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The Other Report on Chernobyl (TORCH)

An independent scientific evaluation of the health-related effects of the Chernobyl nuclear disaster with critical analyses of recent IAEA/WHO reports

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Any errors, of course, remain the sole responsibility of the authors.

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EXECUTIVE SUMMARY

The main conclusions of the report are

- about 30,000 to 60,000 excess cancer deaths are predicted, 7 to 15 times greater than the figure of 4,000 in the IAEA/WHO's press release of September 5, 2005
- predictions of excess cancer deaths strongly depend on the risk factor used
- predicted excess cases of thyroid cancer range between 18,000 and 66,000 in Belarus alone, depending on the risk projection model
- other solid cancers with long latency periods are beginning to appear 20 years after the accident
- Belarus, Ukraine and Russia were heavily contaminated, but more than half of Chernobyl's fallout was deposited outside these countries
- fallout from Chernobyl contaminated about 40% of Europe's surface area
- collective dose is estimated to be about 600,000 person Sv, more than 10 times greater than the 55,000 figure presented by the IAEA/WHO in 2005
- about 2/3rds of Chernobyl's collective dose was distributed to populations outside Belarus, Ukraine and Russia, especially to western Europe
- Cs-137 released from Chernobyl is estimated to be about a third higher than official estimates

Recent IAEA/WHO studies

Our verdict on the two recent IAEA/WHO studies on Chernobyl's health and environmental effects respectively is mixed. On the one hand, we recognise that the reports contain comprehensive examinations of Chernobyl's effects in Belarus, Ukraine and Russia. On the other hand, the reports are silent on Chernobyl's effects outside these countries. Although areas of Belarus, Ukraine and Russia were heavily contaminated, most of Chernobyl's fallout was deposited outside these countries. Collective doses from Chernobyl's fallout to populations in the rest of the world, especially in western Europe, are twice those to populations in Belarus, Ukraine and Russia. This means that these populations will suffer twice as many predicted excess cancer deaths, as the populations in Belarus, Ukraine and Russia.

The failure to examine Chernobyl's effects in the other countries does not lie with the scientific teams but within the policy-making bodies of IAEA and WHO. In order to rectify this omission, we recommend that the WHO, independently of the IAEA, should commission a report to examine Chernobyl's fallout, collective doses and effects in the rest of the world, particularly in western Europe.

The Report: Chernobyl after 20 Years

The report provides an impartial scientific examination of mainly health-related effects of Chernobyl and critically examines recent official reports on Chernobyl. The report contains an Afterword which sets out a first-hand account of the poor health situation in Ukraine by a respected academic from that country. The same situations apply in Belarus and the Russian Federation.

The main chapters of the report cover

- source term
- dispersal and deposition
- health effects
- collective doses and
- predicted excess cancer deaths

Chapter 2 discusses official estimates of the total amount of radioactivity released by the explosions and subsequent fire at Chernobyl. This is called the “source term” and is important because it can verify nuclide depositions throughout Europe and the northern hemisphere. From these, collective doses and predicted excess deaths may be estimated. The most important nuclides are caesium-137 and iodine-131. Our estimate for Cs-137 is about 30% larger than the official IAEA/WHO estimate, and for I-131 about 15% larger.

Chapter 3 illustrates the extremely wide dispersal of Chernobyl fallout over the entire northern hemisphere. 40% of the surface area of Europe was contaminated by Cs-137 to levels greater than 4 kBq/m^2, and 2.3% to levels greater than 40 kBq/m^2: the IAEA/WHO only report the latter data. Moreover, the UNSCEAR and recent IAEA/WHO reports do not discuss Chernobyl fallout and radiation doses in any other country apart from Belarus, Ukraine and Russia: they fail to mention the comprehensive datasets on Chernobyl contamination in Europe published by the EC.

Countries with more than 80% of their surface areas contaminated to levels greater than 4 kBq/m^2 Cs-137 were Moldova, Turkey (the European part), Slovenia, Switzerland, Austria, and the Slovak Republic. 44% of the land area of Germany and 34% of the UK were similarly contaminated. Countries with more than 5% of their surface area contaminated to levels greater than 40 kBq/m^2 were Belarus, Austria, Ukraine, Finland and Sweden. See Annex 3A.

The high levels of Chernobyl fallout resulted in countermeasures and restrictions on contaminated foodstuffs in many areas of Europe. Some continue to this day. In the UK, restrictions remain on 375 farms and 215,000 sheep, particularly in Wales. Similar situations exist in parts of Sweden and Finland as regards stock animals, including reindeer in natural environments. Boar, deer, wild mushrooms, berries and carnivore fish from lakes in certain regions of Germany, Austria, Italy, Sweden, Finland, Lithuania and Poland still have relatively high Cs-137 contamination levels. In the south of Germany, wild boar remains highly contaminated by Cs-137: soil Cs-137 contamination levels are still as high as 100,000 Bq/kg in parts of the Bavarian forest.

Cs-137 contamination levels will remain high for many years into the future governed by the 30 year half-life of caesium-137.

Chapter 4 discusses the incidences of thyroid cancer, leukaemias, solid cancers and non-cancer effects appearing in Belarus, Ukraine and Russia and elsewhere.

Up to 2005, about 4,000 cases of **thyroid cancer** have occurred in Belarus, Ukraine and Russia in those aged under 18 at the time of the accident. There have been two reports of possible increases in thyroid cancer in the Czech Republic and the UK. Depending on the risk model used, estimates of future excess cases of thyroid cancer range between 18,000 and 66,000. The lower estimate assumes a constant relative risk for 40 years after exposure; the higher assumes a constant relative risk over the whole of life. Recent studies may suggest the latter risk projection.

The evidence for **leukemia** is less clear-cut, but some evidence exists for increased incidences in Russian cleanup workers and residents of highly contaminated areas in Ukraine. Better estimates are expected in the near future from on-going studies. Three studies appear to show an increased rate of childhood leukaemia as a result of Chernobyl fallout in West Germany, Greece and Belarus. The preliminary ECLIS study also found a small increase in leukaemia incidence over the whole of Europe.

Most solid cancers have long latency periods of between 20 – 60 years. Now that 20 years has passed since the accident, solid cancers are beginning to appear. An average 40% increase in **solid cancer** incidence was observed in Belarus with most pronounced increase in the most contaminated region. The IAEA/WHO acknowledges preliminary evidence of an increase in the incidence of pre-menopausal **breast cancer** among women exposed at ages lower than 45 years. This was confirmed in Pukkala *et al* (in press), soon to be published.

Two non-cancer effects that are well-documented and for which there is clear evidence of a Chernobyl connection are **cataract induction** and **cardiovascular disease**. Studies in Belarus have suggested a twofold increase in germline **minisatellite mutation** rate. However it remains unclear what clinical symptoms, if any, will result from these changes: this matter requires further study over longer time periods. The **mental health impact** of Chernobyl remains considerable. Massive relocation, loss of economic stability, long-term threats to health in current and possibly future generations, have resulted in increased anomie, diminished confidence, high levels of anxiety and medically unexplained physical symptoms which continue to this day.

Chapter 5 estimates that the world-wide total for the collective dose from Chernobyl fallout is 600,000 person Sv making Chernobyl the worst nuclear accident by a considerable margin. The IAEA/WHO report does not estimate world-wide or Europe-wide collective doses. For collective dose to Belarus, Ukraine and Russia, estimates range from >300,000 person Sv to the IAEA/WHO's estimate of 55,000 person Sv.

Chapter 6 discusses predicted excess cancer deaths from the above collective doses. For Belarus, Ukraine and Russia, published estimates range between 4,000 and 22,000. For the world, published estimates range between 14,000 and 30,000. These estimates depend heavily on the risk factor used: different scientists use different factors. The risk factor used needs to be made explicit. Recent studies indicate that currently-used risks from low doses at low dose rates may need to be increased.

Chapter 1. Introduction

1. On April 26 2006, 20 years will have passed since the world's worst industrial accident. The disaster is now a generation away, yet the word 'Chernobyl' still resonates throughout the world, and its effects are still apparent particularly in Belarus, Ukraine and Russia, the three countries most affected by the disaster. As this report will show, Chernobyl fallout also seriously contaminated other areas of the world. In the United Kingdom, for example, over 2,500 kilometers from Chernobyl, more than 360 farms are still subject to restrictions because of Chernobyl contamination. Ultimately, fallout from Chernobyl was distributed over the entire northern hemisphere.

Aims of the Report

2. The report aims to provide an impartial scientific examination of mainly health-related effects of Chernobyl, and to critically examine recent official reports on Chernobyl from a European point of view. Although the subject matter of the report is clearly scientific, we have tried to write the report in plain English ensuring we explain our terms and avoid jargon, in order to make the report more accessible to members of the public. In some cases, the complexity of the matter may have defeated our intentions, but we have tried to keep the report simple and understandable.

3. The five main chapters of the report cover source term matters, dispersal and deposition issues, health effects, collective doses and predicted excess cancer deaths. Chapter 2 discusses official estimates of the total amount of radioactivity released by the explosions and subsequent fire at Chernobyl. This chapter derives our own estimates of the releases of the most important nuclides, Cs-137 and I-131, which are greater than official estimates. Chapter 3 illustrates the extremely wide diffusion of Chernobyl fallout over Europe and the northern hemisphere. Chapter 4 discusses the incidences of thyroid cancer, leukaemias, solid cancers and non-cancer effects appearing in Belarus, Ukraine and Russia and elsewhere. Chapter 5 estimates collective dose estimates world-wide, and Chapter 6 predicts excess cancer deaths from Chernobyl fallout.

Scope and Limitations

4. Several hundred official and unofficial reports and books have been written about Chernobyl. Web searches for the word "Chernobyl" reveal over 38,000 scientific citations in Google Scholar and about 3,000 peer-reviewed articles in scientific journals in PubMed (http://www.ncbi.nlm.nih.gov/entrez/). Therefore it was necessary to focus on what to us were the most important issues: source term, dispersal and deposition, health effects, collective doses and predicted excess cancer deaths. Unfortunately, the time available did not permit us to examine the socio-economic effects of the disaster, the ecologic effects (see Moller and Mousseaux, 2006; Moller *et al*, 2005) and the present state of the destroyed reactor at Chernobyl and its sarcophagus. These serious subjects deserve detailed examination in other reports.

5. Our emphasis on a scientific approach means that we have relied mainly on scientific articles published in peer-reviewed journals. Mainly but not exclusively: we have also

referenced articles from non-published sources including the websites of a number of international research institutes. Our main criteria for inclusion were whether the authors had approached their subject critically and had been scientifically rigorous with their evidence. Inevitably, there remains an element of subjectivity in our choice of references, and there may well be articles which have escaped our attention.

6. In addition, our work has been inevitably limited by the difficulties in gaining access to, and translating, many scientific reports written in Ukrainian and Russian. These constraints inhibit a full understanding of the impacts of Chernobyl, and we draw attention to this difficulty and to the need for it to be tackled at an official level. Our research has also been limited by the failure to publish their findings on cancer incidences - for example, the ECLIS programme on childhood leukaemias in European countries. Also, our report is a 'snapshot' of a moving scene: much Chernobyl-related research is still underway and new findings may well change our understanding of radiation's effects, just as they have in the past 20 years.

Radiation and Radioactivity

7. Radiation and radioactivity (including their risks, doses, biology and epidemiology) are complex matters which are not easily understood. This brief report does not discuss radiation and radioactivity in detail as this would require a book in itself. However we do provide a note on radiation dose units (see Annex 4), a list of acronyms (see end of report) and a reading list of the more critical articles and books for those interested in learning more about radiation (see end of this chapter). Perhaps the most recent and accessible introduction to radiation and radioactivity in English is the report of the UK Government's Committee Examining the Radiation Risks of Internal Emitters (CERRIE, 2004) which can be downloaded from www.cerrie.org . The CERRIE Committee contained independent scientists and representatives of environmental organisations as well as scientists from official agencies: its report therefore contains a spectrum of views.

8. Although we do not discuss radiation *per se*, we should mention some ancillary matters to radiation, including uncertainty, the limitations of epidemiology and the wide disparity of views on radiation risks.

Uncertainty

9. Many uncertainties surround risk estimates from radiation exposures. The most fundamental is that we are unsure of the dose-response relationship at very low doses. The current theory is that this relationship is linear without threshold down to zero dose (Brenner *et al*, 2003). However it may be supralinear resulting in higher risks, or sublinear resulting in lower risks. See discussion in Annex 6A. The result is that risk estimates from exposures to radiation inevitably contain uncertainties. This does not prevent such estimates being made, but they have to be treated with caution.

10. Another main source of uncertainty lies in our estimates of internal radiation doses, that is, from nuclides which are inhaled or ingested. These are an important source of the radiation resulting from Chernobyl fallout. This issue was comprehensively examined in the 2004 CERRIE report which concluded that uncertainties in the internal dose coefficients[1] for some nuclides could be very large. The uncertainties in internal radiation risks could also be

[1] a dose coefficient expresses the dose given by one decay of a radionuclide in Sv per Bq

large, varying in magnitude from factors of 2 (up and down from the central estimate) in the most favourable cases, to 10 or more in the least favourable cases. These uncertainties depended on factors such as the type of radionuclide, its chemical form, the mode of exposure and the body organ under consideration. Under some circumstances, equivalent doses could be substantially greater or smaller than current best estimates; therefore great care had to be taken when judging the risks of radioactive sources inside the body.

11. The CERRIE report also advised that a precautionary approach should be used. In our view, this means that we should err on the side of caution - in other words, we should be aware that doses and risks might be greater than those presently used.

Difficulties with Epidemiology Studies

12. For a number of reasons, epidemiology studies are a blunt tool for discovering whether adverse effects result from particular exposures. Epidemiology studies may contain many methodological limitations. For example, much epidemiological data on Chernobyl is descriptive (or ecological) with poor case identification, non-uniform registration, variable or uncertain diagnostic criteria and uncertainties in the uniformity of data collation. Predicted excess deaths are often uncertain due to confounding factors, competing causes of death and different risk projection models. For example, one difficulty in interpreting Chernobyl mortality studies is the large recent decrease in average lifespan in all three countries occurring in all areas not just the contaminated ones.

13. Only very large, expensive and lengthy epidemiology studies are able to reveal effects where the signal (added cancers) is weak, and the noise (large numbers of natural cancers) is strong. Instead, we often see many small studies each showing perhaps a few extra cases which prove little. Meta-studies which group together small studies in order to strengthen their statistical significance are a solution, but few have been carried out so far. In addition, various agents can produce significant bias in studies. For example, smoking and alcohol cause major increases in overall mortality and morbidity, and in cancer and cardiovascular disease. Another problem is establishing causality. This often requires estimating doses in order to show a dose – effect relationship. However, as shown by the CERRIE report, there are often large uncertainties in estimating doses - especially from internal radiation sources which are important in Chernobyl exposures.

14. The conclusion is that there needs to be more awareness of the many factors that have to be taken into account when considering epidemiology studies. In short, the results of epidemiology studies need to be interpreted with great care.

Polarised Views on Radiation Risks

15. Widely different views exist on radiation risks between the authors of many official publications and members of the public, especially in Belarus, Ukraine and Russia. In addition, the contents of many unofficial websites reveal a lack of knowledge about radiation and its effects among many members of the public, often coupled with an apparent fear of radiation. It's also apparent that a substantial number of people in Belarus, Ukraine and Russia are suspicious of Governments and official agencies with pro-nuclear policies, seeing them as having an interest in minimising the effects of radiation and controlling public

perceptions about the risks. They are therefore often hostile towards official publications on radiation risks whose findings, in their view, do not match their own experiences.

16. Many unofficial accounts have criticised official reports on the health effects from Chernobyl, in particular for their reluctance to acknowledge the existence of increased effects and their practice of denying links between such increases and radiation from the accident. Notably, during the IAEA/WHO Conference on Chernobyl in Vienna in September 2005, officials from health ministries and academic institutions in Belarus and Ukraine spoke out against the refusals of their Governments and international agencies to recognise what was, in their view, the true scale of Chernobyl's effects.

17. Outspoken criticisms have been made by Malko (1998b) who has accused the international radiation protection community of being unable to objectively assess the health consequences of the accident. He has stated that the international radiation protection community had attempted to play down the consequences from the beginning. He gave numerous examples of official refusals to accept the existence of data from their own health ministries and of their far-fetched explanations for observed effects. Perhaps the most disheartening example was the WHO's initial explanation in 1992 for the large increases in childhood thyroid cancer in Belarus. These were allegedly due to (a) the administration of prophylactic iodine to children after the accident and (b) nitrates in food brought into the country from Asia (Nucleonics Week, 1992).

18. Some agencies have dramatically changed their views on radiation's effects, without discussing the reasons for doing so. One example is the decision by UNSCEAR after about 1998 not to discuss global collective doses from Chernobyl - see chapter 5. In addition, some Governments and official agencies have refused to recognise the data and reports by other official agencies. The Director General of the IAEA, Mr Elbaradei highlighted this when he stated (IAEA/WHO, 2005b)

> "…a lack of trust still prevails … due in part to contradictory data and reports on the precise environmental and health impacts of the accident, among national authorities as well as among the relevant international organizations"

19. It is necessary to tread warily in this battleground of views and values. Nevertheless, it is worth pointing out that, while some official reports may contain equivocations, omissions, misleading language and understatements, others are more forthright and transparent. In our experience, a significant minority of scientists working in official international and national agencies do not necessarily agree with the downplaying of radiation effects. In other words, it would be unwise to reject all official reports, as they sometimes contain valuable information and insights. What are needed instead are critical and discriminating examinations of official reports. We have attempted to do this here, while avoiding both the understatements in some official reports and the discussions of effects clearly not due to radiation in some unofficial reports.

Recommended Reading List

Caufield C (1990) Multiple Exposures: Chronicles of the Radiation Age. Penguin Books. London UK

CERRIE (2004) Committee Examining the Radiation Risks of Internal Emitters www.cerrie.org

Gofman JW (1981) Radiation and Human Health. A Comprehensive Investigation of the Evidence Relating Low-level Radiation to Cancer and Other Diseases. Sierra Club Books. San Francisco

Greenberg M (1991) The Evolution of Attitudes to the Human Hazards of Ionising Radiation and to its Investigators. Am J of Industrial Medicine Vol 20 pp 717-721

Greene G (1999) The Woman Who Knew Too Much. University of Michigan Press. Ann Arbor, MI, US

Lambert B (1990) How Safe is Safe? Radiation Controversies Explained. Unwin. London UK (Out of print but copies may be available in libraries. A good introduction but now out of date.)

Proctor RN (1995) Cancer Wars: How Politics Shapes What We Know and Don't Know about Radiation. Basic Books. New York, NY, US

Rose G (1991) Environmental Health: Problems and Prospects. J of Royal College of Physicians of London Vol 25 No 1, pp 48-52

Stewart AM (1991) Evaluation of Delayed Effects of Ionising Radiation: an Historical Perspective. Am J of Industrial Medicine Vol 20 pp 805-810

Sumner DS, Watson D and Wheldon T (1994) Radiation Risks. Tarragon Press. (Out of print but copies may be available in libraries. A good introduction but now out of date.)

US EPA website contains a relatively unbiased but basic description of radiation and its effects http://www.epa.gov/radiation/understand/index.html

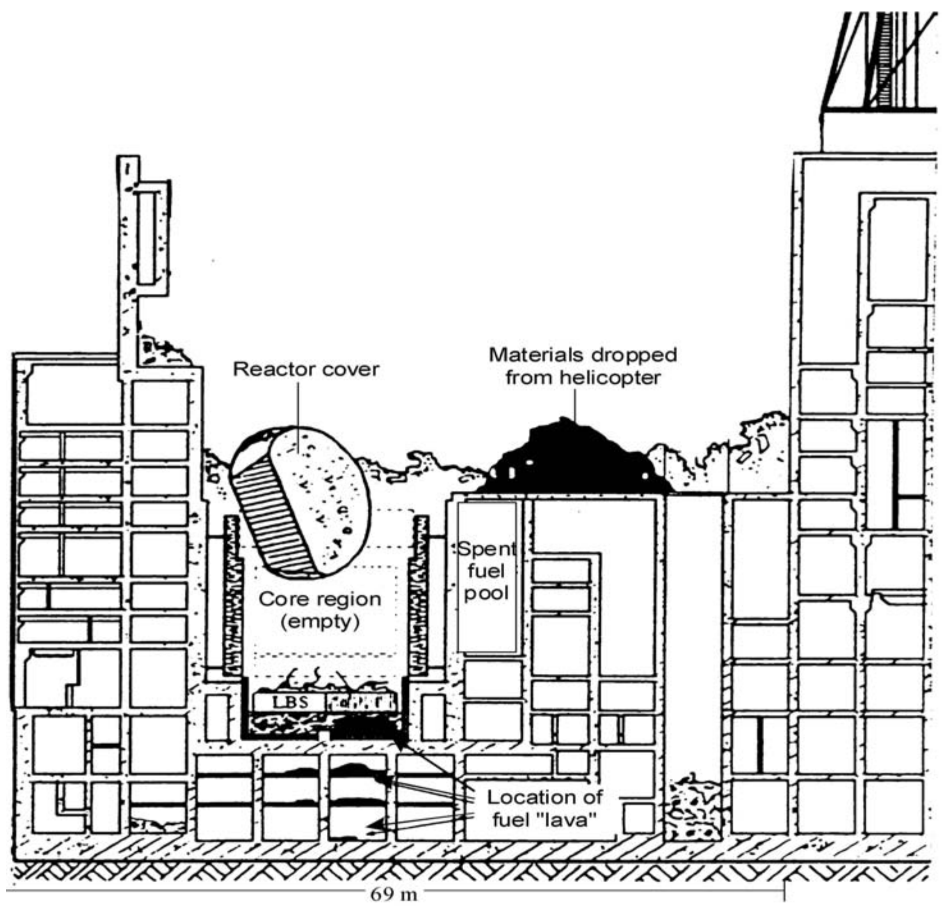
Chapter 2. The Chernobyl Accident and Source Term

The Accident

1. In April 1986, the world's worst industrial accident occurred at the Chernobyl nuclear power plant in Ukraine. The IAEA (1996) has described it as the "foremost nuclear catastrophe in human history" which resulted in the "largest regional release of radionuclides into the atmosphere." WHO (IPHECA, 1995) has estimated that, although different radionuclides were released, the total radioactivity of the material from Chernobyl was 200 times that of the combined releases from the atomic bombs dropped on Hiroshima and Nagasaki. The disaster not only resulted in an unprecedented release of radioactivity but also a series of unpredicted and serious consequences for the public and the environment.

2. Early on April 26, an explosion occurred in Chernobyl reactor 4 followed moments later by a second explosion. The explosions completely destroyed the reactor, sheared all pressure tubes and water coolant channels, and dislodged the upper biological shield weighing 1,400 tonnes. The resulting damage is shown in Figure 2.1. The explosions sent a large cloud of radioactive fission products and debris from the core and reactor 7-9 kilometres into the atmosphere (UNSCEAR, 1988). About 30% of the reactor's fuel was sprayed over the reactor building and surrounding areas and about 1-2% was ejected into the atmosphere. Most of the reactor's inventory of radioactive gases was released at this time.

Figure 2.1 Cross-section view of Chernobyl Unit 4 reactor



3. Worse was to follow. About a day later, combustible gases from the disrupted core caught fire producing flames that reached 50 m (UNSCEAR, 2000) above the reactor. This ignited the graphite moderator containing 1,700 tonnes (Hohenemser, 1988) of carbon which subsequently burned for 8 days. As explained in the OECD/NEA (1995) account (see Annex 2A), the long-lasting graphite fire was the main reason for the extreme severity of the Chernobyl disaster. The graphite fire ceased when all the carbon had been burned. Revealingly, the phrase "graphite fire" does not appear in the UNSCEAR (2000) and IAEA/WHO (2005a and 2005b) reports.

4. Much of the heat generated by the graphite fire, by radioactive decay, and possibly by continuing fission in the remaining fuel was retained by the graphite mass. As a result, temperatures in the destroyed core rose to 2,500°C according to analyses of dispersed fuel particles by Devell *et al* (1986)[2]. These temperatures led to the melting of the fuel remaining in the stricken reactor (metallic uranium melts at 1130°C; zirconium at 1850°C), the total release of gaseous nuclides and the vaporisation, to varying degrees, of volatile and less volatile nuclides. After vaporisation, it is assumed that some plating out occurred on cooler parts of the shattered reactor and its debris: much uncertainty surrounds the fractions of nuclides which condensed in this way.

5. After about 9 days, the temperature of the molten fuel rose sufficiently high to melt the reactor's lower biological shield allowing the remaining molten fuel to flow into subterranean chambers beneath the reactor. Here the fuel cooled and solidified into lava-like formations which remain today. Many reports state that this evacuation is the reason for the significant reduction in radionuclide emissions after the tenth day.

6. Nuclide emissions continued sporadically for a further 20 to 30 days but on a much reduced scale. At the end, the reactor core contained neither fuel nor graphite moderator. During the fire, many tonnes of borated lead and other materials were dropped by helicopter into the reactor in an attempt to extinguish the graphite fire but it appears little reached its target: most fell to one side (Sich, 1996). See figure 2.1. Annex 2A contains a technical description of the disaster by the OECD/NEA (1995) which reveals the serious predicaments resulting from the catastrophic events of April/May 1986.

Source Term

7. Much debate has surrounded the magnitude of the Chernobyl "source term," that is, the amount of radioactivity released from the Chernobyl disaster. Although many reports have been written on Chernobyl's radioactive releases, unfortunately they often raise as many questions as answers. The source term is important because it can be used to verify nuclide depositions throughout Belarus, Ukraine, Russia, the rest of Europe[3] and the northern hemisphere. From these, collective doses and predicted excess deaths may be estimated.

8. Source terms may be estimated in two main ways

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[2] Devell *et al* collected and analysed radioactive fuel particles by electron microscopy. They concluded from their form and composition that the temperature in at least part of the reactor core reached ~2,500°C.
[3] "Europe" has a slightly elastic geographical extent. In this report, Europe extends eastwards to the Ural mountains, that is, it includes some of Russia, all of Ukraine, and all of Belarus.

(i) The first is to use computer programs which model the atmospheric dispersal of pollutants. Fallouts are averaged over blocks of territory and are integrated over space and time. Early efforts at assessing radioactivity source terms using these models produced very low estimates. This was partly because the blocks used were too large in space and time, and partly because rainfall was very localized, so average deposition densities over large areas were inaccurate. Later, more sophisticated attempts were made using extensive gamma measurements and mapping techniques with satellite Geographic Information Systems (European Commission, 1998).

(ii) The second is to estimate the amounts of fission and activation products in the reactor before the accident by using computer programs (such as FISPIN, ORIGEN2, etc) which calculate fuel isotope inventories in reactors. The source term is the difference between the reactor fuel's isotope inventory and the estimated amounts of nuclides in the fuel remaining beneath or nearby the reactor.

Both methods have their drawbacks, particularly their use of questionable assumptions, and both produce estimates with significant uncertainties. The second method produces more realistic estimates and is perhaps burdened with fewer uncertainties.

9. The source term was not used in estimating doses to the affected populations in the three former Soviet republics of Belarus, Ukraine and Russia: these were derived from measured nuclide concentrations and dose reconstructions. Here, measured concentrations were used with external and internal dose factors[4] to estimate doses over various time periods. This method has been criticised because of the lack of data on the habits and diets of local populations: these data are important in assessing internal doses from ingestion and inhalation of nuclides which are responsible for about half of the radiation dose to inhabitants of heavily contaminated areas.

10. In the early years after Chernobyl, large uncertainties existed in initial estimates of the fuel inventory and the amounts which remained, due to the inaccuracy and inadequacy of the Soviet data provided at the time. In subsequent years, later estimates were made (reviewed by Khan, 1990) using the second of the above methods. Ten years later, attempts were made to harmonise estimates and develop a consensus view on the source term (see Devell *et al*, 1995), which were only partially successful. At the same time, reports by Sich (1994, 1994a, 1996) and Borodin and Sich (1996) gave additional information on the fate of the fuel in the stricken reactor.

