

TORCH-2016

An independent scientific evaluation
of the health-related effects of
the Chernobyl nuclear disaster

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Version 1.1 March 31, 2016



FRIENDS OF THE EARTH AUSTRIA
DIE ÖSTERREICHISCHE UMWELTSCHUTZORGANISATION



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Acknowledgements

This report was commissioned by GLOBAL 2000/Friends of the Earth Austria and financed by the Wiener Umweltanwaltschaft (Vienna Ombuds Office for Environmental Protection) to whom many thanks are due.

Thanks to Professor Keith Baverstock, Dr Peter Bossew, Professor Elisabeth Cardis, Dr Yuri Hiranumi, Dr Alfred Körblein, Professor Hanns Moshhammer, and Professor Dillwyn Williams for their helpful insights and information. Any errors remain the responsibility of the author.

Thanks to Dr Alfred Körblein for data plot and regression analysis for the chart on page 48.

Thanks to Peter Roche and Lis Fields for their literature searches. Thanks to Dr Reinhard Uhrig and GLOBAL 2000/Friends of the Earth for their assistance and administrative help.

Thanks to Rebecca Harms MEP for permission to use the title TORCH – 2016 for this report.

Thanks to DG-TREN of the European Commission for permission to reproduce plates from the Atlas of Caesium Deposition on Europe after the Chernobyl Accident (1998) EUR Report 16733. Office for Official Publications of the European Communities, Luxembourg on page 25.

Thanks to Dr Y Demidchik for permission to reproduce figure 5.2 on page 36.

Thanks to Dr Karl Kienzl of the Umweltbundesamt (Austrian Federal Environmental Agency) for permission to reproduce the Cs-137 map of Austria on page 50.

Thanks to Dr Peter Bossew for permission to reproduce iodine-131 contamination maps on page 44–45.
http://www.atomfreie.eu/fileadmin/Daten/Studiathek/2012_03_15_Tschernobylstudie_Kurzfassung_2012.pdf

Thanks to Professor H Moshhammer for permission to reproduce the thyroid cancer cases chart on page 47.

Foreword by Ulli Sima

**Vice Mayor for Environment, Public Infrastructure and Services
City Government of Vienna, Austria**

<https://www.wien.gv.at/english/politics/citygovernment/sima.html>

Chernobyl: April 26th, 1986 is a place and date we shall always remember. The massive explosions and graphite inferno which lasted for 10 days resulted in very large amounts of radioactive matter being spread across almost all of Europe, and in thousands of square kilometres becoming uninhabitable ... for centuries ...

The highest contamination levels were in countries near the nuclear plant, that is Ukraine, Belarus and Russia, but most of Chernobyl's radioactivity actually landed in European countries further away including Austria. In fact, apart from Ukraine, Belarus and Russia, Austria was one of the most affected countries, especially the high radioiodine levels in the Vienna region.

Even now, 30 years later, official warnings against eating wild foods contaminated by Chernobyl's fallout still exist in some countries. But the worst consequences of this tragedy are the thousands of thyroid cancers and leukemias in Ukraine, Belarus and Russia, and the tens of thousands more predicted cancers of all types over the next 50 or 60 years across the whole of Europe. These, together with the vast areas of radioactively contaminated and uninhabitable land, and the humanitarian crises which afflicted Ukraine, Belarus and Russia show that a worst-case nuclear disaster really can happen. And the triple meltdown nuclear accident at Fukushima Daiichi in Japan on March 11th 2011 shows that another worst-case accident can happen at any time again.

As early as 1978, the Austrian people had spoken out against nuclear power in the referendum on the construction of Zwentendorf NPP. They still are strongly opposed and Zwentendorf's shell still lies unused and empty.

As an ecologist and a politician, I have campaigned since my early days – with many allies in other countries – against the dangers of nuclear power, against its undemocratic nature, its secrecy, its unsustainability, its huge costs, its massive state subsidies, and against the unfairness of passing on dangerous nuclear wastes to future generations. In 2011, I founded the Network of Cities for a Nuclear-Free Europe (CNFE), which has grown to a coalition of 30 European cities today. The new TORCH report is another important milestone in our ongoing campaign against the manifest dangers of nuclear power.

Foreword by Rebecca Harms MEP

Co-Chair, Greens/European Free Alliance in the European Parliament
Member, Delegation to the EU-Ukraine Parliamentary Cooperation Committee

http://www.europarl.europa.eu/meps/en/28233/REBECCA_HARMS_home.html

"We did not yet possess a system of imagination, analogies, words or experiences for the catastrophe of Chernobyl."

Svetlana Alexiyevich, writer from Belarus, 2015 Nobel prize laureate

Even 30 years after the nuclear meltdown at Chernobyl, Svetlana Alexiyevich's words still apply. As in a war, thousands of people in Ukraine and Belarus lost everything they held dear in life. The hostile and destructive force, however, did not come from without. The danger lurked within a technology that had been described and hailed as a peaceful one. Until 26th April 1986, we had not been able to imagine a large-scale nuclear incident and its ramifications for us humans and for the world we live in. What was previously inconceivable and unfathomable, caught up with millions of people in Ukraine, in Belarus and Russia. And it affected all of Europe. The cleanup efforts in Chernobyl have now lasted far longer than a quarter of a century. Slowly, we have come to realise that the consequences for human life and the environment will be felt forever. In 1986, Ukraine and Belarus were still Soviet republics. The collapse of the Soviet Union burdened the two new states with most of the indefinite legacy costs of the Chernobyl disaster. It is painful to see that the very part of the European continent which was hit harder than others by all the devastation and suffering of the last century now also had to endure the worst nuclear accident. And it is disconcerting to see that Ukraine, of all places, today has to face renewed destabilisation from the outside.

TORCH, "The Other Report on Chernobyl", which I had commissioned in 2006 on the occasion of the twentieth anniversary of the catastrophe, is now available in an updated edition. Ten years after its initial publication, the report is an attempt to keep the unimaginable in the public mind. Moreover, TORCH 2016 is again highly critical of the IAEA and the WHO for grossly understating the impact of the disaster. Cancer and mortality rates, as well as data on other illnesses, remain in stark contrast to the figures published by the IAEA and the WHO. The updated TORCH 2016 is again based entirely on peer-reviewed sources, and reveals the extent to which both organisations have attempted to this day to downplay and sanitise facts. To me, one of the most important objectives in connection with TORCH is to finally achieve a breakthrough to allow for independent research to be carried out on the effects of Chernobyl that is unencumbered by the influence of the nuclear lobby in the IAEA, and thus, in the WHO. Our experience of the past five years since Fukushima has taught us another lesson about how ill-equipped we are when disaster strikes.

I am grateful to the City of Vienna and Ulli Sima, Councilwoman for Environmental Affairs, as well as GLOBAL 2000, for funding TORCH 2016. I thank Dr. Ian Fairlie for again drawing up this depressing, but important, balance.

Executive Summary

- 5 million people in Belarus, Ukraine and Russia still live in highly contaminated areas
- 400 million people in less contaminated areas
- 37 % of Chernobyl's fallout deposited on western Europe; 42 % of western Europe contaminated
- 40,000 fatal cancers predicted
- 6,000 thyroid cancer cases to date, 16,000 more expected
- increased radiogenic thyroid cancers now seen in Austria
- increased radiogenic leukemia, cardiovascular disease, breast cancers confirmed
- new evidence of radiogenic birth defects, mental health effects and diabetes
- new evidence that children in contaminated areas suffer radiogenic illnesses

Belarus, Ukraine and Russia were the most highly contaminated countries. About 5 million people still live in areas with very high levels of radioactive contamination (Cs-137 >40 kBq/m²) in Belarus (18,000 km²), Ukraine (12,000 km²) and Russia (16,000 km²). 400 million people live in areas contaminated with lower levels of radioactivity (4–40 kBq/m²). 42 % of Europe's land area was contaminated.

Western Europe (defined as all European countries excluding Belarus, Ukraine and Russia) received 37 % of Chernobyl's fallout accounting for about 40 % of Chernobyl's collective dose to the northern hemisphere.

It is estimated that 40,000 fatal cancers will arise over the next 50 years, similar in magnitude to the toll from the Japanese bombs in 1945. 6,000 thyroid cancer cases have arisen so far and 16,000 more cases are estimated to arise over the next 50 years.

New evidence indicates increased thyroid cancer cases in Austria, similar to indicative studies in other countries. Increased surveillance, diagnoses and medical exposures to radio-iodines are partial causes but up to 40 % of increased TC cases after 1990 in Austria may be due to Chernobyl.

New evidence, including quantitative risk estimates, buttress previous indicative studies of increased leukemias, solid cancers, cardiovascular effects, mental health effects, birth defects and other radiogenic effects in the most affected countries.

Persuasive evidence demonstrates continuing ill health among children in highly contaminated areas due to the ingestion of contaminated food. Visits abroad are of considerable benefit to Chernobyl-affected children.

Recommendations are made for the European Commission and national Governments to adopt humanitarian policies to alleviate the continuing plight of children affected by Chernobyl. They should also support existing non-government organisations and medical charities which help these children with visits abroad. 30 years after the accident, humanitarian help is still needed for the children of Chernobyl.

Recommendations are made for the European Commission and national Governments to fund proposed research programmes to assess Chernobyl's long term effects, including the establishment of registries to monitor increasing cancer incidences in Europe.

1

Introduction

Thirty years ago, on April 26 1986, the world's worst nuclear accident occurred at the Chernobyl¹ nuclear power plant (NPP) in Ukraine. The explosions and resulting graphite fire at Reactor 4 over the following ten days ejected 30 % to 60 % of the reactor core's contents (60–120 tonnes) into the troposphere initially over the USSR and most of Europe². As most also reached the stratosphere, most of the northern hemisphere was eventually affected by radioactive fallout³. Approximately 50 people died in the immediate aftermath of the accident, however many thousands of cancer fatalities and other probabilistic effects are estimated to arise over many decades. For example, Imaizumi *et al* (2006) found that a significant dose-response relationship still existed among the Japanese bomb survivors nearly 60 years after they were exposed.

Initially, about 116,000 people were evacuated from the town of Pripyat and areas surrounding the reactor and relocated. After 1986, an additional 230,000 people from contaminated areas in Belarus, the Russian Federation and Ukraine were resettled (UNSCEAR, 2008). About 4,000,000 km² of Europe was contaminated by Chernobyl's fallout – 42 % of Europe's land area. The most contaminated countries were the former USSR republics of Belarus, Russia and Ukraine. In addition, Finland, Sweden, Norway, Austria and the Balkan and Slavic countries were also affected by high levels⁴ of radioactive contamination.

The first TORCH Report (www.chernobylreport.org) was published in 2006 to mark the 20th anniversary of the Chernobyl disaster. The Report concentrated on estimating the released amounts of radioactivity, the radiation doses and likely numbers of resulting cancer deaths which would arise in future years.

Many major reports on Chernobyl's effects were published in late 2005 and 2006 on the 20th anniversary of the disaster: these are listed in Annex D. Thousands more scientific articles have been published between 2006 and 2016. PubMed alone cites over 400 scientific articles on 'Chernobyl cancer' published during the past 10 years, plus 270 more on 'Chernobyl thyroid cancer', and 20 on 'Chernobyl cardiovascular'. Hundreds more articles are cited in Medline, Science Direct, British Library and Science Citation search engines.

This report, TORCH-2016, updates the 2006 TORCH report with the new health evidence which has emerged in the past ten years. It is important to note that the accident had many adverse consequences, including economic, ecological, social and political effects as well as health effects. This report focuses on health effects.

Before we commence, some preliminary matters need to be discussed.

(a) Radiation and Radioactivity

Radiation and radioactivity (including their risks, doses, biology and epidemiology) are complicated matters which are not easy to grasp at first glance. This report only discusses radiation briefly but we do provide a list of radiation acronyms and abbreviations (Annex A), a glossary of radiation terms (Annex B), and a note on radiation dose units (Annex C). In Chapter 4, we shall discuss uncertainty and some difficulties with epidemiology studies.

¹ spelled "Chornobyl" in the Ukrainian language

² A graphic animation of Chernobyl's radioactive plume created by the French IRSN can be seen at <https://www.youtube.com/watch?v=lwxNfy79gl4> (15 MB: 3 minutes playing time).

³ Reactor 4 contained about 190 tonnes of nuclear fuel, 1,700 tonnes of graphite moderator, and a large volume of cooling water.

The explosions ejected about a third of the fuel, mostly to nearby areas; the continuing graphite fire resulted in wider releases of fission and activation products. The fire stopped when all graphite had been incinerated.

⁴ >40 kBq/m² Cs-137.

Perhaps the most 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) www.cerrie.org. The CERRIE Committee contained independent scientists and representatives of environmental organisations as well as scientists from official agencies: its report is written in layman's terms.

(b) Radiation's effects

It is necessary to explain that radiation has two main types of effect: (a) cell-killing from high doses within a few hours or days and (b) probabilistic effects from lower doses over years or decades.

Cell-killing (or deterministic) effects are nausea, vomiting, diarrhoea, hair loss, organ failures, and comas. Above exposures to ~6 Gy deaths may occur within 30 days or so – usually from opportunistic infections. Here, an increased dose results in a larger effect.

Radiation's second effect occurs much later and is a probabilistic (or stochastic) effect. Examples are cancers and genetic mutations. Here, an increased dose results in an increased **probability** of effect. Put simply, one doesn't get a worse cancer but a cancer becomes more likely. Radiation exposures are therefore like cigarette smoking: not everyone who smokes will contract cancer, but the more one smokes the greater one's chance of cancer. In layman's words, receiving a radiation exposure is akin to receiving a negative lottery ticket⁵.

It is necessary to explain these twin radiation effects because, in recent years, some writers have found it difficult to grasp (or appear unwilling to accept) the latter effect. However it is the more important one.

Cell-killing effects

During and immediately after the Chernobyl accident, acute radiation sickness and diarrhoea were diagnosed in 237 emergency workers, of whom 134 were treated clinically. 28 died (from organ failure and resulting opportunistic infections) in 1986; 19 more between 1987 and 2004; and a few more since then. Most of the deaths were among the firefighters.

Probabilistic effects, including cancers

These are more significant in terms of their numbers but they are difficult to pin down because cancers and other stochastic effects can arise long afterwards. Their latency periods (the time between exposure and first appearance of cancer) can be years or several decades. But that is just when the first cancers arise. After then, cancers from the exposure will continue to arise for decades afterwards. For example, thyroid cancers are still arising among the survivors of the Hiroshima and Nagasaki bombings in 1945, more than 60 years later (Imaizumi *et al*, 2006).

Chernobyl's adverse health effects will also continue to emerge over many decades into the future. This means it will be a long time before the full effects of Chernobyl are known.

Indeed, they may never be fully known, because cancer is a common disease and it is presently not possible to clinically distinguish radiogenic cancers from naturally-occurring ones. However despite these caveats we can make realistic estimates of the numbers of fatal cancers likely to occur and, as we shall see in chapter 14, these exceed tens of thousands of people.

⁵ Credit to Jan Beyea in Princeton, US for this metaphor

(c) Polarised Views on Radiation Risks

Widely different views exist on radiation risks among scientists and between scientists and members of the public. In addition, many unofficial websites reveal a lack of knowledge about radiation and its effects among some members of the public, often coupled with an apparent fear of radiation. Many people and groups 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 its risks. They are therefore often hostile towards official publications on Chernobyl's radiation risks whose findings, in their view, do not match their own experiences.

Unofficial accounts have criticised official reports on the health effects from Chernobyl, particularly for their reluctance to acknowledge the existence of increased effects and their practice of denying links between such increases and radiation from the accident. But it is not just lay people: during the IAEA/WHO Conference on Chernobyl in Vienna in September 2005, officials from health ministries and academic institutions in Belarus, Russia and Ukraine spoke out against the refusals by their Governments and international health agencies to recognise what was, in their view, the true scale of Chernobyl's effects.

It is necessary to tread warily in this battleground of views and values. 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, some 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 can contain valuable information and insights. What are needed 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 not due to radiation in some unofficial reports.

(d) Western Europe

For the purposes of this report only, "Western Europe" is arbitrarily defined as all European countries excluding Belarus, Ukraine and Russia. This somewhat unsatisfactory definition is chosen partly to delineate the two main categories of nuclide deposition and effects, partly to maintain consistency with the TORCH 2006 report, and partly because other definitions are also unsatisfactory.

2

Source Terms

"Source term" is a jargon term meaning the total amount of radioactivity released by the explosions and fire at Chernobyl for each radionuclide⁶. These are important because they can verify nuclide⁷ depositions throughout Europe and the northern hemisphere. Collective doses and predicted excess deaths may be estimated from source terms. The most important nuclides are caesium-137 (Cs-137) and iodine-131 (I-131). In 2006, TORCH's estimate for Cs-137 was about 30 % larger than the official IAEA/WHO estimate, and for I-131 about 15 % larger.

Since TORCH 2006, relatively few studies on Chernobyl's source terms have been published apart from two major reviews. First, the UNSCEAR 2008 Report (published in 2011) contained Annex D on health effects due to radiation from the Chernobyl accident. And second, Steinhäuser *et al* (2014) reviewed recent literature on nuclide releases in its comparison of the Chernobyl and Fukushima nuclear accidents. These surveys did not change the main findings in 2006.

Table 2.1: **Release Estimates for main nuclides at Chernobyl. PBq = 10¹⁵ Bq**

	UNSCEAR, 2000 IAEA/WHO, 2005	UNSCEAR, 2008 (published in 2011)	Steinhäuser <i>et al</i> , 2014
Cs-137	85	85	85
Cs-134	47	47	47
Sr-90	10	10	10
I-131	1,760	1,760	1,760

The main changes from 2006 are the estimated releases of various refractory elements⁸ in fuel debris: these were reduced by 50 % to 76 %. And the estimated release of iodine-133 was reduced by 60 %. No explanations were given in UNSCEAR (2008) or Steinhäuser *et al* (2014) for these changes. However their health impacts are not thought to be great as these nuclides are mostly not volatile, relatively short-lived and fell relatively close to the reactor: they were not discussed in the 2006 TORCH report. Of greater interest is a comparison of the nuclide releases at Chernobyl with those at the Fukushima nuclear disaster in Japan in March 2011 as shown in table 2.2.

The table shows that, as regards the more important **volatile and partly volatile nuclides**, including Cs-134, Cs-137 and I-131, the Chernobyl accident released about 10 times more than Fukushima.

As regards **noble gases**, the Fukushima accident was estimated to have released about twice the quantity released at Chernobyl. This is partly because at Fukushima, Units 1, 2 and 3 exploded releasing their gaseous inventories. The spent fuels stored in Fukushima Unit 4's spent fuel pond were also estimated⁹ to have released some of their gaseous inventory. At Chernobyl, one reactor exploded.

The question of whether radioactive noble gases should be treated separately from other released nuclides is considered in Box A. The answer is a guarded 'yes' though some attempt should be made to estimate external skin doses from the beta emissions by noble gases.

⁶ a radionuclide is an atom whose nucleus is unstable. When it disintegrates it gives off radiation.

⁷ nuclide is a shortened form of the word radionuclide. The two words are not the same, but for the purposes of this report, we can treat them as such.

⁸ Zr-95, Mo-99, Ce-141, Ce-144 and Np-239

⁹ Kirchner *et al* (2012) deduced that the fuel in storage pool of Unit 4 also contributed to Fukushima's emissions.

