15.5. Chernobyl Releases and Environmental Consequences

1. Displacement of the long half-life Chernobyl radionuclides by water, winds, and migrating animals causes (and will continue to cause) secondary radioactive contamination hundreds and thousands of kilometers away from the Ukrainian Chernobyl Nuclear Power Station.

2. All the initial forecasts of rapid clearance or decay of the Chernobyl radionuclides from ecosystems were wrong: it is taking much longer than predicted because they recirculate. The overall state of the contamination in water, air,

and soil appears to fluctuate greatly and the dynamics of Sr-90, Cs-137, Pu, and Am contamination still present surprises.

3. As a result of the accumulation of Cs-137, Sr-90, Pu, and Am in the root soil layer, radionuclides have continued to build in plants over recent years. Moving with water to the above-ground parts of plants, the radionuclides (which earlier had disappeared from the surface) concentrate in the edible components, resulting in increased levels of internal irradiation and dose rate in people, despite decreasing total amounts of radionuclides from natural disintegration over time.

4. As a result of radionuclide bioaccumulation, the amount in plants, mushrooms, and animals can increase 1,000-fold as compared with concentrations in soil and water. The factors of accumulation and transition vary considerably by season even for the same species, making it difficult to discern dangerous levels of radionuclides in plants and animals that appear to be safe to eat. Only direct monitoring can determine actual levels.

5. In 1986 the levels of irradiation in plants and animals in Western Europe, North America, the Arctic, and eastern Asia were sometimes hundreds and even thousands of times above acceptable norms. The initial pulse of high-level irradiation followed by exposure to chronic low-level radionuclides has resulted in morphological, physiological, and genetic disorders in all the living organisms in contaminated areas that have been studied—plants, mammals, birds, amphibians, fish, invertebrates, bacteria, and viruses.

6. Twenty years after the catastrophe all game animals in contaminated areas of Belarus, Ukraine, and European Russia have high levels of the Chernobyl radionuclides. It is still possible to find elk, boar, and roe deer that are dangerously contaminated in Austria, Sweden, Finland, Germany, Switzerland, Norway, and several other countries.

7. All affected populations of plants and animals that have been the subjects of detailed studies exhibit a wide range of morphological deformities that were rare or unheard of prior to the catastrophe.

8. Stability of individual development (determined by level of fluctuating symmetry—a specific method for detecting the level of individual developmental instability) is lower in all the plants, fishes, amphibians, birds, and mammals that were studied in the contaminated territories.

9. The number of the genetically anomalous and underdeveloped pollen grains and spores in the Chernobyl radioactively contaminated soils indicates geobotanical disturbance.

10. All of the plants, animals, and microorganisms that were studied in the Chernobyl contaminated territories have significantly higher levels of mutations than those in less contaminated areas. The chronic low-dose exposure in Chernobyl territories results in a transgenerational accumulation of genomic instability, manifested in cellular and systemic effects. The mutation rates in some organisms increased during the last decades, despite a decrease in the local level of radioactive contamination.

11. Wildlife in the heavily contaminated Chernobyl zone sometimes appears to flourish, but the appearance is deceptive. According to morphogenetic, cytogenetic, and immunological tests, all of the populations of plants, fishes, amphibians, and mammals that were studied there are in poor condition. This zone is analogous to a "black hole"—some species may only persist there via immigration from uncontaminated areas. The Chernobyl zone is the microevolutionary "boiler," where gene pools of living creatures are actively transforming, with unpredictable consequences.

12. What happened to voles and frogs in the Chernobyl zone shows what can happen to humans in coming generations: increasing mutation rates, increasing morbidity and mortality, reduced life expectancy, decreased intensity of reproduction, and changes in male/female sex ratios.

13. For better understanding of the processes of transformation of the wildlife in the

Chernobyl-contaminated areas, radiobiological and other scientific studies should not be stopped, as has happened everywhere in Belarus, Ukraine, and Russia, but must be extended and intensified to understand and help to mitigate expected and unexpected consequences.

15.6. Social and Environmental Efforts to Minimize the Consequences of the Catastrophe

1. For hundreds of thousands of individuals (first of all, in Belarus, but also in vast territories of Ukraine, Russia, and in some areas of other countries) the additional Chernobyl irradiation still exceeds the considered "safe" level of 1 mSv/year.