11. In 2000, UNSCEAR estimated that the total radioactive material released from Chernobyl was 12×10^{18} becquerels (Bq)[5] including 6.5×10^{18} Bq of noble gases, mainly krypton and xenon (12×10^{18} means 12 followed by 18 zeroes). According to UNSCEAR (2000), 100% of gases, and 20 - 60% of volatile radionuclides, were released into the atmosphere and carried for large distances. In addition, ~30% of the reactor's fuel was ejected to areas around the reactor during the initial explosions and ~1 - 2% of the fuel was more widely dispersed.

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[4] which relate the absorbed dose in Sv to the degree of land contamination

[5] the amount of a radionuclide is expressed in terms of its 'activity', that is, the number of spontaneous nuclear disintegrations per second releasing radiation. Its unit is the becquerel (Bq). 1 Bq = 1 disintegration per second.

12. UNSCEAR (2000) did not discuss a number of studies - see table 2.2 – which cited larger releases of important nuclides. The UNSCEAR (2000) conclusions were subsequently reiterated in the WHO/IAEA (2005a) report without qualification or discussion. In our view, there is no up-to-date critical discussion of the Chernobyl source term that takes these factors into account. The present report tries to fill this gap and, in particular, attempts to estimate the amounts of Cs-137 and I-131 released from Chernobyl.

Reactor Inventory

13. The reactor contained about 190 tonnes of nuclear fuel, 1,700 tonnes of graphite moderator, and a very large volume of cooling water. The fuel elements mainly consisted of mainly (>95%) uranium oxide. The reactor had been operating since 1983 and its fuel had an average burnup of 11 GWdays per tonne. Therefore it contained considerable quantities of fission products (eg caesium-137) and activation products (eg plutonium 239). The explosions ejected about a third of the fuel, mostly to nearby areas; the continuing graphite fire resulted in much wider releases of fission and activation products.

14. The fission products iodine-131, caesium-134 and caesium-137 have the most radiological significance. Iodine-131 with its short radioactive half-life of 8 days had the greater radiological impact in the short term because of its doses to thyroid. Caesium-134 (half-life = 2 years) and caesium-137 (half-life = 30 years) have the greater radiological impacts in the medium and long terms. Very small amounts of Cs-134 now remain but for the first two decades after 1986, it was an important contributor to doses because of its relatively high dose coefficient[6]. Although strontium-90 also has a relatively long half-life of 29 years and a high dose coefficient, measurements indicate that relatively little (~5%) was released as it is less volatile. Most was deposited within 100 km or so of the reactor. Also relevant are tellerium-132 (half-life = 3.3 days) as the parent of I-132 (half-life = 2.3 hours), and Te-129m (half-life = 33.6 days) as the parent of I-129 (half-life = 16 million years).

15. The latest official estimates (UNSCEAR, 2000; IAEA/WHO, 2005b) of initial nuclide inventories and activities released for the most relevant nuclides are set out in table 2.1. The percentages released were omitted in the official reports but they have been calculated (by dividing each nuclide's release by its initial inventory) and are presented in the final column. Note that many of the official figures are qualified by the tilde sign "~", meaning "approximately". Percentage releases are discussed further in paragraphs 19 and 20 below.

16. Some tables in this report contain greyed columns or cells. These contain data or estimates prepared by this report. Normal unshaded columns contain data or estimates from other reports.

Table 2.1 Initial nuclide inventories and amounts released for key nuclides released from Chernobyl PBq = 10^{15} Bq

Radio nuclide	Half-life	Core Inventory on April 26 1986 - PBq	Activity Released - PBq	Estimated Percentage Released
INERT GASES				
Kr-85	10.72 a	33	33	100
Xe-133	5.25 d	6,500	6,500	100
VOLATILE ELEMENTS				

[6] ie high values of Sv per Bq (delivering high radiation doses to persons who inhale or ingest the nuclide)

Te-129m	33.6 d	1040	240	23
Te-132	3.26 d	4200	~1,150	~27
I-129	15,700,000 a	8.1×10^{-5}	$\sim 8 \times 10^{-5}$	~50
I-131	8.04 d	3180	~1,760	~56
I-133	20.8 h	6700	2,500	37
Cs-134	2.06 a	150	~54	~36
Cs-136	13.1 d	110	36	33
Cs-137	30.0 a	260	~85	~33
ELEMENTS WITH INTERMEDIATE VOLATILITY				
Sr-89	50.5 d	3960	~115	~3
Sr-90	29.12 a	220	~10	~4.5
Ru-103	39.3 d	4810	>168	>3.5
Ru-106	368 d	850	>73	>8.6
Ba-140	12.7 d	4800	240	5
REFRACTORY ELEMENTS (incl fuel fragments*)**				
Zr-95	64.0 d	4810	196	4
Mo-99	2.75 d	5550	> 168	>3
Ce-141	32.5 d	5550	196	3.5
Ce-144	284 d	3920	~ 116	~3
Np-239	2.35 d	58,100	945	1.6
Pu-238	87.74 a	0.93	0.035	3.7
Pu-239	24,065 a	0.96	0.03	3
Pu-240	6,537 a	1.5	0.042	3
Pu-241	14.4 a	190	~6	~3.2
Pu-242	376,000 a	0.0021	0.00009	4.3
Cm-242	18.1 a	31	~0.9	~3

sources: UNSCEAR (2000) and Dreicer *et al* (1996)
*** Based on fuel particle release of 1.5% (Kashparov *et al*, 2003)
Shaded column – derived in this report by dividing column 4 values by column 3 values

17. Most of the radionuclides in table 2.1 will have completely decayed by now. Over the next few decades, interest will continue to focus on Cs-137, with secondary attention on Sr-90 which is more important in areas near Chernobyl. Over the longer term (hundreds to thousands of years), the radionuclides of continuing interest will be the activation products, including the isotopes of plutonium, neptunium and curium. The only radionuclide expected to increase in the coming years is americium-241 which arises from the decay of plutonium-241; the amount of americium-241 will reach a maximum about 100 years after 1986. Doses from americium-241 are expected to be small in comparison with those from Cs-137.

Release Estimates for Main Nuclides

18. Our focus is primarily on the main nuclides mentioned above: tables 2.2 and 2.3 set out published estimates of the percentages released and source terms.

Table 2.2 Estimates of percentage of core inventory released

Study	Cs-137	Cs-134	Sr-90	I-131	Te-132
US DoE Anspaugh *et al*, 1988	40% - 60%	40% - 60%	-	40% - 60%	40% - 60%
Gudikson *et al*, 1989	40%	40%	-	60%	-
Seo *et al*, 1989	57%	-	9%	70%	-
OECD, 1995	20%-40%	20%-40%	4%-6%	50%-60%	25-60%[2]
Sich, 1996	30%	33%	-	41%	15%
Devell *et al*, 1996	33%+10%[1]	33%+10%[1]	4% -6%	50% - 60%	25-60%[2]
Borovoi *et al*, 2001	33%±10%	33%±10%	-	50% - 60%	-
UNSCEAR, 2000 IAEA/WHO, 2005b	~33%	36%	~4.5%	~56%	~27%

1 table data in Devell *et al*, 1996 states “+” without explanation
2 Devell *et al* (1996) report that Te-132 air samples above the reactor and in Nordic countries indicated a release fraction 1 to 2 times that of caesium.

Table 2.3 Estimates of released nuclides from Chernobyl – PBq

Study	**Cs-137**	**Cs-134**	**Sr-90**	**I-131**	**Te-132**
Sorenson,1987	100	-	-	-	-
US DoE (Anspaugh *et al*, 1988)	98	-	-	-	-
Aarkrog, 1994	100	50	8	-	-
OECD, 1995	~85	~54	~10	~1,760	~1,150
UNSCEAR, 2000 IAEA/WHO, 2005b	~85	~54	~10	~1,760	~1,150

19. Tables 2.2 and 2.3 indicate that the percentage of the core inventory Cs-137 released ranged between 20% - 60%, ie between 85 -100 PBq. For iodine, the percentages released ranged between 40% and 70%, and the amount was ~1,760 PBq according to UNSCEAR (2000).

20. Given the length and severity of the graphite fire during which temperatures rose to 2500°C, it may be expected that more than a third of the Cs inventory may have been released. Caesium is volatile: metallic caesium melts at 28°C and boils at 671°C, although a range of Cs compounds with higher melting points would have been present in the molten fuel. Even more volatile is iodine which has an elemental melting point of 114ºC and and a boiling point of 185ºC. In our view, therefore, the above IAEA/WHO percentage release figures may be underestimates. Because of its importance, we investigate the matter further.

Estimates for Cs-137 and I-131

21. Detailed analyses of the source terms for the main nuclides were carried out by Sich (1994, 1996) and Borovoi and Sich (1996). Using photographic evidence and measurements of heat flux and radiation intensities, Sich and Borovoi estimated that 135 tonnes of melted nuclear fuel, that is 71% of the initial inventory of 190 tonnes, remained under the reactor. Other researchers have suggested different values. Purvis (1995) estimated between 27-100 tonnes and Kisselev *et al* (1995, 1996) reported that only 24 tonnes could be identified visually. These differences clearly require further study and explanation.

22. Sich estimated the nuclide concentrations remaining in two compartments (a) the fuel remaining below the reactor, and (b) the fuel ejected by the explosions. The fuel in the first compartment released its volatile nuclides during the 10 day period before the melting of the lower biological shield and the subsequent draining of molten fuel into chambers below the reactor. The fuel in the second compartment would have released its volatile nuclides primarily during the two explosions.

23. In the first compartment, Sich’s measurements indicated that 35%[7] of the fuel’s original Cs-137 remained in the solidified fuel lava, ie 65% had been volatilised. Borovoi and

[7] Sich stated the 0.35 fraction was “surprising”, in other words, it was an unexpectedly large amount, and he surmised that the carbon moderator in the stricken reactor had acted to filter and retain Cs isotopes during the 7

Gagarinski (2001) later estimated that 60% had been volatilised. In the second compartment, ie the fuel ejected by the explosions and fires, Sich estimated that only 30% of its caesium content was volatilised.

The Question of Plate-Out

24. Sich further assumed that, during the 10 day period of maximum releases, 50% of the volatilised caesium and iodine would have "plated-out" on adjacent structures, ie precipitated on cooler surfaces. As far as we are aware, this assumption does not appear to be backed by evidence or arguments. Sich's assumption of 50% plate-out in the first compartment is questionable for many reasons, including

- the 2500°C temperatures (Devell *et al*, 1986)[8] attained in the reactor with similar temperatures in the structures above it.
- the destroyed reactor - see Figure 2.1 - reveals few structures above the reactor on which plate-out could occur.
- some plate-out may have occurred when temperatures were low. However, as temperatures rose throughout the 10 days, earlier plated isotopes may have been revaporised.
- UNSCEAR 2000 (Volume II, page 455, paragraph 15) states "The very high temperatures in the core shaft would have suppressed plate-out of radionuclides and maintained high release rates of penetrating gases and aerosols."
- Sich uses 10%, not 50%, plate-out for his second compartment.
- Sich states his estimates of fractional releases are "probably quite low" and those for plate-out are "probably high". See footnote (a) to his original table in Annex 2B.
- his release estimates are low compared with other estimates using the same method.

25. Despite his unrealistic values for plate-out, Sich's overall methodology is useful. Therefore we have used this to derive better estimates of the source terms for Cs-137 and I-131 in Annex 2C. For Cs-137, our estimated range of the percentage released is 37% - 49% with a point estimate of 43%. This is the same as the higher value of the range 23% to 43% cited by UNSCEAR (2000) and IAEA/WHO (2005b) – see table 2.2. It lies within the 40-60% range estimated by Anspaugh *et al* (1988) for the US Department of Energy - see table 2.3. In Bq terms, our estimate for Cs-137 lies in the range of 95 -128 PBq with a point estimate of 110 PBq. This is about a third greater than the UNSCEAR (2000) estimate and is closer to the 98 PBq estimate estimated by the US DoE (Anspaugh *et al*, 1988).

26. For I-131, our estimated range is 54% to 75% released with a point estimate of 65%. This is slightly higher that the 56% release estimated by UNSCEAR (2000), but similar to the estimates by Gudikson *et al* (1989) and Seo *et al* (1989). Because of the greater uncertainties with iodine releases, only UNSCEAR has made an estimate of the Bq amount released - 1,760 PBq - see table 2.3. Our estimated range for I-131 is 1,700 to 2,300 PBq with a point estimate of 2,000 PBq which is 14% higher than the UNSCEAR (2000) estimate. These estimates will have uncertainties attached to them mainly from the plate-out fractions.

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day fire. However this filtration did not occur with other nuclides: for example over 95% of (less volatile) ruthenium isotopes were released, cf 65% of caesium isotopes.

[8] Devell *et al* (1986) collected and analysed radioactive fuel particles by electron microscopy. They concluded from their form and composition that the temperature in at least part of the reactor core reached ~2,500°C.

Annex 2A: Excerpt from OECD/NEA (1995)

“The Accident

The accident occurred at 01:23 on Saturday, 26 April 1986, when the two explosions destroyed the core of Unit 4 and the roof of the reactor building. In the IAEA Post-Accident Assessment Meeting in August 1986 *(IA86)*, much was made of the operators’ responsibility for the accident, and not much emphasis was placed on the design faults of the reactor. Later assessments suggest that the event was due to a combination of the two, with a little more emphasis on the design deficiencies and a little less on the operator actions.

The two explosions sent a shower of hot and highly radioactive debris and graphite into the air and exposed the destroyed core to the atmosphere. The plume of smoke, radioactive fission products and debris from the core and the building rose up to about 1 km into the air. The heavier debris in the plume was deposited close to the site, but lighter components, including fission products and virtually all of the noble gas inventory were blown by the prevailing wind to the North-west of the plant. Fires started in what remained of the Unit 4 building, giving rise to clouds of steam and dust, and fires also broke out on the adjacent turbine hall roof and in various stores of diesel fuel and inflammable materials. Over 100 fire-fighters from the site and called in from Pripyat were needed, and it was this group that received the highest radiation exposures and suffered the greatest losses in personnel. These fires were put out by 05:00 hr of the same day, but by then the graphite fire had started. Many firemen added to their considerable doses by staying on call on site. The intense graphite fire was responsible for the dispersion of radionuclides and fission fragments high into the atmosphere. The emissions continued for about twenty days, but were much lower after the tenth day when the graphite fire was finally extinguished.

The Graphite Fire

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

A decision was made to layer the graphite fire with large amounts of different materials, each one designed to combat a different feature of the fire and the radioactive release. Boron carbide was dumped in large quantities from helicopters to act as a neutron absorber and prevent any renewed chain reaction. Dolomite was also added to act as heat sink and a source of carbon dioxide to smother the fire. Lead was included as a radiation absorber, as well as sand and clay which it was hoped would prevent the release of particulates. While it was later discovered that many of these compounds were not actually dropped on the target, they may have acted as thermal insulators and precipitated an increase in the temperature of the damaged core leading to a further release of radionuclides a week later.

By May 9, the graphite fire had been extinguished, and work began on a massive reinforced concrete slab with a built-in cooling system beneath the reactor. This involved digging a tunnel from underneath Unit 3. About four hundred people worked on this tunnel which was completed in 15 days, allowing the installation of the concrete slab. This slab would not only be of use to cool the core if necessary, it would also act as a barrier to prevent penetration of melted radioactive material into the groundwater.

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

Annex 2B. Original table reproduced from Sich (1996)

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Table 6 Estimated Volatile Isotope Lower-Bound Activity Releases from Chornobyl [Radionuclides with Significant Half-Lives ($t_{1/2} \geq 1$ d)][a,b]

Basic/initial (t = 0) data				Fuel-containing materials (FCMs)[c]				Central Hall and outside reactor building[d]				Total release, MCi
Isotope	Half-life	Activity, MCi	Mass, kg	Fractional contribution[e]	Fractional release[f]	Fractional (1-plate out)[g]	Release,[h] MCi	Fractional contribution	Fractional release	Fractional (1-plate out)	Release, MCi	
Te-129m	33.6 d	28.1	0.93	~0.71	(0.50)	(0.5)	5.0	~0.29	(0.35)	(0.9)	2.6	7.6
Te-132	78.03 h	121	0.40	~0.71	(0.50)	(0.5)	12.0	~0.29	(0.35)	(0.9)	6.2	18.2
I-129	1.57×10^7 y	(2.0×10^{-6})	(11.3)	~0.71	(0.80)	(0.5)	Neg.	~0.29	(0.50)	(0.9)	Neg.	Neg.
I-131	8.04 d	83.2	0.67	~0.71	(0.80)	(0.5)	16.8	~0.29	(0.50)	(0.9)	7.7	24.5
I-133	20.8 h	146	0.13	~0.71	(0.80)	(0.5)	25.7	~0.29	(0.50)	(0.9)	11.8	37.5
Cs-134	2.062 y	4.6	3.5	~0.71	0.65	(0.5)	1.1	~0.29	(0.30)	(0.9)	0.4	1.5
Cs-136	13.16 d	3.1	2.3	~0.71	0.65	(0.5)	0.4	~0.29	(0.30)	(0.9)	0.1	0.5
Cs-137	30.0 y	7.0	80.4	~0.71	0.65	(0.5)	1.6	~0.29	(0.30)	(0.9)	0.5	2.1
Total		559	99.6				62.6				28.0	91.9

[a]Figures in parentheses are estimates—note that the fractional release estimates are probably quite low and the plate out estimates are probably high.

[b]The release estimates for Te-132, I-133, I-131, and Cs-136 were modified (reduced) to take into account radioactive decay over the active phase.

[c]FCMs are that portion of the core currently located in the lower regions of the reactor building.

[d]"Central Hall and outside reactor building" refers to that portion of the core located on the floor of the Central Hall, outside the reactor building but within the bounds of the station, and beyond the bounds of the station.

[e]Mass fraction of the entire core contributing to this release.

[f]Fractional release from the particular portion of the fuel in question (as obtained or estimated from radiochemical analyses).

[g]Fraction that escaped from the fuel and debris into the environment.

[h](Initial activity corrected for decay over the active phase) * (fractional contribution) * (fractional release) * [fractional (1-plate out)].

(NB. This original table contains a mathematical mistake. The fig for I-131 in the last column should be **3**4.5, not **2**4.5, MCi.)

Annex 2C. Derivation of Cs-137 and I-131 source terms

(i) Tables 2C(i) and 2C(ii) set out our calculations for Cs-137 and I-131 releases using Sich's methodology but with a range of reasonable parameter values. In particular, we assume values of between 20% and 50% plate-out for the first compartment. In addition, we use the later value of 60% estimated by Borovoi and Gagarinski (2001) as the Cs release fraction for both compartments.

Table 2C(i) - Estimated Cs-137 releases using Sich's methodology and a range of reasonable assumptions for plate-out fraction in the first compartment (in bold)

		First Compartment				Second Compartment					
Author	Initial Activity	Fraction Fuel below reactor	Fraction Released	**(1-Plate out)**	Released	Fraction of Fuel ejected	Fraction Released	(1- Plate out)	Released	Total Cs-137 release	% of core inventory released
This report	260 PBq	.71	.6 Borovoi	**.8 this report**	= 88 PBq	.29	.6 Borovoi	.9 Sich	= 40 PBq	128 PBq	49%
This report	260 PBq	.71	.6 Borovoi	**.7 this report**	= 77 PBq	.29	.6 Borovoi	.9 Sich	= 40 PBq	117 PBq	45%
This report	260 PBq	.71	.6 Borovoi	**.6 this report**	= 66 PBq	.29	.6 Borovoi	.9 Sich	= 40 PBq	106 PBq	41%
This report	260 PBq	.71	.6 Borovoi	**.5 this report**	= 55 PBq	.29	.6 Borovoi	.9 Sich	= 40 PBq	95 PBq	37%
Sich	260 PBq	.71	.65 Sich	**.5 Sich**	= 60 PBq	.29	.3 Sich	.9 Sich	= 20 PBq	80 PBq	31%

(ii) To help, we shall work through an example. Go to the first row starting with "This report" on the extreme left. Moving to the right into the green section, we multiply the initial 260 PBq in the reactor x 0.71 x 0.6 x 0.8 to arrive at 88 PBq released from compartment 1. In the yellow section, we multiply the initial 260 PBq x 0.29 x 0.6 x 0.9 to get 40 PBq released from compartment 2. Adding the green and yellow PBq values, we arrive at the total of 128 PBq in the penultimate column. This is 49% of the initial 260 PBq in the final column.

(iii) For Cs-137, from table 2C(i), our estimated range of the percentage released is 37% - 49% with a point estimate of 43%. This is the same as the higher value of the range 23% to 43% cited by UNSCEAR (2000) and IAEA/WHO (2005b). In Bq terms, our estimate for Cs-137 lies in the range of 95 -128 PBq with a point estimate of 110 PBq. This is about a third greater than the UNSCEAR (2000) estimate and is closer to the 98 PBq estimate derived by Anspaugh *et al* (1988) for the US Department of Energy.

(iv) For I-131, in table 2C(ii) we use the later findings by Borovoi and Gagarinski (2001) that no I-129 was found in the fuel below the reactor, indicating all the I-131 was released from the first compartment. We also use their findings that 25% - 37% (average ~30%) of the original I-131 remained in the ejected fuel indicating that an average of 70% of the I-131 was released from the second compartment.

Table 2C(ii). Estimated I-131 releases using Sich methodology and a range of reasonable assumptions for plate-out fraction in the first compartment (in bold)

Author	Initial Activity	First Compartment: Fraction Fuel below reactor	First Compartment: Fraction Released	First Compartment: **(1-Plate out)**	First Compartment: Released	Second Compartment: Fraction of Fuel ejected	Second Compartment: Fraction Released	Second Compartment: (1-Plate out)	Second Compartment: Released	Total Cs-137 release	% of core inventory released
This report	3080 PBq	.71	1 Borovoi	**.8 this report**	=1750 PBq	.29	.7 Borovoi	.9 Sich	=563 PBq	2313 PBq	**75%**
This report	3080 PBq	.71	1 Borovoi	**.7 this report**	=1530 PBq	.29	.7 Borovoi	.9 Sich	=563 PBq	2093 PBq	**68%**
This report	3080 PBq	.71	1 Borovoi	**.6 this report**	=1294 PBq	.29	.7 Borovoi	.9 Sich	=563 PBq	1857 PBq	**60%**
This report	3080 PBq	.71	1 Borovoi	**.5 this report**	=1093 PBq	29	.7 Borovoi	.9 Sich	=563 PBq	1656 PBq	**54%**
Sich 1996	3080 PBq	.71	.8 .Sich	**.5 Sich**	=875 PBq	.29	.5 Sich	.9 Sich	=402 PBq	-	**41%**

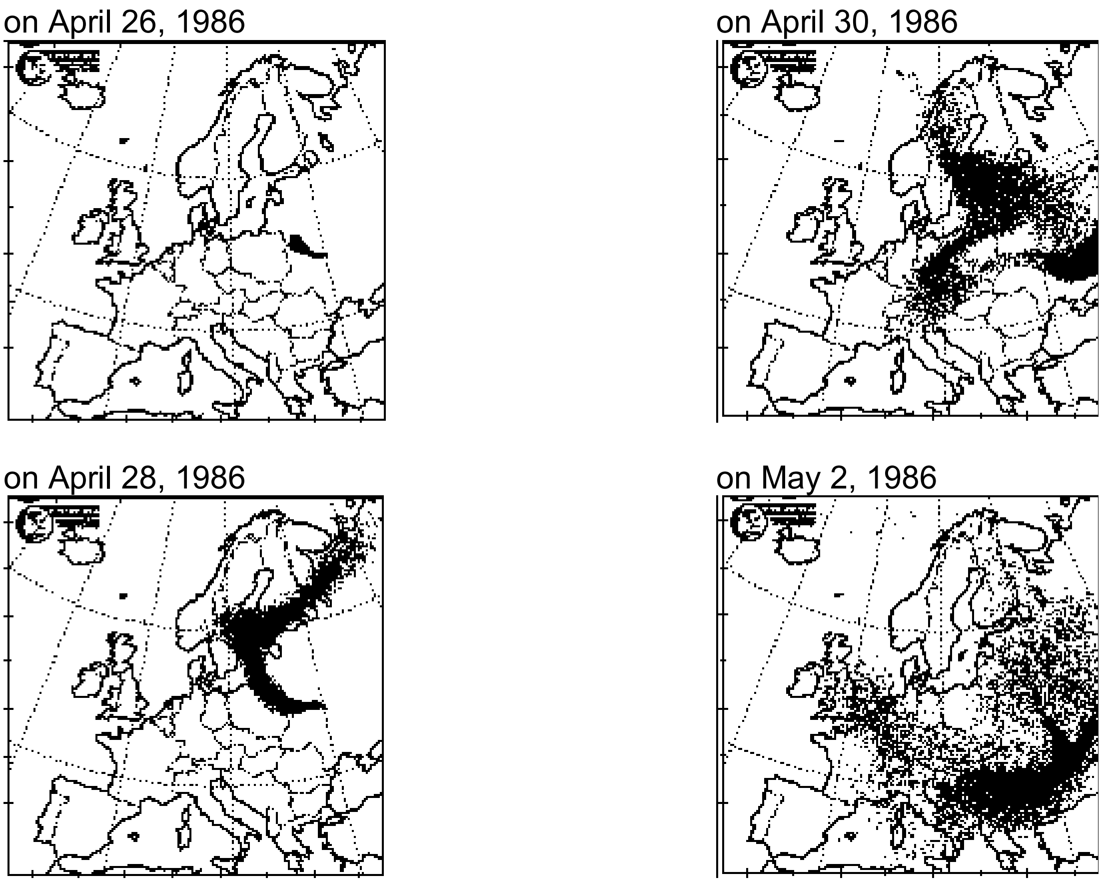
(v) For I-131, from table 2C(ii), our estimated range is 54% to 75% released with a point estimate of 65%. This is slightly higher that the 56% release estimated by UNSCEAR (2000), but similar to the estimates by Gudikson *et al* (1989) and Seo *et al* (1989). Because of the greater uncertainties with iodine releases, only UNSCEAR has made an estimate of the Bq amount released - 1,760 PBq - see table 2.3. Our estimated range for I-131 is 1,700 to 2,300 PBq with a point estimate of 2,000 PBq which is 14% higher than the UNSCEAR (2000) estimate.

Chapter 3. Dispersion and Deposition of Chernobyl Fallout

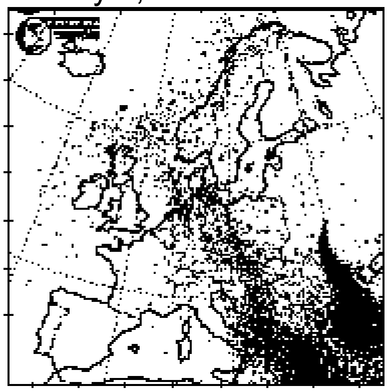
Introduction

1. During the 10 day period of maximum releases from Chernobyl, volatile radionuclides were continuously discharged into the atmosphere. During this period, the prevailing winds changed direction frequently with the result that the radioactive plume was widely spread and Chernobyl's nuclide emissions were dispersed across many parts of Europe, and later across the entire northern hemisphere. For example, relatively high concentrations of nuclides from the Chernobyl plume were measured at Hiroshima Japan, over 8,000 km from Chernobyl (Kiyoshi, 1987). European dispersal is shown in the satellite pictures from the Lawrence Livermore Research Laboratory in the US, reproduced from OECD/NEA (2002) in Figure 3.3.

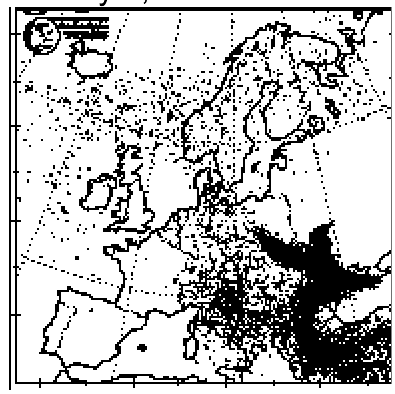
Figure 3.1 Areas covered by the main body of Chernobyl radioactive clouds on successive days during the release



on May 4, 1986



on May 6, 1986



original source: ARAC, Lawrence Livermore Research Laboratory, California, US
reproduced from OECD (2002)

2. Initially, the dry deposition of volatile radionuclides from the Chernobyl plume across Europe and the northern hemispheres was modelled by a number of authors (see discussion in UNSCEAR, 1988 and Hohenemser, 1988). However, rainfall resulted in markedly heterogeneous depositions of fallout throughout Europe and the northern hemisphere. Most ejected fuel was deposited in areas near the reactor with wide variations in deposition density, although some fuel hot particles were transported thousands of kilometres. The heaviest concentrations of nuclides and fuel particles were deposited in Belarus, Russia and Ukraine. More than half of the Cs-137 source term was deposited in countries outside Belarus, Ukraine and Russia (see table 3.6 below): as an approximation, it is assumed that all volatile radionuclides were similarly dispersed.