Table 2.2: **Nuclides released by Nuclear Accidents – PBq = 10¹⁵ Bq**

Nuclide	Half life	Chernobyl (from UNSCEAR, 2008)	Fukushima	Factor difference
Noble Gases				
Xe-133	5.3 d	6,500	14,000*	x 0.5
Kr-85	11 y	33	44 [§]	x 0.75
total		~6,500	~14,000	~x 0.5
Volatile Nuclides				
Cs-134	2.0 y	85 ⁺	12 ^{**}	x 7
Cs-137	30 y	85	12 ^{***}	x 7
I-129	1.6 x 10 ⁷ y	45 x 10 ⁻⁶	5.7 x 10 ⁻⁶	x 8
I-131	8 d	1,760	150 ^{***}	x 12
I-133	21 h	910	146 ^{**}	x 6
Te-132 [§]	3.2 d	~1,150	~180 ^{**}	x 6
Te-129m [§]	34 d	240	15 ^{**}	x 16
Total-all nuclides		5,300 ^{**}	520 ^{**}	~x 10

sources* Stohl *et al* (2012), ** Steinhauser *et al* (2014), ***Chino *et al* (2011), & Ahlswede *et al* (2013)

⁺ applying a 1:1 ratio with Cs-137

[§] Te isotopes are listed as their decay products include radio-iodines

Figure 2.1: **Fukushima Daiichi Nuclear Plant, March 2011**



BOX A: Radioactive noble gases: are they less dangerous than other radioactive nuclides?

Different views exist on whether the nuclide inventories at Chernobyl and Fukushima should be separated into two categories (i) noble gases and (ii) all other nuclides, including radio-caesiums and radio-iodines. This is common practice but as noble gases constitute more than half of total emissions from Chernobyl, they merit more detailed consideration.

On the one hand, many scientists consider radioactive noble gases to be less significant as regards their radiation exposures. This is the case for a number of reasons. First, most emitted noble gases have short half-lives of a few hours or less, apart from Kr-85 (10.8 y) and Xe-133 (5.2 days). Second, most of these gases would have been ejected by the explosions high into the atmosphere and would have decayed by the time they were returned (mostly in rainfall) to land. Third, in most official documents, noble gases are not considered particularly radiotoxic, certainly in comparison with radio-caesiums and radio-iodines. And fourth, they are chemically inert and, as regards internal doses, they have relatively little interaction with the body. For example, inhaled noble gases are exhaled without physically or chemically reacting with the body, although some lung exposures could be significant in the case of gases with very high specific activities shortly after the accident.

On the other hand, it is unwise to be dismissive about the hazards of radioactive noble gases. Most radioactive noble gases are beta-emitters, that is, their decays are accompanied by the emissions of beta particles. Those from the two most significant (i.e. longer-lived) noble gases, Kr-85 and Xe-133, have relatively high energies – 687 keV and 427 keV respectively. This means their beta particles are capable of travelling several metres in air and when these gases reach the ground they will give external skin doses to people living in their vicinity. For example, cloud immersion in radioactive noble gases was the main exposure route for people living downwind of the Three Mile Island nuclear accident in the US in March 1979. And at Chernobyl, it is likely that external skin exposures from radioactive noble gases were major contributors, along with exposures from lung inhalation, to the fatal doses received by many firefighters.

Unfortunately, few official dose estimates were made of skin exposures from Kr-85 and Xe-133 in areas distant from Chernobyl.

On balance, given their different radiotoxicities, half-lives and exposure routes, it is best to present the two categories separately, bearing in mind that both can be hazardous but for different reasons.

3

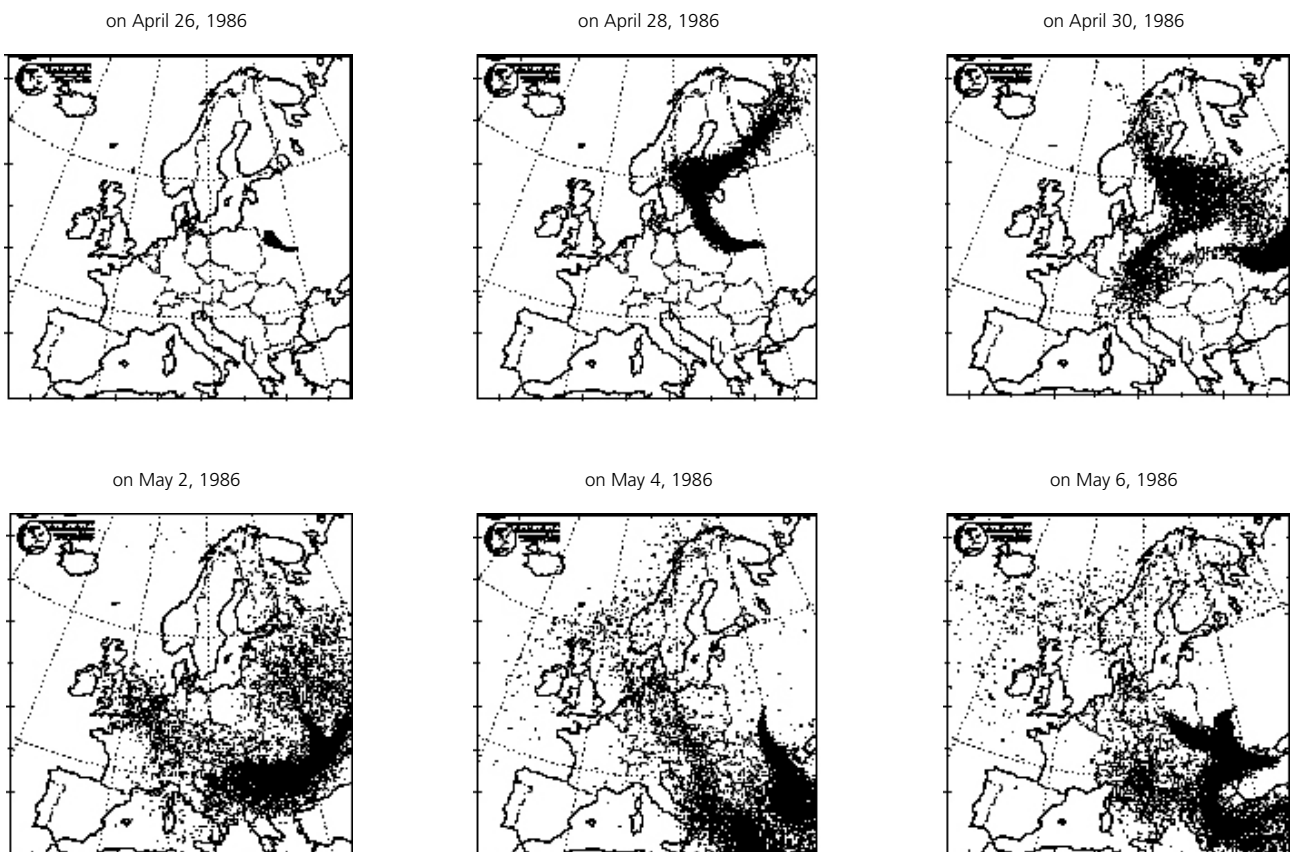
Chernobyl's Fallout: Dispersion, Deposition and Contamination

(a) Dispersion

Between April 26 and May 6 1986, Chernobyl's fallout was very widely dispersed over Europe and the northern hemisphere (Fairlie, 2007). According to UNSCEAR (1990), 47 % of the fallout was deposited on Belarus, Ukraine and Russia and the rest deposited around the world, mainly in Western Europe.

A graphic animation of Chernobyl's radioactive plumes was created by the French Government's IRSN and can be seen at <https://www.youtube.com/watch?v=lwxNfy79gl4> (15 MB download: 3 minutes' playing time) Timed maps of the dispersion are set out in figure 3.1 below.

Figure 3.1: Chernobyl plumes on successive 2-day period



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

(b) Total amounts deposited in each country

Table 3.1 sets out the amounts of Cs-137 deposited in each country from official estimates ranked by amount.

Table 3.1: **Cs-137 deposition PBq = 10¹⁵ Bq**
Ranked by amount

Country	PBq	Country	PBq	Country	PBq
Russia	29	Greece	0.95	Hungary	0.35
Belarus	15	Italy	0.93	Ireland	0.35
Ukraine	13	France	0.93	Slovakia	0.32
former Yugoslavia*	5.4	United Kingdom	0.88	Latvia	0.25
Finland	3.8	Czech Rep	0.6	Estonia	0.18
Sweden	3.5	Lithuania	0.44	Turkey (Euro part)	0.16
Bulgaria*	2.7	Albania*	0.4	Denmark	0.087
Norway	2.5	Moldova	0.4	Netherlands	0.062
Romania	2.1	Slovenia	0.39	Belgium	0.053
Germany	1.9	Spain	0.38	Luxembourg	0.008
Austria	1.8	Croatia	0.37	Total	90.75
Poland	1.2	Switzerland	0.36		

data from table III.1 in EC (1998)

*data from US DoE (1987) [Yugoslavia reduced by 0.76 PBq to avoid double-counting Slovenia and Croatia]

It can be seen from this table that that Russia, Belarus and Ukraine were the most contaminated countries in terms of Bq amounts. Together these three countries amounted to 57 PBq out of the European total of 91 PBq, i.e. 63 %.

However as some countries are much larger than others, we need to examine Cs-137 contaminations using other yardsticks, including **area, percent of country contaminated** and average **concentrations** (Bq per m²).

(c) Total land areas contaminated

Between 1995 and 1998, the European Commission and Member States measured Cs-137 levels throughout Europe, Belarus, Ukraine and the western areas of Russian using extensive gamma measurements from low altitude (50–150 m) flights (EC, 1998). Hundreds of thousands of measurements were carried out, and about 10,000 soil samples were taken in Central and Western European countries. 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/m² are reproduced in table 3.2 below together with totals added by this report (greyed column).

Table 3.2: Areas (1,000 km²) contaminated by caesium-137 to specified levels in Europe kBq/m² Ranked by area

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	Total* 1000 m ²
Russia (European part)	1110	250	180	44	7.2	5.9	2.2	0.46	1,600
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	-	-	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
Slovakia	32	6.8	0.61	0.02	-	-	-	-	39
Switzerland	26	6.4	2.3	0.73	-	-	-	-	35
Totals (all countries)	2,427	767	452	166	22	19	7	3.62	3,864

source: EC (1998)

*greyed column inserted by this report

In terms of absolute **land area**, it can be seen from table 3.2 that about 3.8 million km² of Europe was contaminated, amounting to about 40 % of its surface area of 9.7 million km². Russia, Ukraine, Romania, Norway, Finland, Germany, Sweden and Belarus were the most affected countries in terms of total land areas.

According to Yablokov *et al* (2009), nearly 5 million people still live in areas with very high levels (>40 kBq/m²) of radioactive contamination in Belarus (18,000 km²), Ukraine (12,000 km²) and European Russia (16,000 km²). Another 400 million people live in areas with medium levels of contamination (Cs-137 4 to 40 kBq/m²).

(d) Percentage of country contaminated

Because some countries are very large in comparison with others, it is also necessary to examine the **percentage of their land areas** which were affected. Accordingly, official EC estimates of high residual amounts of radioactivity from Chernobyl until 2056 are set out in table 3.3 below. Countries are ranked by the percentage of their land area which was highly contaminated. Countries which had a significant (>5 %) percentage of their land highly contaminated are highlighted in yellow.

Table 3.3: **Land areas of countries which will remain highly affected by Cs-137 >40 kBq/m² by area**

Country	Land area highly contaminated 1,000 km ²	Land area 1,000 km ²	Percentage highly contaminated
Belarus	46	210	22%
Austria	11	84	13%
Ukraine	38	600	6.3%
Finland	19	340	5.6%
Sweden	23	450	5.2%
Italy	8.4	280	3%
Slovenia	0.61	20	3%
Norway	7.2	320	2.3%
Switzerland	0.73	41	1.8%
Russia (European part)	60	3,800	1.6%
Greece	1.3	130	1%
Romania	1.2	240	0.5%
Czech Republic	0.22	80	0.28%
Poland	0.52	310	0.16%
Germany	0.32	350	0.09%
United Kingdom	0.16	240	0.06%
Totals	218.95	9,700*	Europe = 2.3%

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

yellow = countries with more than 5 % of land area which will remain highly contaminated

The countries significantly affected (in terms of percentage of their land areas) by high levels of Cs -137 are Belarus, Austria, Ukraine, Finland and Sweden.

A comparison with the effects of the Fukushima nuclear accident in Japan is instructive.

According to Japan's Science Ministry¹⁰, an area of 30,000 km² in Japan was contaminated to a level above 10 kBq per km² of Cs-137. It can be calculated from table 3.2 above that 1,437,000 km² of Europe and the former USSR was contaminated above this level – about a factor of 50 larger. The Japanese Science Ministry⁸ also stated that 8% of Japan's land area was contaminated to this level. In comparison, it can be calculated from table 3.2 that 37% of Europe was affected to the same level.

(e) Average Levels of Cs-137 Contamination

The final yardstick is average **deposition density** (kBq/m²) at the time of deposition. Most studies on the health effects after Chernobyl dwell on Belarus, Russia and Ukraine. This is justified by the very serious nuclide concentrations in these countries, as indicated in the countries/areas highlighted in yellow in table 3.4.

This table shows just how seriously various areas of Belarus, Ukraine and Russia were affected.

At the same time, this table indicates that the relative neglect of all other European countries is not merited. It shows that, outside the three countries next to Chernobyl, other countries were seriously affected as well, including Austria, Slovakia, Slovenia, and Moldova.



¹⁰ <http://thinkprogress.org/climate/2011/11/28/377120/radiation-japan-fukushima-stunting-childrens-growth/>

Table 3.4: Average Cs-137 and I-131 Deposition Densities in seriously affected countries – kBq per m² (at time of main deposition)

Country or Oblast (Region)	Cs-137 deposition density	I-131 deposition density
Belarus, Gomel Oblast	154	1,280–3,230
Belarus Moglev Oblast	61	500–1280
Belarus, Brest Oblast	18.2	380
Belarus, Grodno Oblast	8.0	184
Belarus, Minsk City	6.2	140
Belarus Minsk Oblast	5.8	130
Belarus, Vitebsk Oblast	1.1	26
Russia, Bryansk Oblast	110	840–1,200
Russia, Tula Oblast	67	530
Russia, Orel Oblast	41	330
Russia, Kaluga Oblast	14	110
Ukraine, Zhytomer Oblast	~50	~650
Ukraine, Rivne Oblast	~40	~500
Ukraine, Kiev Oblast	~30	~400
Ukraine, remainder	~20	~250
Ukraine, Kiev City	~15	~200
Ukraine, Chernihiv Oblast	~15	~200
Austria	18.7	94
Slovakia	16.3	40
Slovenia	16.3	96
Moldova	10.1	52

source: Drozdovitch *et al* (2007)
 yellow = very seriously affected

(f) Increased Bioavailability

Indeed there are reasons for suspecting that the further away from Chernobyl the greater the bioavailability and possible health impact of its fallout. An important characteristic of fallout is its solubility in water as this determines the initial mobility and bioavailability of deposited radionuclides in soils and surface waters after deposition. The smaller the particles the greater their solubility. But small particles also travelled the farthest from Chernobyl.

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).

(g) Dose Impacts

It is necessary to explain what these contamination levels mean in terms of their likely doses to people living in these areas. Using a conversion factor of 2.18 nSv/hr per kBq/m² (Beck, 1980) for Cs-137, we can calculate an annual dose of 20 µSv per kBq/m².

Although uncertainty is inevitably associated with any dose conversion factor, we can estimate a dose of ~0.8 mSv per year from external exposures to 40 kBq/m² of Cs-137 for rural workers in Belarus, Ukraine and Russia. This is about the same level as the annual public limit of 1 mSv used for the regulation of radiological practices: doses above this limit are not authorised¹¹.

Similarly, a lower contamination level of 4 kBq/m² means that an area of one square meter would, on average, emit the external radiation from 4,000 Cs-137 decays each second. Use of the above dose coefficient results in an external dose of about 0.08 mSv per year¹². Assuming a linear no-threshold dose-response relationship, some additional cancers would result at these levels, but they would be difficult to ascertain in epidemiology studies. To assess the health effects of low radiation doses, we need to estimate collective doses – see Chapter 14.

(h) Mapping

The Cs-137 contamination levels were mapped by the European Commission's researchers. Their report clearly indicates the widespread deposition of Cs-137.

More detailed maps are available of Cs-137 depositions in Belarus, Ukraine and the Russian Federation in EC publications (De Cort *et al*, 1998). These were reproduced in TORCH (2006).

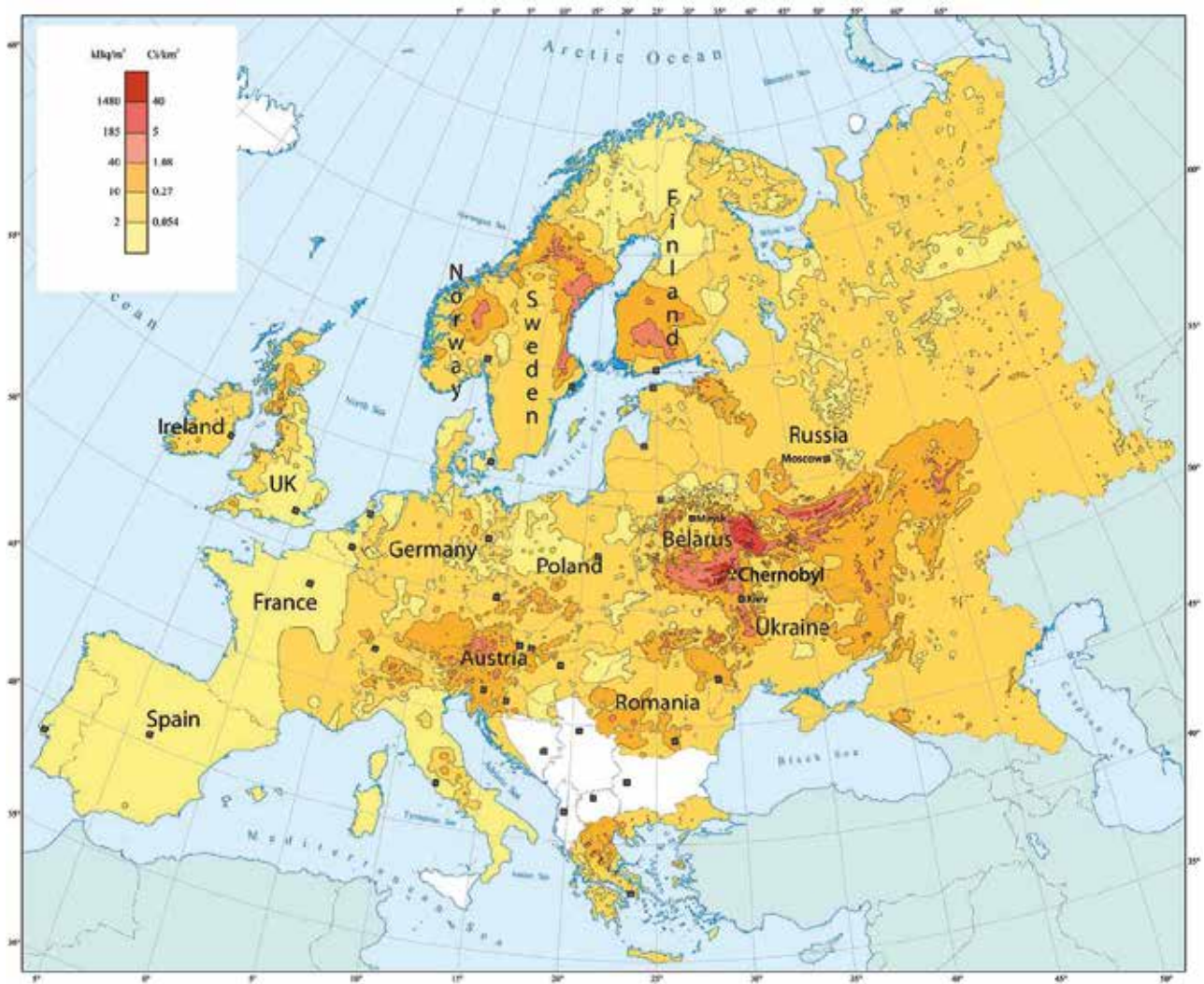
The EU and its staff are to be congratulated for their painstaking, lengthy work in determining these nuclide contamination levels and in making these Chernobyl deposition maps. It represents a huge amount of work.