2. Currently for people living in the contaminated regions of Belarus, Ukraine, and Russia, 90% of their irradiation dose is due to consumption of contaminated local food, so measures must be made available to rid their bodies of incorporated radionuclides (see Chapter IV.12–14).

3. Multiple measures have been undertaken to produce clean food and to rehabilitate the people of Belarus, Ukraine, and European Russia. These include application of additional amounts of select fertilizers, special programs to reduce levels of radionuclides in farm products and meat, organizing radionuclide-free food for schools and kindergartens, and special programs to rehabilitate children by periodically relocating them to uncontaminated places. Unfortunately these measures are not sufficient for those who depend upon food from their individual gardens, or local forests, and waters.

4. It is vitally necessary to develop measures to decrease the accumulation of Cs-137 in the bodies of inhabitants of the contaminated areas. These levels, which are based upon available data concerning the effect of incorporated radionuclides on health, are 30 to 50 Bq/kg for children and 70 to 75 Bq/kg for adults. In some Belarus villages in 2006 some children had levels up to 2,500 Bq/kg!

5. The experience of BELRAD Institute in Belarus has shown that active decorporation measures should be introduced when Cs-137 levels become higher than 25 to 28 Bq/kg. This corresponds to 0.1 mSv/year, the same level that according to UNSCEAR a person inevitably receives from external irradiation living in the contaminated territories.

6. Owing to individual and family food consumption and variable local availability of food, permanent radiation monitoring of local food products is needed along with measurement of individual radionuclide levels, especially in children. There must be general toughening of allowable local food radionuclide levels.

7. In order to decrease irradiation to a considered safe level (1 mSv/year) for those in contaminated areas of Belarus, Ukraine, and Russia it is good practice to:

- Apply mineral fertilizers not less than three times a year on all agricultural lands, including gardens, pastures, and hayfields.
- Add K and soluble lignin to forest ecosystems within a radius up to 10 km from settlements for effective reduction of Cs-137 in mushrooms, nuts, and berries, which are important local foods.
- Provide regular individual intake of natural pectin enterosorbents (derived from apples, currants, etc.) for 1 month at least four times a year and include juices with pectin daily for children in kindergartens and schools to promote excretion of radionuclides.
- Undertake preventive measures for milk, meat, fish, vegetables, and other local food products to reduce radionuclide levels.
- Use enterosorbents (ferrocyanides, etc.) when fattening meat animals.

8. To decrease the levels of illness and promote rehabilitation it is a good practice in the contaminated areas to provide:

- Annual individual determination of actual levels of incorporated radionuclides using a whole-body radiation counter (for children, this must be done quarterly).
- Reconstruction of all individual external irradiation levels from the initial period after the catastrophe using EPR-dosimetry and measurement of chromosomal aberrations, etc. This should include all victims, including those who left contaminated areas—liquidators, evacuees, and voluntary migrants and their children.
- Obligatory genetic consultations in the contaminated territories (and voluntary for all citizens of childbearing age) for the risks of severe congenital malformations in offspring. Using the characteristics and spectra of mutations in the blood or bone marrow of future parents, it is possible to define the risk of giving birth to a child with severe genetic malformations and thus avoid family tragedies.
- Prenatal diagnosis of severe congenital malformations and support for programs for medical abortions for families living in the contaminated territories of Belarus, Ukraine, and Russia.
- Regular oncological screening and preventive and anticipatory medical practices for the population of the contaminated territories.

9. The Chernobyl catastrophe clearly shows that it is impossible to provide protection from the radioactive fallout using only national resources. In the first 20 years the direct economic damage to Belarus, Ukraine, and Russia has exceeded 500 billion dollars. To mitigate some of the consequences, Belarus spends about 20% of its national annual budget, Ukraine up to 6%, and Russia up to 1%. Extensive international help will be needed to protect children for at least the next 25 to 30 years, especially those in Belarus because radionuclides remain in the root layers of the soil.

10. Failure to provide stable iodine in April 1986 for those in the contaminated territories led to substantial increases in the number of victims. Thyroid disease is one of the first consequences when a nuclear power plant fails, so a dependable system is needed to get this simple chemical to all of those in the path of nuclear fallout. It is clear that every country with nuclear power plants must help all countries stockpile potassium iodine in the event of another nuclear plant catastrophe.