3. An important characteristic of fallout is solubility in water as this determines the initial mobility and bioavailability of deposited radionuclides in soils and surface waters after deposition. In fallout sampled at Chernobyl, water-soluble and exchangeable forms of Cs-137 varied from 5% to >30% (Bobovnikova *et al*, 1991). Water-soluble and exchangeable forms of Sr-90 deposited on 26 April accounted for only about 1%, but increased to 5% –10% in subsequent days due to the smaller size of particles emitted by the graphite fire. At further distances, the fraction of soluble condensed particles increased considerably because of their smaller particle sizes: for example almost all Cs-137 deposited in 1986 in the United Kingdom was water-soluble and exchangeable (Hilton *et al*, 1992).

4. Radiation exposures to humans from Chernobyl occurred via four main pathways

(i) External exposures by the Chernobyl plume as it passed overhead
(ii) Inhalation of nuclides in the plume
(iii) Continuing external radiation from nuclides deposited on the ground
(iv) Ingestion of contaminated food

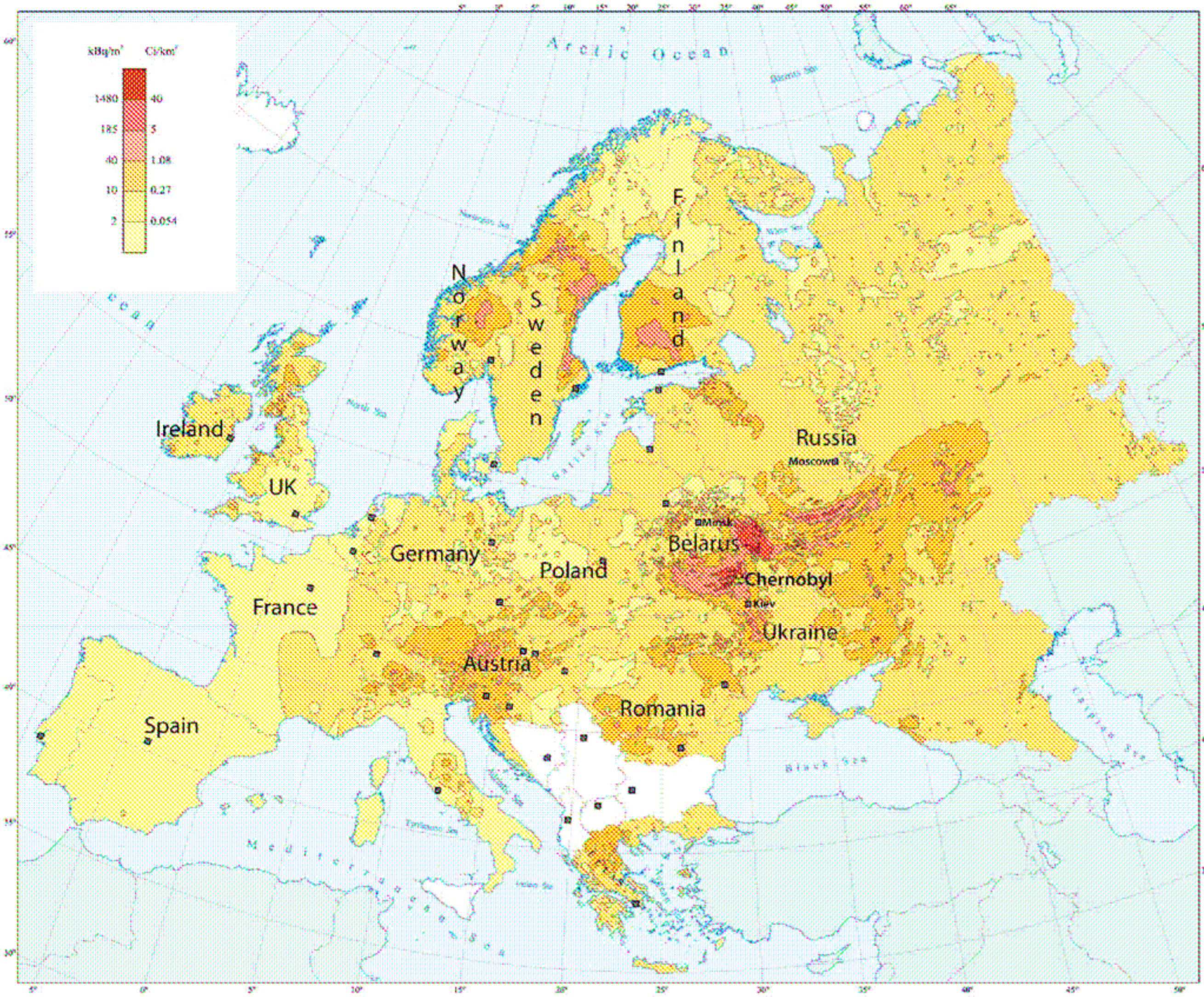
At the time of the accident, pathways (i) and (ii) were very important, especially (ii) for thyroid doses. Twenty years later, pathways (iii) and (iv) are the main contributors to dose.

Deposition Density Measurements

5. Between 1995 and 1998, the European Commission and Member States measured Cs-137 contamination levels throughout Europe using extensive gamma measurements from low altitude flights (EC, 1998). The quality of the EC mapping was determined largely by the density of sampling and measurement points. Hundreds of thousands of measurements were carried out in Ukraine, Belarus, Russia and Sweden by aero-gamma surveys conducted on map scales of 1:200k and 1:1,000k at flight altitudes of 50 -150 m. About 10,000 soil samples were taken in Central and Western European countries. The territories of Norway, Finland, UK, Greece, Germany, the Netherlands, Austria, and Switzerland were investigated most thoroughly. The EC's comprehensive contamination data for Cs-137 concentrations above 4 kBq/m^2 are reproduced in table 3.1 below.

6. The contamination data were mapped and Figure 3.2 reproduces plate 1 from EC, 1998. This indicates the very widespread nature of Cs-137 contamination throughout Europe.

Figure 3.2 Caesium-137 contaminated areas in European countries



reproduced with permission from De Cort *et al*, 1998

7. In addition, particularly large areas of Belarus, Ukraine and Russia were contaminated with high levels of radioactivity, as shown in figures 3.3, 3.4 and 3,5.

Figure 3.3 Caesium-137 contaminated areas in Belarus

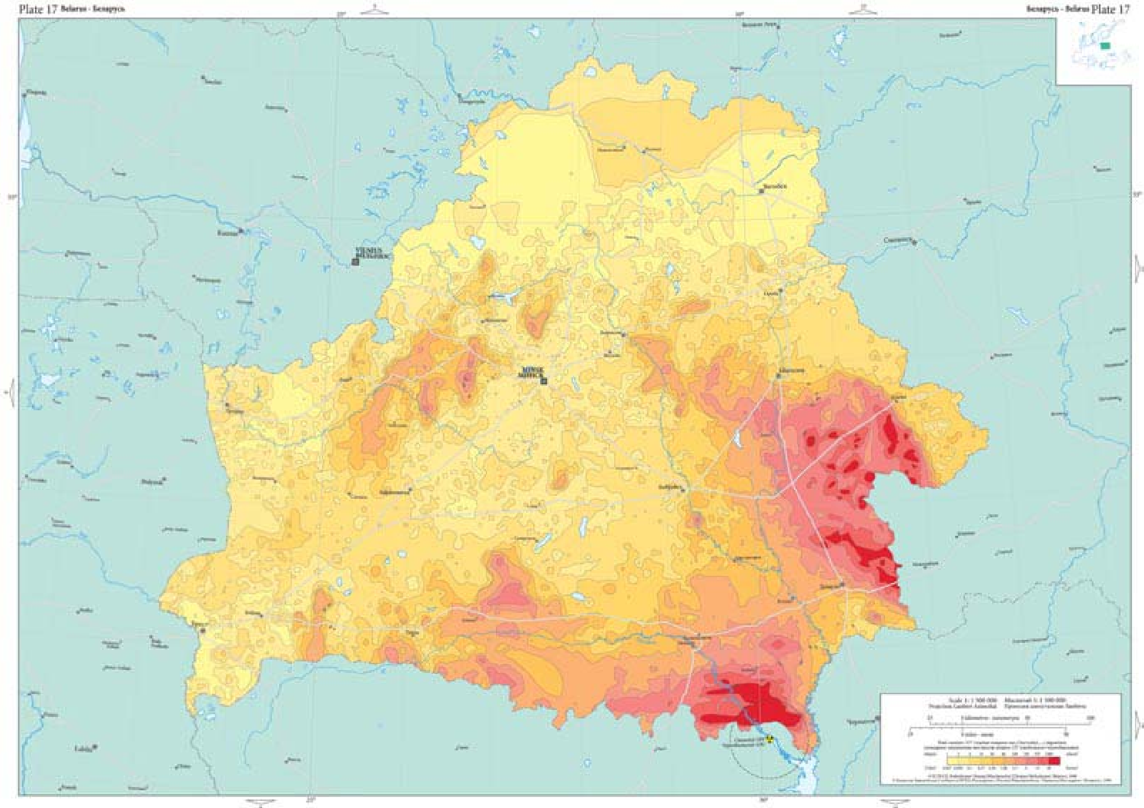


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Figure 3.4 Caesium-137 contaminated areas in Ukraine

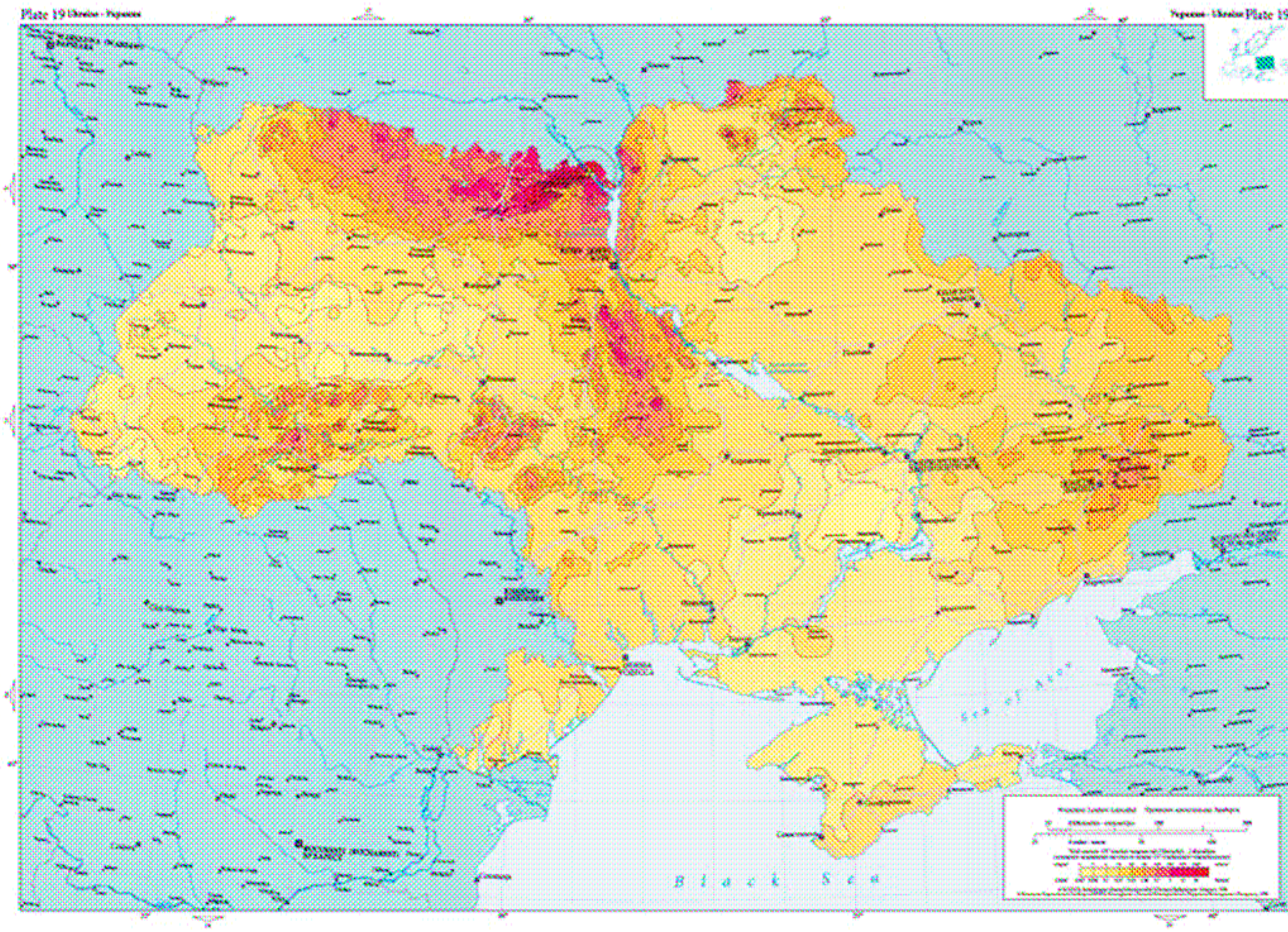

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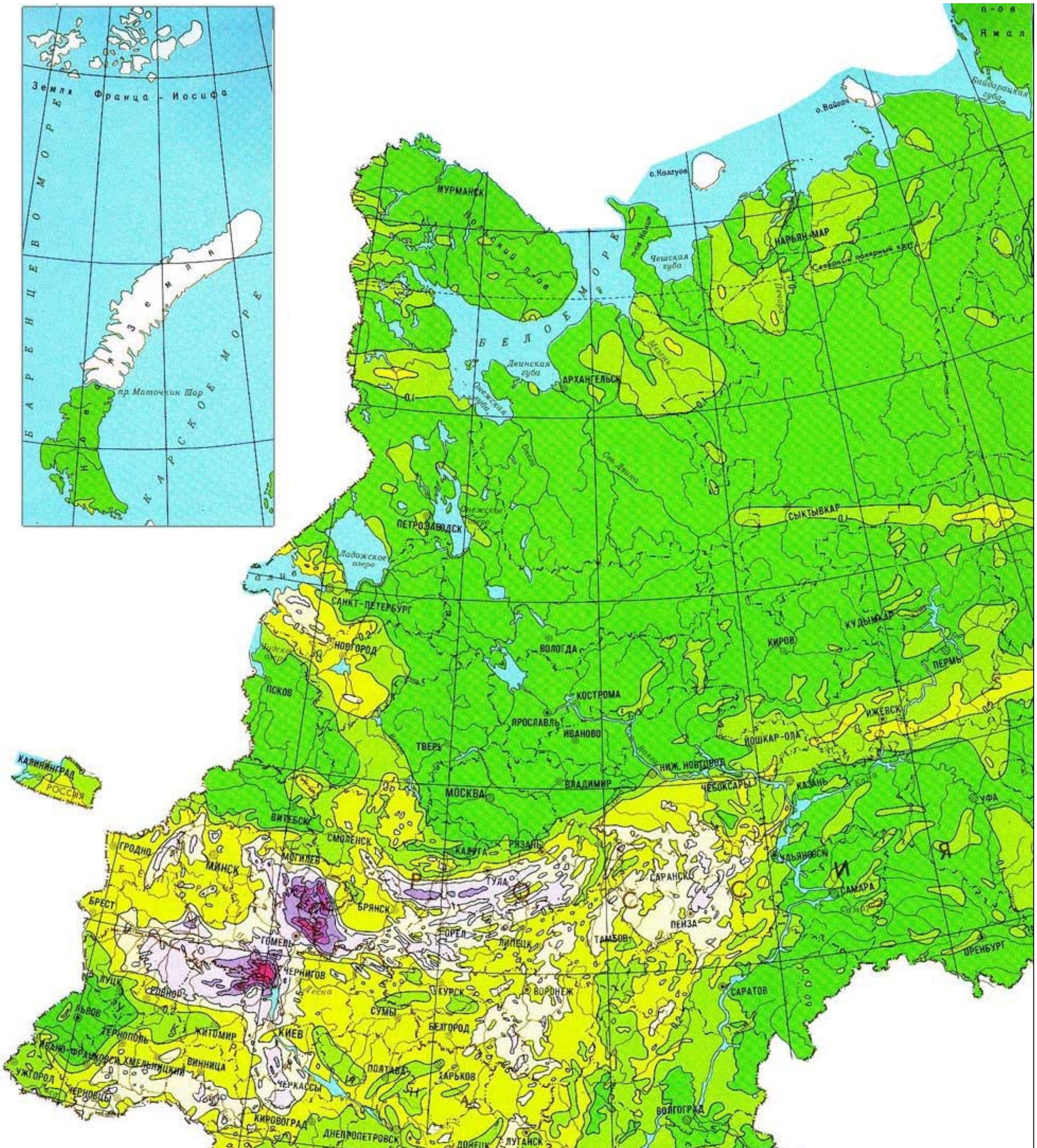
Figure 3.5 Caesium-137 contaminated areas in former USSR



Земля Франца-Иосифа
БАРЕНЦЕВО МОРЕ
пр. Маточкин Шар
КАРСКОЕ МОРЕ
МУРМАНСК
о. Колгуев
о. Вайгач
Чешская губа
НАРЬЯН-МАР
БЕЛОЕ МОРЕ
Двинская губа
АРХАНГЕЛЬСК
ПЕТРОЗАВОДСК
Ладожское озеро
СЫКТЫВКАР
САНКТ-ПЕТЕРБУРГ
НОВГОРОД
ПСКОВ
ВОЛОГДА
КИРОВ
КУДЫМКАР
ПЕРМЬ
КОСТРОМА
ЯРОСЛАВЛЬ
ИВАНОВО
ИЖЕВСК
ТВЕРЬ
ЙОШКАР-ОЛА
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КАЛИНИНГРАД
РОССИЯ
МОСКВА
ВЛАДИМИР
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КАЗАНЬ
УФА
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КАЛУГА
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reproduced from IAEA/WHO (2005b)

Table 3.1 Areas contaminated by Caesium-137 in European countries
Areas (1,000 km^2) contaminated above specified levels (kBq/m^2)

Country	**4-10 kBq/m^2**	**10-20 kBq/m^2**	**20-40 kBq/m^2**	**40-100 kBq/m^2**	**100-185 kBq/m^2**	**185-555 kBq/m^2**	**555-1480 kBq/m^2**	**>1480 kBq/m^2**	**Totals**
Russia (European part)	1110	250	180	44	7.2	5.9	2.2	0.46	1600
Ukraine	240	120	43	29	4.3	3.6	0.73	0.56	441
Romania	120	54	13	1.2	0	0	-	-	188
Norway	89	44	23	7.1	0.08	0		0	163
Finland	50	32	59	19	0	0	-	-	160
Germany	110	29	14	0.32	0	0	-	-	153
Sweden	55	31	33	23	0.44	>0.01	-	-	142
Belarus	50	22	16	21	8.7	9.4	4.4	2.6	134
Italy	37	37	15	7	1.3	0.05	-	-	97
Poland	71	10	3.5	0.52	0	0	-	-	85
United Kingdom	64	15	1.7	0.09	0.04	0.03	-	-	81
Austria	17	28	25	11	0.08	-	-	-	81
Greece	37	21	8.3	1.2	0.04	-	-	-	68
Czech Rep	42	13	3.5	0.21	0.01	-	-	-	59
France	54	1.2	0	0	0	-	-	-	55
Lithuania	48	0.05	0	0	-	-	-	-	48
Ireland	47	1.3	0.01	0	-	-	-	-	48
Croatia	29	11	0.03	0	-	-	-	-	40
Slovak Rep	32	6.8	0.61	0.02	-	-	-	-	39
Switzerland	26	6.4	2.3	0.73	-	-	-	-	35
Hungary	29	5.2	0.23	0	-	-	-	-	35
Moldova	13	19	1.9	0	-	-	-	-	34
Turkey (European part)	23	0.04	0	0	-	-	-	-	23
Latvia	21	0	0	0	-	-	-	-	21
Slovenia	2.5	8.1	8.7	0.61	-	-	-	-	20
Estonia	8.7	1.7	0.28	0	-	-	-	-	11
Denmark	0.8	-	-	0	-	-	-	-	0.8
Netherlands	0.64	-	-	0	-	-	-	-	0.64
Luxembourg	0.12	-	-	0	-	-	-	-	0.12
Belgium	0.09	-	-	0	-	-	-	-	0.09
Totals	**2427**	**767**	**452**	**166**	**22**	**19**	**7**	**3.62**	**3,864**

source: EC (1998)
greyed column inserted by the authors of this report

8. The data in the final column in table 3.1 was calculated by adding the data in the columns to the left. The final column indicates that the European area contaminated by Chernobyl (above the 4 kBq/m^2 Cs-137 level) is about 3,900,000 km^2, which is about 40% of the surface area of Europe (9,700,000 km^2). This percentage is surprisingly large, yet it was not reported in the 1998 EC report, and to our knowledge, it has not appeared in any other official publications.

9. Of this total, 218,000 km^2, or about 2.3% of Europe's surface area was contaminated to levels greater than 40 kBq/m^2. This is the area cited by the IAEA/WHO and UNSCEAR reports. Therefore it is seen that IAEA/WHO and UNSCEAR have been economical with their use of the available data, to say the least, as they have chosen to report upon only highly contaminated areas.

10. A more detailed table showing the percentage areas of each country affected by Chernobyl contamination is contained in Annex 3A. This indicates that Belarus and Austria

were the countries most affected by higher levels of contamination (>40 kBq/m^2 Cs-137) in terms of area. However, other countries were seriously affected; for example, more than 5% of Ukraine, Finland and Sweden were contaminated to high levels. Annex 3A also reveals that > 80% of the surface areas of Moldova, Turkey (the European part), Slovenia, Switzerland, Austria, and the Slovak Republic were contaminated to lower levels (> 4kBq/m^2 Cs-137) and that 44% of Germany and 34% of the UK were similarly affected.

Official Reactions

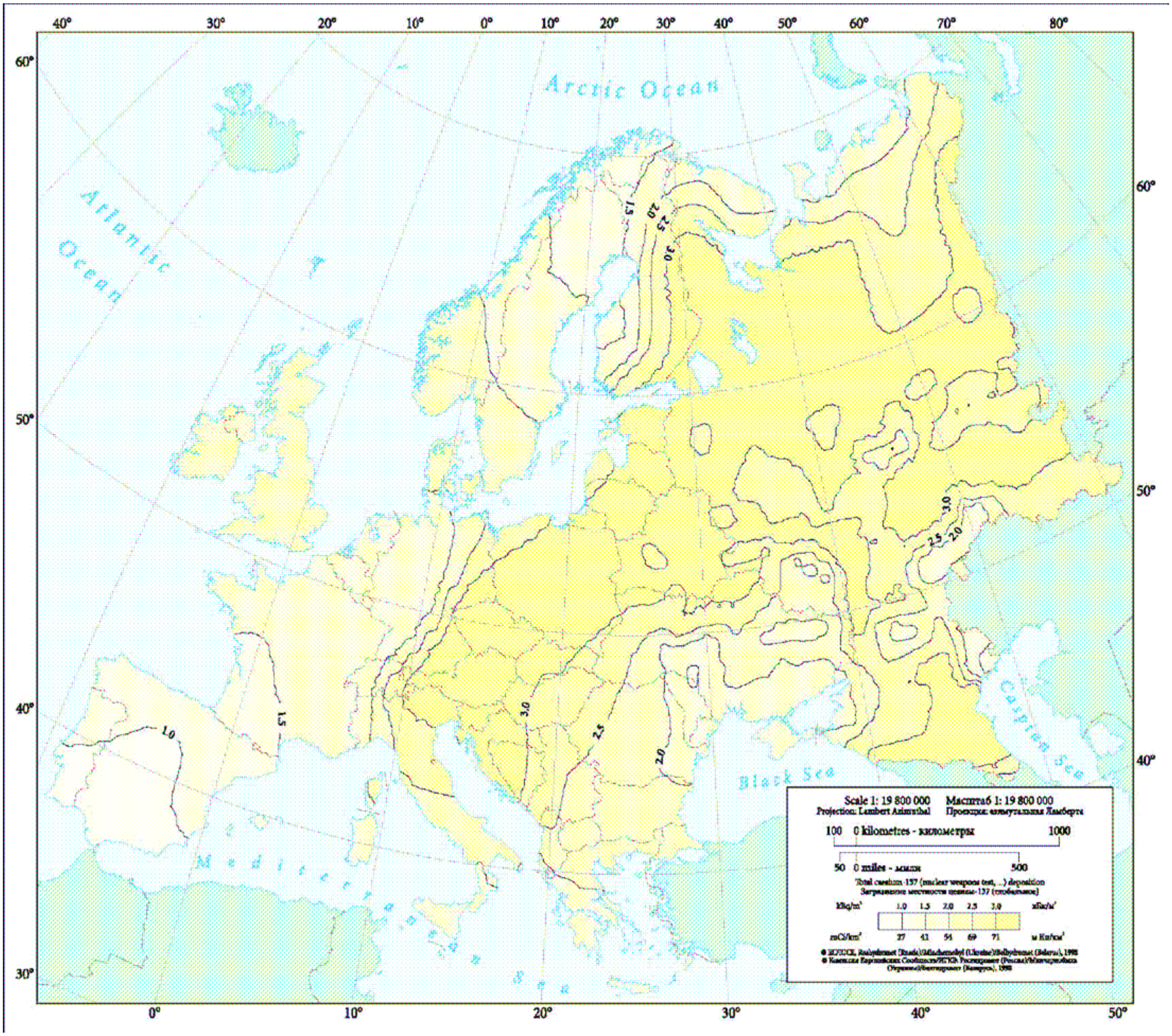
11. When the accident occurred in 1986, many governments denied or minimised the accident's effects (Medvedev, 1990). This was particularly true of the former Soviet Union, but it was by no means the only country in denial. The UK Government, for example, was accused of minimising Chernobyl's effects (Edwards, 1989) and misleading the public (Weaver, 1986). In France, allegations were recently made in legal proceedings by environmental groups[9] that French official bodies had suppressed information about the spread of radioactive fallout over France from the Chernobyl disaster. In December 2005, the magistrate investigating the allegations, Maitresse Marie-Odile Bertella-Geffroy, handed over a report she had commissioned from two independent scientists, Paul Genty and Professor Gilbert Mouthon at Chimie et Physique Biologiques et Medicales, ENVA, France. This stated that the French Government's Central Service for Protection against Radiation (SCPRI) had known of high levels of contamination in Corsica and south-eastern France but had kept the details under wraps. Instead it had issued imprecise maps that concealed high levels of fallout in certain areas. The case is continuing (The Australian, 2005).

Cs-137 from Test Bomb Fallout

12. Considerable amounts of Cs-137 were deposited on Europe by fallout from the atomic bomb tests in the 1950s and 1960s, and residual low levels of between 0 and 3.5 kBq per m^2 still existed in 1986, as shown in figure 3.6.

Figure 3.6 Test bomb Cs-137 levels in Europe before Chernobyl

[9] including CRIIRAD, AFMT and about 200 plaintiffs



reproduced with permission from De Cort *et al*, 1998

13. These test bomb concentrations need to be considered when estimating Chernobyl depositions. It is for this reason that table 3.1 above is restricted to data for concentrations greater than 4 kBq/m^2. In fact, the relevant table in the EC report cites concentrations for below 4 kBq/m^2 down to 0 - 1 kBq/m^2. In our view, the interpretation of such low-level data (0-4 kBq/m^2) is difficult because of the possible presence of test bomb Cs-137: accordingly they are not cited here. We acknowledge that this is a somewhat arbitrary decision, but in our view a cut-off level has to be applied, otherwise one could be measuring mostly bomb Cs-137 rather than Chernobyl-related Cs-137.