It is regretted that these data and deposition maps have neither been referred to nor reproduced in any subsequent publications by Member States, UNSCEAR, WHO, and the IAEA.

¹¹ 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 stricter limit of 0.15 mSv per year

¹² a relatively "low" dose of radiation, about the same as the radiation dose from a chest X-ray. However this has a countervailing benefit for the individual who is X-rayed, whereas no benefit accrues to those exposed by Chernobyl releases

Figure 3.2: Reproduces plate 1 from De Cort *et al* (1998)



reproduced with permission from De Cort *et al* (1998)

(i) Continuing High Levels of Contamination in Wild Foods

Immediately after the Chernobyl accident, countermeasures and restrictions on contaminated foodstuffs were implemented by many European countries. Many have now been lifted but they remain in some areas on wild reindeer, boar, deer, wild mushrooms, berries and carnivore fish. For example, areas of Germany, Austria, Italy, Sweden, Finland, Lithuania and Poland still have raised Cs-137 contamination levels in natural or wild foodstuffs.

Over the next hundred years or so, Cs-137 land concentrations will gradually decline. This will be partly due to environmental causes (i.e. Cs-137 entering deeper levels of some soils), but will be mostly due to radioactive decay governed by the 30 year half-life of caesium-137 as stated by the IAEA/WHO (2005). In practice, this means that Cs-137 contamination levels in wild foods will remain high for a long time into the future.

Indeed, in April 2005, the European Energy Commissioner stated this when he wrote¹³ that Cs contamination in certain food products would not decline appreciably in the near future. He stated

“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. 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.”

This statement of fact remains as applicable in 2016 as it was in 2006.

(j) Conclusions

The main points from the above tables and maps are as follows:

- (a) Chernobyl's nuclides were widely and heterogeneously dispersed throughout Europe.
- (b) Belarus, Russia and Ukraine were the most seriously affected countries.
- (c) Austria and the Balkan and Slavic countries were also significantly affected.

Outside of Belarus Russia and Ukraine, more attention should be paid to Austria. This country had the highest average Cs-137 integrated activity in diet in 1986 /1987, and the highest average Cs-137 deposition density. It also had the fourth highest average Cs-137 integrated activity in air. As for I-131, it had the second highest average deposition density, and fifth highest average integrated activity in air. All at times of main deposition.

¹³ written answer to a Question P-1234/05DE by MEP Rebecca Harms dated April 4, 2005

4

Health Effects from the Chernobyl Accident: Introduction

(a) Categories of exposures to people

According to UNSCEAR (2008), five main categories of people were exposed to radiation from Chernobyl. These numbers have changed considerably from earlier reports, especially the large increase in the numbers of clean-up workers.

1. About 530,000 **clean-up workers** (formerly called 'liquidators') sent into the Chernobyl exclusion zone for decontamination work, sarcophagus construction, and other clean-up operations between 1986 and 1989. Their average dose was ~100 mSv.
2. About 115,000 **evacuees** who were evacuated within two weeks of the accident and 16,000 more before the autumn of 1986. Their average dose was ~33 mSv.
3. About 6.4 million **residents of contaminated areas** in Belarus, Ukraine and Russia. Their average dose was ~10 mSv.
4. About 100 million people who lived in in Belarus, Ukraine and Russia whose average dose was about 1.3 mSv.
5. Approximately 500 million **living in the rest of Europe** whose average dose was about 0.3 mSv.

(b) Categories of health effects

The health effects resulting from Chernobyl fallout are discussed under the following chapters on

- Thyroid cancer
- Leukemia
- Breast and Other Solid cancers
- Cardiovascular Effects
- Birth Defects
- Effects among Children
- Mental Health and Other Effects

The many scientific articles on these effects up to 2005/6 were reviewed previously in IAEA/WHO (2005), BEIR VII (2005) and TORCH (2006). Most of TORCH's comments are still relevant and it is recommended that the older report be referred to for additional detail.

This report will briefly summarise the previous TORCH report's findings where necessary but will concentrate on the more important of the new articles on adverse health effects which have been published since 2006, mainly in peer-reviewed journals.

(c) Caveats on Epidemiological Studies

This report examines many epidemiological studies: these can be a blunt tool for discovering whether adverse effects result from particular exposures. Too often, epidemiology studies contain methodological limitations such as poor case identification, non-uniform registration, variable or uncertain diagnostic criteria and uncertainties in the uniformity of data collation.

A major problem is that of omission: quite simply, that no studies exist in particular areas, or subjects or time periods. For example there are no recent studies on mental health effects, birth defects, or Down Syndrome after Chernobyl. Although this is rarely admitted or discussed, these are usually the result of political decisions.

Another major problem is that of missing cases due to migrations. Ogrodnik *et al* (2013) observed that

“The Chernobyl accident led to large-scale migrations in Belarus and Ukraine, notably within Kiev oblast. Further migration occurred following the USSR's breakup in 1991. About 14.9% of Ukraine's population consists of immigrants as of 2010. There are large Ukrainian émigré populations in Canada, Spain and Poland.”

Also, keeping track of case numbers in National Registers is difficult. With some diseases or birth defects, patients can and do avoid registration or move away to other areas to avoid identification, stigma and embarrassment.

This means that negative findings in epidemiology studies may lead to incorrect findings. It must always be remembered that absence of evidence in an epidemiology study does not provide evidence of absence (Altman and Bland, 1995). A corollary is that published studies with negative findings are generally unimportant unless the negative finding is very large: positive studies are what matter.

Even then, only very large, expensive and lengthy epidemiology studies are able to reveal effects where the signal (added radiogenic cancers) is weak and the noise (large numbers of background cancers) is strong. Instead, we often see many small studies each showing perhaps a few extra cases which are indicative but not conclusive. Meta-studies which group together small studies in order to strengthen their statistical significance are a solution, but very 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 "dose" in order to show a dose-risk relationship, but estimating doses is a big problem, as we shall see below.

(d) Uncertainty in dose estimates

Many uncertainties surround dose estimates from radiation exposures. These may be from external sources, eg gamma rays from Cs-137 on the ground. And they can come from the radiation from internal nuclides, that is from the inhalation of radioactive aerosols and gases and ingestion of radioactively contaminated food. These are important comprising 30 % to 50 % of the radiation from Chernobyl's fallout.

A major source of uncertainty is the estimation of internal radiation doses. This issue was comprehensively examined by the UK Government's CERRIE Report (2004) which showed that to estimate internal doses at least six computer models were used –

1. Source term models (how much was emitted by the accident)
2. Environmental transport models (weather patterns, rainfall and wind speeds)
3. Biokinetic models (for nuclide Bq uptakes and distributions within organs/tissues)
4. Dosimetric models (to convert Bq intakes into dose (grays))
5. Radiation Weighting Factors (w_R) to take account of different radiation types (RBEs)
6. Tissue Weighting Factors (w_T) – to sum doses in each organ to obtain whole body doses

Each step from one model to the next has associated uncertainties: these uncertainties have to be factored together. In particular, uncertainties in the dose coefficients¹⁴ for some nuclides can be very large indeed (CERRIE, 2004).

In sum, very large uncertainties can exist in estimates of internal dose. For example, Likhtarov *et al* (2006) found a large difference (330 %) between direct and indirect measurements of radiation resulting in excess relative risks of 3.89 vs 13.03 from direct vs indirect measurements, respectively.

(e) Uncertainty in risk estimates: the linear no threshold (LNT) Model of Radiation Risks

After estimating the dose, we need to estimate its risk, ie harm. Uncertainties exist here as well.

The most fundamental uncertainty is the nature of the dose-risk relationship at very low exposures below about 50 mSv (Shore, 2009). The current theory accepted by most international and national radiation authorities is that this relationship is linear without threshold down to zero dose (Brenner *et al*, 2003). This is called the linear no threshold (LNT) model. There is strong evidence for this at high doses but at doses lower than about 50 mSv, the relationship could be supralinear resulting in higher risks, or sublinear resulting in lower risks, or bi-phasic resulting in both. The result is that risk estimates from low exposures to radiation inevitably contain uncertainties. This does not prevent such estimates being made, but they have to be treated with caution.

The use of the LNT model is an important matter in radiation science. In recent years, LNT has been criticised often for spurious non-scientific reasons by ill-informed journalists. However two recent studies provide very strong evidence of increased leukemias (Leuraud *et al*, 2015) and solid cancers (Richardson *et al*, 2015) in nuclear industry workers at extremely low doses. The former is discussed in more detail at <http://www.ianfairlie.org/news/update-new-powerful-study-shows-radiogenic-risks-of-leukemia-in-workers-more-than-double-the-previous-estimate/>.

Leuraud *et al* (2015) found increased leukemia risks even at dose rates as low as 1.1 mGy per year and Richardson *et al* (2015) observed increased risks of solid cancer at a median dose of 4.2 mGy. Unlike the Japanese bomb survivors' study, these studies actually observed risks at low dose rates rather than extrapolating them from high levels. 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).

¹⁴ a dose coefficient expresses the dose given by one decay of a nuclide, and is expressed usually in Sv per Bq

The latest report from the Japanese bomb survivors on solid cancers (Ozasa *et al*, 2012) concluded that the risk of solid cancers continue to increase throughout life with a linear dose-response relationship, and that a formal dose-threshold analysis indicated no threshold; i.e., zero dose was the best estimate of the threshold for solid cancers.

In addition, radiobiology theory indicates that 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. Therefore good reasons exist for supposing that radiogenic risks are directly proportional to dose all the way down to zero, i.e. there is no-threshold. This means there is no "safe" dose of radiation.

In 2003, an eminent group of the world's foremost radiobiologists re-affirmed the LNT and stated that it provided a real estimate of radiation risks (Brenner *et al*, 2003).

(f) Statistically Significant Findings

When reporting the findings of epidemiology studies, the word "significant" is often used. This is a specialist adjective used in statistical tests to convey the narrow meaning that the likelihood of an observation being a chance finding or a fluke is less than 5% (assuming 5% significance level is used). It does not mean "important" or "relevant".

There are some problems here. The first is that the test level used in statistical tests is arbitrary. There is no scientific justification for using a 5% or any other significance level: it is merely a matter of convenience: 10% tests are now increasingly the norm.

This means it is quite possible for results which are "not significant" when a 5% test is applied, can become "significant" when a less strict 10% test is used. For this reason, good epidemiologists tend to avoid using the words "significant" or "significance" altogether and use confidence intervals instead (Morris and Gardner, 1988). Indeed the American Statistics Association has recently published important new guidelines to this effect. <http://amstat.tandfonline.com/doi/pdf/10.1080/00031305.2016.1154108#8>

Second, scientifically speaking, it's bad practice to dismiss results (or to imply this) merely because they do not meet a statistical test. This is because the probability (p-value) that an observed effect may be a chance finding is affected by both magnitude of effect **and the physical size of the cohort being studied**. This means the use of an arbitrary cut-off (conventionally $p = 5\%$) can lead to incorrectly concluding that there's no effect. This is called a type II (false negative) error in statistics, and it often occurs due to low statistical power, **i.e. low numbers of observed cases** rather than lack of effect¹⁵. In other words, the rejection of findings for statistical test reasons can hide true risks.

This happens too often in Chernobyl studies, where it is apparent that some scientists appear anxious to discount findings of increased risks in their own countries.

¹⁵ low case numbers are not the fault of researchers but due to the facts that many conditions are relatively rare (e.g. leukemia) and that very large numbers of exposed people are needed to pick up a few observed cases. Such studies are necessarily lengthy and expensive.

Studies with small positive findings which do not meet the 5 % test should NOT be rejected. Instead the observed % increase should be reported along with the confidence interval¹⁶ so readers can make up their own minds. That is, they could say that a relative risk was, for example, 1.50 with a confidence interval of 0.98 to 2.30. This would mean that the observed relative risk was 1.50 and that the real value lay between 0.98 and 2.30¹⁷.

It will be seen that epidemiology studies examined here use one or other of the above methods. In order to clarify matters, this report will preface the word "significant" with the word "statistically" to alert readers that a test is being applied by the authors and to be on guard. Where possible, the actual confidence interval will be reported so readers can make up their own minds.

(g) Conclusion

Readers need to be aware of the many factors that have to be taken into account when considering epidemiology studies: they should reduce their expectations accordingly.

In particular, when considering estimated doses and risks, the CERRIE (2004) Report advised that a precautionary approach should be used. This means that we should err on the side of caution – real doses and their risks might be greater than those estimated.

In sum, the results of epidemiology studies must be approached warily and be interpreted with care.

¹⁶ the confidence interval is calculated from the data observations

¹⁷ in this example, such a finding would have been declared "not significant" under the old method

5

Thyroid Cancer

(a) Introduction

Thyroid cancer (TC) is relatively uncommon but its prevalence is increasing world-wide (Burgess and Tucker, 2006; Colonna *et al*, 2007). In the US, TC is expected to be the fifth most common cancer among women (Sherman and Fagin, 2005). Thyroid cancer is generally two or three times as prevalent in woman than in men: different countries report different ratios (Zimmermann and Galetti, 2015). The female/male gender TC ratio has apparently increased in areas affected by Chernobyl (Fuzik *et al*, 2013).

Deaths from thyroid cancer are uncommon, as thyroidectomies are routinely performed in advanced cases of thyroid cancer. This does not mean that we should not worry about thyroid cancer: the quality of life for most thyroidectomy patients is reduced. Contrary to some reports, TC deaths are increasing worldwide (Sherman and Fagin, 2005; Ries *et al*, eds, 2008; Howe *et al* 2001).

The latency period for a cancer is defined as the time required for the first expected cancers to arise after exposure. This is about four years for TC but there is a suggestion it may arise earlier in high exposure situations. Williams (2007) considered that the radiogenic latency period for TC post Chernobyl may be partly due to the very large size of the TC outbreak. Notice that it is the period for the **first** cancers to arrive: later cancers will continue to appear. For example, in 2005, TC cases were still arising among the Japanese bomb survivors who were exposed in 1945, i.e. 60 years previously (Imaizumi *et al*, 2006).

(b) Increases in Belarus, Ukraine and Russia

Four years after the Chernobyl accident, very large increases in thyroid cancer were observed in young people in Belarus (Pryszazhiuk *et al*, 1991; Kazakov *et al*, 1992; Baverstock *et al*, 1992) and later in Ukraine (Tronko *et al*, 1994) and the Russian Federation (Tsyb *et al*, 1994).

Cardis *et al* (2005) examined TC incidence rates¹⁸ in Belarus children aged under 15 years at the time of diagnosis. These rose from 0.3 per million before the accident (1981–85) to 4.0 per million after the accident (1986–1990), and to 30.6 per million between 1991–1994.

In the extremely highly contaminated Gomel region of Belarus, even more dramatic increases were seen in the same three time periods from 0.5 to 10.5 to 96.4 per million respectively (Cardis *et al*, 2005). These are very large increases indeed, perhaps the largest ever quantified for any disease after toxic discharges.

By 2004, 740 TC cases had been observed (Cardis *et al*, 2005) in Belarus alone among those exposed as children (aged 0–14 years). According to Williams (1994; 2002) the evidence that these increases were related to exposures to iodine-131¹⁹ (half-life 8.3 days) was compelling.

¹⁸ incidence is defined as the number of **new** cases reported each year under existing detection and reporting practices.

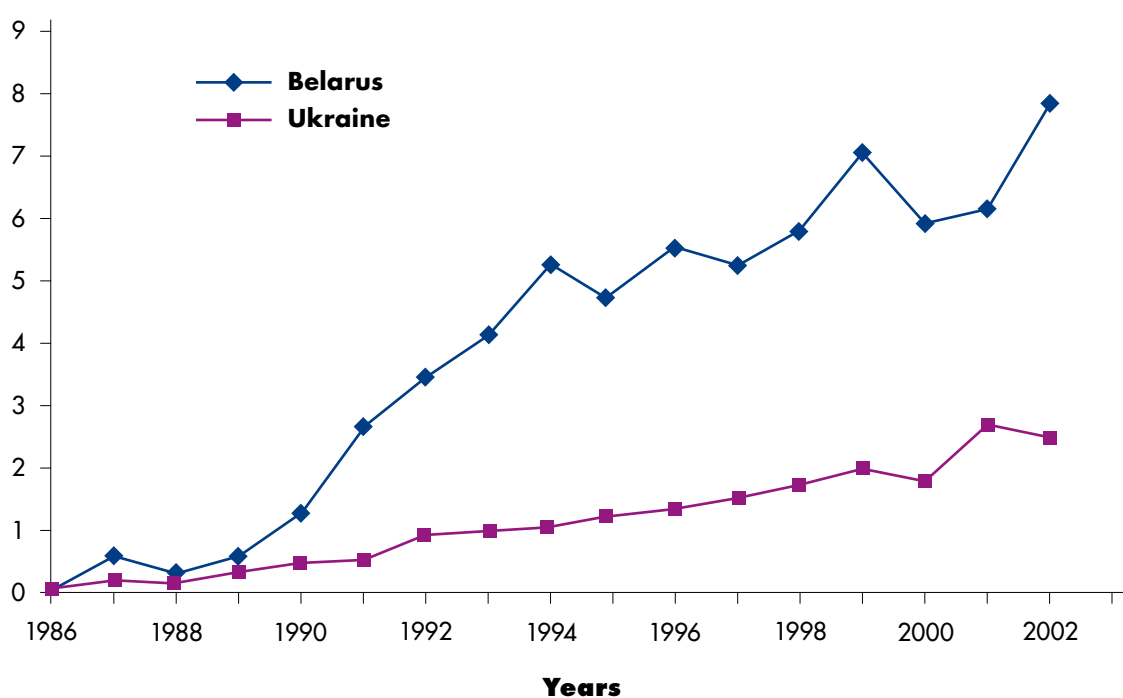
It is usually expressed as a rate, i.e. the number of people per million in the population being studied. It is different from prevalence which is defined as "the proportion of a population that has a disease at a specific point in time" by Rothmann and Greenland (1998)

¹⁹ and possibly to other shorter-lived isotopes of iodine, collectively called radio-iodines

UNSCEAR (2008) estimated that about 6,000 cases of thyroid cancer had arisen in Belarus, Ukraine and Russia to date (i.e. 2011) among those aged under 18 years (4,000 aged under 15) at the time of the accident. UNSCEAR (2008) stated a "substantial fraction" of these were estimated to be radiogenic. It can be seen from figures 5.1 and 5.2 below that this fraction is likely to be about 9/10ths in Belarus.