11. The tragedy of Chernobyl shows that societies everywhere (and especially in Japan, France, India, China, the United States, and Germany) must consider the importance of independent radiation monitoring of both food and individual irradiation levels with the aim of ameliorating the danger and preventing additional harm.

12. Monitoring of incorporated radionuclides, especially in children, is necessary around every nuclear power plant. This monitoring must be independent of the nuclear industry and the data results must be made available to the public.

15.7. Organizations Associated with the Nuclear Industry Protect the Industry First—Not the Public

1. An important lesson from the Chernobyl experience is that experts and organizations tied to the nuclear industry have dismissed and ignored the consequences of the catastrophe.

2. Within only 8 or 9 years after the catastrophe a universal increase in cataracts was admitted by medical officials. The same occurred with thyroid cancer, leukemia, and organic central nervous system disorders. Foot-dragging in recognizing obvious problems and the resultant delays in preventing exposure and mitigating the effects lies at the door of nuclear power advocates more interested in preserving the status quo than in helping millions of innocent people who are suffering through no fault of their own. It need to change official agreement between WHO and IAEA (WHO, 1959) providing hiding from public of any

information which can be unwanted of nuclear industry.

15.8. It Is Impossible to Forget Chernobyl

1. The growing data about of the negative consequences of the Chernobyl catastrophe for public health and nature does not bode well for optimism. Without special large-scale national and international programs, morbidity and mortality in the contaminated territories will increase. Morally it is inexplicable that the experts associated with the nuclear industry claim: "It is time to forget Chernobyl."

2. Sound and effective international and national policy for mitigation and minimization of Chernobyl's consequences must be based on the principle: "It is necessary to learn and minimize the consequences of this terrible catastrophe."

15.9. Conclusion

U.S. President John F. Kennedy speaking about the necessity to stop atmospheric nuclear tests said in June 1963:

> . . . The number of children and grandchildren with cancer in their bones, with leukemia in their blood, or with poison in their lungs might seem statistically small to some, in comparison with natural health hazards, but this is not a natural health hazard—and it is not a statistical issue. The loss of even one human life or the malformation of even one baby—who may be born long after we are gone—should be of concern to us all. Our children and grandchildren are not merely statistics toward which we can be indifferent.

The Chernobyl catastrophe demonstrates that the nuclear industry's willingness to risk the health of humanity and our environment with nuclear power plants will result, not only theoretically, but practically, in the same level of hazard as nuclear weapons.

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Conclusion to Chapter IV

In the last days of spring and the beginning of summer of 1986, radioactivity was released from the Chernobyl power plant and fell upon hundreds of millions of people. The resulting levels of radionuclides were hundreds of times higher than that from the Hiroshima atomic bomb.

The normal lives of tens of millions have been destroyed. Today, more than 6 million people live on land with dangerous levels of contamination—land that will continue to be contaminated for decades to centuries. Thus the daily questions: how to live and where to live?

In the territories contaminated by the Chernobyl fallout it is impossible to engage safely in agriculture; impossible to work safely in forestry, in fisheries, and hunting; and dangerous to use local foodstuffs or to drink milk and even water. Those who live in these areas ask how to avoid the tragedy of a son or daughter born with malformations caused by irradiation. Soon after the catastrophe these profound questions arose among liquidators' families, often too late to avoid tragedy.

During this time, complex measures to minimize risks in agriculture and forestry were developed for those living in contaminated territories, including organizing individual radiation protection, support for radioactive-free agricultural production, and safer ways to engage in forestry.

Most of the efforts to help people in the contaminated territories are spearheaded by state-run programs. The problem with these programs is the dual issue of providing help while hoping to minimize charges that Chernobyl fallout has caused harm.

To simplify life for those suffering irradiation effects a tremendous amount of educational and organizational work has to be done to monitor incorporated radionuclides, monitor (without exception) all foodstuffs, determine individual cumulative doses using objective methods, and provide medical and genetic counseling, especially for children.

More than 20 years after the catastrophe, by virtue of the natural migration of radionuclides the resultant danger in these areas has not decreased, but increases and will continue to do so for many years to come. Thus there is the need to expand programs to help people still suffering in the contaminated territories, which requires international, national, state, and philanthropic assistance.