14. Nevertheless, in terms of actual amounts deposited, more Cs-137 from Chernobyl was deposited (at concentrations lower than 4 kBq/m^2) over Europe than is shown in table 2.1 above. In other words, the area values of Chernobyl contamination in table 2.1 should be

considered minimum values. Unfortunately, a further complication exists with the EC's methodology for estimating Cs-137 levels: this is discussed in paragraphs 22-23.

Contamination Levels - What do they mean?

15. Table 3.2 sets out the definitions of the contamination zones in Belarus, Ukraine and Russia.

Table 3.2 Zones of contamination in Belarus, Russia and Ukraine

Contamination density Cs-137 Ci/km^2 (kBq/m^2)	Official designation of zones		
	Belarus*	Russia**	Ukraine***
1-5 (37 -185)	Periodic radiation monitoring	Privileged socio-economic status	Zone of enhanced radiological control
5-15 (185-555)	Zone with the right to resettle	Right to resettle (if dose > 1 mSv/year)	Zone of guaranteed resettlement
15-40 (555-1500)	Zone of secondary resettlement	Mandatory resettlement if ^{137}Cs >40 Ci/km^2 or dose >5 mSv/a. Voluntary if below this	Zone of obligatory resettlement
>40 (>1500)	Zone of priority resettlement		
Territories adjacent to Chernobyl (including 30-km zone). Population evacuated 1986 - 1987	Zone of evacuation (exclusion zone)	Resettlement zone (exclusion zone)	Exclusion zone

sources: * Goskomchernobyl, 2001 ** Russian Federation, 1992 *** Ukraine, 2001

16. After the Chernobyl accident, the then Soviet Union introduced various criteria for managing contaminated areas. It established 1 curie (Ci) per km^2 (equal to 37 kBq/m^2) as the lowest Cs-137 contamination level at which occasional controls were required: voluntary resettlement was permitted above this level in practice. Stricter controls were applied in more heavily contaminated areas. Subsequently, the 1 curie level was adopted by Belarus, Ukraine and Russia. It is often viewed as a "safe" level by the media and public, but in fact this is not the case. It is merely an administrative number, arbitrarily chosen most probably for its convenience, being 1 curie per km^2. The reality is that there is no absolutely "safe" level of exposure to radioactivity. No matter how low the exposure level, some small risk will accrue. To determine how much and to establish whether this is acceptable, it is necessary to estimate the radiation doses from external exposures to radioactive Cs-137 (which we do in the next paragraph) and then estimate collective doses (which we do in Chapter 5).

17. In *système internationale* (SI) units, 1 curie per km^2 is 40 kBq/m^2 rounded to one significant figure[10]. This concentration means that an area of one square meter would, on average, emit the external beta and gamma radiation from 40,000 Cs-137 decays each second. Determining the annual external radiation "dose" from external contamination is not straightforward and depends on many factors, such as whether people live and work outside, and whether they live in wooden or concrete homes, etc. Table 3.3 sets out official estimates of external dose coefficients expressed in microsieverts (µSv) per kBq/m^2 of Cs-137 in the

[10] 1.0 curie is equal to 3.7 x 10^9 becquerels. But since the administrative limit is expressed as a single significant figure ie 1 (and not 1.0), the equivalent is more correctly expressed as 4 x 10^9 Bq.

year 1996 from UNSCEAR (2000). This indicates an approximate average dose of 10 μSv per kBq/m^2 per year in 1996.

Table 3.3 Official estimates of absorbed dose rate in air / Cs-137 density
(Normalized absorbed dose rate in air in 1996)
[Columns 1 and 2 are the same annual dose rates expressed in different units. Column 1 is expressed in **n**Gy per **hour** per kBq/m^2. Column 2 is expressed in **μ**Gy per **year** per kBq/m^2.]

	Column 1	Column 2
Country	Dose rate (nGy per hour per kBq/m^2 Cs-137)	Dose rate (μGy per year per kBq/m^2 Cs-137)
Belarus	1.0	8.7
Russia	0.85	7.4
Ukraine1	1.5	13
Ukraine2	1.1	9.6
average	-	9.7

estimates from table 32 of UNSCEAR (2000)
estimates in greyed column estimated by the authors of this report

18. From table 3.3, we may derive an average dose conversion factor[11] of about 10 μSv per year from exposure to 1 kBq/m^2 of Cs-137. Although some uncertainty is inevitably associated with this dose conversion factor, we derive an approximate dose estimate of 0.4 mSv per year from external exposures to 40 kBq/m^2 of Cs-137 for rural workers in Belarus, Ukraine and Russia. This is about the same level as the annual dose constraint of 0.3 mSv used in the UK for the regulation of radiological practices: doses to critical groups above this constraint are not authorised. Other countries maintain more stringent limits. For example, guidance from the US Environmental Protection Agency (US EPA, 1997) on minimum clean-up levels for radioactively contaminated land stipulates a maximum dose of 0.15 mSv per year. This equates to a lifetime risk of fatal cancer of 3×10^{-4} (assuming a risk of 5% per Sv over 40 years) and achieves an excess upper-bound lifetime cancer risk of 10^{-4} to 10^{-6} which is applied to all carcinogens in the US[12].

19. Similarly, a contamination level of 4 kBq/m^2 means that an area of one square meter would, on average, emit the external radiation from 4,000 Cs-137 decays each second. Using the above dose coefficient results in an external dose of about 0.04 mSv per annum. This is a relatively "low" dose of radiation, about the same as the radiation dose from a chest X-ray in a modern hospital[13]. Assuming a linear no-threshold dose-response relationship, some health effects (ie a low number of additional cancers) would occur from external exposures at these levels, although it would be almost impossible to ascertain these small numbers of increased cases by means of epidemiology studies. To assess health effects correctly in these situations of low radiation doses, we need to estimate collective doses – see Chapter 5.

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[11] in theory, this should be multiplied by ~0.9 to convert Gy to Sv, but we shall not introduce this factor here.
[12] in 2005, the UK Government proposed new limits allowing permanent habitation on radioactively contaminated land where annual doses did not exceed 10 mSv. However these have been objected to by environmental groups, and they have not been implemented as of the date of drafting this report.
[13] although this has a countervailing benefit for the individual who is X-rayed, and no benefit accrues to those exposed by Chernobyl releases.

Cs-137 Contamination

20. The countries in table 3.1 are ranked by the size of their contaminated areas. This is interesting, but it hides large variations in the amounts of Cs-137 (in Bq) deposited in each country. These amounts are shown in tables 3.4 and 3.5 which rank countries by the Bq amounts of Cs-137 contamination. These data are from two sources EC (1998) and US DoE (1987). Most data are from the EC Atlas but this does not cover Bulgaria, Albania and most of former Yugoslavia which are covered in the US data. The EC data includes amounts from areas with very low Cs-137 concentrations, ie 0 - 4 kBq per m^2.

Table 3.4 Cs-137 deposition ranked by country

Country	PBq	Country	PBq	Country	PBq
Russia (Europe part)	29	Italy	0.93	Ireland	0.35
Belarus	15	France	0.93	Slovak Rep	0.32
Ukraine	13	United Kingdom	0.88	Latvia	0.25
Finland	3.8	Czech Rep	0.6	Estonia	0.18
Sweden	3.5	Lithuania	0.44	Turkey (Europe part)	0.16
Norway	2.5	Moldova	0.4	Denmark	0.087
Rumania	2.1	Slovenia	0.39	Netherlands	0.062
Germany	1.9	Spain	0.38	Belgium	0.053
Austria	1.8	Croatia	0.37	Luxembourg	0.008
Poland	1.2	Switzerland	0.36	**Total**	**85**
Greece	0.95	Hungary	0.35		

data reproduced from table III.1 in EC, 1998

Table 3.5 Cs-137 deposition ranked by country

Country	PBq
Yugoslavia	5.4
Bulgaria	2.7
Albania	0.4
TOTAL	**8.5**

data reproduced from US DoE, 1987
[Yugoslavia reduced by 0.76 PBq to avoid double-counting Slovenia and Croatia in table 3.4]

21. These tables indicate that the three former Soviet Union republics received the highest Bq amounts of Cs-137 fallout and that former Yugoslavia, Finland, Sweden, Bulgaria, Norway, Rumania, Germany, Austria and Poland each received more than 1 PBq (10^{15} Bq) Cs-137, which is a large amount of radioactivity (cf the EU Cs-137 limit of 600 Bq/kg see table 4.2).

22. As shown in table 3.4, the total Cs-137 deposited on Europe was estimated by the EC (1998) to be 85 PBq. An additional 8.5 PBq should be added to include Chernobyl fallout on Yugoslavia, Bulgaria and Albania, giving a total of ~94 PBq in Europe. The EC report stated that Cs-137 previously deposited on Europe from test bomb fallout in 1950s and 1960s should be deducted from these estimates. In 1996, about 20 PBq remained from this fallout. However, a problem exists with the EC's methodology for arriving at the latter estimate. The EC report stated that the average estimated contribution from weapons fallout in each 1 x 1 km area cell was subtracted from the total caesium-137 estimated for the same cell. Nevertheless, where the average fallout level exceeded the total deposition, the contribution from Chernobyl was assumed to be zero. The report admitted that, as a result,

> "this approach has clear limitations and may result in large uncertainties in estimates of the amount of Chernobyl caesium-137 deposited in some countries. These uncertainties will be greatest for those countries with the lowest levels of deposition. ….this aspect warrants further attention in future with a view to making more rigorous estimates of Chernobyl deposition in the less affected countries."

23. So there are uncertainties in the EC's estimates of the amounts of caesium-137 from residual test bomb fallout and of the Chernobyl caesium-137 amounts in some countries. This means that the EC's deposition estimates are unsuitable for estimating the Chernobyl source term, and in fact the EC report refrains from doing this.

Effects throughout Europe

24. The high levels of contamination from Chernobyl resulted in countermeasures and restrictions on the use of contaminated foodstuffs being introduced in many areas of Europe. Some of these restrictions are continuing to this day because unexpectedly high levels of Cs-137 remain in the plants and soils of upland pastures. It was discovered that acid soils promote the mobility and bioavailability of Cs and that many grass plants on upland pastures accumulate it. These findings apply to varying extents to such countries as the UK and Ireland. These findings are one of a number of surprising new findings resulting from the Chernobyl accident.

25. In the United Kingdom, approximately 2,500 km from Chernobyl, fallout was deposited on sheep-grazing upland areas in Wales, Cumbria and Scotland following heavy rainfall. As a result, 8,900 farms were placed under restriction. In particular, the movement, sale and slaughter of 4,225,000 sheep were restricted in order to stop contaminated animals from entering the food chain. As of 2005, these restrictions remain on 375 farms and 215,000 sheep (RIFE, 2005).

26. Similar situations exist in parts of Sweden and Finland as regards stock animals, including reindeer, in natural and near-natural environments. From a 2002 survey in EU Member States, wild game (including boar and deer), wild mushrooms, berries and carnivore fish from lakes in certain regions of Germany, Austria, Italy, Sweden, Finland, Lithuania and Poland could occasionally reach caesium-137 contamination levels of several thousand Bq/kg[14].

27. In Germany, the Federal Office for Radiation Protection (BfS) stated in its 2004 annual report[15] that wild boar remained highly contaminated by Cs-137, especially in the south of the country. According to studies carried out in 2004 in the Bavarian forest, soil contamination levels were still as high as 100,000 Bq/kg. Cs-137 levels in wild boar muscle were between 60 and 40,000 Bq/kg with an average of 6,800 Bq/kg. This average is >10 times the 600 Bq/kg EU limit, see table 4.2. Only 15% of the boar samples were within the EU limit, and 20% exceeded 10,000 Bq/kg. The EU limit was also exceeded in less contaminated areas of Germany, the Pfaelzerwald for instance, which had soil Cs-137 contamination levels of up to several thousand Bq/m^2. Recent data from the Rhineland-Palatinate Research Institute for

[14] information contained in written answer to Question P-1234/05DE by MEP Rebecca Harms dated April 4, 2005
[15] http://www.bfs.de/bfs/druck/jahresberichte/jb2004_kompl.pdf

Forest Ecology and Forestry has revealed that more than 20% of wild boar samples had Cs-137 levels greater than 600 Bq/kg, with a peak value of 8,200 Bq/kg in 2004[16].

28. In 2005, the European Commissioner for Transport and Energy, Andris Piebalgs explained[17] that restrictions will need to be continued for many years.

> "… one cannot count on notable changes in the radioactive caesium contamination of certain products from natural … environments. The radioactive caesium contamination level of these products is essentially dependent on the half-life of this radionuclide….30 years. The restrictions on certain foodstuffs from certain Member States must therefore continue to be maintained for many years to come."

Continuing High Levels of Contamination

29. Over the next few hundred years, Cs-137 concentrations will gradually decline. This decline will be due to a very small degree from environmental causes (ie Cs-137 entering deeper levels of some soils), but will mostly will be a result of radioactive decay (IAEA/WHO, 2005b). In practice, this means that Cs-137 contamination levels in wild foods will remain high for a long time in the future. Indeed, in April 2005, the European Energy Commissioner, Andris Piebalg, admitted as much when he wrote that Cs contamination in certain food products would not decline appreciably in the near future. He stated[18]

> "Due to the experience gained since the Chernobyl accident, the Commission believes that in the Member State regions significantly affected by the ….accident, one cannot count on notable changes in the radioactive caesium contamination of certain products from natural or near natural environments."

30. This was repeated in the IAEA/WHO (2005b) report which stated that Cs-137 and Sr-90 concentrations and transfer coefficients[19] had decreased only slowly in most plant and animal foodstuffs during the last decade. This indicated that these radionuclides were close to equilibrium in labile and non-labile pools of soil within agricultural ecosystems. The IAEA/WHO concluded that as far as nuclide concentrations in plant and animal foodstuffs were concerned:

> "Given the slow current declines, and the difficulties in quantifying long-term effective half-lives for currently available data because of high uncertainties, it is not possible to conclude that there will be any further substantial decrease over the next decades, except due to the radioactive decay of ^{137}Cs and ^{90}Sr with half-lives of about 30 years."

31. Annex 3B (table 3B(i)) sets out official estimates of residual amounts of radioactive nuclides in the global environment from Chernobyl over the next 50 years until 2056 from official data. However, 2056 is only 70 years after the Chernobyl accident and is an arbitrary choice of date. Scientifically speaking, a more rigorous date would be 2286, ie 300 years after

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[16] information contained in written answer to Question P-1234/05DE by MEP Rebecca Harms dated April 4, 2005
[17] written answer to Question P-1234/05DE by MEP Rebecca Harms dated April 4, 2005
[18] written answer to a Question P-1234/05DE by MEP Rebecca Harms dated April 4, 2005
[19] parameter describing the velocity of transport of a nuclide usually through soil

Chernobyl. The reason is that a convention exists among radiation protection scientists that 10 half lives[20] are necessary to ensure radioactivity levels decline to an acceptably "safe" level. In the case of Cs-137, this would be about 300 years after 1986, or 2286. Indeed, for this reason, conventional proposals[21] for dealing with radioactive waste usually propose initial storage for 300 years to allow Cs-137 and Sr-90 decay sufficiently to enable its safe handling.

32. Due to the slow radioactive decay of Cs-137, radiation doses from external exposures to Cs-137 will decline slowly over the next few hundred years. Table 3B(ii) in Annex 3B contains estimated future external doses expressed per contamination level (kBq/m^2) of Cs-137. In addition, table 3B(iii) contains estimated future doses from both internal and external radiation (1996-2056) to adults living in rural areas contaminated to 555 kBq/m^2 (15 Ci/km^2).

Restricted reporting by UNSCEAR (2000) and IAEA/WHO (2005a, 2005b)

33. Unfortunately, the UNSCEAR (2000) and IAEA/WHO (2005a, 2005b) reports do not discuss the comprehensive datasets on European contamination in EC (1998) and do not cite EC (1998) among their references. No explanation is given for this omission. Moreover, the UNSCEAR (2000) and IAEA/WHO (2005a. 2005b) reports do not discuss deposition and radiation doses in any country apart from Belarus, Ukraine and Russia. Indeed, UNSCEAR (2000) stated[22]

> "Information on the contamination levels and radiation doses in other (ie other than Belarus, Ukraine and Russia) countries will be presented only if it is related to epidemiology studies conducted in those countries."

This restriction also apparently applies to the 2005 IAEA/WHO reports.

34. It appears that IAEA/WHO decided to focus in their reports only on countries with high-density depositions of Cs-137 which meant Belarus, Ukraine and Russia. Although heavy depositions certainly occurred there, the omission of any examination of Chernobyl fallout in the rest of Europe and the northern hemisphere is questionable. Most of the Cs-137 source term from Chernobyl was deposited outside Belarus, Ukraine and Russia. This was indicated by the US DoE (1987) and by UNSCEAR (1988) [23] which stated that less than half of the Cs-137 source term was deposited in the then USSR (including Belarus, Ukraine and Russia), with the majority deposited elsewhere, including the rest of Europe (39%), Asia (8%), Africa (6%), and the Americas (0.6%) [24]. UNSCEAR (2000) [25] also stated that 40 PBq of Cs-137 was deposited in Belarus, Ukraine and Russia, ie less than half its source term. These data are set out in table 3.6.

[20] 10 half lives will reduce the original activity by a factor of about 1000 (in fact by 1024)
[21] see UK Committee on Radioactive Waste Management draft report (CoRWM, 2006)
[22] volume II, Annex J, page 453, paragraph 6
[23] page 342, paragraph 201
[24] table 24 of UNSCEAR, 1988
[25] volume II, Annex J, page 462, paragraph 41

Table 3.6 Cs-137 depositions – PBq

Report	Belarus, Ukraine and Russia	Rest of Europe	Rest of World (excl Europe and Belarus, Ukraine and Russia)	Total	% in Belarus, Ukraine and Russia
US DoE (Goldman *et al*, 1987)	~33	~33	~32	~98	~33%
UNSCEAR, 1988	29	26	15	70	42%
EC, 1998	57	28 + 9*	-	-	-
UNSCEAR, 2000	40	-	-	85	47%

*for Yugoslavia, Bulgaria and Albania from US DoE data (1986)
shaded cells = estimated by this report

35. IAEA/WHO's decision to discount nuclide depositions and radiation exposures in European countries and the northern hemisphere outside Belarus, Ukraine and Russia is unfortunate. This restriction makes it difficult to estimate the collective dose impact of the disaster as these depend on Cs-137 depositions, as we shall see in Chapter 5.

Annex 3A. Chernobyl contamination by area in each country

Table 3A(i) Cs-137 contamination >40 kBq/m²

Country	Total area 1,000 Km^2	area contaminated >40 kBq/m^2 Cs-137: 1,000 Km^2	% OF COUNTRY
Belarus	210	46.1	22%
Austria	84	11	13
Ukraine	600	38	6.3
Finland	340	19	5.6
Sweden	450	23.4	5.2
Italy	280	8.35	3
Slovenia	20	0.61	3
Norway	320	7.2	2.3
Switzerland	41	0.73	1.8
Russia (Europe part)	3,800	60	1.6
Greece	130	1.26	1
Rumania	240	1.2	0.5
Czech Republic	79	0.22	0.28
Poland	310	0.52	0.16
Germany	350	0.32	0.09
United Kingdom	240	0.16	0.06
Slovak Republic	49	0.02	0.04
Totals	**9,700***	**218.95**	**2.3%**

data from EC (1998) *includes areas of unlisted countries for which data is not available

Table 3A(ii) Cs-137 contamination 4 - 40 kBq/m²

Country	Total area	area contaminated to 4 - 40 kBq/m^2 Cs-137	% OF COUNTRY
Moldova	34	34	100%
Turkey (Europe part)	24	23	96
Slovenia	20	19.3	96
Switzerland	41	34.7	85
Austria	84	70	83
Slovak Republic	49	39	80
Rumania	240	187	78
Czech Republic	79	59	75
Lithuania	65	48	74
Croatia	56	40	71
Ireland	70	48	68
Ukraine	600	403	67
Greece	130	66.3	51
Norway	320	156	49
Germany	350	153	44
Belarus	210	88	42
Finland	340	141	41
Russia (Europe part)	3,800	1,530	40
Hungary	93	35	38
United Kingdom	240	81	34
Latvia	64	21	33
Poland	310	85	27
Sweden	450	119	26
Estonia	45	11	24
Italy	280	59	21
France	550	55	10
Luxembourg	2.6	0.12	5
Denmark	45	0.8	2
Netherlands	35	0.64	2
Belgium	31	0.09	0.2
Totals	**9,700***	**3,864**	**40%**

data from EC (1998) *includes areas of unlisted countries for which data is not available

Annex 3B. Future Effects from Chernobyl

Table 3B(i) Residual radionuclides in the global environment from Chernobyl

Nuclide	Half-life years	PBq Released in 1986	PBq Remaining in 1996	PBq Remaining in 2006	PBq Remaining in 2056
Sr-90	28.8	8	6	4.9	1.5
Cs-134	2.06	48	1.6	0.05	0
Cs-137	30.1	85	68	54	17
Pu-238	87.7	0.03	0.03	0.03	0.02
Pu-239	24,400	0.03	0.03	0.03	0.03
Pu-240	6,500	0.044	0.044	0.044	0.04
Pu-241	14.4	5.9	3.6	2.3	0.2
Am-241	432	0.005	0.08	0.12	0.2

source: Dreicer *et al*, 1996
Greyed column estimated by this report
Am-241 is the decay daughter of Pu-241, and therefore increases in magnitude. Am-241 doses are currently not thought to exceed doses from other nuclides

Table 3B(ii). External effective doses per Cs- 137 density for residents of contaminated areas, expressed over various time periods

Normalized effective dose (µSv per kBq/m^2 Cs-137) for rural workers for time period indicated

Country	1986	1986 - 1995	1996 - 2056	1986 - 2056
Former USSR	13-28	47- 62	48	95-110
Belarus	19	55	-	-
Russia	15	37	28	65
Ukraine	24	60	28	88

source: table 31, UNSCEAR, 2000

Table 3B(iii). Estimated future doses (1996 - 2056) to adults living in rural areas contaminated with 555 kBq/m^2 Cs-137

Exposure Path	Average Person mSv	Critical Group mSv
External Radiation	20	27
Ingestion	10	33
Inhalation	0.1	0.3
TOTAL	30	60

source: table VII, Dreicer *et al*, 1996

Chapter 4. Health Effects Resulting from the Chernobyl Accident

Introduction

1. The immediate impacts of the Chernobyl accident on human health are now well known. Acute radiation sickness was diagnosed initially in 237 emergency workers, of whom 134 were treated clinically. 28 of them died in 1986 and a further 19 died between 1987 and 2004: more premature deaths may occur.

2. Less certain are the long term consequences of the accident. Exposure to ionising radiation can induce cancer in almost every organ in the body. However, the latency period[26] between exposure to the radiation and appearance of the cancer can be many years and even several decades. Clearly, therefore, it will be a long time before the full effects of Chernobyl are known. Indeed, they may never be fully known, as cancer is a common disease and it may be impossible to distinguish additional cancers from the large number that would occur anyway.

3. Many publications list four categories of people affected by the Chernobyl accident.

(a) About 600 **emergency workers**, who were involved during the first day of the accident. Of these, 22 workers received whole-body doses of external radiation greater than 4 Gy and 21 received doses greater than 6 Gy.

(b) About 240,000 **cleanup workers** or **liquidators** who, from 1986 to 1989, were sent in to the power station or the zone surrounding it for decontamination work, sarcophagus construction, and other cleanup operations. Their average dose was 100 mSv.

(c) About 100,000 **persons who were evacuated** within 2 weeks of the accident and 16,000 more before the autumn of 1986. Their average dose was 33 mSv.

(d) The approximately 5 million **residents of contaminated areas** in Belarus, Ukraine and Russia. Their average dose was 10 mSv. In addition, about 270,000 people were living in highly contaminated areas (more than 555 kBq/m^2 Cs-137). Their average dose was 50 mSv.

4. In addition two other categories exist, which are often not discussed in official reports and are conspicuously omitted from the IAEA/WHO (2005) reports:

(e) Approximately 600 million **people who live in the rest of Europe.**

(f) Approximately 4 billion **people who live in the northern hemisphere**[27]

The effects in these last two categories are more diffuse and indeed have been difficult to detect in epidemiology studies. Nevertheless, they can be estimated using collective doses. These are considered in Chapter 5.

5. The health effects resulting from Chernobyl will be discussed under the following headings:

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[26] the latency period is the time interval between the exposure to radiation and the appearance of cancer
[27] little atmospheric mixing occurs between the northern and southern hemispheres

(1) Thyroid cancer
(2) Leukaemia
(3) Solid cancers
(4) Non-cancer effects
(5) Heritable effects
(6) Mental health and psycho-social effects.

6. There have been a large number of publications in all these categories, many of which have been reviewed in the recent IAEA/WHO (2005a) report and the US BEIR VII (2005) report. Papers continue to appear steadily, together with many anecdotal reports. Because of the often long delay between exposure to radiation and the appearance of its effects, lengthy follow up times are necessary before definite conclusions can be drawn. For example, an important source of information about the induction of cancer by radiation are the survivors of the Hiroshima and Nagasaki bombings, who have now been followed up for more than 50 years; it is only relatively recently (Preston *et al*, 2003) that clear evidence has emerged of non-cancer effects due to radiation, for example cardiovascular disease. It is therefore likely that a clear picture of the effects of Chernobyl will not emerge for many years.

7. In this report, we shall concentrate on more recent publications, using mainly those published in peer-reviewed journals, always mindful of the many uncertainties involved in trying to unravel the past and the even greater ones in predicting the future. In view of the use of the words 'grays' and 'sieverts', a short note on radiation units is set out in Annex 4.

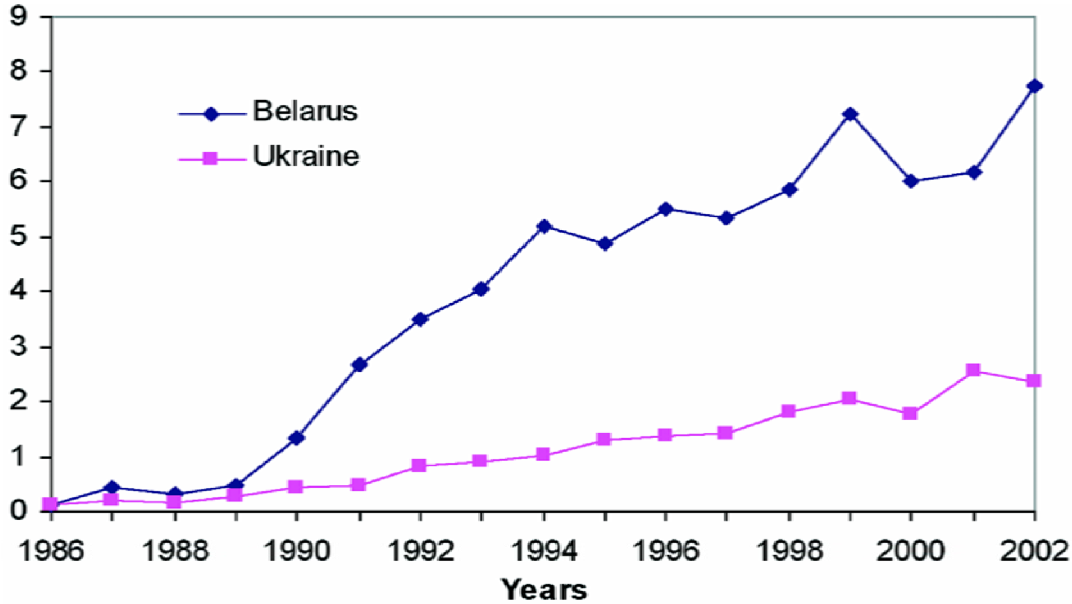
(1) Thyroid Cancer

8. The first reports of an increase in thyroid cancer in children in the early 1990s (Prisyazhiuk *et al*, 1991; Kazakov *et al*, 1992; Baverstock *et al*, 1992) were greeted with considerable scepticism, as it was thought that more cancers were being seen simply because more were being looked for – a 'screening effect'. Moreover, the cancers had appeared only four years or so after the radiation exposure, whereas the latency period of thyroid cancer was thought to be ten years or more (UNSCEAR, 1988). Another reason for scepticism was the belief that internal radiation from iodine-131 was not as carcinogenic as external radiation. For example, there was no evidence of an increased incidence of thyroid cancer in patients treated with iodine-131 for overactive thyroid (Hennemann, 1986).