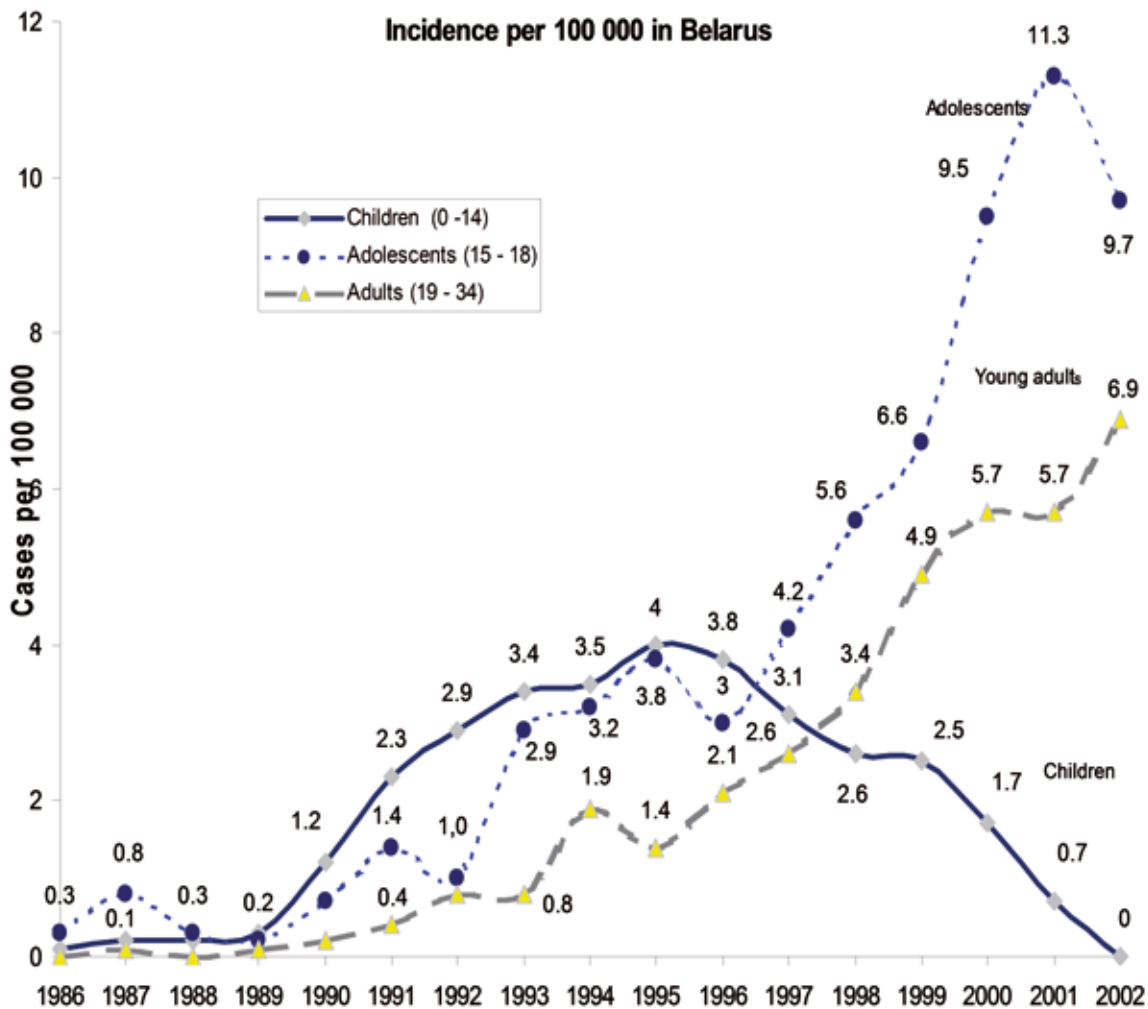
As the TC incidence rates in adults have continued to increase (see below), it is thought that the number of **cases** of thyroid cancer in these three countries will also have increased, however no recent data on TC numbers have been published. The rise in annual incidence rates up to 2002 in Belarus and Ukraine are shown in figures 5.1 and 5.2.

Figure 5.1: **Annual thyroid cancer incidence rates per 100,000 in those who were children and adolescents under 18 years old in 1986**



source: Jacob *et al* (2005)

Figure 5.2: Annual incidence of thyroid cancer in Belarus in age groups at year of diagnosis



source: Cardis *et al* (2006). Original data from Dr Yuri Demidchik.

In figure 5.2, the peak incidence in the 0–14 age group in Belarus occurred in 1995, and in the 15–18 age group it peaked in 2001. In addition, the graph indicates that the incidence of thyroid cancer among young adults continued to rise at least until 2002. Later data (Demidchik *et al*, 2007) showed that it continued to rise at least until 2007. However figure 5.3 below from Okeanov 2014 contains later data which shows some levelling off but the TC incidence rate among rural females appear to be still increasing in 2012, i.e. 26 years after Chernobyl.

Figure 5.3: Thyroid cancer incidence rate in Belarus 1970–2012

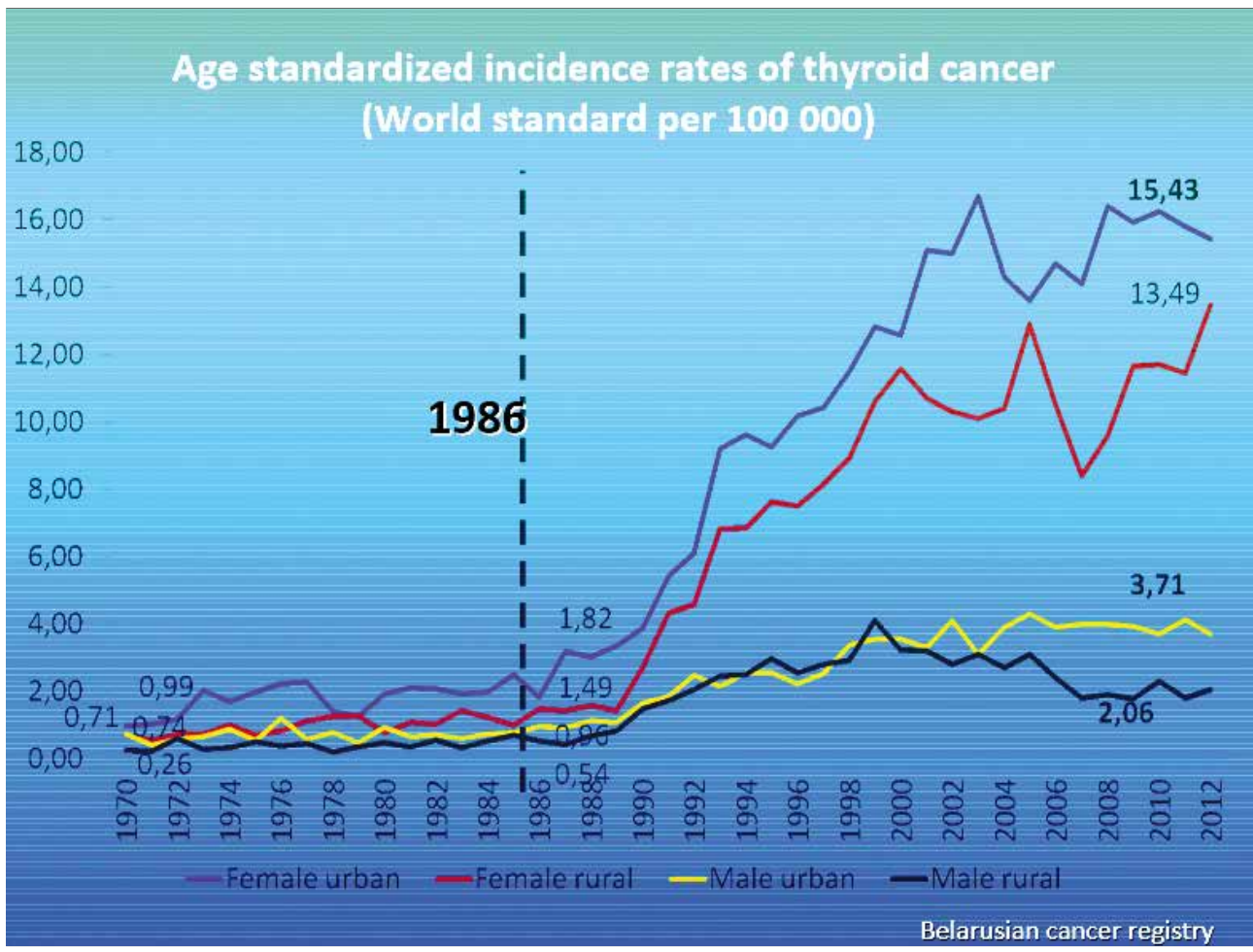


figure reproduced from PPT Presentation: Cancer Epidemiology Cancer Epidemiology In The Republic Of Belarus (Okeanov, 2014)
http://www.tschernobylkongress.de/fileadmin/user_upload/Arnoldshain_Doku/Zubec-Olga.pdf
 source: Belarus Cancer Registry

Figure 5.3 is important as it shows

- (a) dramatic increases in TC incidence rates starting 2 to 4 years after Chernobyl in 1986.
- (b) the female/male incidence ratio increased from ~2 before the accident to ~ 5 afterwards
- (c) the incidence rates remain elevated especially among women, and
- (d) the incidence rates among rural women may still be increasing

Demidchik *et al* (2007) confirmed that thyroid cancer risks would

“remain elevated in such people for their lifespan[s]. Therefore, further surveillance ... will be essential ... in order to be better prepared for ... thyroid cancer[s] in the future.”

Brenner *et al* (2011) found no evidence of a decrease in TC incidence over 22 years up to 2011. Recently Fuzik *et al* (2013) also observed excess TC cases in older age groups as well as in children and adolescents. Similar to Okeanov (2014) they observed TC increases between 1989 and 2009 in females aged 40–49 at the time of the accident in high exposure regions compared with low exposure regions.

(c) Magnitude of Increased Risk

The 2006 TORCH Report observed that for children aged under 15 at time of exposure the relationship between TC risk and TC dose was linear down to very low doses. This enables us to make predictions of the number of TC cases expected to arise in future.

In order to predict the numbers of cancer cases which may arise from radiation exposures, we need to use a risk projection model. Two main types exist: absolute and relative risk models.

Put very simply, absolute (or additive) risks are expressed as the number of cases (or deaths) per unit exposure e.g. 0.1 fatal cancers per sievert (Sv) of radiation. Relative (or multiplicative) risks are instead expressed as a percentage of **the background risk of cancer in that population**²⁰. The number estimated by the latter model is usually greater than the number estimated using the former model.

In recent years, it has become clear (from human evidence e.g. the Japanese bomb survivors) that relative risk models often give better projections of cancer deaths than absolute risk models. One corollary is that, numerically speaking, radiation risks are now greater than previously thought, i.e. when only additive risks were used. The reason is that the Absolute Risk = Relative Risk x Background Rate and the background rates for most cancers especially thyroid cancers are increasing.

Cancers in certain organs including thyroid are better described by relative than absolute risk models, so we need to use relative risks (RR) here.

A major study after Chernobyl (Ron *et al*, 1995) found that the best estimate of the RR for thyroid cancer in highly exposed areas in Belarus at the level of one gray was 8.7 (95 % confidence interval 2.1–28.7²¹). This means the risk of contracting TC in exposed individuals, divided by the risk of contracting TC in unexposed individuals was 8.7.

In layman's language, this means that those whose thyroids were exposed to one Gy of radiation (over a period of time) suffered a ~770 % increase in thyroid cancer over those who were not exposed. This is very high, but similar to the RR estimates of Cardis *et al* (2005b), Jacob *et al* (2005, 2006) and Likhtarov *et al* (2006) in their studies of thyroid cancer risk in Ukraine and Belarus. A RR of 8.7 is a large increase in risk. As we shall see in chapter 7, it is similar in scale to the large increases in leukemia risk seen among Chernobyl clean-up workers.

Cardis *et al* (2005) observed a linear dose-response relationship for TCs from low to high doses up to 1.5–2 Gy. The risk of radiation-related thyroid cancer was three times higher in iodine-deficient areas (RR= 3.2, 95 % CI = 1.9 to 5.5) than elsewhere. Administration of potassium iodide (KI) as a prophylactic reduced this risk of radiation-related thyroid cancer by a factor of 3 (RR = 0.34, 95 % CI = 0.1 to 0.9) for KI consumption versus no consumption.

(d) Thyroid Cancer in People exposed as Adults

In 2006, it was widely assumed that TC risks were restricted to people exposed when they were very young or to adolescents. In an earlier study, Ivanov *et al* (1997) had examined data on 168,000 clean-up workers from Russia

²⁰ why radiogenic cancer risks should be related to the background cancer rate in the population is a good question. Part of the answer may be that background cancers themselves are, to some extent, due to background radiation.

²¹ this means we can be 95 % sure that the true result lies in this interval

and showed a statistically significant²² effect even among those exposed as adults. The estimated Relative Risk (RR) per Gy for thyroid cancer was 6.31, consistent with estimates by Cardis *et al* (2005b).

Later the same team (Ivanov *et al*, 2008) found a statistically significant increase in TC, corresponding to a standardized incidence rate²³ (SIR) of 3.47 [95 % CI: 2.80; 4.25] among adult workers. The highest incidence rate (SIR = 6.62, 95 % CI: 4.63; 9.09) was shown for emergency workers who took part in the early recovery operations in April–July 1986. The estimated SIR value increased to 7.97 (95 % CI: 5.24; 11.52) if a 10 year latency period were used.

Kesminiene *et al* (2011) also found raised TC levels in Chernobyl liquidators. Although most received relatively low doses (median = 69 mGy), a statistically significant dose-response relationship was found with total thyroid dose. The RR per Gy was 4.8 [95 % CI: 2.0–11.9]²⁴.

Similarly Rahu *et al* (2013) found a higher proportion of thyroid cancers in Baltic clean-up workers compared to the male population (PIR²⁵ = 2.76; 95 % CI 1.63–4.36), especially among those who started their mission shortly after the accident i.e. in April–May 1986 (PIR = 6.38; 95 % CI 2.34–13.89).

However increased TC risks in those exposed as adults appear to be considerably lower than in those exposed as children. For example, although Richardson (2009) found exposures in adulthood were positively associated with thyroid cancer among women A-bomb survivors, the risk was lower than in those exposed during childhood. In more detail, Furukawa, Preston *et al* (2013) observed that both ERR and EAR for TC significantly and rapidly decreased with increasing age-at-exposure by 53 % ($p = 0.03$) and 70 % ($p = 0.002$), respectively, per decade increase in exposure age. It is concluded that increased TC risks do arise in those exposed as adults: the consistency of the evidence of raised TC risks among adult liquidators is notable. However they fall off rapidly with increased age at exposure, especially after the age of about 20 years.

(e) Thyroid cancers in Ukraine

In an initial study, Prysazhnyuk *et al* (2002) observed that the slow increase in TC incidence in Ukraine became steeper after the Chernobyl accident, that is they observed a dog-leg increase upwards. This effect was also observed by Fuzik *et al* (2011) in a comparative analysis of thyroid cancer incidence in Ukraine after Chernobyl in a cohort almost as large as the general population. In 2013, the same team (Fuzik *et al*, 2013) confirmed the radiogenic excess of thyroid cancer in individuals who were children and adolescents in 1986, and also in females aged as old as 40–49 in 1986.

In a quantitative risk analysis, Likhtarov *et al* (2006) estimated the excess relative risk per gray in Ukraine was 8.0 (95 % CI = 4.6–15). These were similar to the results of other studies from contaminated areas, as well as studies of external radiation exposure.

²² "Statistically significant" means we can be 95 % sure (in this study) the result was not a chance finding

²³ Standardised Incidence Ratio (SIR) means the number of observed cases divided by the number of expected cases or O/E

²⁴ assuming the LNT model of radiation risk is used

²⁵ PIR = Proportional Incidence Ratio = the observed number of cancer cases divided by the expected number, where the latter is the proportion of the cancer of interest to all cancers in a population

More recently, Prysyzhnyuk *et al* (2014) continued to observe statistically significant large TC increases among several segments of the Ukrainian population. The authors confirmed that TC **incidence rates were still increasing in people exposed when they were adults**. The authors stated that therefore

“profound attention in further studies should be drawn ... to malignancies with longer latent periods: lung, stomach, colon, ovary, urinary bladder, kidney cancer and multiple myeloma.”

Vasylenko *et al* (2013) recently carried out Whole Body Counts of Cs-137 in residents of supervised settlements of Narodytsky district, in the Zhytomyr oblast of Ukraine. Significant (2–3.5 times) seasonal increases of incorporated Cs-137 up to 350 kBq per body were observed. The main intakes were from the consumption of locally-produced milk and natural/forest products such as berries and mushrooms.

(f) How many more thyroid cancers will occur?

Before the Chernobyl accident, the principal source of information about radiation-induced thyroid cancer in children were studies in which children had been exposed to external X-rays for medical reasons. A survey of these (Ron *et al*, 1995) showed that the thyroid cancer risk was still increased more than 40 years after the initial exposure. A study of thyroid cancer incidence in the survivors of the Japanese atomic bombs (Imaizumi *et al*, 2006) found a significant dose-response relationship still existing nearly 60 years after exposure. The authors also observed that the effects were much greater in those exposed at younger ages.

Therefore uncertainty exists in predicting the total number of thyroid cancers likely to result from Chernobyl because these are expected to arise for decades to come.

An attempt at prediction can be made by assuming that the future risk levels will be similar to that seen with external radiation. Using this method, Jacob *et al* (2000) estimated that starting in 1997, 15,000 thyroid cancers would occur in Belarus although with an uncertainty range of 5,000–45,000. The UNDP (2002) had estimated that in Belarus the numbers of thyroid cancers were likely to rise to between 8,000 to 10,000.

Cardis (2015) recently slightly lowered these predictions. Her new prediction is that 16,000 extra TC cases would occur in the whole of Europe up to 2065, with two thirds (~11,000) arising in the three countries Belarus, the Russian Federation and Ukraine combined. The corollary is that about 5,000 extra TC cases are predicted to arise in other European countries up to 2065.

(g) Thyroid cancers in countries outside Belarus, Ukraine and Russia

Given the above evidence of increased TCs in Belarus Ukraine and Russia, it is useful to examine the situation in other exposed countries. This is because at least some of the I-131 source term was deposited outside the former USSR countries as seen in the I-131 maps in Chapter 5.

It is perhaps not surprising that increased TC incidence rates have been observed in some European countries affected by Chernobyl's fallout.

In **Poland**, a substantial increase in TC incidence was observed especially since 1991 in women and in 1992–1993 and 1999–2000 in men (Roszkowska and Goryński, 2004).

The **Czech Republic** received a moderate amount of I-131 in fallout from Chernobyl as shown by the I-131 maps in Chapter 6. This is also shown in table 3.6 above: the Czech Republic had a relatively high I-131 average deposition density and I-131 average integrated activity in air. Murbeth *et al* (2004) reported a uniform annual increase from 1976 to 1999 of 2.0 % per year in the age-standardized thyroid cancer incidence rate (95 %-CI: 1.3-2.7, $p < 0.0001$).

More important, the authors observed an additional statistically significant increase in the thyroid cancer incidence of 2.6 % per year after 1990 (95 %-CI: 1.2-4.1, $p = 0.0003$). They stated

“an unexpected uniformly accelerated increase of thyroid cancer in all age categories was observed from 1990 onwards”.