9. However, further work (Astakhova *et al*, 1998; Jacob *et al*, 2000; Heidenreich *et al*, 1999) confirmed that there was indeed a dramatic increase in childhood thyroid cancer, and there is now overwhelming evidence that this is related to exposure to iodine-131 and possibly to other isotopes of iodine with shorter half-lives. Between 1990 and 1997, childhood thyroid cancer increased by a factor of about 30 in the most heavily contaminated areas (Tawn, 2001). The short latency period, 3-4 years, may well have been influenced by the promptness with which screening of school children occurred in areas of high fallout (Astakhova, 1998).

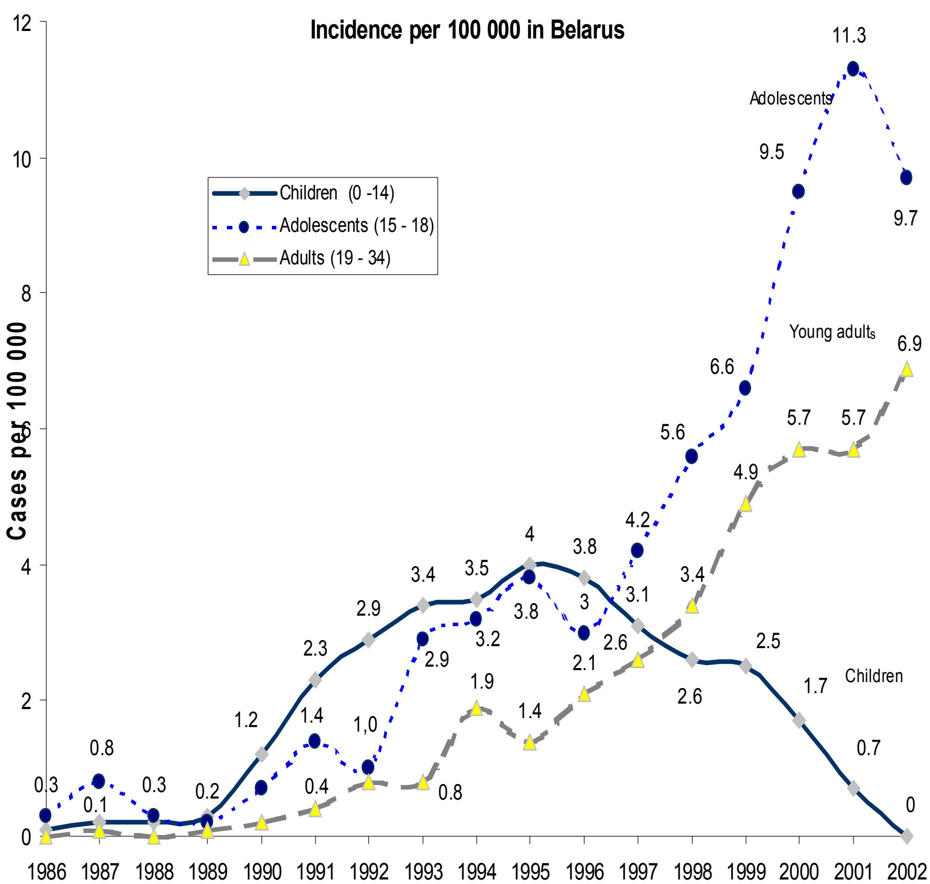
10. Up to 2005, there have been about 4,000 cases of thyroid cancer in Belarus, Ukraine and Russia (Cardis, 2005a) in those who were under 18 at the time of the accident; 3,000 of these were under 15. Annual incidence rates up to 2002 in Belarus and Ukraine are shown in figure 4.1.

Figure 4.1. Annual thyroid cancer incidence rates per 100,000 in those who were children and adolescents in 1986



source: Jacob *et al* (2005)

Figure 4.2 Annual incidence of thyroid cancer in Belarus



source: reproduced from lecture presentation by E Cardis to IAEA/WHO Conference Chernobyl: Looking Back to Go Forward. September 2005. Original data from Dr Yuri Demidchik.

11. As can be seen in figure 4.2 for Belarus, the peak incidence in the 0-14 age group was in 1995, and for the 15-18 age group, the peak was in 2000. In addition, the incidence of thyroid cancer among adults is rising. (Cardis, 2005a).

12. Several important points emerge from the many papers published on this topic:

(i) the younger the person exposed, the greater the subsequent risk of developing thyroid cancer. For a given intake of radioiodine, children will receive the highest thyroid dose, as their thyroid glands are smaller and still growing

(ii) there is no clear evidence that exposure to iodine-131 *in utero* has caused thyroid cancer, but the relevant studies have limited statistical power[28]

(iii) the risk of thyroid cancer is greater when there is iodine deficiency

(iv) dietary iodine supplements can reduce the risk, even if administered some time after the exposure to radiation

13. Before the Chernobyl accident, the principal source of information about radiation-induced thyroid cancer in children was several studies in which children had been exposed to external X-rays. A survey of these studies (Ron *et al*, 1995) showed that the thyroid cancer risk was still increased more than 40 years after the initial exposure. For children aged under 15 at the time of exposure there was a linear relationship between risk and dose down to 100 mGy. The best estimate of the excess relative risk per gray (ERR/Gy)[29] was 7.7 (95% confidence intervals [30] 2.1 to 28.7). This is consistent with the estimate by Cardis (2005b) in which the ERR/Gy varied between 4.5 to 7.4, depending on the model used (95% confidence intervals 1.0 to 16.3). More recently, Jacob *et al* (2005, 2006) from their study of thyroid cancer risk in Ukraine and Belarus, also estimated ERR/Gy values close to those observed by Ron *et al* (1995).

How many more thyroid cancers can we expect?

14. Because we do not know at this stage how the risk will change in the future, there are considerable uncertainties in estimating the total number of thyroid cancers that are likely to result from Chernobyl. In the words of the IAEA/WHO report [pp 39-40]:

[28] The power of a study is the probability of detecting a given difference. Even if a difference is real, if it is small and the size of the groups we are comparing is small, there will only be a very small probability of detecting the difference.

[29] Relative risk (or Odds Ratio) is the risk of contracting a particular disease for an *exposed* individual, divided by the risk of contracting that disease in an *unexposed* individual. So if the relative risk (RR) of thyroid cancer is 8.7 per gray (8.7/Gy), this means that a radiation dose of 1 gray (Gy) to the thyroid will make that individual 8.7 times more likely to contract thyroid cancer. Excess relative risk (ERR) = relative risk (RR) – 1; so a relative risk of 8.7 corresponds to an excess relative risk of 7.7.

[30] If we were to carry out a large number of similar studies, the true value of the risk would lie within the 95% confidence interval in 95% of the studies. So essentially the confidence interval gives *a range of values with which the data are compatible.*

> ‘although thyroid cancer risk is continuing at a high level, and there is no reason to expect a decrease in the next 15 or more years, at the present time the follow-up of Chernobyl-exposed children is too short to determine the long-term risks’.

15. Some attempt at prediction can be made by assuming that the change in risk in the future will be similar to that seen with external radiation. Jacob *et al* (2000) estimate that for Belarus, starting in 1997, 15,000 thyroid cancers will occur with an uncertainty range of 5,000-45,000. The UNDP (2002) says that ‘according to conservative estimates, the numbers of thyroid cancers are likely to rise to 8,000 to 10,000’. Cardis *et al* (1999) predict the lifetime number of thyroid cancers that would develop among children in Belarus aged less than 5 years at the time of the accident. Depending on the risk projection used, their estimates range between 18,000 and 66,000 excess thyroid cancers. The lower estimate assumes a constant relative risk for 40 years after exposure; the higher assumes a constant relative risk over the whole of life. Of course, thyroid cancers are also expected in Russia and Ukraine.

16. A very recent study (Imaizumi *et al*, 2006) of thyroid cancer incidence in the survivors of the Japanese atomic bombs found that a significant dose-response relationship still existed nearly 60 years after exposure, and that the effects were significantly greater in those exposed at younger ages. This suggests that of the above two risk projections, the latter may be more likely with a consequently larger number of thyroid cancers.

Thyroid cancer in adults

17. Although there is now good evidence from a number of studies that the increased incidence of thyroid cancer in children is related to Chernobyl, the association is less clear in adults. Table 4.1 contains a review by Moysich *et al* (2002) of studies of adult thyroid cancer incidences.

Table 4.1 Studies of adult thyroid cancer incidence

Reference	Country	Kind	Period	Comparison Type	Exposure variables	Findings
Mettler *et al*, 1992	Ukraine	descriptive	1990	Prevalence of thyroid nodules	high and low contam villages	No differ in prevalence of thyroid nodules
Prisyazhniuk *et al*, 1995	Ukraine	descriptive	1980-1993	Incidence rates over time	-	No sig increase
Inskip *et al*, 1997	Estonia	liquidator cohort	1995	Prevalence of thyroid nodules	questionnaire; measurements	No differ in prevalence of thyroid nodules
Ivanov *et al* 1997a, 1997b	Russia	incidence, mortality	1986-1990	Incidence in cohort vs population	Assigned ext doses during clean-up exposures	>incidence in liquidators SIR=670 95% CI=420-1030
Ivanov *et al* 1997c	Russia	Descriptive incidence	1981-1995	Incidence rates over time		No sig increase in contam vs non-contam areas
Rahu *et al*, 1997	Estonia	Liquidator cohort	1986-1993	Incidence in cohort vs population	questionnaire	No excess thyroid cancer incidence
Ivanov *et al*, 1999	Russia	descriptive incidence	1982-1995	Incidence rates over time	Contam vs non-contam areas	>nos of thyroid cancers in contam areas

source: Moyisch *et al*, 2002

18. One study which has shown a significant effect examined data on 168,000 cleanup workers from Russia (Ivanov *et al*, 1997d). The ERR/Gy for thyroid cancer was found to be 5.31 (95% CI: 0.04, 10.58) which is consistent with the value of 7.7 estimated by Cardis (see paragraph 13 above).

Thyroid cancers outside Belarus, Ukraine and Russia

19. In total, about 2,000 PBq of iodine-131 was released in the Chernobyl accident, and more than half of this was deposited outside Belarus, Ukraine and Russia. One might therefore expect some thyroid cancers to occur elsewhere, at least in the more contaminated countries. The 2005 IAEA/WHO reports did not consider this, except to refer to the Sali review (Sali *et al*, 1996). Although this concluded that no increase in thyroid cancer among children was observed, it also pointed out that "no study focussed specifically on childhood thyroid cancer, since the disease is so rare and *a small increase could have gone undetected in these studies".* (emphasis added)

20. Since 1996, there have in fact been a number of reports of possible increases in thyroid cancer in other European countries. Murbeth *et al* (2004) reported an increase in the Czech Republic. They found the incidence of thyroid cancer had increased by 2.6% per year (95%-CI: 1.2 - 4.1, p=0.0003) in all age categories after 1990. The Czech Republic received a moderate amount of radioactive fallout: as shown in Annex 3A, with three quarters of its surface area slightly contaminated (ie to a level greater than 4 kBq/m^2). The authors came to the reasonable conclusion that "one should look carefully at collective dose and at the groups of persons low in individual organ dose but high in number". This recommendation has not been followed up by the IAEA/WHO (2005) reports which, as we stated earlier, fail to examine health effects in Europe outside Belarus, Ukraine and Russia.

21. Cotterill *et al* (2001) reported an increasing incidence of thyroid cancer in the North of England, particularly Cumbria one of the two areas in the UK receiving the heaviest fallout. They pointed out that iodine-131 concentrations in rainwater were as high as 784 Bq/litre and in goat's milk as high as 1,040 Bq/litre. These concentrations are higher than the EU's Food Intervention Levels shown in table 4.2.

Table 4.2 EU Food Intervention Levels (Bq/kg)

	Baby Foods	Dairy Produce	Other Foods
Sr-90	75	125	750
I-131	150	500	2,000
Sum of Cs-137 and Cs-134	370	370	600
Plutonium-239	1	20	80

source: European Council Regulations (Euratom) Nos 3955/87, 944/89, 2218/89, 4003/89, 737/90 and 1609/2000

22. Shortly after the accident, Baverstock (1986) estimated that young children might receive thyroid doses between 10 and 20 mGy resulting in a 10-20% greater risk of thyroid cancer. Thyroid doses of 20 mGy are not negligible; the study of childhood thyroid cancer in Belarus and Russia by Jacob *et al* (1999) points out that the risk of thyroid cancer was

elevated even in the lowest dose group, which received an average dose of only 50 mGy (range 25 to 98 mGy).

23. Although Cotterill *et al* state that factors such as earlier detection of tumours may have contributed to the increasing incidence, their conclusion is that ‘further collaborative international studies are needed to investigate changes in the incidence of thyroid cancer in children and young adults’. To the best of our knowledge, this has not been done.

24. A contrary view was taken by Colonna *et al* (2002), who examined the incidence data for thyroid cancer from eight French cancer registries over the period 1978-1997. Their analysis showed an increase in thyroid cancer but not a recent one, which therefore could not be due to Chernobyl (the authors suggest that it could be a screening effect). Obviously there are many uncertainties here, and it is clear that further work is necessary to establish the extent of thyroid cancer in all countries, not just Belarus, Ukraine and Russia, which received significant depositions of iodine-131.

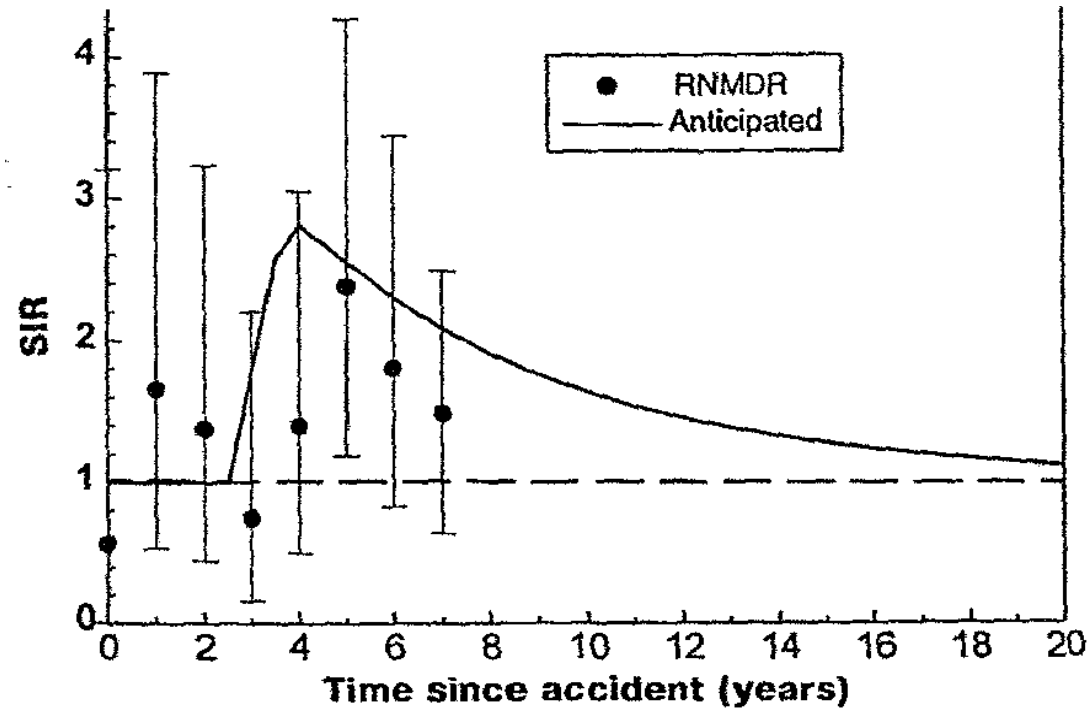
(2) Leukaemia

25. Leukaemia is a well-documented effect of ionising radiation, with a relatively short latency period of between 2 and 5 years.

Leukaemia in cleanup workers

26. Fairly clear evidence indicates that leukaemia incidence increased in the clean-up workers: there was a two-fold increase in the most highly exposed group, although dose estimates are uncertain. More precise estimates are expected in the near future from on-going studies (Cardis 2005a). Ivanov *et al* (1997d) in their study of Russian cleanup workers suggest that one of every two leukaemias diagnosed in emergency workers today could be radiation-induced. They also point out that the incidence of leukaemia in the Russian cleanup workers is consistent with the incidence predicted from the atomic bomb survivors - see figure 4.3.

Figure 4.3 Anticipated and Observed Standardised Incidence Ratios of Leukaemia in Russian Clean-up Workers (bars give 95% confidence intervals)



source: reproduced from Ivanov *et al* (1997d)

Leukaemia in residents of contaminated areas

27. Noshchenko *et al* (2001) have suggested that there was an increased risk of leukaemia and acute leukaemia among children who were born in 1986 and were resident in radioactively contaminated territories. They suggested this increased risk may be associated with exposure to radiation. A case-control study by Noshchenko *et al* (2002) examined residents aged 0-20 at the time of the Chernobyl accident in the most radioactively contaminated territories of the Ukraine. They estimated the risk of radiation-induced acute leukaemia for the period 1987-1997. The mean value of the estimated accumulated dose to the bone marrow was 4.5 mSv, and the maximum was 101 mSv. A statistically significant increased risk of leukaemia was found among males whose estimated radiation exposure was higher than 10 mSv. This association was statistically significant for acute leukaemia cases that occurred in the period 1993-1997, particularly for acute lymphoblastic leukaemia. A similar association was found for acute myeloid leukaemia, diagnosed in the period 1987-1992.

Leukaemia in other European countries

28. A number of studies appear to show an increased rate of childhood leukaemia as a result of the Chernobyl fallout in parts of Europe. These were recently reviewed by the UK Government's Committee Examining Radiation Risks of Internal Emitters (CERRIE, 2004) which reported increases in infant leukaemia in West Germany, Greece and Belarus. The IAEA/WHO (2005a) report on health effects downplayed the importance of these studies, mainly because in their view the studies did not show a clear link between the incidence of leukaemia and the degree of contamination (ie with dose).

29. However, given the large uncertainties in estimating doses from the degree of contamination, the absence of a strong association between leukaemia incidence and

contamination does not rule out a radiation effect. The IAEA/WHO report (2005a) itself lists the gaps in our knowledge of doses, including:

- “There is a lack of information on intercomparison between the various dosimetric methods, though studies are currently in progress.
- Doses to be received in the future can only be predicted.
- The reliability of interviews used to assess factors which affect an individual’s dose has not been definitively assessed.
- Internal doses resulting from intakes of Sr-90 and of Pu-239 have received limited attention.
- Methods to estimate doses received by those exposed *in utero* need further work on the dosimetric methodology and validity of such dose estimates.
- The conversion of effective doses into absorbed organ-specific doses such as bone marrow dose needs to be delineated.”

30. In 1988, the European Childhood Leukaemia-Lymphoma Incidence Study (ECLIS) was set up by IARC to investigate possible changes in incidence rates of childhood leukaemia and lymphoma in Europe following the Chernobyl accident (Parkin, 1993). Data were drawn from 36 cancer registries in 23 European countries. The study’s follow-up report for the period 1980-1991 (Parkin, 1996) found a small increase in leukaemia incidence in Europe as a whole (13 cases observed against 7.3 expected in the highest dose category), but there did not appear to be any association between the overall risk of leukaemia in the period 1987-91 and the estimated doses received. However, they added “at this stage of follow-up, the study has low power to detect a trend in risk with dose.”

31. Regarding the possible consequences of radiation doses received *in utero*, Parkin et al (1996) stated that they found

> '”no suggestion of an increase in risk of childhood leukaemia for children exposed *in utero*, even among the 1987 birth cohort in Belarus, some of whom would have received *in utero* exposures in excess of 1 mSv”.

However, both BEIR VII (2005) and the IAEA/WHO(2005a) suggested that there may well be an effect:

> ”Focusing on the risk of leukaemia by age of diagnosis (six months intervals) in relation to the estimated dose from the Chernobyl fallout received *in utero*, preliminary results suggest a small increase in risk in infant leukaemia and leukaemia diagnosed between 24-29 months.” (IAEA/WHO, 2005a)

This issue remains unresolved. We recommend in paragraph 33 below that funding be made available to IARC to clarify this matter.

32. The 1996 ECLIS paper was re-evaluated by Hoffmann (2002) who stated that leukaemia incidence in the birth cohort of 1987 was increased in the two highest exposure categories. He concluded that Chernobyl fallout could well have caused a small, but significant, excess of childhood leukaemia cases in Europe, possibly due to the induction of chromosome aberrations in early pregnancy. He went on to say that “…if indeed Chernobyl fallout has caused childhood leukaemia cases in Europe, we would also expect an increased incidence for other childhood cancers and excess malignancies in adults as well as non-malignant diseases of all ages*. Neither of these endpoints has as yet been systematically studied.*” [emphasis added]

33. Although most of the data from the ECLIS study has now been collected and studied, the final results of the study have not been published. This is unfortunate: we recommend that funds be made available to permit the IARC to finish and publish its study, and, while doing so, to resolve the evidence on the possible consequences of radiation doses received *in utero*.

(3) Other solid cancers

Cancers in cleanup workers

34. Using data for cleanup workers from the Belarus National Cancer Registry, Okeanov *et al* (2004) compared baseline incidence rates for overall cancer and various cancers between 1976-85 with those between 1990-2000. An average 40% increase in cancer incidence was observed in all regions with the most pronounced increase in the most contaminated region. The 56% increase between the two time periods was statistically significant. In 1997-2000, male liquidators had statistically significantly raised risk of cancers of all sites, colon, lung and bladder cancer compared with adults in the least contaminated region - as shown in table 4.2. Based on the estimated collective dose to all cleanup workers in Belarus, Ukraine and Russian (see table 5.1), we might expect around 1,000 – 2,000 excess deaths from solid cancers due to Chernobyl-related radiation exposures in this group.

Table 4.2 Relative risk (RR) in cancer incidence (truncated age-standardised rate for ages 20-85 per 100,000 population) in Belarus liquidators 1997-2000, compared with control adults in least contaminated area (ie Vitebsk)

Cancer	Incidence in controls	Incidence in liquidators	RR	95% confidence intervals
All sites	373.3	449.3	1.20*	1.14 – 1.27
Breast (female)	58.6	61.3	1.05	0.81 – 1.35
Lung	52.4	67.3	1.28*	1.13 – 1.46
Stomach	41.7	44.9	1.08	0.92 – 1.26
Colon	17.0	22.3	1.31*	1.03 – 1.67
Rectum	19.0	18.4	0.97	0.77 – 1.23
Kidney	14.8	17.9	1.21	0.97 – 1.50
Bladder	10.9	17.0	1.55*	1.21 – 1.99

source: Okeanov *et al* (2004)
*statistically significant differences

Breast cancer in Belarus, Ukraine and Russia

35. Breast cancer is particularly important, because the risk of breast cancer among women exposed in childhood and adolescence is the next highest risk after leukaemia and thyroid cancer risks, as regards radiation-induced cancer (IAEA/WHO, 1995). Moreover, iodine (and therefore radioiodine) is concentrated in the breast and salivary glands in addition to the thyroid.

36. The IAEA/WHO report (2005a) acknowledges preliminary evidence of an increase in the incidence of pre-menopausal breast cancer among women exposed at ages lower than 45 years. This has been confirmed in a soon-to-be published study by Pukkala *et al* (in press) which describes trends in the incidence of breast cancer in Belarus and Ukraine. Their results

suggest that women who reside in the most contaminated districts have an increased risk of breast cancer compared with women in less contaminated areas. Doses were estimated using average whole body doses accumulated since the accident, both from external exposure and the ingestion of long-lived radionuclides. Those living in the most contaminated districts had an average cumulative dose of 40 mSv or more. In these districts, a significant two-fold increase in risk was observed during the period 1997-2001 compared with the least contaminated districts (the RR in Belarus was 2.24, 95% CI 1.51-3.32 and in Ukraine the RR was 1.78, 95% CI 1.08-2.93). The increase, though based on a relatively small number of cases, appeared approximately 10 years after the accident; it was highest among women who were younger at the time of exposure, and was observed for both localised and metastasised cancers. The authors conclude that "it is unlikely that this excess could be entirely due to increased diagnostic activity in these areas."

Bladder and Kidney Cancer

37. Romanenko et al (2003) have reported that the incidence of urinary bladder cancer in the Ukraine has increased from 26.2 to 43.3 per 100,000 person-years between 1986 and 2001. Romanenko et al (2000) have also reported that the incidence of cancer of the kidney has increased from 4.7 to 7.5 per 100,000 person years.

Cancer in other European countries

38. Sali *et al* (1996) did not show any significant increases in cancer incidence in other European countries, but they pointed out the lack of statistical power and the fact that the study only covered the first nine years after the accident. Apart from leukaemia and perhaps thyroid cancer in children, there is evidence that the minimum latency period for most solid cancers is at least 10 years, so positive results would not have been expected in 1996. According to Tondel *et al* (2004), there has been an increase in the total incidence of cancer in northern Sweden; they estimate the excess relative risk to be 0.11 per 100 kBq/m^2 of Cs-137 (95% confidence intervals 0.03 to 0.20) corresponding to a relative risk of 1.21 for the most contaminated areas.

(4) Non-cancer effects

39. Over the last twenty years, a large number of health effects have been attributed to the Chernobyl accident, including reduced fertility, increased incidence of stillbirths, birth defects, Down's syndrome and infant mortality. Evaluation of the many reports and claims is extremely difficult, given the prevailing context of political changes, adverse economic circumstances and the apparent deterioration of many health and well-being indices. The following problems are associated with many of these reports of adverse health effects:

- diagnostic criteria often differ
- insufficient control groups exist
- the studies have low power, and
- confounding factors are present, notably smoking and alcohol

In response to this, the IAEA/WHO has stated "there remains an overall need to design future studies with extreme care in order to be able to obtain useful, unbiased and non-confusing information" (IAEA/WHO, 2005a).

40. Many commentators have highlighted the marked general deterioration in health indicators in Belarus, Ukraine and Russia. To give a graphic illustration - over the last 15

years, the average lifespan for a male in Russia has decreased from over 70 to about 61 years and in the Ukraine from 67 to 61 years: in western Europe, the average male life span is about 75. The reasons for the considerable declines in health indicators in Belarus, Ukraine and Russia are complex and due to a number of interrelated factors as described in the UNDP (2002) report. Without access to government data, it is very difficult to assess whether continuing exposures to low residual levels of radioactivity is a factor in the general deterioration in health in Belarus, Ukraine and Russia. However it is noted that the declines have occurred in all areas of Belarus, Ukraine and Russia and not merely those areas affected by radioactive fallout.

41. Two non-cancer effects that are now reasonably well-documented and for which there is clear evidence of a Chernobyl connection are cataract induction and cardiovascular disease.

(a) Cataract Induction

42. Cataract-opacity (cloudiness of the eye lens) is an effect of exposure to radiation. The latency period seems to be inversely proportional to dose, so long follow-up times are necessary for small exposures. As with childhood thyroid cancer, this is another area where previous thinking on radiation's effects is being revised as a result of Chernobyl. In 1990, the ICRP had stated that the threshold for opacities sufficient to cause impairment of vision was in the range 2 to 10 Gy (ICRP, 1991). In contrast, IAEA/WHO now states that "a focus of the Chernobyl eye studies is a hypothesis that radiation cataract/opacifications detectable by an experienced examiner may occur at doses lower than previously thought. These studies do not appear to support the older classic literature on radiation cataracts, which concluded that a relatively high threshold (e.g. 2 Gy) must be exceeded for cataracts to appear after ionising radiation exposure." (IAEA/WHO, 2005a) Studies of the cleanup workers suggest that cataracts might be caused by doses as low as 0.25 Gy. Lens changes related to radiation have been observed in children and young people aged between 5 and 17 living in the area around Chernobyl (Day *et al*, 1995).