This dog-leg effect was dependent on gender: females 2.9 % per year (95 %-CI: 1.3-4.7, $p = 0.0006$), and males 1.8 % per year (95 %-CI: -1.0-4.7, $p = 0.2127$). The authors concluded 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 apparently not been followed up by the IAEA, WHO and the EC.

In **East Slovakia**, the incidence of thyroid cancer in the 10 year period after Chernobyl was investigated in the Roznava region and compared with a control period before the accident. The cumulative incidence of TC was 1.3 times higher than the period before the accident even in adults (median age: 47 y). Most (45 %) cases were in 1990–1995 (Icso *et al*, 1998).

The **United Kingdom** received moderate levels of fallout but some areas were highly contaminated. Cotterill *et al* (2001) reported an increased incidence of thyroid cancer in the North of England, particularly in Cumbria, one of two areas in the UK which received the highest levels of fallout. They observed that iodine-131 concentrations were as high as 784 Bq/litre in rainwater and 1,040 Bq/litre in goat's milk. These concentrations exceed the EU's then Food Intervention Levels for dairy produce. Although Cotterill *et al* stated that factors such as earlier detection of tumours may have contributed to the increasing incidence, their conclusion was that

“further collaborative international studies are needed to investigate changes in the incidence of thyroid cancer in children and young adults”.

As far as is known, this has not been done.

In **France**, which received low radio-iodine levels from Chernobyl, Verger *et al* (2003) reported that, between 1975 and 1995, the incidence of thyroid cancer in France increased by a factor of 5.2 in men and 2.7 in women, thereby raising public concerns about Chernobyl's effects. At the request of the French Government, the French IRSN sought to quantify the risk of thyroid cancer associated with the Chernobyl fallout in France. Using various dose models, the authors predicted that 1.3 to 22 excess thyroid cancer cases would arise in the 1991–2000 period, compared with the 212 spontaneous cases predicted to arise²⁶. In other words, 0.5 % to 10.5 % of TC cancers

²⁶ Also 11.2 to 55.2 excess TC cases would arise between 1991 and 2015, compared with 1,342 spontaneous cases (0.8 to 4.1 %).

arising were predicted to be caused by Chernobyl fallout. The authors stated that their risk calculations indicated that the Chernobyl fallout could not explain the entire increase in thyroid cancers in France, and that it was improbable that an epidemiological study could demonstrate such an increase.

The observed TC increases in **Austria** are discussed in the next chapter.

(h) Conclusions

Summing up, since the 2006 TORCH report, we see continuing increases in TC cases in Belarus and Ukraine. These increases are now seen among adults, ie those who were exposed as children and adolescents. The estimated morbidity risks per Gy in the most contaminated areas are high with a relative risk of ~8 at the level of one Gy. This translates to ~700 % increases over the background rates in these areas. The raised incidence rates for adults are expected to peak in the near future in Belarus but will continue above the pre-accident rates for many years.

Cardis (2015) recently predicted that 16,000 (95 % uncertainty range 3,500 to 72,000) extra thyroid cancer cases would occur over future years to 2065 in the whole of Europe. Of these, two-thirds, i.e. ~11,000 would occur in the three countries Belarus, the Russian Federation and Ukraine. The corollary is that the remaining third (~5,000) would occur in Western European countries.

Increased TC incidence rates after the accident have also been reported in Slovakia, Austria, Czech Republic and Poland. These countries were not as heavily contaminated as the severely contaminated areas of Belarus, Ukraine and Russia but their contamination levels were relatively high = they matched or exceeded the levels in less contaminated areas of Belarus, Ukraine and Russia. Raised TC levels were even observed as far away (~2,500 km) as Northern England.

The lack of observed TC levels in other European countries is due to the fact that no studies have been carried out partly due to the lack of central funding and missing registers (e.g. Germany).

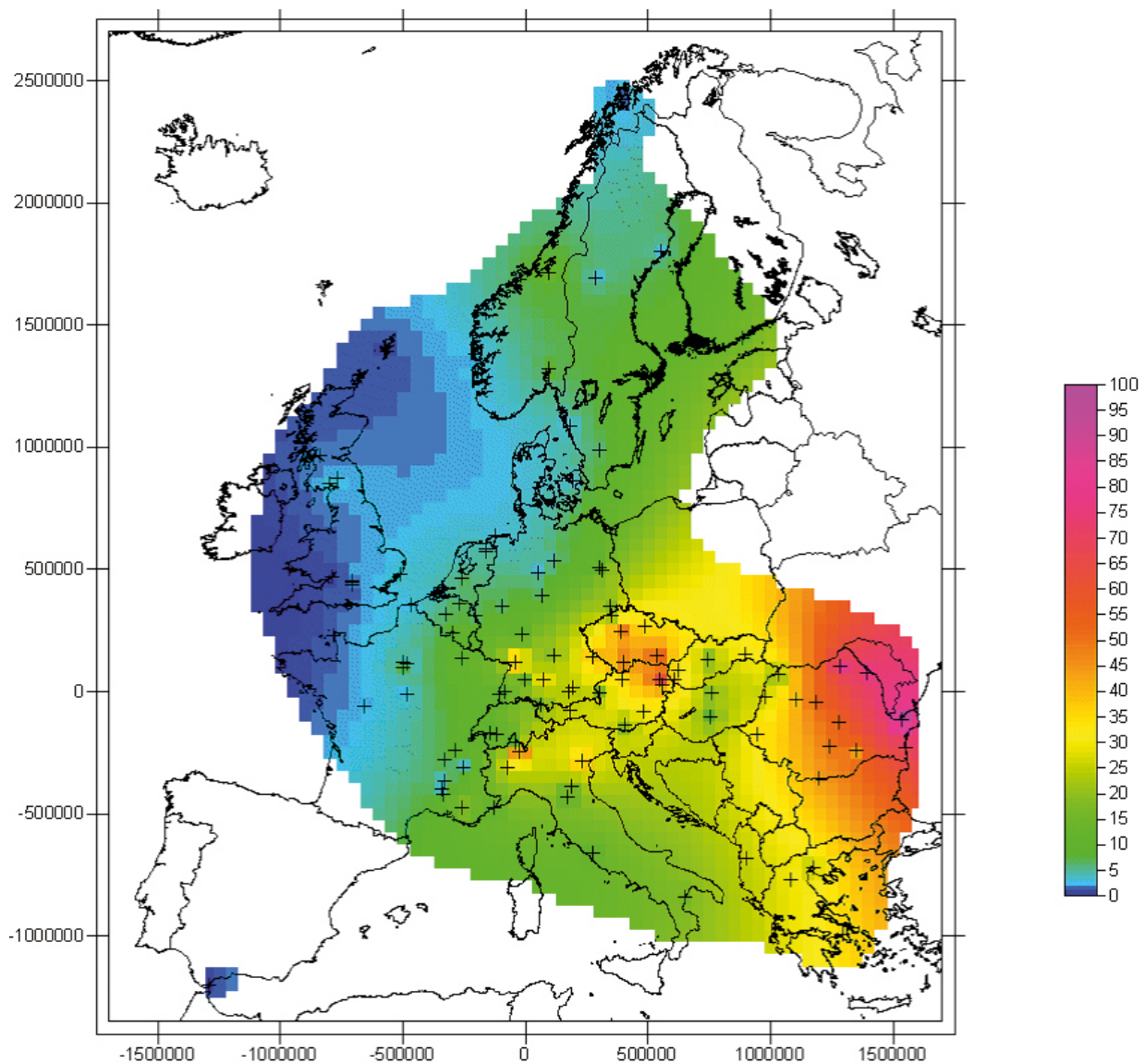
6

Thyroid Cancer In Austria

(a) Radio-iodine Distribution

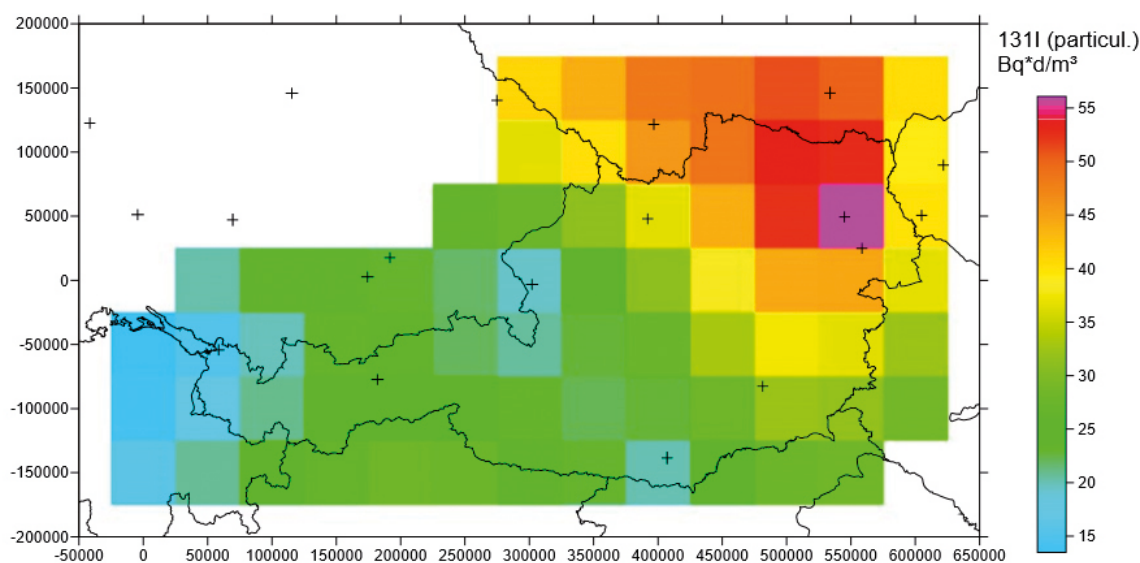
Important for thyroid cancer are the iodine-131 (I-131) maps in figures 6.1 and 6.2. Austria had the second highest average I-131 deposition density, outside Belarus, Ukraine and Russia, see table 3.4 in chapter 3.

Figure 6.1: **Distribution of cumulative I-131 activity concentrations in the air over Europe in May 1986 in $Bq \cdot d/m^3$ = becquerels x days per cubic metre of air.**



$Bq \cdot d/m^3$ = Bq x days per cubic metre of air
Reference: Seidel *et al* (2012)
Original source: <https://rem.jrc.ec.europa.eu/RemWeb/activities/Remdb.aspx>

Figure 6.2: **Distribution of cumulative I-131 activity concentrations in the air over Austria in May 1986 in Bq*d/m³**



Reference: Seidel *et al* (2012)
Original source: <https://rem.jrc.ec.europa.eu/RemWeb/activities/Remdb.aspx>

These maps of particulate iodine distribution in Europe and Austria are of considerable interest, as they are not widely known. This report will represent their first dissemination to a wider public outside Austria.

It is noticeable that they differ considerably from the caesium-137 (Cs-137) maps – see figures 6.6 and 6.7 below. The (presumably very small) particles containing iodine in various forms²⁷ would have been suspended in aerosols and spread throughout Europe. Radio-iodines would also have been distributed as iodine gas, I₂. This means that the actual radio-iodine Bq.d/m³ figures will be higher than the particulate data shown in figures 6.1 and 6.2. It is not known how much higher.

UNSCEAR (2008) reported that the main I-131 uptake was ingestion via the grass pasture-cow-milk pathway. Presumably some radio-iodine would also have been inhaled as aerosol and gas and a smaller amount would have been absorbed through skin.

As regards inhalation, few measurements were taken at the time of the accident, but Hölglye and Malátová (2012) used iodine-131 levels in urine from two healthy males in Vienna in May 1986 to estimate iodine intakes and committed effective doses. These were higher than initial estimates based on air sampling. A similar conclusion was made by Malátová and Skrkal (2006) regarding iodine inhalation in then Czechoslovakia.

In other words, inhalation should be taken into account as a significant pathway. Part of the reason is that intakes via air inhalation took place much quicker after the plumes passed than ingestion of milk via the pasture-cow-milk pathway. This would have led to intakes of several iodine isotopes²⁸ with shorter (i.e. less than a day) half-lives and consequently higher specific activities, i.e. doses.

²⁷ Unfortunately little is known of the particle sizes nor of the speciation of the iodine containing particles, but these presumably included the doubly radioactive caesium iodide, ¹³⁷Cs¹³¹I

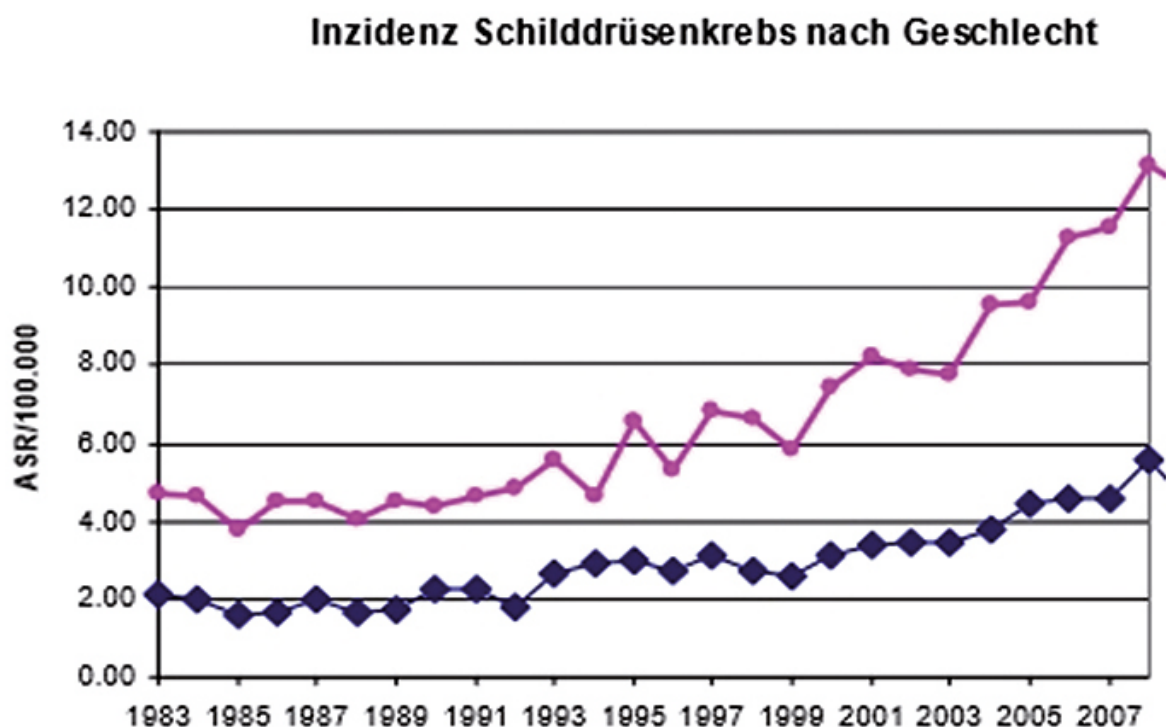
²⁸ Including I-133 with a half-life of 20.8 hours, and Te-132 with a half-life of 3.2 days whose decay product is I-132 with a half-life of 2.3 hours

The Government of the County of Upper Austria Report (Seidel, 2012) stated that the highest I-131 activity concentrations in air were measured in the Vienna region²⁹. This can be seen from figure 6.2. This is of relevance as about 30 % of Austria's population lives in the greater Vienna region, so the collective doses to the thyroid in this area would have been significant. As far as is known, no studies were made of thyroid uptakes and collective doses to the thyroid in Vienna at the time or since.

(b) Thyroid Cancer Incidence

The only study of thyroid cancer in Austria is a report (Seidel, 2012) commissioned by the Government of the County of Upper Austria. The report was written by a research team at the Universität für Bodenkultur Wien / University of Natural Resources and Applied Life Sciences. This contained the following chart reproduced in figure 6.3.

Figure 6.3: **Age-standardized incidence rate of thyroid cancer by gender for Austria in the period 1983–2008**



magenta = women: blue = men

Source: Seidel C, F-J. Maringer, A. Baumgartner, T. Waldhör, P. Bossew (2012) Gesundheitliche Folgen in Oberösterreich 25 Jahre nach Tschernobyl – neue Betrachtungen hinsichtlich der Inhalations- und Ingestionsdosis durch ¹³¹I und ⁹⁰Sr. Bericht an das Amt der Oberösterreichischen Landesregierung, Abt. Umweltschutz. Translation³⁰

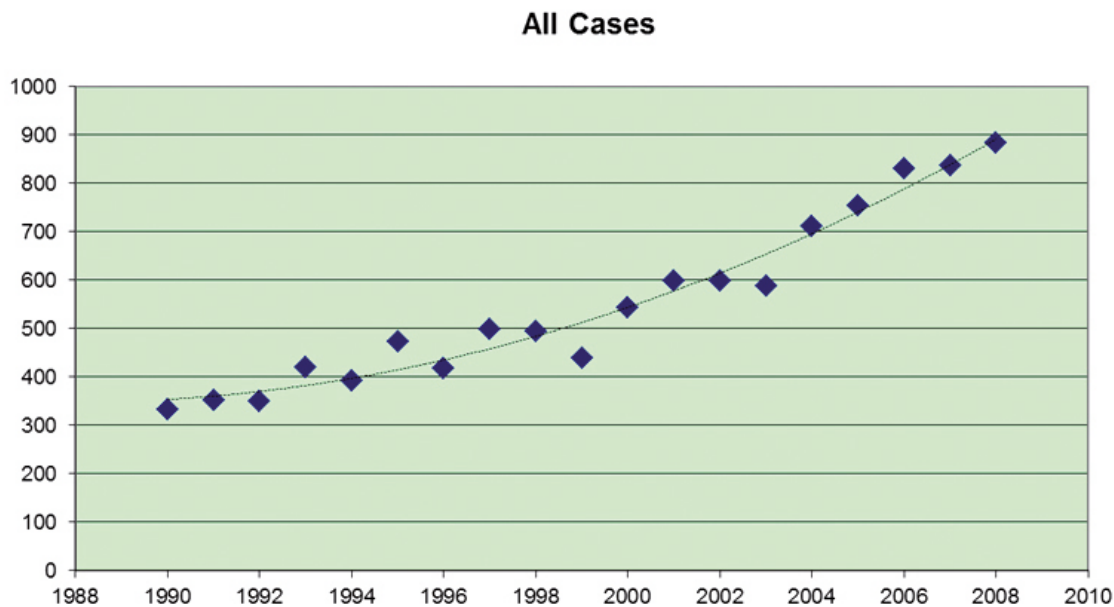
http://www.atomfreie.eu/fileadmin/Daten/Studiathek/2012_03_15_Tschernobylstudie_Kurzfassung_2012.pdf

²⁹ And Prague in then Czechoslovakia

³⁰ Health Consequences in Upper Austria 25 years after Chernobyl – new considerations regarding the inhalation and ingestion dose by I-131 and Sr-90. Report to the Office of the Government of Upper Austria, Department of Environmental Protection.

In addition, Moshhammer (2015) reported the following data on all (male and female) TC cases from the Österreichische Gesellschaft für Hygiene, Mikrobiologie und Präventivmedizin in Vienna. See Figure 6.4.

Figure 6.4: **All thyroid cancer cases in Austria**



source: Moshhammer (2015)

The most recent available TC incidence data (up to 2012) was obtained from STATISTIK AUSTRIA³¹, and was plotted by Dr Alfred Körblein in Figure 6.5.

This diagram resembles the plot of TC incidence data for Belarus in figure 5.1. It also resembles the temporal trend in seen in Czechoslovakia (Murbeth *et al*, 2004) after 1990 and in Ukraine (Prysyazhnyuk *et al* (2002). These data with their dog-leg increases after 1990 suggest that Chernobyl fallout could be an explanatory factor as the latency period for thyroid cancer is about four years³².

(c) Dog-Leg Function

In a personal communication, Dr Körblein has pointed out that trend lines other than a dog-leg function could also fit the data in figure 6.5, and that a continuous function marginally fits the data better using statistical fitness tests. However fitness tests, like p-tests, are tools not arbiters, as they could lend support to spurious findings.

Fitness tests must therefore be viewed in conjunction with other information available to the scientist. For example, what does external evidence indicate, what has happened in other similarly affected areas, what does radiobiological theory suggest, is there another reasonable explanation for what is found, and what do other careful scientists think.

³¹ Österreichisches Krebsregister (Stand 02.10.2015). Erstellt am 14.10.2015.

1) Maligne invasive Fälle, inkl. DCO-Fälle.

2) Jeweils auf 100,000 Personen/Männer/Frauen, Standardbevölkerung = WHO-Weltbevölkerung, 2001.

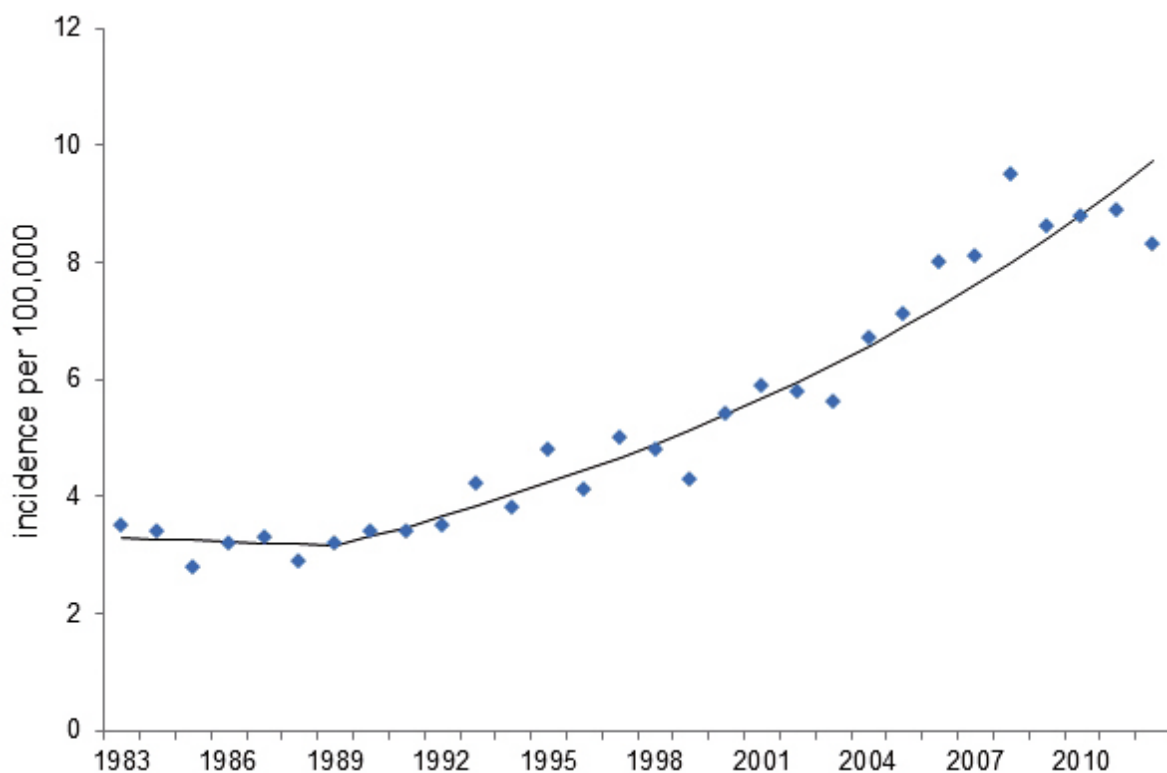
3) Erkrankungsrisiko bis zum 75. Lebensjahr in Prozent.

³² it is widely considered that the latency period for TC is four years, i.e. the time period before the first cancers appear

In this case, one needs to take into account the documented arrival of the Chernobyl plumes over Austria in 1986, the observed high concentrations I-131 over densely-populated regions of Austria, the similar observations in other European countries exposed to Chernobyl plumes, the four year latency period for thyroid cancer, and the lack of other satisfactory explanations for the observed cancer increases. After a careful consideration of these factors, it is concluded that a dog-leg function best explains the available data to date.

However the report by the Government of the County of Upper Austria (Seidel *et al*, 2012) denied this explanation. It stated (on its page 23) that the increasing time trend of TC rates (as shown in its figure 22) was observed in many other countries worldwide and was explained by improved registration and better diagnostic methods which can detect smaller tumours. Original German text³³. It added on its page 25 that the age-standardized incidence rate in Austria did not differ from the average rate in other countries. Original German text³⁴.

Figure 6.5: Thyroid cancer incidence in Austria (both genders) with regression line using a dog-leg model allowing for a trend change after 1989



source: data plot and regression analysis by Körblein (2015)

³³ In Abbildung 22 ist ein Anstieg der Inzidenz bei beiden Geschlechtern seit ca. 1991 ersichtlich. Dieser Trend wird in vielen anderen Ländern der Welt beobachtet und wird dem höheren Erfassungsgrad (Meldegenauigkeit) sowie vor allem der Einführung verbesserter diagnostischer Verfahren zugeschrieben. Diese ermöglichen die vermehrte Erfassung von kleineren Tumoren (Wartofsky 2010, Davies und Welch 2006, Enewold *et al.* 2009).

³⁴ In Abbildung 25 ist zum Vergleich mit anderen Ländern die Verteilungen der Inzidenzraten für Männer und Frauen aus dem IARC Bericht "Cancer Incidence in Five Continents" (2007) dargestellt. Die für die Darstellungen verwendete altersstandardisierte Rate unterscheidet sich von den für diesen Bericht erstellten Raten auf Grund einer unterschiedlichen Standardbevölkerung. Mit einer Österreichrate von 2.8 (Männer) und 6.5 (Frauen) befindet sich Österreich im Mittelfeld.

Given the importance of the matter, it is recommended that the Government of the County of Upper Austria report should be translated into English and be submitted for publication in a scientific journal. This would enable the report to be peer reviewed.

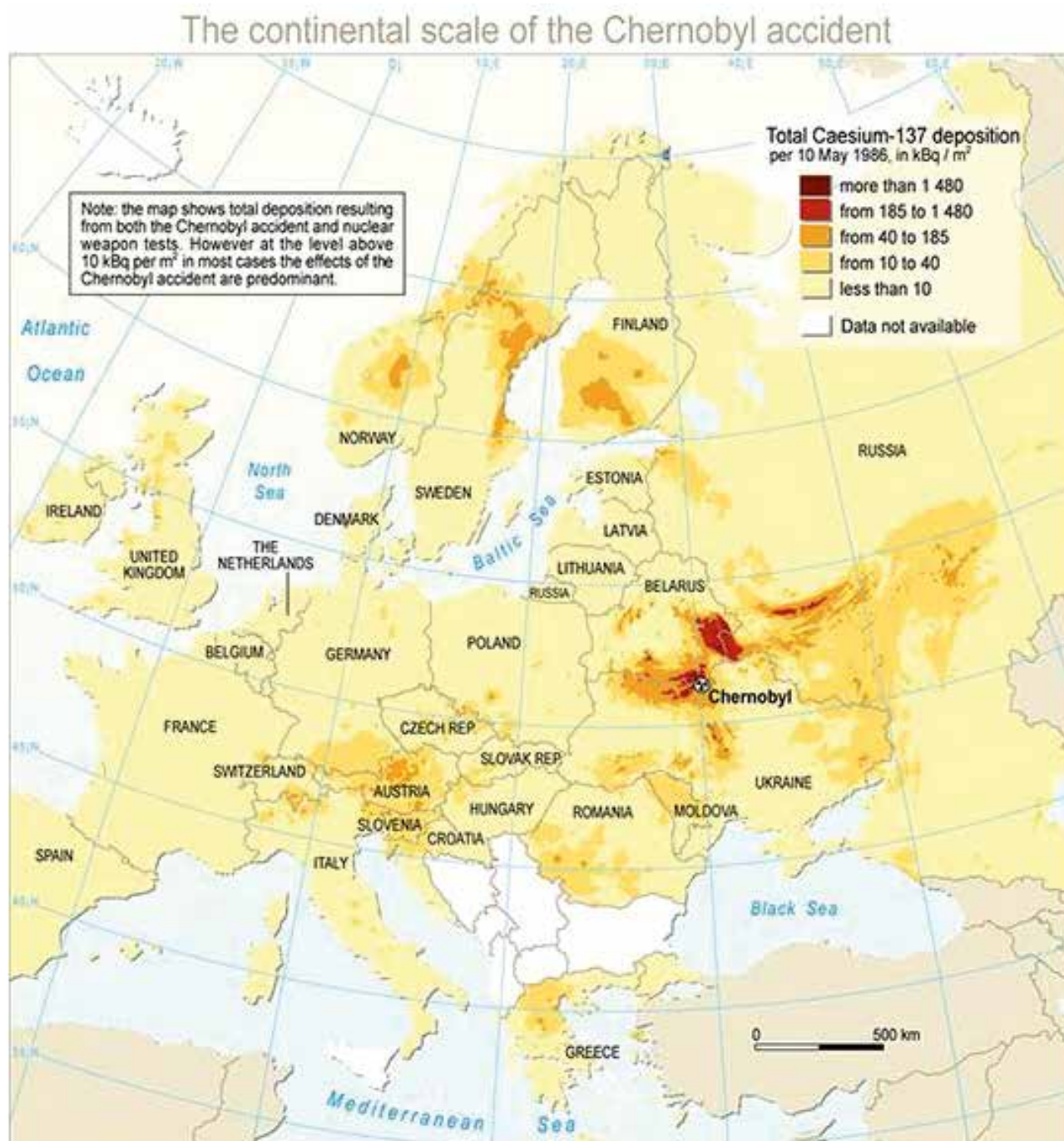
The actual reasons for increased TC rates is a matter on which different views exist in scientific circles. Chapter 7 discusses these in more detail.

With regard to age-standardised average rates of TC in Austria being similar to other countries, this may well be the case but one has to be careful of using country-wide averages, as they may hide increases in specific areas. For example, I-131 volume concentrations in the Vienna region were at least three fold greater than in other areas in Austria – see figure 6.2.

(d) Other Cancers in Austria?

As reported by Bossew *et al* (2012), Austria was one of the more severely affected countries in terms land area contaminated by Chernobyl's plumes. This is seen in figures 6.6 and 6.7.

Figure 6.6: Cs-137 concentrations in Europe



Source: European Commission, Joint Research Center, Environment Institute; Institute of Global Climate and Ecology (Moscow); Roshydromet (Russia); Minchernobyl (Ukraine); Belhydromet (Belarus). *Atlas of Caesium Deposition on Europe after the Chernobyl Accident, 1998.*

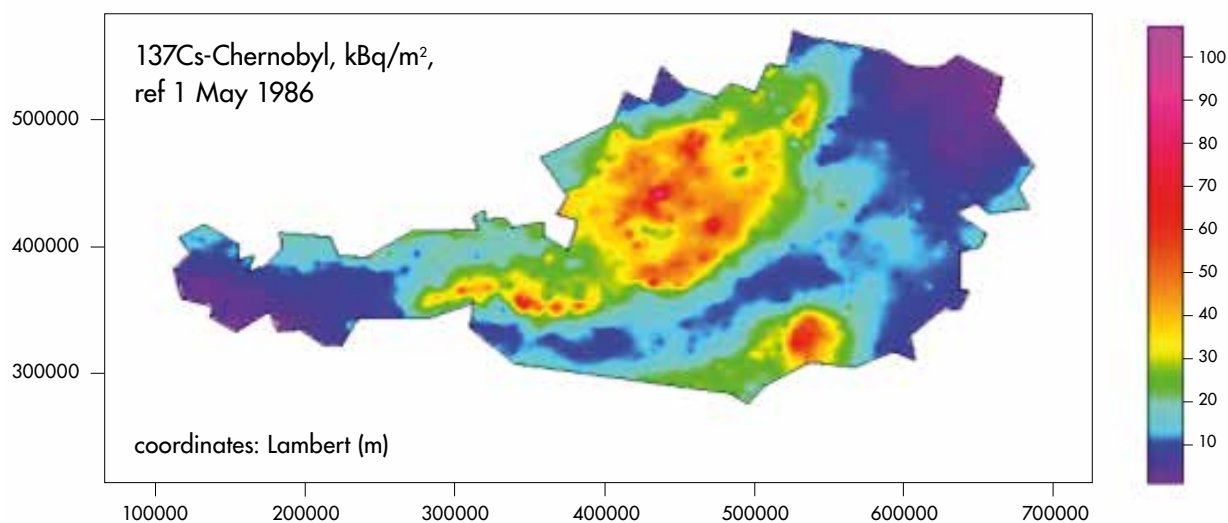
Map by UNEP/GRID-Arendal, May 2007.

THE MAP DOES NOT IMPLY THE EXPRESSION OF ANY OPINION ON THE PART OF ENVSEC PARTNER ORGANISATIONS CONCERNING THE LEGAL STATUS OF ANY COUNTRY, TERRITORY, CITY OR AREA OF ITS AUTHORITY, OR DELINEATION OF ITS FRONTIERS AND BOUNDARIES.

source: <http://maps.grida.no/go/graphic/the-continental-scale-of-the-dhiemohyl-accident>

Figure 6.7 in more detail indicates that large areas of upland Austria were contaminated by Cs-137 above 40 kBq per m² as of May 1 1986.

Figure 6.7: Cs-137 levels in Austria



Source Bossew *et al* (1996) <http://www.umweltbundesamt.at/umweltsituation/kernenergie/oesterreich/>
legend units = kBq per m²

Tables 3.2 to 3.4 in chapter 3 are also relevant. They indicate that Austria was the country with

- the highest Cs-137 **deposition density** (outside Belarus, Ukraine and Russia)
- the highest Cs-137 level in **diet** in 1986/1987 (outside Belarus, Ukraine and Russia)
- second highest affected country area-wise (after Belarus) re **very high levels** of Cs-137 **contamination**
- the third highest country area-wise (after Moldova and Slovenia) re **medium and high levels** of Cs-137 **contamination**

Chapter 14 indicates that Austria was also one of the countries with large collective doses from Chernobyl.

However, despite these data, there have been no cancer studies in Austria apart from the Seidel *et al* (2012) report on thyroid cancer. The only health study in Austria after Chernobyl that has been found is a 1992 study by Haeusler *et al* (1992) which observed no statistically significant changes in the incidence of birth defects, abortion rate, or counselling rates at pregnancy termination clinics.

(e) Conclusions

It is concluded that some of the observed TC cases in the Vienna region of Austria since 1990 are likely to have been caused by exposures to the Chernobyl plumes. The reasons are as follows

- (a) the Vienna region (with ~30 % of Austria's population) received relatively high depositions of I-131 from Chernobyl compared to other European countries
- (b) the temporal (dog-leg) pattern of the observed TC increases in Austria is similar to those seen in then Czechoslovakia and Belarus

- (c) the increased female/male ratio in TC incidences seen in Austria is similar to the ratios seen in Czechoslovakia and Belarus and
- (d) the explanations (improved registration and better diagnostic methods) offered by the Government of the County of Upper Austria report (Seidel *et al*, 2012) for the observed TC increases are unlikely to fully explain the observed TC increases.

The next chapter considers this question in detail and estimates that a small but significant fraction was involved, perhaps between 8 % and 40 %.

More research is recommended on this matter, in particular an initial exploratory study of TC incidence rates in the Vienna region and in all Austria between 1980 and 2015. In view of the high Cs-137 levels in Austria post-Chernobyl, it is also recommended that initial exploratory studies be carried out on leukemias and all cancers after 1986.

7

Impacts of Screening and Improved Diagnostic Procedures

(a) Introduction

A major, unresolved, issue in thyroid cancer (TC) studies after radiation exposures is the degree to which raised TC incidence rates may be caused by

- increased surveillance
- improved diagnostic procedures, and
- other unknown factors

For example, disentangling the reasons for increased TC incidence rates now emerging at Fukushima in Japan is a contentious issue: scientists remain divided on the matter. However this report concerns Chernobyl and there are many differences between the situations at Chernobyl and Fukushima.

As UNSCEAR (2013) pointed out, the thyroid doses resulting from Chernobyl were much higher than those after Fukushima. It estimated that the average adult dose to the thyroid was 7.8–17 mGy in Fukushima Prefecture. On the other hand, the mean thyroid doses in highly contaminated areas of Belarus were estimated (Zablotska *et al*, 2011) to be 643 mGy (SD \pm 1663 mGy) and 560 mGy (SD \pm 1180 mGy) in Ukraine (Likhtarov *et al*, 2014) after the accident. In other words, about 50 to 60 times greater, although we need to remember that considerable uncertainties exist in all these estimates.

Widespread repeated screening and improved diagnostic procedures are likely to have some effect on TC incidence rates. On the other hand, it is necessary to be careful and recall that, in the early 1990s it was widely but incorrectly believed that the TC increases observed in Belarus were due to increased screening.

Today, most scientists agree that the increased TC incidences in heavily affected areas of Belarus, Ukraine and the Russian Federation are clearly radiogenic and related to Chernobyl. The patterns of dog-leg accelerations in TC incidences seen after 1990, increased female/male ratios and more aggressive tumours are notable. However there is a reluctance to ascribe to Chernobyl the observed increases in thyroid cancers in west European countries also affected by its fallout. Clearly, radio-iodine exposures were lower in the latter countries. However, to the degree these countries or areas were contaminated with I-131, some of their reported increases may be Chernobyl-related.

Table 3.4 in Chapter 3 indicates that several European countries, including Austria, were as severely affected as the less contaminated parts of Belarus, Ukraine and Russia.

(b) Increased Surveillance or Screening

In their substantial (11,000 persons) cohort study on thyroid cancer in Ukraine, Brenner *et al* (2011) found large, statistically significant, increases in TC risks. The authors specifically addressed whether the observed increases in risks were due to increased screening. They stated

“Because everyone in our cohort was screened regardless of dose, confounding by screening intensity is unlikely.”

They explained that because excess relative risk (ERR) is the ratio of excess radiation cancers to background cancers, the fact that it was unaffected by screening implied that screening proportionally increased both background and radiogenic cancers with small tumours. In their words

“at least some of the small tumours were caused by radiation.”

The authors also noted that among the Japanese bomb survivors in 1945 no significant difference in observed risks was observed between those who were screened and those who were not (Akiba *et al*, 1991). Similar arguments were used by Ron (2009) and Prysyazhnyuk (2011) in their rebuttals to proponents of the increased surveillance theory. Also, Schneider *et al* (1993) observed no significant difference in observed TC risks among children externally irradiated for enlarged tonsils and adenoids before and after 1974, when the radiation issue had become recognized and a screening program was initiated.

(c) Improved Diagnostic Procedures

As regards better detection procedures and protocols, many doctors have observed that smaller tumours are now detected by the use of better equipment in recent years. It is unclear whether small tumours are also caused by exposures to Chernobyl's radioactivity.