(b) Cardiovascular diseases

43. Here again an ICRP pronouncement has been contradicted by new evidence. ICRP Publication 60 had stated (para 62, page 16) "It seems that no stochastic effects in the exposed individual other than cancer (and benign tumours in some organs) are induced by radiation. In particular, any life-shortening found in exposed human populations and in experimental animals after low doses has been shown to be due to excess radiation-induced cancer mortality" (ICRP, 1991). But the most recent follow-up of the Hiroshima and Nagasaki survivors shows clearly that there is a linear dose-response relationship for myocardial infarction among survivors exposed at less than 40 years of age (Preston *et al*, 2003). In fact, statistically-significant radiation effects are seen for

- heart disease (ERR/Sv = 0.17, 95% CI 0.08 to 0.26)
- stroke (ERR/Sv = 0.12, 95% CI 0.02 to 0.22)
- respiratory disease (ERR/Sv = 0.18, 95% CI 0.06 to 0.32) and
- digestive disease (ERR/Sv = 0.15, 95% CI 0.00 to 0.32)

44. A large study of Chernobyl emergency workers (Ivanov *et al*, 2000) showed a significantly increased risk of cardiovascular disease. The ERR/Sv was 0.54 (95% CI 0.18 –

0.91), three times higher than the value from the atomic bomb survivors, although the 95% confidence intervals overlap, meaning that the two ERR values could be consistent with one another.

(5) Heritable effects

45. It is well known that radiation can damage genes and chromosomes. The relationship between genetic changes and the development of future disease is complex however and the relevance of such damage to future risk is often unclear. We might expect that parental exposure to radiation would produce an increased incidence of inherited disease in the children of exposed individuals. Nevertheless no evidence of increased genetic damage has yet appeared in the children of the Hiroshima and Nagasaki survivors. This could be because the samples are not large enough to show a statistically significant effect - in other words, there is insufficient statistical power. As a result, estimates of genetic risk in humans are usually based on data from animal experiments.

46. On the other hand, a number of recent studies have examined genetic damage in those exposed to radiation from the Chernobyl accident. Some have examined changes in minisatellites, which are sequences of repeated DNA particularly prone to mutations. These are often used as markers for measuring the effects of low doses of radiation, although whether such mutations affect the future health of those exposed is unknown. Potentially important are changes in the DNA of eggs and sperm (collectively referred to as germline DNA) as this DNA becomes incorporated into every cell in the children of the exposed individuals.

47. Studies of the population of Mogilev province in Belarus have suggested a twofold increase in the germline minisatellite mutation rate (Dubrova *et al*, 1996; Dubrova *et al*, 1997). Analysis of another cohort of irradiated families from Ukraine confirmed these findings and showed that in both groups the observed increase was attributed to mutation induction in exposed fathers but not mothers (Dubrova *et al*, 2002). In contrast to the Belarus study which used non-irradiated families from the United Kingdom as the control group, the Ukraine study used fully-matched controls and exposed groups of families. Conversely, Livshits *et al* (2001) and Kiuru *et al* (2003) found exposure to radiation had no significant effect on minisatellite mutations in the children of Chernobyl cleanup workers compared with the children of control families from the Ukraine. However, Livshits *et al* did find that the subgroup of children conceived either while their fathers were working at Chernobyl or up to two months later had a higher frequency of mutations than children conceived at least four months after their fathers had stopped working at the site. Slebos *et al* (2004) also examined DNA from lymphocytes in the children of cleanup workers and found no significant difference in mutation frequency between children conceived before their father's exposure and those conceived after. They pointed out, however, that their sample size was small giving the study low the statistical power.

48. Clearly this is a matter requiring further studies over longer time periods. Future studies may indicate that this could be another area where established views about radiation's effects may need to be revised.

(6) Mental Health and Psycho-social effects

49. The Chernobyl accident has had profound and far-reaching psycho-social effects. The origins of these effects are complex, and are related to several factors, including:

- Anxiety about the possible effects of radiation, often leading to extreme pessimism, depression, apathy and fatalism
- Changes in lifestyle, particularly diet, alcohol and tobacco
- Feelings of being a victim, leading to a sense of social exclusion and an expectation of external support, including financial help and special medical treatment
- Stress associated with evacuation and resettlement (see UNDP, 2002)

50. In a short report such as this it is difficult, if not impossible, to do justice to the scale of these problems. Chapter 15 of the IAEA/WHO report (2005a) which describes the mental, psychological and central nervous system effects of Chernobyl states:

> "The mental health impact of Chernobyl is the largest public health problem caused by the accident to date. The magnitude and scope of the disaster, the size of the affected population, and the long-term consequences make it, by far, the worst industrial disaster on record. Chernobyl unleashed a complex web of events and long-term difficulties, such as massive relocation, loss of economic stability, and long-term threats to health in current and, possibly, future generations, that resulted in an increased sense of anomie and diminished sense of physical and emotional balance. It may never be possible to disentangle the multiple Chernobyl stressors from those following in its wake, including the dissolution of the Soviet Union. However, the high levels of anxiety and medically unexplained physical symptoms continue to this day. The studies also reveal the importance of understanding the role of perceived threat to health in epidemiology studies of health effects."
>
> "What the Chernobyl disaster has clearly demonstrated is the central role of information and how it is communicated in the aftermath of radiation or toxicological incidents. Nuclear activities in Western countries have also tended to be shrouded in secrecy. The Chernobyl experience has raised the awareness among disaster planners and health authorities that the dissemination of timely and accurate information by trusted leaders is of the greatest importance."

Annex 4. Radiation Dose Units

A measure of the effect of radiation is the amount of energy it deposits in unit mass of body tissue. This quantity is called the **absorbed dose**. The unit of absorbed dose is the **gray** (Gy). One gray is equal to the energy deposition of 1 joule in 1 kilogram of tissue.

The biological effects of alpha particles and neutrons (high LET[31] radiation) are in general much greater than the effects of beta particles and gamma rays (low LET radiation) of the same energy. The **Radiation Weighting Factor** w_R is introduced to take account of the different biological effectiveness of alpha and beta particles, neutrons, X and gamma rays.

The quantity **equivalent dose** is then defined as: equivalent dose = absorbed dose x w_R

The unit of equivalent dose is the **sievert** (Sv).

In studies of low dose radiation, the sievert is too large a unit and doses are usually given in millisieverts (mSv) where 1 Sv = 1,000 mSv (see below)

For low LET radiation, $w_R = 1$, so grays and sieverts will be numerically equivalent.

However, for alpha particles $w_R = 20$, so an absorbed dose of 1 mGy produced by alpha particles will have an equivalent dose of 20 mSv.

Systeme Internationale Nomenclature (commonly used units)

E = exa	= 10^{18}	d = deci (one tenth)	= 10^{-1}
P = peta	= 10^{15}	c = centi (one hundredth)	= 10^{-2}
T = tera (one trillion)	= 10^{12}	m = milli (one thousandth)	= 10^{-3}
G = giga (one billion)	= 10^{9}	μ = micro (one millionth)	= 10^{-6}
M = mega (one million)	= 10^{6}	n = nano (one billionth)	= 10^{-9}
K (often k) = kilo (one thousand)	= 10^{3}	p = pico (one trillionth)	= 10^{-12}

Common examples are:

PBq = petabecquerel (one million billion becquerels)	= 10^{15} Bq
TBq = terabecquerel (one trillion becquerels)	= 10^{12} Bq
GBq = gigabecquerel (one billion becquerels)	= 10^{9} Bq
mSv = millisievert (one thousandth of a sievert)	= 10^{-3} Sv
μSv = microsievert (one millionth of a sievert)	= 10^{-6} Sv
nSv = nanosievert (one billionth of a sievert)	= 10^{-9} Sv

also, re computers
TB = terabytes
GB = gigabytes
MB = megabytes

[31] LET= linear energy transfer, ie the energy transferred per unit length of the radiation track

Chapter 5. Collective Doses

Introduction

1. Radiation exposures are mainly measured in two ways: individual doses and collective doses. As their names suggest, individual doses are per person: collective doses are the sum of individual doses to all exposed persons in a defined area, for example a workforce, a country, a region, or indeed the world. This may appear straightforward, but within many governments, the nuclear industry and, to a lesser extent, within radiation protection circles, there is a noticeable reluctance to use and discuss collective doses. For example, although legal limits exist in most countries for individual doses, to our knowledge none exists for collective doses. This means that few, if any, legal or administrative sanctions exist against high collective doses. Also, of the ICRP's three main principles of justification, optimisation and limitation (of radiation exposures), only the first two refer to collective dose[32].

2. This reluctance is partly due to the uncertainties involved, and partly due to the fact that from a given collective dose one can estimate the numbers of future cancer deaths, which some radiation protection authorities do not wish to emphasise. Despite this reluctance, scientifically speaking a good case exists for using collective doses. This arises from linear-no-threshold (LNT) hypothesis for radiation's effects. This theory predicts that radiation's effects continue to exist even at very low doses, declining linearly with dose without a threshold. That is, there is no dose below which effects do not occur. A corollary of the LNT is that it is scientifically correct to estimate collective doses even where individual doses are very low, for example below background radiation doses. This is discussed in more detail in Annex 6A. The recent reports by the IAEA/WHO (2005a, 2005b) and UNSCEAR (2000) give short shrift to collective doses particularly when individual doses are low.

3. This chapter discusses collective dose estimates made by official studies for Belarus, Ukraine and Russia; the rest of Europe; the rest of the world; and total global doses. We shall also make an estimate for collective doses from very long-lived nuclides including C-14 and I-129.

4. Collective doses are estimated by assessing the average doses to populations exposed to radiation. Such dose assessments take into account

- deposition densities of Cs-137 and other nuclides
- population numbers in affected areas
- estimates of average external dose from deposited nuclides
- estimates of average internal dose from ingestion and inhalation of nuclides
- habits and diets of affected populations (in some reports), and
- conversion factors from Gy to Sv (from organ doses to whole body doses)

5. It is necessary to identify clearly the time periods over which a collective dose is estimated. For example, the exposed populations in Belarus, Ukraine and Russia received

[32] in the 1980s and 1990s, the ICRP (without informing the public) debated the issue of collective dose, but was unable to agree on recommending a limit.

approximately one third of their collective dose in the first year after Chernobyl. Approximately another third was received in the next nine years (ie 1987 to 1996), and about another third will be received between 1997 and 2056, ie 70 years after Chernobyl. Unfortunately, time periods are missing, glossed over or left to footnotes in some official reports. In other reports, no consistency exists: one year, 10 years, 20 years and 70 years are variously used. This is unscientific as it makes proper comparisons very difficult and is indicative of the poor attitude towards collective dose in official reports.

6. No greater time periods than 70 years are used, to our knowledge. This limitation to 70 years (the so-called lifetime period) is illogical as collective doses will continue to arise from Cs-137 exposures well into the next century and beyond. A 300 year period (ie 10 halflives of Cs-137) would be more relevant, but such a period does not appear in the literature on Chernobyl we have examined.

A. Collective Dose Estimates for Belarus, Ukraine and Russia

7. The report prepared by Cardis *et al* (1996) for the IAEA/WHO Conference in 1996 on the 10th anniversary of Chernobyl contained the following table reproduced below

Table 5.1 Estimates of Collective Effective Doses to 1996 in Belarus, Ukraine and Russia by Cardis *et al*, 1996

Population	Number	Collective effective dose[(a)] (person Sv)
Liquidators (1986-1987)	200,000	20,000
Evacuees	135,000	1,600
Persons living in contaminated areas Cs-137 > 555 kBq/m^2	270,000	10,000 - 20,000
Persons living in contaminated areas Cs-137 > 37-555 kBq/m^2	6,800,000	35,000 -100,000
Total	7,405,000	67,000 - 140,000

(a) These doses are for 1986-1995; over the longer term (1996-2056), the collective dose will increase by approximately 50% (footnote in original)

In view of the Cardis *et al*' advice to increase the collective dose by 50%, we do this below

Total	7,405,000	100,000 – 210,000

source: Cardis *et al* (1996)

8. Table 5.2 compares estimates of collective doses in Belarus, Ukraine and Russia reports by national and international agencies and others including Cardis *et al* (1996).

Table 5.2 Estimated Collective Doses in Belarus, Ukraine and Russia

Study	Collective effective dose - Person Sv	Exposure period
US DoE (Anspaugh *et al*, 1988)	326,000*	50 years
UNSCEAR 1988 (Bennett 1995,1996)	216,000	to 2056
Cardis *et al* (1996) table 5.1 using footnote	100,000 - 210,000	to 2056
Malko (1998a)	165,000	lifetime
Ukraine Government (2001)	58,000 (Ukraine)	2056
IAEA/WHO (2005b)	55,000	2006

* (person Gy)

9. The IAEA/WHO's collective dose assessment of 55,000 person Sv is the lowest estimate by some margin: it is considerably lower than the estimates by Cardis *et al* presented to the IAEA/WHO 1996 conference and shown in table 5.1. It is lower than the Ukrainian Government's estimate for Ukraine alone. Note that the IAEA/WHO estimate is only to 2006 and they make no estimate for future doses, unlike the other studies. The studies by Cardis *et al* (1996), Malko (1998) and Bennett (1995, 1996) were comprehensive using the latest available data. It is difficult to understand the IAEA/WHO's decision not to include these estimates in their report to the 2005 Conference. The studies by Bennett in particular are relevant: his methodology is set out in Annex 5A.

B. Collective Doses in the Rest of Europe

10. Estimates for collective doses in the rest of Europe are set out in table 5.3. More detailed country by country estimates are contained in Annex 5B.

Table 5.3 Collective dose estimates for Europe (excluding Belarus, Ukraine and Russia)

Study	Collective Dose person Sv	Period
US DoE (Anspaugh *et al*, 1988)	580,000	50 years
UNSCEAR, 1988 (Bennett 1995,1996)	318,000	to 2056
OECD/NEA, 1996	68,000	in first year

11. The OECD/NEA estimate is only for the first year (ie 1986 to 1987) in which only about 30% of the collective dose would have been received. To obtain a proper estimate to 2056, we need to increase this value by a factor of about 3.4:.

OECD/NEA, 1996	~230,000 (ie 68,000 x 3.4)	to 2056

12. The OECD/NEA estimate should be treated as a minimum as it excludes non-OECD countries, including Bulgaria, Rumania and Yugoslavia that are known to have received large depositions of Chernobyl fallout. It is not possible to make an estimate of the collective doses in these countries, as information on the populations affected by the Chernobyl depositions is not available. However, their collective doses may have been relatively large.

C. Collective Doses in the Rest of the World (excluding the whole of Europe)

13. Bennett (1995) estimates a collective dose commitment of 66,000 person Sv and Anspaugh *et al* (1988) 28,000 person Sv to all areas of the world outside Europe. In order to check these estimates, we make an order-of-magnitude estimate from the following assumptions

- population of the Northern Hemisphere (less population in Belarus, Ukraine and Russia and rest of Europe) $= 4 \times 10^9$
- Average Cs-137 deposition density throughout northern hemisphere (from 4×10^{16} Bq Cs-137/surface area of 2.45×10^{14} m^2)

(Bennett (1996) cites range of 1,000 kBq/m^2 to 0.01 kBq/m^2) = 0.16 kBq/m^2

- Average external dose from Cs-137 density of 1 kBq/m^2 1986-2056 (from table 3A (ii), Annex 3A) = 90 μSv

- Therefore average external dose from Cs-137 density of 0.16 kBq/m^2 =14μSv
- Add contribution from other nuclides (30% of Cs-137 dose) = 4 μSv
- Add contribution from internal doses (50% of external dose - see Annex 3A, table 3A(iii)) = 7 μSv

---

Total average dose 1986-2056 per person = 25 μSv

Therefore the estimated collective dose = 4 x 10^9 x 25 Sv^{-6} person Sv which is ~100,000 Person Sv and which is not far from Bennett's estimate of 66,000 person Sv.

D. Global Collective Doses

14. Table 5.4 sums the contributions from sections A to C above.

Table 5.4 Total Collective Doses from Chernobyl Discharges- person Sv

Area	**US DoE Anspaugh *et al* (1988)***	**UNSCEAR Bennett (1995, 1996)**	**OECD/NEA (1996)**	**Cardis *et al* (1996)**	**Malko (1998)**	**IAEA/WHO (2005b)**
Belarus, Ukraine and Russia	326,000	216,000	-	100,000 – 210,000**	165,000	55,000
Rest of Europe	580,000	318,000	230,000***	-	-	-
Rest of World	28,000	66,000	-	-	-	-
TOTAL	930,000	600,000	-	-	-	-

* person Gy
** see table 5.1
*** see paragraph 11 of this chapter

15. The earlier study by Anspaugh *et al* estimated a collective dose of 930,000 person Gy (approximately the same as 930,000 person Sv) on the basis of environmental data available at the time and the use of early dose assessment and risk models. Bennett's estimate of 600,000 person Sv is probably more reliable, as UNSCEAR had access to more data and more recent data.

16. The collective dose estimates described above are not mentioned in the UNSCEAR (2000) or the IAEA/WHO (2005b) reports. We consider that some explanation for this omission should be given, particularly as Bennett himself was the Scientific Secretary of UNSCEAR until the late 1990s, and was Chairman of the September 2005 IAEA/WHO Conference. His estimates were regularly cited in official reports in the 1980s and 1990s until about 1996. From this examination of collective dose estimates, it is clear that Bennett's estimates are reliable and his studies still relevant.

Collective Doses From Long-Lived Nuclides

17. The worldwide distribution of some nuclides with long half-lives result in small exposures to the population of the world (~6 billion people) for many years into the future. This matter is not considered by any of the above studies therefore an estimate is made below in table 5.5. Releases of Cl-36 and Tc-99, two other globally distributed nuclides with very long half-lives, are unknown but should be added. Global dose coefficients (person Sv/TBq) rounded to two significant figures were obtained from Simmonds *et al* (1996) and Mayall *et al* (1993). Estimated nuclide releases are from Kirchner and Noack (1988) and UNSCEAR (2000).

Table 5.5 Collective doses from long-lived nuclides

Nuclide	Half-life (years)	Estimated Release (TBq)	Global Dose Coefficient (Person Sv per TBq released to air)	Collective dose Person Sv
C-14	5,740	100	110	11,000
I-129	15,700,000	0.08	9,500	760
Kr-85	10.7	33,000	0.004	130
H-3	12.3	1,400	0.002	2.8
Total				12,000

18. The result of 12,000 person Sv is relatively small in comparison with the above collective dose estimates of 600,000 and 930,000 person Sv respectively by Bennett and Anspaugh *et al*. But it should be kept in mind when considering predictions of excess cancer deaths.

Comparison with other Releases

19. Bennett (1995) compared the collective dose from Chernobyl's fallout with the collective doses from other man-made releases. These are set out in table 5.6. It can be seen from this table that the Chernobyl accident certainly is the most serious nuclear accident. Indeed the fallout from Chernobyl is second only to the fallout from the hundreds of atomic test bombs detonated above ground in the 1950s and 1960s.

Table 5.6 Committed Collective Doses from Man-Made Radionuclide Releases

Release	Collective Eeffective dose person Sv
Atomic test bombs (in atmosphere) 1950s and 1960s	30,000,000
Chernobyl accident USSR 1986	600,000
Nuclear power production (to 1995)	400,000
Radioisotope production and use (to 1995)	80,000
Nuclear weapons fabrication (to 1995)	60,000
Kyshtym accident USSR 1957	2,500
Windscale accident UK 1957	2,000

source: Bennett (1996)

Annex 5A. Bennett's Study

(i) Bennett (1995, 1996) and UNSCEAR (1988, 1994) arrived at their estimates by using a Cs-137 deposition vs distance relationship to make dose estimates for the northern hemisphere of the world. Based on Cs-137 deposition estimates in all areas of the northern hemisphere (derived from his deposition-distance relationship and transfer factors relevant for the latitudinal area), he derived effective dose commitments for all regions. These doses multiplied by the populations of the regions give the collective effective dose commitments.

(ii) Bennett stated that a general decrease of radionuclide deposition with distance from the release site could be expected, with variability due to wind and rainfall differences. In the Chernobyl accident, the release continued for ten days and the wind changed to all directions. Therefore some variability was averaged out and Bennett observed a relatively uniform decrease in Cs-137 deposition with distance to the capital cities or the approximate population centres of the relevant countries. A log-log plot of average Cs-137deposition in countries outside the USSR was made of Cs-137 measurements with distances from the accident site. This allowed Bennett to determine an approximate deposition-distance relationship ranging from about 10 kBq/m^2 at 1,000 km to ~ 0.01 kBq/m^2 at 10,000 km. With this relationship, Cs-137 deposition densities were estimated in all regions of the northern hemisphere where measurements were unavailable.

(iii) Bennett estimated that the total collective dose from the Chernobyl accident was 600,000 person Sv, distributed 53% to European countries, 36% to the former USSR, and the remaining 11 % to the rest of the northern hemisphere. The calculations indicated that 70% of the collective dose was due to Cs-137, 20% to Cs-134, 6% to I-131 and the remaining 4% to short-lived radionuclides deposited immediately after the accident. The lifetime dose on average was approximately 60% from external irradiation and 40% from ingestion. According to Bennett, approximately one third of the 600,000 man Sv total effective dose committed by the accident was received during the first year following the accident. The remainder would be delivered over “some tens of years”, mainly determined by the 30 year half-life of Cs-137.

Annex 5B. Collective Dose Estimates in European countries

(i) Table 5C(i) sets out collective dose estimates in European countries by the UK NRPB[33], the US DoE, and the OECD/NEA.

Table 5C(i) Collective Doses to European Countries. Person-Sv

Country	Population millions	NRPB, 1987 (all time)	DoE, 1987 (50 years)	OECD/NEA, 1996 (first year)
Albania	-	-	-	-
Austria	7.4	-	-	4,900
Belgium	10	940	880	400
Bulgaria	-	-	-	-
Czechoslovakia	-	-	-	-
Denmark	5.2	1,100	820	140
Finland	4.9	-	-	2,500
France	55	5,600	12,000	1,300
East Germany	-	-	-	-
West Germany	61	30,000	58,000	18,000
Greece	9.8	8,500	4,700	3,600
Hungary	-	-	-	-
Ireland	3.5	950	1,800	370
Italy	56.6	27,000	52,000	28,000
Luxembourg	0.37	42	76	45
Netherlands	14.5	1,200	3,400	950
Norway	4.2	-	-	700
Poland	-	-	-	-
Portugal	9.3	2.3	low	58
Rumania	-	-	-	-
Spain	37.7	57	low	-
Sweden	8.3	-	-	1,700
Switzerland	6.5	-	-	1,400
Turkey	52	-	-	830
UK	56.6	1,000	15,000	2,100
Yugoslavia	-	-	-	-
TOTAL	**400**	**78,000**	**149,000**	**67,000**

(ii) These estimates are difficult to compare as different studies exclude different countries and apply to different time periods. The OECD study which was prepared by an NEA committee of national experts is considered to be relatively reliable. Nevertheless, it only presents an estimate for the first year after Chernobyl, during which only about 30% of the collective dose occurs, Therefore it is necessary to increase the total 3.4 fold to extend the doses until 2056. This would result in a European collective dose of about 230,000 person Sv.

[33] Formerly the UK National Radiological Protection Board, now subsumed within the UK Health Protection Agency-Radiation Protection

Chapter 6. Predicted Excess Cancer Deaths

1. An estimate of the number of world-wide cancer deaths may be made from the estimates of collective doses in the previous chapter. The scientific justification and the method for this procedure are set out in Annex 6A.

Predictions for Belarus, Ukraine and Russia

2. IAEA/WHO (2005a) reported the following numbers of predicted excess cancer deaths in table 16.4 of its report.

Table 6.1 Predicted Excess Cancer Deaths in Belarus, Ukraine and Russia (from lifetime exposures of 95 years)

Population	Number	Average dose Sv	Cancer type	Predicted excess cancer deaths
Liquidators (1986-87)	200,000	0.1	solid cancers	2,000
			leukaemias	200
Evacuees from 30 km zone	135,000	0.01	solid cancers	150
			leukaemias	10
Residents of SCZs	270,000	0.05	solid cancers	1,500
			leukaemias	100
Residents of other contamin areas	6,800,000	0.007	solid cancers	4,600
			leukaemias	370
Totals	7,405,000			8,930

source: table 16.4 in IAEA/WHO (2005a)

3. This table gives fairly detailed estimates of expected cancer deaths in Belarus, Ukraine and Russia expressed over a lifetime. These estimates were previously reported in 1996 (IAEA/WHO) but they were apparently not mentioned in the IAEA Press briefings and not commented upon in the media at the time. In September 2005, some of these data were mentioned in the IAEA Press Release (2005c) issued at the IAEA/WHO conference on Chernobyl. The IAEA Press Release stated that 4,000 excess cancer deaths were expected. It is considered that this statement was being "economical" with the data in table 6.1 above. It would appear that the IAEA decided to refer only to the expected deaths among those who received higher doses, ie the liquidators and residents of Severely Contaminated Zones (SCZs). The other lower dose categories were ignored. At the least, this is a manipulative use of data. At worst, it is a misleading use of data, as the real figure - as can be seen above - is nearly 9,000 excess cancer deaths.

Global Predictions of Excess Cancer Deaths

4. If we assume that the linear no-threshold hypothesis of radiation's effects is correct, we may apply a risk factor[34] to the collective doses cited in Chapter 5 to derive predictions of the

[34] expressed in cancer deaths per sievert. 5% per Sv means that if 100 people were each exposed to 1 Sv of radiation, there would be 5 excess deaths from radiation-induced cancer

excess cancer deaths that will result from Chernobyl exposures. Table 6.2 sets out the predictions by various international studies of the numbers of excess cancer deaths from Chernobyl. Uncertainties inevitably surround these estimates, but they serve to indicate the probable magnitude of the effects of the Chernobyl disaster. They are our best estimates given the currently available information, although few of these excess deaths are likely to be discernible by epidemiology studies.

Table 6.2 Predicted Excess Cancer Deaths from Exposure to Chernobyl Discharges

Study	Population	Risk factor used Per Sv	Excess cancer deaths
IAEA/WHO Press Release (2005c)	Belarus, Ukraine and Russia	assumed to be 5%	4,000
Cardis *et al*, 1996	Belarus, Ukraine and Russia	11% inferred from data	~9,000
Malko (1998)	Belarus, Ukraine and Russia	13% inferred from data	22,000
Rytomaa (1996)	World	5% inferred from data	30,000
US DoE (Goldman, 1987)	World	~3%	28,000
US-NRC, 1987	World	~1.5% inferred from data	14,000
UNSCEAR 1988 (Bennett, 1996)	World	5%	30,000

in greyed cells, prediction is calculated by this report (ie 5% of 600,000 person Sv)

5. The figure of 4,000 reported in the IAEA/WHO Press Release (2005c) at the IAEA/WHO Conference on Chernobyl held in Vienna in September 2005 is the lowest value of predicted excess fatal cancers in table 6.2. In terms of good scientific practice, it would have been preferable for the IAEA/WHO report to place its estimate in the context of other published predictions of excess cancer deaths.

Radiation Risk Estimates and DDREFs

6. Table 6.2 indicates that various authors use different radiation risk estimates to predict the numbers of excess fatal cancers. The current ICRP recommendation (ICRP, 1991) is to apply an average risk factor (over all populations, ages and sexes) of 5% per Sv for fatal cancers. This risk figure comes from studies of the Japanese atomic bomb survivors. However, the risk factor from Japan[35] is halved because the ICRP takes the view that radiation at low doses and low dose rates (like that from Chernobyl fallout) is less dangerous than high dose, high dose rate radiation (like that from the atomic bomb blast). In scientific jargon, this is known as applying a dose and dose-rate effectiveness factor (DDREF) of 2.

7. The ICRP's rationale has been that animal and cell studies show low doses of radiation at low dose rates to be less damaging than high doses at high rates. However, the BEIR VII Committee of the US National Academy of Sciences on ionising radiation has taken a

[35] the most recent estimate from the atomic bomb survivors (Preston *et al*, 2003) is an average of 12% per Sv

different view of the evidence. Its recent report (BEIR, 2005) recommends that a median[36] DDREF of 1.5 rather than 2 should be used for solid cancers. This in turn suggests that the correct risk factor for most cancers should be increased from 5% to about 7% per Sv.

8. As regards DDREFs, it is notable that the US EPA (1994) has not used a DDREF for breast and thyroid cancers for many years. Also, an increasing number of scientists (for example Cardis *et al*, 1996; Malko,1998) refrain from using a DDREF factor, partly[37] because the supporting evidence for their use are animal and cell studies and not human epidemiology studies. Indeed, two recent epidemiology studies (Cardis *et al*, 2005b; Krestinina *et al*, 2005) indicate the opposite, ie that exposures to protracted radiation might be more not less damaging (as regards cancer induction) than high dose-rate exposures by as much as 2.5 times. This matter is the subject of continuing discussion in radiation protection circles.

9. In view of these matters, we consider that the inappropriate use of DDREFs may well lead to inaccurate estimates of future cancer deaths. For this reason, we set out in table 6.3 a range of estimated excess cancer deaths using reasonable risk factors derived from different values for DDREF and from not using a DDREF.

Table 6.3 Predicted Excess Cancer Deaths from Exposure to Chernobyl Discharges

Study	Population	Risk factor used	Excess cancer deaths
UNSCEAR 1988 (Bennett, 1996)	World	10% per Sv (using no DDREF)	60,000
UNSCEAR 1988 (Bennett, 1996)	World	6.7% per Sv (using BEIR DDREF of 1.5)	40,000
UNSCEAR 1988 (Bennett, 1996)	World	5% per Sv (using ICRP DDREF of 2)	30,000

greyed cells = calculated by this report from data in Bennett, 1996

10. In table 6.3, we derive three predictions of excess cancer deaths, and our best estimate lies in the range 30,000 to 60,000. Although our predictions are higher than other estimates of predicted excess cancer deaths by Goldman (1987) and Rytomaa (1996) – see table 6.2, they have been derived using a simple scientific procedure. If future studies were to confirm that a DDREF should not be applied (ie that the Japanese risk estimates should not be divided by any figure), then the higher figure of our estimated range would be applicable. If future epidemiology studies were to go further and indicate that protracted radiation might be more rather than less damaging (as regards cancer induction) than high dose-rate exposures, then the above estimates would need to be increased still further.

Inappropriate Comparisons with Background Radiation

11. Official reports (eg IAEA/WHO, 2005a) often compare the numbers of expected excess cancer deaths with the much larger numbers of cancer deaths expected from background radiation over the same time period. In our view, such comparisons are inappropriate, as they conflate man-made radiation with naturally-occurring radiation. They may also be misleading

[36] with a range of 1.1 to 2.3
[37] also because the use of DDREFs is inconsistent with the accepted practice of extrapolating risks linearly from data at high doses to low doses

because they invite the uninformed public to infer that background radiation is somehow "safe". In reality, background radiation is a killer. For example, the former UK NRPB has calculated that an average background dose rate of 2.6 mSv/a in the UK population results on average in about 6,000 to 7,000 future cancer deaths per year (Robb 1994). This matter is explored further in Annex 6B.

Annex 6A. Collective Dose and the Linear No-Threshold Theory

(i) Epidemiology evidence exists of an excess risk of radiation-induced cancer at doses at least as low as 10-50 mSv and that this risk is directly proportional to dose. The latest study of cancer in nuclear industry workers (Cardis, 2005c), in which the overall average cumulative recorded dose was 19.4 mSv, suggest, according to the authors that ‘an excess risk of cancer exists, albeit small, even at the low doses and dose rates typically received by nuclear workers in this study’. The most recent follow-up of the Hiroshima and Nagasaki survivors (Preston *et al*, 2003) shows that ‘the excess solid cancer risks appear to be linear in dose even for doses in the 0-150 mSv range’. In the particular case of thyroid cancer, there is evidence that the risk is directly proportional to dose, down to doses as low as 10 mSv (Ron *et al*, 1995).

(ii) However, at doses of a few mSv or lower, risks have to be inferred by extrapolation from higher doses, as epidemiology studies would require unfeasibly large numbers of people to be studied to achieve adequate statistical power. Radiobiology can help here: because the transformation of a cell to a pre-cancerous state may result from the lowest possible dose of radiation - a single radiation track traversing a single cell nucleus – good reasons exist for supposing that the risk is directly proportional to dose right down to zero, i.e. there is no-threshold (NRPB, 1995; Stather, 1995).

(iii) The ICRP’s view (2004) is that the LNT relationship should be used as it provided a “conservative” estimate of risks. The word “conservative” has a special meaning in radiation protection. It means that because, in the ICRP’s view, the real risk is likely to be lower, acting on the higher risk estimate gives an added safety margin. Recently, an eminent group of the world’s foremost radiobiologists re-affirmed the LNT and stated that it provided a real estimate of radiation risks and not a “conservative” one (Brenner *et al*, 2003).

(iv) Assuming the risk of cancer is directly proportional to dose with no threshold, it follows that the number of cancer deaths can be estimated as follows:

- number of cancer deaths = number of people exposed x average dose (Sv) x risk factor (cancer deaths per Sv)
- the product (numbers exposed x average dose) is the **collective dose**, so
- predicted number of excess cancer deaths = collective dose x risk factor

(v) More detailed discussions of collective dose are contained in Fairlie and Sumner (2000) and Sumner and Gilmour (1995), and of the biological justification for the LNT in Brenner *et al* (2003).

Annex 6 B. Inappropriate Comparisons with Background Radiation

(i) Offical reports often compare collective doses from man-made radiation with the much larger collective doses received from background radiation, in attempts to put them "in context". Such comparisons invite the public to conclude that, because doses from man-made radiation are smaller than those from background radiation, they are therefore acceptable. Many objections can be made against these assertions.

(ii) First, comparisons with natural background doses invite the inference that background radiation is “safe”. This is not the case, of course: background radiation is a killer. For example, the former UK NRPB has calculated, using a 5% per Sv risk factor, that an average UK background dose rate of 2.6 mSv per year in a population of 55 million will result on average in about 6,000 to 7,000 future cancer deaths per year, about 4% to 5% of the 160,000 cancer deaths occurring each year in the UK (Robb, 1994).

(iii) Second, comparisons with background radiation conflate different risks, ie naturally-occurring and anthropogenic risks. Risks from anthropogenic releases are (or were in the case of past exposures) subject to by social and political decisions. Risks from background radiation are not.

(iv) Third, it is notable that comparisons with background are not used to justify the acceptability of industrial discharges of chemical toxins that also occur naturally, such as aflatoxin, ozone or dioxin.

(v) Finally, and notably, the current ICRP system of radiation protection of limitation, optimisation and justification (ICRP, 1991) notably does not use comparisons with natural background radiation as a criterion of radiological acceptance. This is a deliberate omission, as the issue of using background radiation has often been discussed at ICRP committee meetings. In recent years, the past chairman of the ICRP had attempted to jettison the ICRP’s principles and to introduce background radiation as a criterion of acceptance. These attempts failed as they were not supported during the ICRP’s consultations on updating its 1991 recommendations which took place in 2004. Indeed, in the past, many scientists have stated (NRPB, 1990), (Webb *et al,* 1983), (section 8.3.4 in Bush *et al,* 1984) that comparisons of radiation exposures from anthropogenic releases with natural background radiation are inappropriate.

Chapter 7. Conclusions

1. It is widely agreed that the Chernobyl disaster was unprecedented and unique in the history of civil nuclear power. Its effects are clearly still occurring and the full consequences may take centuries to unfold. Even then, it is likely that many details will never be known.

2. The main conclusions of our report are

- about 30,000 to 60,000 excess cancer deaths are predicted, 7 to 15 times greater than IAEA/WHO's published estimate of 4,000
- predictions of excess cancer deaths strongly depend on the risk factor used
- predicted excess cases of thyroid cancer range between18,000 and 66,000 depending on the risk projection model used
- other solid cancers with long latency periods are beginning to appear 20 years after the accident
- Belarus, Ukraine and Russia were heavily contaminated, but more than half of Chernobyl's fallout was deposited outside these countries
- fallout from Chernobyl contaminated about 40% of Europe's surface area
- collective dose is estimated to be about 600,000 person Sv, more than 10 times greater than official estimates
- about 2/3rds of Chernobyl's collective dose was distributed to populations outside Belarus, Ukraine and Russia, especially to western Europe
- Cs-137 released from Chernobyl is estimated to be about a third higher than official estimates

Recent IAEA/WHO studies

3. Our verdict on the two recent IAEA/WHO (2005a, 2005b) studies on health and environment respectively is mixed. On the one hand, we recognise that the reports comprehensively examine Chernobyl's effects in Belarus, Ukraine and Russia. They contain a great deal of important information which will repay future study. Clearly much scientific effort was put into the reports by the respective scientific teams and their chairpersons, and they are welcomed for this reason.

4. On the other hand, the reports contain some deficiencies, for example the lack of discussion on Chernobyl's source term and the low estimates of collective dose in Belarus, Ukraine and Russia. Significantly they are silent[38] on Chernobyl's effects outside Belarus, Ukraine and Russia. Most of Chernobyl's fallout was deposited outside these countries. Countries in the rest of the world, especially in Europe, will suffer twice as many predicted excess cancer deaths (and collective doses) as Belarus, Ukraine and Russia.

[38] except for one table on Cs-137 contaminatio n levels in a few Europeam countries

5. We recognise that the failure to examine Chernobyl's effects in all other countries does not lie with the scientific teams but with higher echelons of the IAEA and the WHO. We recommend that the WHO, independently of the IAEA, should now commission a report to examine Chernobyl's effects in all other countries in order to rectify the omission. We also recommend that UNSCEAR, presently located within the IAEA's headquarters in Vienna, should be relocated to a more neutral venue.

Uncertainties

6. As we have shown in this report, the reconstruction of the accident and the prediction of its health consequences involve many uncertainties: in the size of the source term, the distribution of fallout, the relationship of contamination to doses received, and the estimation of health effects from radiation doses. To estimate the likely effects, value judgements have to be made; values of various parameters have to be assumed when we use models; and some assumptions may be arbitrary. This is particularly the case with predictions of excess cancer deaths from Chernobyl's collective doses. These strongly depend on the risk factor used, but divergent views exist on what is the correct factor. Up to a few years ago, 5% per Sv was widely used: nowadays 10% per Sv or more is increasingly used. This obviously results in increased numbers of predicted excess cancer deaths, therefore close scrutiny of the risk factor used is needed.

7. As a result, many of the doses, predicted effects and risks we cite in this report will be subject to considerable uncertainties. We draw attention to these uncertainties and recommend that a precautionary approach be adopted when using them.

Scientific Lessons

8. Many lessons are still being learned from Chernobyl. Some of them should already be part of the scientific approach, but at the risk of stating the obvious, we set them out below

- (i) We must not jump to conclusions, especially about the absence of radiation effects with long latency periods. The studies published so far have follow-up periods that are smaller than the typical latency periods for solid cancers induced by radiation. Many studies are still in progress, and their results are awaited. For example, the follow-up studies of the atomic bomb survivors, which have now continued for more than 60 years, are still yielding new, and sometimes surprising, information.
- (ii) Many years ago, a British politician, Oliver Cromwell, stated: "Always think it possible that thou art mistaken". It has now been shown that the initial scepticism that greeted the first reports of childhood thyroid cancer from Chernobyl was unjustified. This should make us more careful about deciding what is and what is not a radiation effect. In other words, we need to keep a very open mind on Chernobyl's effects.
- (iii) "Absence of evidence is not evidence of absence" (Altman and Bland, 1995). A real effect can elude detection because of low statistical power, often because the samples are too small. The lack of statistical power is a recurrent theme in many of the studies published so far.

The Future

9. As for the future, we recommend that follow-up studies are continued and broadened, with satisfactory funding and the involvement of independent scientists. A good model in this respect is the Radiation Effects Research Foundation (RERF) in Japan, which continues to follow-up effects in the atomic bomb survivors and whose funding is independently secured. In this connection, we note the apparent lack of independence in the relations between the WHO and the IAEA as regards the WHO's studies on Chernobyl effects. The WHO should be able to carry out health-related research and publish health reports on radiation matters independently of the IAEA, just as other UN agencies publish reports independently of each other. In our view, there is no reason why the WHO alone should not investigate these matters and publish its results without the permission of the IAEA.

10. Collaborative work is sometimes limited by the inability of Western scientists to gain access to, and/or translate, many scientific reports written in Ukrainian and Russian. These language constraints inhibit a full understanding of the impacts of Chernobyl; we draw attention to this difficulty and to the need for it to be tackled at an official level. In the past, laudable attempts have been made with this aim (Shershakov and Kelly, 1996) but translations of more recent reports are needed.

11. Finally, there remains the question of the future of nuclear power. A number of countries are currently considering the renewal and/or enlargement of their nuclear power programmes. Chernobyl should give us all pause for thought before we embark on any revival of nuclear power. Even though future reactors have been stated to be inherently safer than the Chernobyl design, accidents can still occur and it is important that robust plans are agreed internationally for dealing with any future accidents (see Williams, 2001). We should keep in mind the view of the philosopher George Santayana that those who are unable to learn from history are condemned to repeat it.

Afterword

THE CURRENT SITUATION IN UKRAINE: February 2006

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The radiation accident at Chernobyl in April 1986 is still affecting the lives of many people in Ukraine and is still determining its national economic policy. There are many problems in Ukraine resulting from radio-ecological Chernobyl catastrophe including:

- the remaining reactors at Chernobyl which are currently closed;
- the “Shelter” and its reconstruction;
- the exclusion zone and radioactive waste - there are more than 800 temporary storage places for radioactive wastes containing about 300,000 Ci (Cs), 12,000 Ci (Sr) and 300 Ci (Pu) and about 110,000 Ci (Cs), 44,000 Ci (Sr) and 110 Ci (Pu) in permanent stores (7);
- the radioecological monitoring of 4.8% of the surface area of Ukraine (including 2,300 settlements);
- the radiological monitoring the Dneiper river water basin, which provides water for 32 million people and for the irrigation of 1.8 million hectares of land;
- the health monitoring of over 2,646,000 citizens, including 643,000 children, who received acute radiation doses during the accident and are still exposed to low doses of radiation in the contaminated territories;
- the social protection of these citizens and personnel of the Chernobyl nuclear plant, including residents of Slavutich town.

As a result of the accident, 2,300 settlements in 12 Ukraine Oblasts were exposed to radioactive contamination. This corresponds to 55,000 km2 including some 25,000 km2 of forests. In addition, in 1986, 91,000 people were evacuated from the 30 km exclusion zone around Chernobyl. Where Cs-137 contamination levels exceeded 555 kBq/m2, (ie II zone), compulsory evacuation was required in Ukraine. These contamination levels were estimated to result in an annual exposure of >5 mSv, five times greater than the legal limit. The radiation dose criteria for the zone of guaranteed settlement (III zone) is 1 to 5 mSv and for the zone of strengthened ecological control (IV zone) is 0.1 to 0.5 mSv. The lesser contaminated zones III and IV are presently used for agricultural production. The Chernobyl accident stopped traditional methods of forestry engineering. There is now a need to introduce new technologies and new work equipment to be used in conditions of radioactive contamination (2, 3, 7).

Ukrainian experts estimate the economic damage to Ukraine will be $200 billion up to 2015 (7, 9). In comparison, Ukraine’s GDP in 2001 was $37 billion. In 1992, Ukraine spent 15% of its entire budget dealing with the effects of Chernobyl. In 1996, the figure was 6%, and in recent years it has been 5% (4, 9).

The radiation exposures to the Chernobyl liquidators ranged between 50 mSv and 7 Sv.(1) Evacuated people from the 30 km exclusion zone received exposures between 10mSv and >700 mSv. People in contaminated areas in Ukraine, by conservative calculations, received exposures between 2 to 74 mSv (1, 4). Their total accumulated collective dose amounts to 46,000 man/Sv. The International Chernobyl project (1991) expected that the average exposure to those in contaminated areas during 70 years (1986-2056) will amount to 160 mSv. This means that the Ukraine population in contaminated areas will continue to be exposed to radiation for many years. About 80-95% of radiation doses are from the consumption of contaminated food (milk, meat, vegetables, forest products), and the remainder is from external radiation – primarily surface Cs-137.

In accordance with the Law of Ukraine on "Status and Social Protection of Citizens Affected by Chernobyl Catastrophe," about 7% of Ukraine's population was affected by Chernobyl, not including the citizens of Kiev (although they were also irradiated). By 2005, this amounted to 2, 646, 000 citizens, including (9):

- 165,000 residents of evacuated areas
- 253,000 liquidators
- 643,000 children born to the accident liquidators, and
- 1,563,000 people from 2, 293 settlements in contaminated areas

9, 500 people in 1,337 families still remain in zones of compulsory evacuation. For these people, life is very difficult and amounts to a humanitarian catastrophe. They lack all infrastructure, all services, the right for land use, and all medical care. They are subject to very high exposures from radioactive contamination. Most young families abandoned these lands independently without assistance and a dramatic ageing of the population took place.

In 2004, more than 2,320,000 Chernobyl survivors continued to receive periodic medical examinations. The Ukraine National Registry system has registered all Chernobyl survivors and has commenced automatic long-term health monitoring. By January 2005, the Registry had compiled information on 2,240,000 persons. The percentage of the adult population diagnosed ill after medical examination, is constantly growing. At present, 94% of accident liquidators, 89% of evacuees; 85% of residents of radioactively contaminated territories, and 79% of children directly or indirectly affected by the accident are officially considered ill under the Ukraine National Registry. These indices, although very large, could in fact be worse if screening were carried out thoroughly. But there is neither the finance nor political will for thorough screening in Ukraine.

According to the dose distribution in the Ukrainian population in 1986, thyroid exposures in children were distributed as follows (7, 12):

- ~85% of all children < 3 years old and children irradiated *in utero* received between 0.1 and 1 Gy;
- about 60% of children 4-15 year old and 50% of teenagers received between 50-300 mGy;
- >15, 000 children born between 1979-1986 before the accident received more than 2 Gy.

By January 2005, 3,270 patients had been operated on for thyroid cancer in Ukraine (9). Children from 17,000 communities (ie 60% of all communities of Ukraine) received thyroid doses greater than the limits in force. The total collective dose to the thyroid in Ukraine is estimated to be 1,300,000 man/Gy, of which about half (607,000 man/Gy) is to 0-18 year olds. Also the cumulative incidence of thyroid diseases is expected to increase in future. (7, 12) Various experts estimate that the lifetime risk of thyroid cancer for children who were 0-4 years old at the time of the accident will reach 30%. (12, 13). These estimates cannot be treated as final (12) until the completion of cohort epidemiology studies (over the next 20 years when all the radiation–induced thyroid cancers in the exposed population will have arisen).

For cancers in the exposed adult population, there has been a 2-fold increase in breast cancer, and a 2 to 7 fold increase in thyroid cancer. (7)

In the post-accident period, increases in cardiovascular, neurological, respiratory, digestive, and bone-muscular diseases have been registered among the affected populations. Over 105,000 disabled exposed people are registered in Ukraine, including over 2,000 children. They are disabled from diseases related to a complex of factors from the Chernobyl catastrophe and require annual therapy. The children are registered as invalids due to cancers, congenital malformations, and diseases of endocrine, nervous, respiratory and digestive systems. (8)

Genomic instability from long-term low-level radiation exposure is a newly discovered effect which remains under investigation. Uptakes of low levels of caesium, strontium, plutonium and other radionuclides by mothers and their fetuses may cause additional cancers, leukaemias and congenital diseases in the first generation. This makes the problem especially urgent. Unfortunately, there is little coordination between post-Chernobyl researchers in Ukraine, as there has been no systematic collection, standardisation and evaluation of findings as yet. This means that valuable findings are not properly analyzed or compared with other findings. Data from the National Chernobyl Registry are not properly assessed which makes it impossible to estimate the real levels of radiation effects on the population from the accident at present. The main health effects considered to be connected to Chernobyl exposures are cancers and diseases of the cardiovascular, blood and nervous systems; and among children – cancers and congenital malformations.(9).

During 2005, mortality indices increased slightly among the population affected by Chernobyl and total mortality in Ukraine also increased. Mortality indices among liquidators are constantly increasing. The highest mortality level is among the adult population resident in radioactively-contaminated territories. At the same time, birth rates in all observation groups are distinctly decreasing. Taking into account a decreased latency period of oncological abnormalities, the survival of Chernobyl victims becomes even more problematic. (9)

It is widely accepted that the Chernobyl accident has resulted in a complex of direct and indirect factors which adversely affect the health of exposed people. These factors are considered by the affected people themselves to be significant and dangerous. They include the following:

- radioactive contamination of the environment by caesium, strontium, and plutonium
- ingestion of contaminated food
- anxiety over higher illness rates among children.

On the 4th International Conference on «Chernobyl Children – Medical Consequences and Socio-Psychological Rehabilitation», a persistent complex of post-accident pathogenic factors was reported (11). This complex included radiation exposure, psychological stress, evacuation and resettlement with subsequent socio-economic effects etc., all of which adversely affected the somatic and psychological health of children.

Long-term monitoring in the three affected countries has made it possible to select cohorts of children and teenagers exposed to radiation, with a view to

- continued observation of genetic and oncological diseases;
- epidemiology investigations on the health of survivors of different ages;
- studies on new approaches to the diagnosis, prophylaxis and treatment of low dose radiation-related diseases (with special attention to molecular-genetic studies and estimating the impact of genomic instability on morbidity of offspring);
- changing approaches to overcoming of psychosocial problems of affected children.

The Conference also demonstrated that epidemiology research had been conducted on thyroid cancer in children and teenagers at the time of the accident, when studies on radiation-induced non-cancer diseases were lacking. (11)

Abnormal psychological development has been detected in 60-70% of children and teenagers exposed to radiation. This is two times higher than among general population. More than 60% of teenagers see their futures away from home because radiation pollution; (7, 10) affected areas would suffer from depopulation and decline if this occurred. Therefore, the coordination of efforts between governments, international organizations and voluntary organizations and all people of goodwill towards the solution of this complex of economic, ecological, medical and social problems of affected children and youth is very important. (8, 10).

The report of the UNDP Chernobyl Program in Ukraine in 2003-2005 revealed that the chronic crisis in the Chernobyl community resulted from its extremely low material status which restricted its access to medical care.(6) All affected people point to the extremely low level of medical care at the place of dwelling and the very high costs of better health care at oblast centres and in Kiev. The international community has been informed about the humanitarian needs of the affected people, and since 1986 has rendered the affected people invaluable assistance (6, 7, 10).

The UN report Human Consequences of the Chernobyl Nuclear Accident: A Strategy for Recovery outlined a ten-year strategy for tackling and reversing the downward spiral on development. (5) It is clear that the environmental effects of Chernobyl cannot be considered in isolation from its social, economic and institutional aspects within Ukraine. The international and national communities are interested not only in the safety of the reactor Sarcophagus but also in the knowledge to be gained about the long-term effects of radioactive fallout on health, and disaster management and rehabilitation needed in post-accident responses. However, scientific interest in the lessons of Chernobyl cannot be satisfied in isolation from the well-being of those whose lives have been shattered by Chernobyl (10, 11).

There is little doubt that the Ukraine will have to undergo a long-term period of rehabilitation. In order to realize the program on the minimization of Chernobyl's social-economic, health, and radio-ecological effects, it will be necessary to mobilize not only national efforts but also the efforts of international communities. Chernobyl in Ukraine is not only a painful memory of the past, but a major current problem and an even greater future challenge (5).

References to Afterword

1. The International Chernobyl Project. Assessment of Radiological Consequences and Evaluation of Protective Measures. Report by an International Advisory Committee. Vienna: IAEA, 1991.

2. Health Consequences of the Chernobyl accident. Results of the IPHECA pilot projects and related national programmes. Scientific Report. WHO. Geneva. 1996.

3. The Radiological Consequences of the Chernobyl Accident. European Commission and Belarus, Russian and Ukrainian Ministries on Chernobyl Affairs, Emergency Situations and Health. A.Karaoglou, G.Desmet. G.N.Kelly and H.G.Menzel (editors). ECSC-EC-EAEC, Brussels- Luxenbourg.1996.

4. UNSCEAR 2000. Report to the General Assembly. Annex J. Exposures and Effects of the Chernobyl Accident.

5. International Journal of Radiation Medicine (2000). Special issue. 2-4(6-8). 3-109.

6. Human Consequences of the Chernobyl Nuclear accident. A strategy for recovery. A Report Commissioned by UNDP and UNICEF with the support of UN-OCHA and WHO. UNDP in Ukraine.

7. Information Needs of the Chernobyl-affected Population in Ukraine: an Analysis of Focus Groups Responses. UNDP Chernobyl and Development Programme. Kiev, Ukraine, 2003.

8. Ten years after the Chernobyl NPP accident. National Report of Ukraine. 1996. Minchernobyl. Kiev, 1996.

9. Information-reference materials on minimization of Chernobyl accident consequences. Ministry of Ukraine of Emergencies. “Chernobylinterinform” agency Агентство. Kiev 2004.

10. Information-reference materials on minimization of Chernobyl accident consequences. Verhovna Rada of Ukraine. Parliamentary debates initiated to 19th anniversary of the Chernobyl accident. Kiev. April 24, 2005.

11. Conclusions of the 3-rd International Conference “Health effects of the Chernobyl accident: results of 15-year follow-up studies”(Kiev 2001). International Journal of Radiation Medicine(2001). 3(1-4)/ 3-8.

12. Resolution of the 3rd International Conference “Chernobyl Children- Health Consequences and Psychosocial Rehabilitation”(Kiev 2003). International Journal of Radiation Medicine (2004). 6 (1-4) pp 201-206.

13. Likhtarev IA, Kairo IA, Shpak VM *et al*. Radiation – induced and background thyroid cancer of Ukrainian children (dosimetric approach). Int Journal of Radiation Medicine (1999) 3-4, 51-66.

14. Lengfelder, Edmund, et. al.: 14 Jahre nach Tschernobyl: Schilddrüsenkrebs nimmt zu. Fortschritte der Medizin, 41 Nr. 16 / 2000 (142.Jg.), p. 353.

15. Lengfelder E., Rabes H, Scherb H, *et al*. Assessment of Chernobyl Health Consequences meets with resistance. Factors Influencing the Assessment of Chernobyl Health Consequences and the Contribution of International Non-Governmental Organisations to Research and Treatment of Thyroid Pathologies in Belarus. Current Concerns (2004), 2.

References to Main Report

Aarkrog A (1994) Past and Recent Trends in Radioecology. Environment International 20, No 5, pp 633-643

Altman DG and Bland JM (1995) Absence of evidence is not evidence of absence. British Medical Journal 311: 485

Anspaugh LR, Catlin RJ, and Goldman M (1988) The Global Impact of the Chernobyl Reactor Accident. Science 242. pp 1513-1519

Astakhova LN, Anspaugh LR *et al* (1998) Chernobyl-related thyroid cancer in children of Belarus: a case-control study. Radiation Research 150, 349-356

Baverstock K, Egloff B, Pinchera A, Ruchti C and Williams D (1992) Thyroid cancer after Chernobyl. Nature, 359, 21-22

Baverstock K (1986) A preliminary assessment of the consequences for inhabitants of the UK of the Chernobyl accident. International Journal of Radiation Biology. Volume 50, Number 1. pp iii – xiii

BEIR (2005) Health Risks from Exposure To Low Levels Of Ionizing Radiation (Phase 2). Committee on Biological Effects of Ionizing Radiation. National Academy of Sciences, Washinton DC US . June 2005

Bennett B (1995) Exposures from Worldwide Releases of Radionuclides. In Proceedings of an International Atomic Energy Agency Symposium on the Environmental Impact of Radioactive Releases. Vienna, May 1995. IAEA-SM-339/185

Bennett B (1996) Assessment by UNSCEAR of Worldwide Doses from the Chernobyl Accident in Proceedings of an IAEA Conference One Decade after Chernobyl: Summing up the Consequences of the Accident, Vienna, 8-12 April 1996. Pp 117 – 126

BfS (2005) Jahresbericht 2004. Federal Office for Radiation Protection. D – 38201 Salzgitter. Germany

Bobovnikova TsI, Makhonko KP, Siverina AA, Rabotnova FA, Volokitin A (1991) Physical chemical forms of radionuclides in atmospheric fallout after the Chernobyl accident and their transformation in soil. Atomnaya Energiya No. 5, pp. 449–454

Borovoi AA and Gagarinsky A Yu (2001) Release of Radionuclides from the Destroyed Reactor at Chernobyl NPP, Atomnaya Energiya, 90 No.2 pp 137-45

Borovoi AA and Sich AR (1995) The Chernobyl accident revisited, part II: The state of the nuclear fuel located within the Chernobyl sarcophagus phase. Nuclear Safety 36(1) pp 1-32

Brenner DJ, Doll R, Goodhead DT, Hall EJ, Land CE, Little JB, Lubing JH, Preston DL, Preston JR, Puskin JS, Ron E, Sachs RK, Samet JM, Setlow RB and Zaider M (2003) Cancer risks attributable to low doses of ionizing radiation: assessing what we really know. (2003) PNAS November 25, 2003, vol. 100 no. 24 13761–13766

Bush RP, Smith GM, and White IF (1984) Carbon-14 Waste Management CEC Report EUR 8749, Luxembourg

Cardis E (2005a) Cancer effects of the Chernobyl accident (presentation at IAEA/WHO Conference ‘Environmental and Health Consequences of the Chernobyl Accident’)

Cardis E *et al* (2005b) Risk of Thyroid Cancer after exposure to iodine-131 in childhood Journal of the National Cancer Institute, 97, 724-732

Cardis E, Vrijheid M, Blettner M, Gilbert E, Hakama M, Hill C *et al* (2005c) Risk of cancer after low doses of ionising radiation: retrospective cohort study in 15 countries. BMJ 331. 77-87

Cardis E, Amoros E, Kesminiene A (1999) Observed and predicted thyroid cancer incidence following the Chernobyl accident: evidence for factors influencing susceptibility to radiation induced thyroid cancer. In: Thomas G, Karaoglou A, Williams ED eds. Radiation and Thyroid cancer. Singapore: World Scientific Publishing Co, 1999: 395-404.