Brenner *et al* (2011) in their study of TC cases in Ukraine stated

“... it remains controversial ... whether ... small tumours are induced by radiation to the same extent as large tumours.”

Accordingly the authors specifically assessed whether their observed dose responses varied with tumour size. They found elevated risks were associated with both large and small tumours and the difference between them was not statistically significant. They concluded that current evidence suggested both small and large thyroid tumours were related to radiation exposure, but additional data were needed to determine if their dose responses differed.

Ceresini *et al* (2012) investigated increased TC incidence rates in Italy and considered whether improved diagnostic procedures were a factor. They stated

“Many authors have attributed the increasing incidence of thyroid cancer to improved diagnostic procedures to detect thyroid nodules. However, there are several arguments against this hypothesis.

*First, thyroid cancer mortality has reportedly remained unchanged (Davies and Welch, 2006; Boyle and Ferlay, 2004) or even increased in recent years (Sherman and Fagin, 2005; Ries *et al*, eds, 2008; Howe *et al* 2001). If earlier diagnosis were the only explanation for the increased incidence, the mortality rate for thyroid cancer would be expected to be reduced.*

Second, studies from the United States indicate that the increase in the incidence of thyroid cancer between 1988 and 2005 occurred across tumors [sic] of all sizes. (Chen AY, Jemal A, Ward EM, 2009). An increase in the frequency of small tumors [sic] would be expected if the increased incidence rates were because of an earlier diagnosis.

Third, the diagnostic approach to thyroid nodules has not significantly changed over the last 10 years.”

(d) Unknown Factors

Thyroid cancer incidence rates are increasing in many countries throughout the world and it is not really known why this is the case. Ceresini *et al* (2012) stated

*“An increase in the incidence of thyroid cancer has been reported over the past 30 years worldwide (Burgess and Tucker, 2006; Colonna *et al*, 2007; Davies and Welch, 2006; Leenhardt *et al*, 2004; Liu *et al* 2001; Reynolds *et al*, 2005; Smailyte *et al*, 2006).”*

*“In the United States, the incidence of thyroid cancer is rising more than that of other cancers (Davies and Welch, 2006; Mitchell *et al*, 2007) and by the end of 2011 this tumour was expected to be the fifth most common cancer among women (Sherman and Fagin, 2005). The incidence of thyroid cancer is also increasing in Europe, where the average incidence, estimated in a 2004 survey, has been reported to be 5.0 and 12.9 cases per 100,000 residents per year among men and women, respectively (Boyle and Ferlay, 2005). The average incidence of thyroid cancer in Italy has been calculated at 5.2 and 15.5 cases per 100,000 residents per year among men and women, respectively (AIRT Working Group, 2006).”*

A major review of this matter (Pellegriti *et al*, 2013) stated

“Many experts believe that the increased incidence of thyroid cancer is apparent, because of the increased detection of small cancers in the preclinical stage. However, a true increase is also possible, as suggested by the observation that large tumors [sic] have also increased and gender differences and birth cohort effects are present. Moreover, thyroid cancer mortality, in spite of earlier diagnosis and better treatment, has not decreased but is rather increasing. Therefore, some environmental carcinogens in the industrialized lifestyle may have specifically affected the thyroid.”

“The increased incidence of thyroid cancer is most likely due to a combination of an apparent increase due to more sensitive diagnostic procedures and of a true increase, a possible consequence of increased population exposure to radiation and to other still unrecognized carcinogens.”

Many authors, including Pellegriti *et al* (2013), have alluded to increased exposures from medical diagnostic procedures using radio-iodines as being a cause. These are probably involved in the very large increases in TC seen in the US since 1990 (Zimmermann and Galetti, 2015). Whether this is also the case in European countries is difficult to say.

(e) Conclusions

Care is needed in deciding what fraction of thyroid cancer cases after Chernobyl may be radiogenic. As stated by O’Kane *et al* (2011) in their Ukraine study

“conclusions drawn from screening studies about the frequency of late-developing, rapidly growing thyroid nodules following radiation exposure should be interpreted with caution.”

Key factors will be the reported concentrations of radio-iodines deposited in the areas concerned and the collective doses which resulted. Another factor is the existence of dog-leg accelerated TC increases after about 1990, i.e.

approximately four years after the accident (the latency period for appearances of thyroid tumours in children). Another will be the existence of an increase in female/male TC ratios observed after 1990.

It is likely that small but significant fractions of the observed TC cases in Austria and in other countries since 1990 are likely to have been caused by the Chernobyl plumes. It is difficult to be precise about the size of the fractions. One estimate was made by epidemiologists (Verger *et al*, 2003) from the French Government's IRSN who estimated thyroid doses for French citizens exposed after Chernobyl. They calculated that 0.8 % to 4.1 % of the increased TC cancers arising in France between 1991 and 2015 would be caused by Chernobyl's fallout³⁵.

However the I-131 air concentration in the Vienna region (which contained about 30 % of Austria's population in 1986) was approximately 10 times greater than in France – see the iodine-131 maps in figures 6.1 and 6.2 in the previous chapter. This would suggest that between 8 % and 41 % of the increased TC cancer cases in the Vienna region of Austria were caused by Chernobyl fallout. It is recommended that TC studies be carried out in Vienna, Austria, and other European countries and areas with relatively high I-131 air concentrations.

³⁵ the team also predicted that for the shorter 1991–2000 period, 0.5 % to 10.5 % of TC cases in France would be caused by fallout

8

Leukemia

(a) Introduction

It is well-documented that leukemia, a blood cancer, is closely associated with radiation exposures. Leukemia has the highest risk attributable to radiation of all radiogenic cancers and has a relatively short latency period of 2 to 5 years. Previous studies described in TORCH 2006 had clearly indicated statistically significant increases in leukemias among the Chernobyl liquidators. However because of the low levels of leukemia in unexposed populations, the difficulties in establishing doses, and the lack of leukemia data, it had proved difficult to show leukemia increases among residents in Belarus, Ukraine and Russia.

(b) Leukemia in Clean-Up Workers

The quantitative estimation of radiogenic risks requires good data and very large studies of exposed populations. Nevertheless two recent large studies, among Russian and Ukrainian clean-up workers respectively, have now estimated leukemia risks from radiation. Ivanov *et al* (2012) established a time-averaged excess relative risk per gray (ERR/Gy) of 4.98 for leukemia among the Russian workers. And Zablotska *et al* (2013) established that the ERR/Gy for leukemia among the Ukrainian workers was lower at 2.38 (95 % CI: 0.49, 5.87). The difference is probably due to the use of different protocols and the uncertainties involved in dose estimation. The latter authors attributed 16 % of the increased leukemia cases to radiation exposures from Chernobyl.

Surprisingly, Zablotska *et al* (2013) also found similar, slightly greater, risks for Chronic Lymphocytic Leukemia (CLL) (ERR=2.58: 95 % CI: 0.02, 8.43) than for other forms of leukemia, (ERR/Gy = 2.21: 95 % CI: 0.05, 7.61). This is surprising as the conventional wisdom was that CLL was not a radiogenic cancer because of the lack of CLL cases among the Japanese bomb survivors.

A very recent study on the matter by the same team (Finch *et al*, 2016) confirmed the CLL excess among Chernobyl clean-up workers and showed that CLL has a very low survival rate with the risk of death statistically significantly increased. The hazard ratio for fatal CLL was 2.38 (95 % confidence interval 1.11–5.08) after comparing cases with doses ≥ 22 mGy to those with doses < 22 mGy. This is the first study to examine the association between bone marrow radiation doses from the Chernobyl accident and CLL in Chernobyl clean-up workers. It is an important study as the estimated median bone marrow dose was 22.6 mGy which is very low and provides strong backing for the linear no threshold (LNT) model.

In layman's language, these findings mean that Russian workers exposed to one Gy of radiation over a period of time experienced a ~500 % increase in leukemia over those who were not exposed, and Ukrainian workers a 240 % increase. These are large increases, comparable in magnitude to the large increases in thyroid cancer risk observed by Cardis *et al* (2005b) of 550 % to 840 %.

It is of interest that Ivanov *et al* (2012) also found that the radiogenic leukemia risk derived from Russian emergency workers was similar to, but larger than, that derived from the life span study (LSS) cohort of Japanese atomic bomb survivors in 1945, the longest (ongoing) epidemiology study of radiation risks in the world. The time-averaged excess relative risk per Gray was 4.98 for the Russian cohort and 3.9 for the Japanese LSS cohort for leukemias. See Box B.

BOX B. The End of DDREFs

The above evidence that protracted doses to workers are more dangerous than the acute ones to bomb survivors is of interest to radiation scientists.

Until recently, international radiation authorities (ICRP) had used risks derived from the Japanese bomb study but they arbitrarily halved them, in order to account for the observation in animal and cell studies that doses given all at once (as occurred when the bombs were dropped) were more dangerous than the same dose spread over years (as in radiation workers). In radiation jargon, they applied a Dose and Dose Rate Effectiveness Factor (DDREF) of 2.

Much debate had ensued since the ICRP's original recommendation to do this in 1976, as no human (i.e. epidemiological) evidence existed for this non-precautionary recommendation.

For example, the US EPA (1994) decided not to use a DDREF for breast and thyroid cancers, and several scientists (Cardis *et al*, 1996; Malko, 1998) did as well. Indeed, two epidemiology studies (Cardis *et al*, 2005b; Krestinina *et al*, 2005) had indicated the opposite, i.e. that exposures to protracted radiation were **more** rather than less damaging than high dose-rate exposures by as much as 2.5 times. Ivanov *et al* (2012) have now provided solid evidence that protracted doses to workers are at least 25 % more dangerous than doses given all at once as in the case of the bomb survivors.

It remains to be seen whether the ICRP will rescind their 1976 recommendation: to date they have not. In the meantime, other radiation bodies, e.g. WHO and UNSCEAR have stopped using DDREFs.

(c) Leukemia in residents of seriously contaminated areas

Noshchenko *et al* (2010) estimated the radiation-induced risk of acute leukemia between 1987 and 1997 among residents under 5 years old at the time of the accident in the most contaminated territories of Ukraine. Their risk of leukemia was statistically significantly increased (Odds Ratio³⁶ = 2.4 [95 % CI: 1.4–4.0]) among those with radiation doses higher than 10 mGy ($p=0.01$). Malko *et al* (2010) found a statistically significant increased leukemia risk RR = 1.47 (95 % CI : 1.01–2.14) among infants in Belarus in 1986–1992.

(d) Leukemia in other European countries

Studies indicate increased rates of childhood leukemia as a result of Chernobyl fallout in other European countries. In **Finland**, Auvinen *et al* (1994) found a dose-risk relationship of 7 % per mSv (95 % CI -27 % to 41 %) which was not statistically significant. However they merely concluded that "an important increase in childhood leukemia can be excluded". In **East Slovakia**, Ico *et al* (1998) compared leukemia incidence in the 10 year period after

³⁶ Similar to Relative Risk for these purposes

the Chernobyl with a control period before the accident and observed a 2.1 times higher cumulative incidence of acute lymphatic leukemia (median age 11 y) but this was not statistically significant. In **Italy**, Magnani *et al* found a statistically significant 2.6 % annual increase in incidence rate of acute lymphatic leukemia among 1 to 4 year olds (adjusted by age and gender; 95 % [CI: 1.13–4.13]).

In 2004, the UK Government's Committee Examining Radiation Risks of Internal Emitters (CERRIE, 2004) reported increases in infant leukemia in **West Germany** (Steiner *et al*, 1998), **Greece** (Petridou *et al*, 1996) and **Ukraine** (Noshchenko *et al*, 2002). The IAEA/WHO (2005) report downplayed these studies: in their view, they did not show a clear link between the incidence of leukemia and the degree of radioactive contamination – i.e. with dose. However this is an unconvincing reason, as the absence of association between leukemia incidence and contamination levels does not necessarily rule out a radiation effect: many assumptions are used in moving from Bq per m² to millisieverts. See discussion on uncertainties in chapter 4.

(e) The ECLIS Saga

In 2006, the view uniformly adopted by official organisations was that exposure to Chernobyl fallout was unlikely to have caused measurable leukemia risks in European countries. Nevertheless in 1988, International Agency for Research on Cancer (IARC) established the European Childhood Leukemia-Lymphoma Incidence Study (ECLIS) to investigate incidence rates of childhood leukemia and lymphoma in Europe following Chernobyl (Parkin, 1993).

The study's report for 1980–1991 (Parkin, 1996) found a small increase in leukemia incidence in Europe as a whole but no association between leukemia risk in 1987–91 and estimated doses. However they admitted their study had low power to detect this. Regarding the possible consequences of radiation doses received *in utero*, Parkin *et al* (1996) found

“no suggestion of an increase in risk of childhood leukemia for children exposed in utero, even among the 1987 birth cohort in Belarus”.

However, both US BEIR VII (2005) and IAEA/WHO (2005) suggested that there may well be an *in utero* leukemia effect. The latter stated

“Focusing on the risk of leukemia 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 leukemia and leukemia diagnosed between 24–29 months.”

The 2006 TORCH report recommended that funding be made available to IARC to clarify this matter. Such funds have still not been made available. Although most of the data from the ECLIS study has now been collected and studied, the final results of the study have still not been published. This is unfortunate. It is recommended again 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*.

In 2001, the 1996 ECLIS paper was re-evaluated by Hoffmann (2002) who stated that the leukemia incidence in the 1987 birth cohort was increased in the two highest exposure categories and an increasing trend with estimated cumulative radiation dose had been observed. In the results section, he stated that the ECLIS study had actually found a 2.2 % ± 3.2 % increase of leukemia risk per mSv in children but ECLIS had dismissed this because it was not statistically significant. But ECLIS had also mentioned statistically significant increases in **infant** mortality in Germany (Steiner *et al*, 1998) and Greece (Petridou *et al*, 1996). And further down, he stated that there were in-

creases in the 1987 cohort, corresponding to infant leukemia in the ECLIS study, which might include induction of chromosome aberrations in early pregnancy. He concluded that Chernobyl fallout could have caused a small, but statistically significant, excess of childhood leukemia cases in Europe.

Hoffmann added

*“... if indeed Chernobyl fallout has caused childhood leukemia 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. **None of these endpoints has as yet been systematically studied.**”*
[emphasis added]

The situation remains the same in 2016.

(f) Conclusion

It is concluded that increased leukemias have been well established among the clean-up workers in Ukraine and Russia with very high risk factors similar to those observed for thyroid cancer. Slightly lower risks have also been observed among residents of seriously contaminated areas in Ukraine and Belarus. Indications of increased leukemia risks among infants have now been observed in Finland, Slovakia, Germany, Greece, and Italy. However the IARC's long-standing ECLIS project which would clarify this matter has been stymied mainly by lack of central funding. It is recommended that funding be provided for ECLIS to finish its study.

9

Breast and other Solid Cancers

(a) Introduction

Cardis *et al* (2007) have stated

*“Breast cancer is the most common cancer and one of the leading causes of death among women worldwide, with nearly 1,000,000 new cases per year (Ferlay *et al*, 2001). Known risk factors include genetic susceptibility and exposure to ionising radiation [Ronckers *et al*, 2005].”*

Increased breast cancers were first noted in the life span study (LSS) study of Japanese bomb survivors (Tokunaga *et al*, 1994). Breast cancer is important, as it is the third highest – after leukemia and thyroid cancer – in terms of radiation-induced cancer risk among women exposed in childhood and adolescence (IAEA/WHO, 1995). Moreover, iodine (and therefore radio-iodine) is concentrated in the breast and salivary glands in addition to the thyroid. Older studies (including Petralia *et al*, 1999) suggest the latency period for breast cancer is between 8 and 15 years.

(b) Breast cancer in clean-up workers

Islamova (2004) observed a statistically significant 84 % increase in breast cancer incidence among Russian female clean-up workers in her PhD dissertation. SIR = 1.84 (95 % CI 1.23–2.45). Similarly, Prysyzhnyuk *et al* (2014) noted a statistically significant 63 % increase in breast cancer among Ukrainian clean-up women workers who participated in early recovery operations during 1986–1987. Between 1994 and 2011, the standardised incidence ratio (SIR) in this group was 1.63 (95 % CI 1.44–1.81), i.e. a 63 % increase similar to that found by Islamova (2004).

(c) Breast cancer in general population

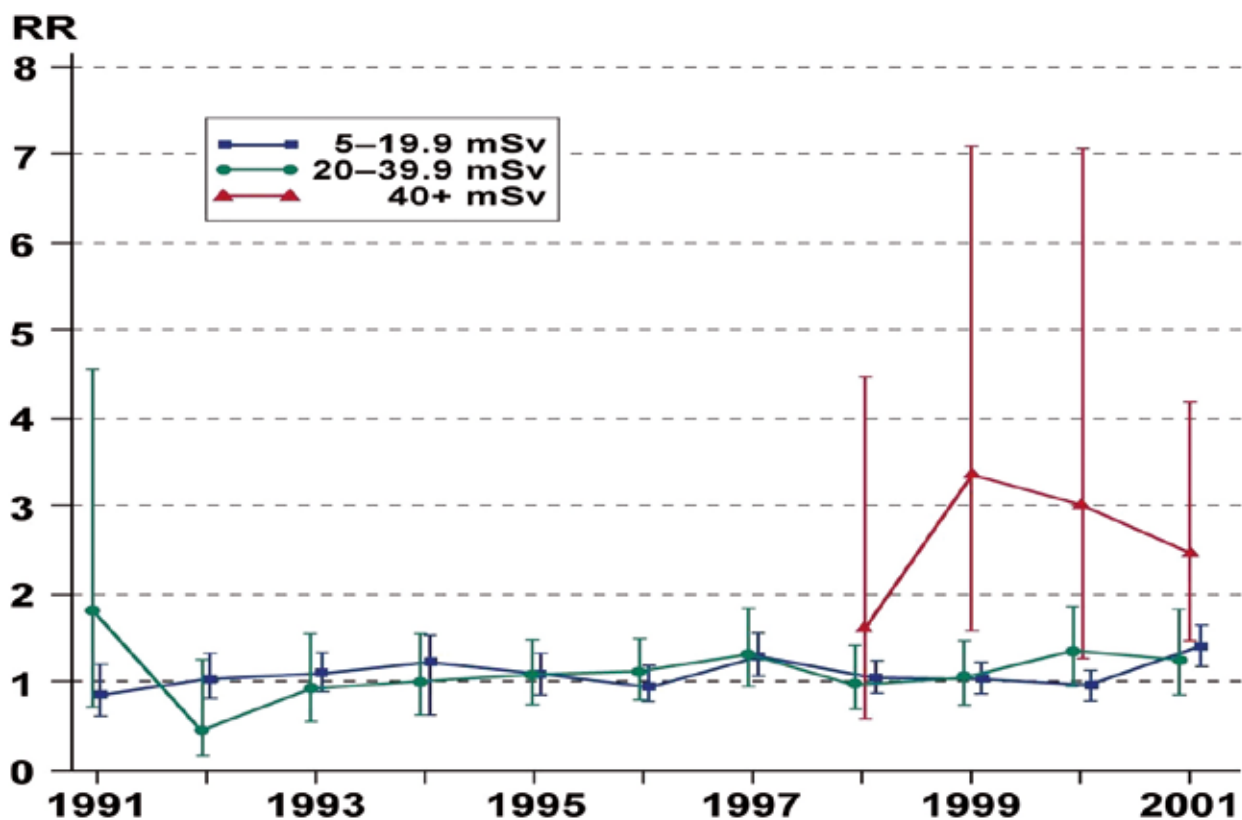
The IAEA/WHO report (2005) acknowledged an increase in pre-menopausal breast cancer among women exposed when they were less than 45 years old in Belarus and Ukraine. This was confirmed by Pukkala *et al* (2006) who described trends in the incidence of breast cancer in highly contaminated areas in Belarus and Ukraine. See Figure 9.1

In the most contaminated districts of Ukraine and Belarus, the authors observed statistically significant increases in breast cancer risk compared with the least contaminated districts during the period 1997–2001. The observed RRs were 2.24 (95 % CI 1.51–3.32) i.e. a 124 % increase in Belarus, and 1.78 (95 % CI 1.08–2.93) i.e. a 78 % increase in Ukraine.