Cardis E, Anspaugh L, Ivanov VK, Likhtarev K. Mabuchi AE, Okeanov AE, Prisyazjhniuk K (1996) Estimated Long Term Health Effects of the Chernobyl Accident. In Proceedings of an IAEA Conference One Decade after Chernobyl: Summing up the Consequences of the Accident, Vienna, 8-12 April 1996 Pp 241- 271. (See table 1. Estimates of Collective Effective Doses for Population Groups of Interest)

CERRIE (2004) Report of the Committee Examining Radiation Risks of Internal Emitters London, October 2004 www.cerrie.org (accessed February 12, 2006)

Colonna M *et al* (2002) Incidence of thyroid cancer in adults recorded by French cancer registries (1978-1997) Eur J Cancer 38 1762-1768

CoRWM (2006) UK Committee on Radioactive Waste Management. Draft Report
http://www.corwm.org.uk/pdf/0700.2%20-%20Final%20report%20-%20draft%20for%20January%202006%20plenary.pdf
(accessed February 5, 2006)

Cotterill SJ, Pearce MS, Parker L (2001) Thyroid cancer in children and young adults in the North of England. Is increasing incidence related to the Chernobyl accident? Eur J Cancer 37(8): 1020-26

Day R, Gorin MB and Eller AW (1995) Prevalence of lens changes in Ukrainian children residing around Chernobyl Health Physics 68 632-42

De Cort M, Dubois G, Fridman ShD, Germenchuk MG, Izrael YuA, Janssens A, Jones AR, Kelly GN, Kvasnikova EV, Matveenko II, Nazarov IM,.Pokumeiko YuM, Sitak VA, Stukin ED, Tabachny LYa. Tsaturov YuS and Avdyushin SI (1998) Atlas of Caesium Deposition on

Europe after the Chernobyl Accident. EUR Report 16733. Office for Official Publications of the European Communities, Luxembourg

Devell L, Guntay S and Powers DA (1995) The Chernobyl Reactor Accident Source Term: Development of a Consensus View. OECD/NEA Report NEA/CSNI/R(95) 24. Issy-les-Molineaux, F-92130 France

Devell L, Tovedal H, Bergström U, Appelgren A, Chyssler J and Andersson L (1986) Initial observations of fallout from the reactor accident at Chernobyl. Nature. 321. 192 – 193

Dreicer M, Aarkrog A, Alexakhin R, Anspaugh L, Arkhipov NP, Johansson K-J (1996) Consequences of the Chernobyl accident for the natural and human environments. Background Paper 5. In: One Decade after Chernobyl: Summing up the Consequences of the Accident, IAEA, Vienna, pp. 319–361

Dubrova YE, Grant G, Chumak AA, Stezhka VA, Karakasian AN (2002) Elevated minisatellite mutation rate in the post-Chernobyl families from Ukraine. Am J Human Genet 71:801-809

Dubrova YE, Nesterov VN, Krouchinsky NG, Ostapenko VA, Neumann R, Neil DL and Jeffreys AJ (1996) Human minisatellite mutation rate after the Chernobyl accident. Nature 380 683-686

Dubrova YE, Nesterov VN, Krouchinsky NG, Ostapenko VA, Vergnaud G, Giraudeau, Buard J and Jeffreys AJ (1997) Further evidence for elevated human minisatellite mutation rate in Belarus eight years after the Chernobyl accident. Mutat. Res. 381, 267-278

Edwards R (1989) Chernobyl fallout 40 times worse than admitted. The Guardian. 28 January, 1989.

Euratom Directive 96/29 of the Council of the European Union of 13 May 1996, laying down Basic Safety Standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation

European Commission (1996) The Radiological Consequences of the Chernobyl Accident. EUR 16544 EN. Brussels

European Commission (1998) Atlas of Caesium Deposition on Europe after the Chernobyl Accident. European Commission. EUR 19810 EN RU. Brussels

Fairlie I and Sumner DS (2000) In Defence of Collective Dose. J Radiol Prot 20 pp 1–10

Goldman *et al* (1987) Health and Environmental Consequences of the Chernobyl Nuclear Power Plant Accident. US Department of Energy. Report ER-0332. Prepared by the Interlaboratory Task Group. Washington DC

Goldman M (1987) Chernobyl: a Radiological Perspective. Science. 238. pp 622-3

Goskomchernobyl (2001) State Committee of the Republic of Belarus on the Consequences of the Disaster at the Chernobyl NPP. 15 Years after the Chernobyl Disaster: Consequences in the Republic of Belarus and Overcoming Them. Minsk: Trioleta

Gudiksen PH, Harvey TF, and Lange R (1989) Chernobyl Source Term, Atmospheric Dispersion and Dose Estimation. Health Physics 37 pp 697 - 706

Hatch M, Ron E, Bouville A, Zablotska L and Howe G (2005) The Chernobyl Disaster: Cancer following the Accident at the Chernobyl Nuclear Power Plant Epidemiologic Reviews 27 56-66

Heidenreich WF, Kenigsberg J, Jacob P, Buglova E, Goulko G, Paretzke HG, Demidchik EP and Golovneva A (1999) Time Trends of Thyroid Cancer Incidence in Belarus after the Chernobyl Accident Radiation Research 151 617-625

Hennemann G, Krenning EP and Sankaranarayanan K (1986) Place of radioactive iodine in treatment of thyrotoxicosis. The Lancet, i, 1369-1372

Hilton J, Cambray RS, Green N (1992) Fractionation of radioactive cesium in airborne particles containing bomb fallout, Chernobyl fallout, and atmospheric material from the Sellafield site, J. Environ. Radioact. 15: 103–108.

Hoffmann W (2002) Has fallout from the Chernobyl accident caused childhood leukaemia in Europe? The European Journal of Public Health 12 (1): 72-75

IAEA/WHO/EC (1996) One Decade After Chernobyl: Summing up the Consequences of the Accident.

IAEA/WHO (2005a) Health Effects of the Chernobyl Accident and Special Health Care Programmes. Report of the UN Chernobyl Forum Expert Group “Health” (EGH) Working draft. July 26 2005

IAEA/WHO (2005b) Environmental Consequences of the Chernobyl Accident and their Remediation. Report of the UN Chernobyl Forum Expert Group “Environment” (EGE) Working draft. August 2005

IAEA/WHO (2005c) Press Release issued at Conference “Chernobyl: Looking Back to Go Forwards” 6-7 September 2005.

ICRP (1991) 1990 Recommendations of the ICRP. ICRP Publication 60 Annals of the ICRP 21, Nos 1-3, Oxford

ICRP (2004) Relative Biological Effectiveness (RBE), Quality Factor (Q), and Radiation Weighting Factor (w_R). ICRP Publication 92. Annals of the ICRP 33 No, 4. Pergamon Press, Oxford

Imaizumi M *et al* (2006) Radiation Dose-Response Relationships for Thyroid Nodules and Autoimmune Thyroid Diseases in Hiroshima and Nagasaki Atomic Bomb Survivors 55-58 Years after Radiation Exposure. JAMA. 295. 1011-1022

Inskip PO, Hartshorne MF, Tekkel M, *et al* (1997) Thyroid nodularity and cancer among Chernobyl cleanup workers from Estonia. Radiat Res; 147: 225-35

IPHECA (1995) Health Consequences of the Chernobyl Accident, Results of the International Programme on the Health Effects of the Chernobyl Accident (IPHECA). Summary Report. World Health Organisation

Ivanov VK *et al* (2000) Radiation-epidemiology analysis of incidence of non-cancer diseases among the Chernobyl liquidators. Health Physics 78, 495-501

Ivanov VK, Gorsky AI, Tsyb AF, *et al* (1999) Dynamics of thyroid cancer incidence in Russia following the Chernobyl accident. J Radiol Prot; 19: 305-18

Ivanov VK, Tsyb AF, Gorsky AI, *et al* (1997a) Thyroid cancer among "liquidators" of the Chernobyl accident. Br J Radiol 70: 937-41

Ivanov VK, Tsyb AF, Gorsky AI, *et al* (1997b) Leukaemia and thyroid cancer in emergency workers of the Chernobyl accident: estimation of radiation risks (1986-T 995). Radiat Environ Biophys 36: 9-16

Ivanov VK, Tsyb AF, Nilova EV, *et al* (1997c) Cancer risks in the Kaluga oblast of the Russian Federation 10 years after the Chernobyl accident. Radiat Environ Biophys; 36: 161-67

Ivanov VK *et al* (1997d) Case-control analysis of leukaemia among Chernobyl accident emergency workers residing in the Federation, 1986-1993. J. Radiol. Prot. 17:137-157

Jacob P, Bogdanova TI, Buglova E, Chepurniy M, Demidchik Y, Gavrilin Y, Kenigsberg J, Meckbach R, Schotola C, Shinkarev S, Tronko MD, Ulanovsky A, Vavilov S, Walsh L (2006) Thyroid cancer risk in areas of Ukraine and Belarus affected by the Chernobyl accident. Radiat Res. 165(1) 1-8

Jacob P, Meckbach R, Ulanovski A, Schotola C and Pröhl G (2005) Thyroid exposure of Belarusian and Ukrainian children due to the Chernobyl accident and resulting thyroid cancer risk. GSF-Bericht 01/05, Neuherberg: GSF-Forschungszentrum mbH, 72S.; mit Anhang

Jacob P, Kenigsberg Y, Goulko G, Buglova E, Gering F, Golovneva A, Kruk J, Demidchik EP (2000) Thyroid cancer risk in Belarus after the Chernobyl accident: Comparison with external exposures. Radiat Environ Biophys 39: 25-31

Kashparov VA, Lundin SM, Zvarich SI, Yoschenko VI, Levtchuk SE, Khomutinin YuV, Maloshtan IN, Protsak VP (2003) Territory contamination with the radionuclides representing the fuel component of Chernobyl fallout. The Science of The Total Environment 317: 105-119.

Kazakov VS, Demidchik EP, Astakhova LN (1992) Thyroid cancer after Chernobyl. Nature 359, 21

Khan SA (1990) The Chernobyl Source Term: A Critical Review. Nuclear Safety. 31. No 3 pp 354-373

Kirchner G and Noack CC (1988) Core history and nuclide inventory of the Chernobyl core at the time of accident. Nuclear Safety 29: 1-5

Kisselev AN and Checherov KP (1995) Lava-like fuel containing masses in Unit 4 of Chernobyl NPP (based on research in 1986-1993). p. 54-63 in: OECD Documents "Sarcophagus Safety '94". The State of the Chernobyl Nuclear Power Plant Unit 4. Proceedings of an International Symposium, Zeleny Mys, Chernobyl, Ukraine, March 1994. OECD/NEA, France, 1995

Kisselev AN, Surin AI and Checherov KP (1996) Post-accident research on Unit 4 of the Chernobyl nuclear power plant. Atomic Energy 80(4): 240-247
Kiuru A *et al* (2003) Hereditary minisatellite mutations among the offspring of Estonian Chernobyl cleanup workers. Radiat. Res. 159, 651-655

Kiyoshi S *et al* (1987) Observation of Fallout in Hiroshima Caused by the Reactor Accident at Chernobyl. Int J of Rad Biol. Volume 51, Number 2. pp 201-207

Krestinina LY, Preston DL, Ostroumova EV, Degteva MO, Ron E, Vyushkova OV, *et al* (2005) Protracted radiation exposure and cancer mortality in the Techa River Cohort. Radiat Res 164(5): 602-611

Likhtarov *et al* (2005) Post-Chornobyl Thyroid Cancers in Ukraine. Report 1: Estimation of Thyroid Doses Radiat. Res. 163, 125–136 (2005).

Livshits LA, Malyarchuk SG, Lukyanova EM, Antipkin YG, Arabskaya LP, Kravchencko SA, Matsuka GH, Petit E, Giraudeau F, Gourmelon P, Vergnaud G and Le Guen B (2001) Children of Chernobyl Cleanup Workers do not show elevated rates of mutations in minisatellite alleles. Radiation Research 155, 74-80

Malko MV (1998a) Assessment of the Chernobyl Radiological Consequences. In Research Activities about the Radiological Consequences of the Chernobyl NPS Accident. KURRI-KR-21. March 1998 http://www.rri.kyoto-u.ac.jp/NSRG/reports/kr21/KURRI-KR-21.htm accessed January 31 2006

Malko MV (1998b) Chernobyl Accident: the Crisis in the International Radiation Community. In Research Activities about the Radiological Consequences of the Chernobyl NPS Accident. KURRI-KR-21. March 1998 http://www.rri.kyoto-u.ac.jp/NSRG/reports/kr21/KURRI-KR-21.htm accessed January 31 2006

Marshall E (1987) Recalculating the Cost of Chernobyl. Science. 236. pp 658-9

Mayall A, Cabianca T, Morris TP, Nightingale A, Simmonds JR and Cooper JR (1993) Collective Doses from Sellafield. NRPB Report M453 (Chilton Oxon)

Medvedev Z (1990) The Legacy of Chernobyl. Norton. New York and London

Mettler FA, Williamson MR, Royal HD, *et al* (1992) Thyroid nodules in the population living around Chernobyl. JAMA 1992; 268: 616-19

Møller AP and Mousseau TA (2006) Biological Consequences of Chernobyl: 20 years on. Trends in Ecology and Evolution. In Press.
http://cricket.biol.sc.edu/chernobyl/papers/Moller-Mousseau-TREE-2006-PR1.pdf
accessed February 27, 2006

Møller AP, Mousseau TA, Milinevsky G, Peklo A, Pysanets A and Szép T (2005) Condition, reproduction and survival of barn swallows from Chernobyl. Journal of Animal Ecology. 74, 1102–1111
http://cricket.biol.sc.edu/chernobyl/papers/Moller_et_al%20_JAE_2005.pdf
accessed February 27, 2006

Moysich KB, Menezes RJ Michalek A.M. *et al* (2002) Chernobyl-related ionising radiation exposure and cancer risk: an epidemiological review. Lancet Oncology, Volume 3, Number 5, 1 May 2002, pp. 269-279(11)

Műck K, Prőhl G, Likhtarev I, Kovgan L, Meckbach R and Golikov V (2002) A consistent radionuclide vector after the Chernobyl accident. Health Phys. 82 pp 141-156

Murbeth S, Rousarova M, Scherb H, Lengfelder E (2004) Thyroid cancer has increased in the adult populations of countries moderately affected by Chernobyl fallout. Med Sci Monit 10(7): CR300-306

Noshchenko AG, Moyisch KB, Bondar A, Zamostyan PV, Drosdova VD and Michalek AM (2001) Patterns of acute leukaemia occurrence among children in the Chernobyl region International Journal of Epidemiology 30 125-9

Noshchenko AG, Zamostyan PV, Bondar OY and Drozdova VD (2002) Radiation-induced leukaemia risk among those aged 0-20 at the time of the Chernobyl accident: a case-control study in the Ukraine. Int J Cancer 99 609-618

NRPB (1987) A Preliminary Assessment of the Radiological Impact of the Chernobyl Reactor Accident in EC countries. Report R-123

NRPB (1990) Industry Comments on ICRP Draft Recommendations National Radiological Protection Board M-238 Chilton, Oxon. UK.

NRPB (1995) Risk of Radiation-induced Cancer at Low Doses and Low Dose Rates for Radiation Protection Purposes National Radiological Protection Board Documents of the NRPB Vol 6, No 1, Chilton, Oxon

Nucleonics Week (1992) WHO says Belarus Cancers May Stem from More than Chernobyl. December 17, 1992 pp 12-13

OECD/NEA (1988) The Radiological Impact of the Chernobyl Accident in OECD Countries. Paris

OECD/NEA (1995) Chernobyl Ten Years On: Radiological And Health Impact. An Assessment by the NEA Committee On Radiation Protection And Public Health. November 1995 Nuclear Energy Agency. Paris

http://www.nea.fr/html/rp/reports/2003/nea3508-chernobyl.pdf accessed February 5, 2006
OECD/NEA (1996) The Radiological Impact of the Chernobyl Accident in OECD Countries in Western Europe. Paris OECD

OECD/NEA (2002) Assessment of Radiological and Health Impacts: 2002 Update of 1996 report - Chernobyl: Ten Years On. Paris. OECD
http://www.nea.fr/html/rp/chernobyl/c04.html accessed February 5, 2006

Okeanov AE, Sosnovskaya EY, Priatkina OP (2004) A national cancer registry to assess trends after the Chernobyl accident. Swiss Med Wkly 134:645-9

Parkin, DM, Cardis E, Masuyer E *et al* (1993) Childhood leukaemia following the Chernobyl Accident - The European childhood leukaemia-lymphoma incidence study (ECLIS). Eur. J. Cancer 29A, 89-95

Parkin, DM, Clayton, D, Black, RJ *et al* (1996) Childhood leukaemia in Europe after Chernobyl: 5 year follow-up. British Journal of Cancer 73, 1006-1012

Preston DL, Shimuzu Y, Pierce DA, Suyama A and Mabuchhi K (2003) Studies of mortality of Atomic Bomb survivors. Report 13: Solid Cancer and Non-cancer Disease Mortality: 1950-1997 Radiation Research 160, 381-407

Prisyazhniuk A, Gristchenko V, Zakordonets V, *et al* (1995) The time trends of cancer incidence in the most contaminated regions of the Ukraine before and after the Chemobyl accident. Radiat Environ Biophys; 34: 3-6

Prisyazhiuk A, Pjatak OA, Buzanov VA *et al*. (1991) Cancer in the Ukraine, post-Chernobyl. Lancet 338: 1334-5

Pukkala E, Poliakov S, Ryzhov A, Kesminiene A, Drozdovich V, Kovgan L, Kyyrönen P, Malakhova I V, Gulak L and Cardis E Breast cancer in Belarus and Ukraine after the Chernobyl Accident. (2006) International Journal of Cancer, in press
http://www3.interscience.wiley.com/search/allsearch?mode=viewselected&product=journal&ID=112467545&view_selected.x=47&view_selected.y=9&view_selected=view_selected
accessed March 7 2006

Purvis EE (1995)The Chernobyl 4 accident sequence: update-April 1995. Report of the Ukrainian Academy of Sciences. Intersectorial Scientific and Technical Center (ISTC) "UKRYTIE". Kiev

Rahu M, Tekkel M, Veidebaum T, *et al* (1997) The Estonian study of Chernobyl cleanup workers: II. Incidence of cancer and mortality. Radiat Res; 147: 653-57

RIFE-10 (2005) Radioactivity in Food and the Environment, 2004. Environment Agency, Environment and Heritage Service, Food Standards Agency, Scottish Environment Protection Agency. London

Robb JD (1994) Estimates of Radiation Detriment in a UK Population. NRPB Report R-260 National Radiological Protection Board, Chilton, Oxon

Romanenko A, Morell-Quadreny L, Nepomnyaschy V, Vozianov A and Llombart-Bosch A (2000) Pathology and proliferative activity of renal-cell carcinomas (RCCS) and renal oncocytomas in patients with different radiation exposure after the Chernobyl accident in Ukraine. Int J Cancer 87:880-883

Romanenko A, Morimura K, Wanibuchi H, Wei M, Zaparin W, Vinnichenko W, Kinoshita A, Vozianov A and Fukushima S (2003) Urinary bladder lesions induced by persistent chronic low-dose ionising radiation. Cancer Sci 94: 328-333

Ron F, Lubin JH, Shore RE, Mabuchi K *et al* (1995) Thyroid cancer after exposure to external radiation: a pooled analysis of seven studies. Radiation Research 141 259-277

Ruff T (2005) Supplementary information requested of the Medical Association for Prevention of War (Australia) at Inquiry Hearing on 19 August 2005. Medical Association for Prevention of War (Australia). 9 November 2005

Russian Federation (1992) The Law on the Social Protection of Population Affected by the Consequences of the Chernobyl Accident. Moscow

Rytomaa T (1996) Ten Years after Chernobyl. Ann Med. 28(2):83-7

Sali D, Cardis E, Sztanyik L *et al*. (1996) Cancer consequences of the Chernobyl accident in Europe outside the former USSR: a review. Int J Cancer 67: 343-352

Seo T, Imanaka T and Koide H (1988) Released Radioactivity by the Chernobyl Accident, Kagaku, 58 No.2 108-117. Sich AR (1994) Chernobyl accident management actions. Nuclear Safety 35(1)

Shershakov VM and Kelly GN (1996) The Health and Environmental Impact of Chernobyl – A Compilation of Papers by Russian Scientists. Radiat Prot Dosim Vol 64 1,2 whole edition.

Sich AR (1994) The Chernobyl accident revisited: Source term analysis and reconstruction of events during the active phase. (PhD Thesis). Massachusetts Institute of Technology, Cambridge, MA.

Sich AR (1996) The Chernobyl accident revisited, part III: Chernobyl source term release dynamics and reconstruction of events during active phase. Nuclear Safety 36(2) pp 195-217.

Simmonds JR, Lawson G and Mayall A (1996) Methodology For Assessing The Radiological Consequences Of Routine Releases Of Radionuclides To The Environment. Report CEC, DG XI, XI-5026/94, Radiation Protection-72 (Luxembourg: CEC)

Slebos RJC, Little RE, Umbach DM, Antipkin Y, Zadaorozhnaja TD, Mendel NA, Sommer CA, Conway K, Parrish E, Gulino S and Taylor JA (2004) Mini- and microsatellite mutations in children from Chernobyl accident cleanup workers Mutation Research 559 143-151

Sorenson B (1987) Chernobyl Source Term. Nuclear Safety 28, 443

Stather J, Muirhead C, and Cox R 1995 Radiation-Induced Cancer At Low Doses and Low Dose Rates, Radiological Protection Bulletin **167** 8-12

Sumner D and Gilmour P (1995) Radiation Protection and Moral Theory. Environmental Values 4 241-255

Tawn EJ *et al* (2001) From: Report on the Academy of Medical Sciences Scientific Meeting: Radiation, Health and Chernobyl London 10 October 2001. J Radiol Prot 21 415-416

The Australian (2005) http://theaustralian.com.au/common/story_page/0,5744,17585819%255E23109,00.html accessed February 6, 2006

Tondel M, Hjalmarsson P, Hardell L, Carlsson G, Axelson O (2004) Increase of regional total cancer incidence in north Sweden due to the Chernobyl accident? J Epidemiol Community Health 58 1011-1016

Ukraine Government (2001) Fifteen Years of the Chernobyl Disaster: the Experience of Overcoming: the National Report of Ukraine. Kyiv: Chernobyl Radioecological Center of the Ministry of Emergencies of Ukraine.

UNDP (2002) The Human Consequences of the Chernobyl Nuclear Accident. A Report Commissioned by UNDP and UNICEF with the support of UN-OCHA and WHO. United Nations. New York.

UNSCEAR (1988) United Nations Scientific Committee on the Effects of Atomic Radiation, 1988 Report to the General Assembly, with scientific annexes. United Nations, New York

UNSCEAR (1994) United Nations Scientific Committee on the Effects of Atomic Radiation, 1994 Report to the General Assembly, with scientific annexes. United Nations, New York

UNSCEAR (2000) United Nations Scientific Committee on the Effects of Atomic Radiation, 2000 Report to the General Assembly, with scientific annexes. Annex J. United Nations, New York

US DoE (1987) Report of Interlaboratory Task Group. Health and Environmental Consequences of the Chernobyl Nuclear Power Plant Accident. US Department of Energy DOE/ER-0332 NTIS Springfield VA 22161

US EPA (1997) Memorandum: Establishment of Cleanup Levels for CERCLA Sites with Radioactive Contamination. Ed Luftig SD. Washington, DC US Environmental Protection Agency

US EPA (1994) Estimating Radiogenic Cancer. EPA Report 402-R-93-076. Washington DC: Environmental Protection Agency.

US NRC (1987) Report on the Accident at the Chernobyl Nuclear Power Station, US NRC, NUREG-1250, Rev. 1, US Nuclear Regulatory Commission Washington, DC

Weaver D (1986) How Ministers Misled Britain about Chernobyl. New Scientist. October 9

Webb G *et al* (1983) Natural Radiation and Waste Disposal. NRPB R-156. National Radiological Protection Board Chilton, Oxon

Williams D, Abrosimov A, Bogdanova T, Demidchik EP, Ito M, LiVolsi V, Lushnikov E, Rosai J, Sidorov Y, Tronko MD, Tsyb AF, Vowler SL, Thomas GA (2004) Thyroid carcinoma after Chernobyl latent period, morphology and aggressiveness. British J of Cancer 90, 2219-2224

Williams D (2001) The World Needs to Improve its Handling of International Disasters (Editorial) BMJ Vol 323, 643-644. 28 March

Acronyms and Abbreviations

(see Annex 4 for radiation dose units and SI nomenclature)

AFMT	L'Association Française des Malades de la Thyroïde
ARAC	Atmosphere Release Advisory Centre, Lawrence Livermore Research Laboratory, US
BfS	German Federal Office for Radiation Protection
Bq	becquerel (unit of radioactivity)
CERRIE	UK Committee Examining the Radiation Risks of Internal Emitters
Ci	curie (unit of radioactivity)
CRIIRAD	Commission de Recherche et d'Information Indépendantes sur la Radioactivité
DDREF	dose and dose rate effectiveness factor
DG TREN	Directorate-General for Transport and Energy of the EC
DNA	deoxyribose nucleic acid
DoE	US Department of Energy
EC	European Commission
ECLIS	IARC European Childhood Leukaemia-Lymphoma Incidence Study
EPA	US Environmental Protection Agency
ERR	excess relative risk
EU	European Union
Gy	gray (unit of absorbed radiation dose)
IAEA	International Atomic Energy Agency
IARC	International Agency for Research on Cancer
ICP	International Chernobyl Project
ICRP	International Commission on Radiation Protection
IPHECA	International Project on the Health Effects of the Chernobyl Accident
LET	linear energy transfer
LNT	linear no-threshold (theory of radiation’s dose-effect relationship)
NEA	Nuclear Energy Agency of the OECD
NCI	US National Cancer Institute
NRC	US Nuclear Regulatory Commission
NRPB	former UK National Radiological Protection Board
OCHA	UN Office for the Coordination of Humanitarian Affairs
OECD	Organisation for Economic Cooperation and Development
RERF	Radiation Effects Research Foundation
SCPRI	French Government Central Service for Protection against Radiation
Sv	sievert (unit of equivalent or effective radiation dose)
UNDP	United Nations Development Programme
UNICEF	United Nations Children’s Fund
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USSR	former Union of Soviet Socialist Republics
WHO	World Health Organisation