The increases, though based on a small number of cases, appeared approximately 10 years after the accident; they were highest among women who were younger at the time of exposure (RR = 3.33, 95 % CI 1.71–6.5). The authors concluded it was unlikely that the increase could be entirely due to increased diagnostic activity in these countries.

In a US review, Ogrodnik *et al* (2013) reviewed the published literature on breast cancer incidence after what they termed the “gruesome” Chernobyl disaster up to 2010. Their re-analysis revealed that the incidence of breast cancer in Chernobyl-disaster-exposed women could be higher than previously thought.

Figure 9.1: Time trend in breast cancer RR by average cumulative dose category in regions of Belarus and Ukraine most contaminated by the Chernobyl accident (doses lagged by 5 y; age at exposure <45)



Source: Pukkala *et al* (2006)

(d) Other Solid Cancers in clean-up workers

Okeanov *et al* (2004) compared baseline incidence rates for solid cancers (apart from thyroid and breast cancers) in Belarus clean-up workers between 1976–85 with incidence rates between 1990–2000. They found a 56% increase which was statistically significant.

In the later period 1997–2003, they observed statistically significantly raised risks in solid cancers of all the organs they studied. Their data was updated in 2014 and is presented in table 9.1.

Table 9.1: Relative risk (RR) in cancer incidence (truncated age-standardised rate for ages 20–85) per 100,000 population in Belarus liquidators 1997–2003, compared with control adults in the least contaminated area (updated data).

Cancer	Incidence Rate in Controls	Incidence Rate in Liquidators	RR	95% CI
All sites	379.3	464.6	1.23	1.18–1.27
Thyroid	12	32.2	2.62	2.23–3.07
Bladder	11.4	18.7	1.65	1.37–1.98
Colon	16.7	22.2	1.33	1.11–1.59
Lung	52.6	66.3	1.26	1.14–1.39
Kidney	15.4	19.1	1.24	1.05–1.47
Stomach	40.8	46.9	1.15	1.02–1.29

Data from PPT Presentation: Cancer Epidemiology Cancer Epidemiology in the Republic of Belarus
http://www.tschernobylkongress.de/fileadmin/user_upload/Arnoldshain_Doku/Zubec-Olga.pdf

The 6 year follow-up period (1997–2003) for individual cancers is relatively short. If a longer period had been studied it is likely that more cases would have arisen and the relative risks (RRs) would have increased.

The above 23 % increase in Belarus clean-up workers is similar to the 17 % increase SIR = 1.17 (95 % CI: 1.14–1.20) in all solid cancers found by Prysazhnyuk *et al* (2007) in their study of more than 60,000 Ukrainian clean-up workers. It is also similar to the 18 % increase observed in the study of 67,000 Russian clean-up workers by Kashcheev *et al* (2015) compared with the baseline cancer incidence in Russia between 1992 and 2009. (SIR = 1.18, 95 % confidence interval 1.15–1.22). These data are set out in table 9.2.

Table 9.2: Increases in Solid Cancers (all sites) in Clean-up Workers

Study	Country	RR (95% CI)	Observed Increase
Kashcheev <i>et al</i> , 2015	Russia	1.18 (1.15–1.22)	18%
Okeanov <i>et al</i> , updated 2014	Belarus	1.23 (1.18–1.27)	23%
Prysazhnyuk <i>et al</i> , 2007	Ukraine	1.17 (1.14–1.20)	17%

A statistically significant 52 % increase in **oesophageal** cancers was observed by Rahu *et al* (2013) in Baltic clean-up workers compared to the male populations in the Baltic countries (PIR³⁷ = 1.52; 95 % CI 1.06–2.11). Among the general population in highly contaminated areas, Romanenko *et al* (2000) reported that the incidence of **kidney** cancer in Ukraine had increased from 4.7 to 7.5 per 100,000 person years after the accident. Romanenko *et al* (2003) added that the incidence of **bladder** cancer in residents of Ukraine had increased from 26.2 to 43.3 per 100,000 person-years between 1986 and 2001.

It is noticeable that these increases in solid cancers are considerably smaller than the ~800 % increases observed for thyroid cancer in Chapter 5, and the 240 % to 500 % increases in leukemia observed for leukemia in Chapter 8.

³⁷ Proportional Incidence Ratio

10

Cardiovascular Diseases and Strokes

(a) Introduction

Radiation-induced cardiovascular diseases (CVD) include coronary heart disease and arteriosclerosis³⁸/ atherosclerosis³⁹ in the vascular system. Strokes⁴⁰ are usually included in studies on CVD. Until the mid-1960s, heart tissue was thought to be relatively radio-resistant. Even as late as the 1980s, the issue of whether radiation exposure led to CVD was controversial and the relationship was not confirmed until the late 1990s. It is now well established (Little MP *et al*, 2008; Kreuzer *et al*, 2015) that cardiovascular risks are raised after moderate to high exposures to radiation. In fact, these risks limit the survival times of cancer patients after radiation treatment (Heidenreich and Kapoor, 2009).

(b) Causation

Various theories exist to explain how radiation causes CVD, but no consensus exists at present. However these diseases have longish latency periods, appear not to have a threshold, and are progressive. In other words they have some characteristics of radiogenic cancer effects. Hildebrandt (2010) stated

“In recent years, there is growing epidemiological evidence of excess risk of late occurring cardiovascular disease at much lower radiation doses and occurring over much longer intervals after radiation exposure without a clear cut threshold. However, the epidemiological evidence available so far for non-cancer health effects after exposure to moderate or low radiation doses is suggestive rather than persuasive. The mechanisms of radiation-induced vascular disease induction are far away from being understood. However, it seems to be very likely that inflammatory responses are involved.

If ... inflammatory response is ... the most likely cause of radiation-induced cardiovascular disease after low dose exposure, this ... implies a role for non-targeted radiation effects.”

If the latter point about non-targeted effects⁴¹ is correct, this could be significant for low-dose CVD effects, i.e. these could be greater than we currently think (Kadhim *et al*, 2013). Kreuzer *et al* (2015) state that evidence is emerging that low radiation doses could in fact increase the long-term risk of cardiovascular disease.

“This would have major implications for radiation protection with respect to medical use of radiation for diagnostic purposes and occupational or environmental radiation exposure. Therefore, it is of great importance to gain information about the presence and possible magnitude of radiation-related cardiovascular disease risk at doses of less than 0.5 Gy.

³⁸ arteriosclerosis is the thickening, hardening and loss of elasticity of artery walls. This restricts the blood flow to organs and tissues and leads to severe health risks

³⁹ atherosclerosis is a specific form of arteriosclerosis in which an artery wall thickens as a result of invasion of white blood cells and proliferation of intimal smooth muscle cells creating a fibro-fatty plaque.

⁴⁰ stroke occurs when low blood flow (often from atherosclerosis) to the brain results in damage and death to brain cells. Strokes are often fatal: essentially from brain malfunction

⁴¹ meaning that radiation's effects are not on the DNA molecule

Molecular epidemiological studies can improve the understanding of the pathogenesis and the risk estimation of radiation-induced circulatory disease at low doses. Within the European DoReMi (Low Dose Research towards Multidisciplinary Integration) project, strategies to conduct molecular epidemiological studies in this field have been developed and evaluated.”

It remains to be seen whether central funding will be provided for this recommended research.

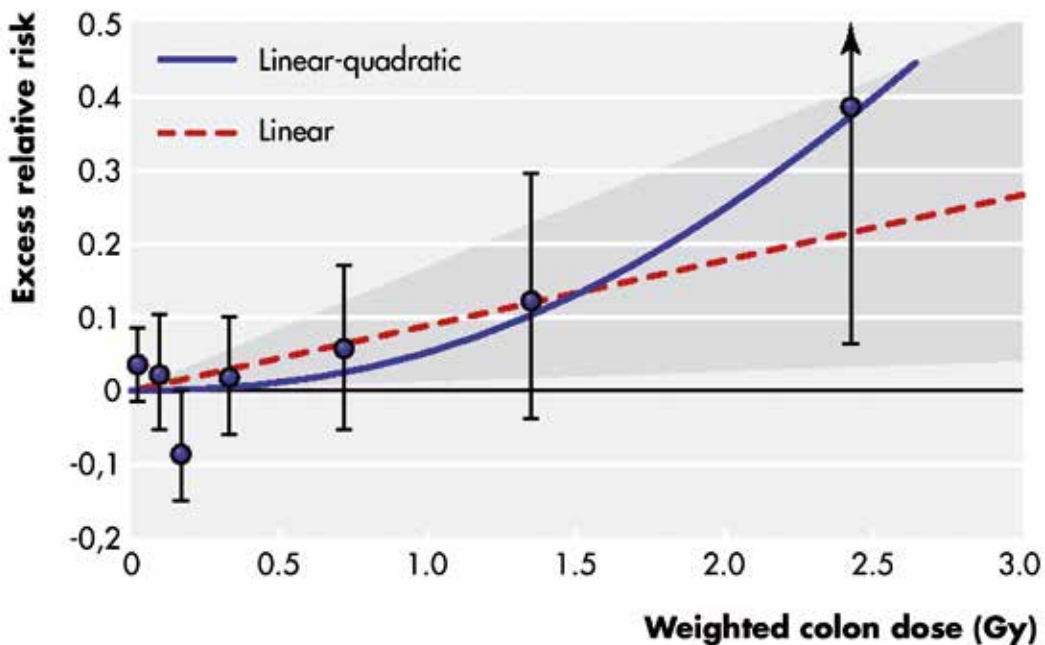
Other studies in this area have found indications of increased risks at low doses. For example, Bruno *et al* (2013) found an “early peculiar pattern of pre-clinical vascular involvement” after radiation exposures which supported the view that low-level radiation contributed to cardiovascular disease.

(c) Quantitative Risks

Shimizu *et al* (2010) indicated linear, possibly linear quadratic, dose-effect relationships among the Japanese bomb survivors down to about 0.1 Gy, although the precise relationship at lower doses remained unclear. See figure 10.1 for deaths from stroke and figure 10.2 for deaths from heart disease.

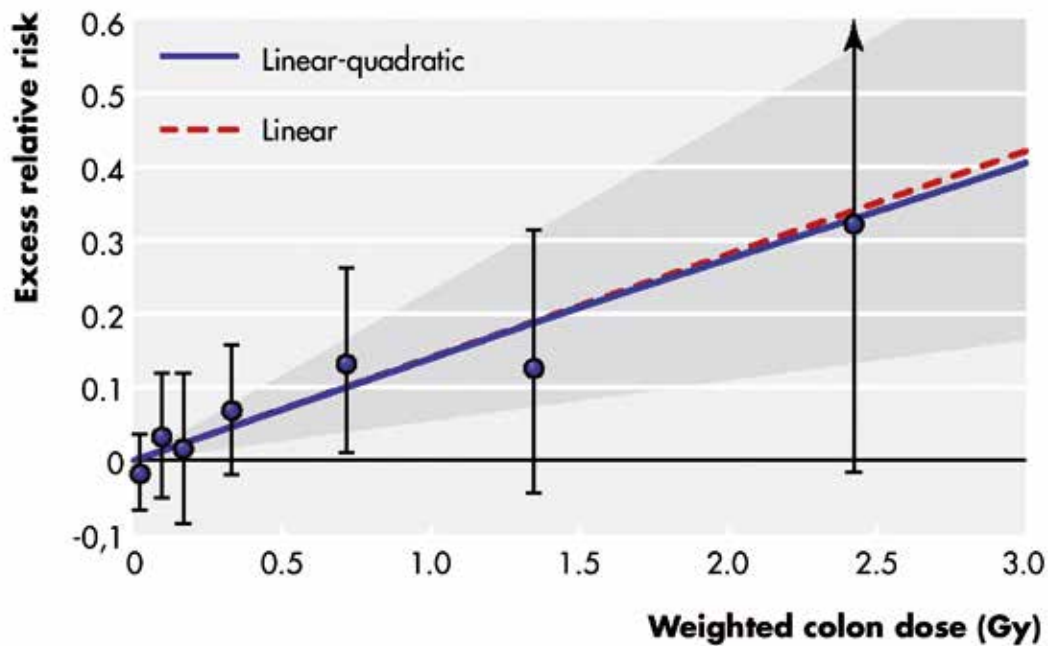
They concluded that stroke and heart disease combined now account for about one-third of the radiation-associated excess deaths – as does cancer in the atomic bomb survivors. In other words, radiogenic stroke and cardiovascular disease risks are in the same league as radiogenic cancer risks and should now be taken into consideration by radiation authorities in setting limits to radiation exposures.

Figure 10.1: Radiation dose-response relationship (excess relative risk per Gy) for death from stroke, showing linear and linear-quadratic functions.



source: Shimizu *et al* (2010)
 shaded area is the 95 % confidence region for fitted linear line. Vertical lines are 95 % confidence intervals for risk per specific dose categories.
 Point estimates of risk for each dose category are indicated by circles.

Figure 10.2: **Radiation dose-response relationship (excess relative risk) for death from heart disease, showing linear and linear-quadratic functions.**



source Shimizu *et al* (2010)

Shaded area is the 95 % confidence region for fitted linear line. Vertical lines are 95 % confidence intervals for risk per specific dose categories. Point estimates of risk for each dose category are indicated by circles.

For stroke, the estimated excess relative risk per gray was 0.09 (95 % confidence interval 0.01 to 0.17, $P=0.02$) using the LNT model. For heart disease, the estimated excess relative risk per gray was 0.14 (0.06 to 0.23 $P<0.001$). A linear model provided the best fit, suggesting excess risks even at very low doses. However, the dose-response effect between 0–0.5 Gy was not statistically significant.

An older but large study of Chernobyl emergency workers (Ivanov *et al*, 2000) showed an increased risk of cardiovascular disease which was statistically significant. The ERR/Sv was 0.54 (95 % CI 0.18–0.91), i.e. four times higher than the heart disease risk for atomic bomb survivors. However their 95 % confidence intervals overlapped, meaning that the two ERR values could be consistent with one another.

As for **coronary heart disease**, Krasnikova and Buzunov (2014) observed statistically significant increases in risks of coronary heart disease in 8,600 male Chernobyl clean-up workers at doses as low as 150 mSv. For the 0.15–0.25 Gy dose group, the RR was 5.6 (95 % CI 2.5–15.9) i.e. a 460 % increase. Statistically significant risks for coronary heart disease were also identified with regard to non-radiation factors (smoking, adverse working conditions, diseases; age and psycho-emotional overstrain). These were considered to be mostly responsible for development of coronary heart disease.

Buzunov *et al* (2013) estimated **circulatory system** disease death rates in people living in contaminated areas in Ukraine after Chernobyl (1988–2010). They found that the increases in death rates were statistically significant among a higher dose cohort (21–51 mSv) compared with a lower dose cohort (5.6–20 mSv). Mortality from circulatory diseases was higher among males than females. It is interesting that CVD effects were seen at such low doses.

It is recommended that further studies be carried out on radiogenic cardiovascular diseases. As current radiation dose limits in use around the world are based on cancer risks alone, it is recommended that these should be tightened (i.e. lowered) to take into account CVS and stroke risks.

11

Birth Defects

(a) Introduction

Birth defects are more common than most people think: about 3.3 % of US live births have a major birth defect (Parker *et al*, 2010). Major birth defects account for 20 % of US infant deaths as well as 2.3 % of premature death and disability (McKenna *et al*, 2005). Cleft palate, neural tube defects (NTDs), and congenital heart defects are the most common classes of birth defects (Parker *et al*, 2010). These defects are thought to originate in the first trimester of pregnancy as a result of inherited disease or environmental interactions (Brent, 2004). Environmental risk factors for birth defects include folate deficiency, maternal smoking, alcohol abuse and radiation.

It is well established that radiation is a teratogen⁴² at high doses (Bishop, 1966): the evidence for teratogenic effects at low doses is limited. Auvinen *et al* (2001) observed a statistically significant increase in spontaneous abortions in Finland after the accident, which were related to radiation exposure. Körblein and Küchenhoff (1997) observed a statistically significant increase in perinatal mortality in Germany in 1987.

No statistically significant increases in major birth defects or other untoward pregnancy outcomes were seen among children of the Japanese bomb survivors, but the monitoring of pregnancies in Hiroshima and Nagasaki only began in 1948, i.e. three years after the bombs in 1945. Straume (1991, 1993) observed that teratogenic risks from internal tritium⁴³ exposures were about six times greater than tritium's cancer risks.

Epidemiology studies on the teratogenic effects of low-dose radiation are difficult: they require adequate grouping of birth defects, sufficient baseline data, large case numbers and highly reliable registries (Haeusler *et al*, 1992). In addition, past studies on radiogenic birth defects have often suffered from differing diagnostic criteria, insufficient control groups, low statistical power and confounding factors.

For these reasons, studies in this area are approached warily: only studies which address the above factors are reported.

(b) Nervous System Birth Defects

An example is the very large study (Timchenko *et al*, 2014) of birth defects in over 147,000 pregnancy outcomes in a highly affected region in Russia between 2000 and 2010. The frequency of birth defects was estimated among newborns, stillborns and spontaneous abortions in both clean and polluted territories. The authors found small but statistically significant increases in all birth defects and larger increases in nervous system birth defects in affected areas. The latter include spina bifida, conjoined twins (Siamese twins), microcephaly⁴⁴, microphthalmia⁴⁵, teratomas⁴⁶, and neural tube defects⁴⁷ (NTDs).

⁴² teratogenesis concerns changes caused by environmental interference to a developing fetus, that is, a fetus with normal genes.

⁴³ tritium, H-3, is the radioactive isotope of hydrogen with a half-life of 12.3 years

⁴⁴ abnormal smallness of the head, a congenital condition associated with incomplete brain development

⁴⁵ microphthalmia is a disorder in which one or both eyes are abnormally small

⁴⁶ a tumour composed of tissues not normally present at the site (often the gonads).

⁴⁷ NTDs are birth defects of the brain, spine, or spinal cord which occur in the first month of pregnancy. The two most common are spina bifida and anencephaly. In spina bifida, the fetal spinal column is incompletely closed. Anencephaly is absence of most of the brain, skull and scalp.

Table 11.1: Frequency of birth defects in Polluted/Clean areas in Russia per 1,000 pregnancy outcomes

Status	Frequency of all birth defects in Polluted territories	Frequency of all birth defects in Clean territories	% increase	statistical significance
newborns	26.10 ± 0.80	24.23 ± 0.47	7.7%	✓ p < 0.05
newborns + stillborns	26.54 ± 0.81	24.78 ± 0.48	7.1%	✓ p < 0.05
Status	Frequency of nervous system birth defects in Polluted territories	Frequency of nervous system birth defects in Clean territories	% increase	statistical significance
newborns	1.09 ± 0.17	0.75 ± 0.08	45%	✓ p < 0.05
newborns + stillborns	1.22 ± 0.18	0.81 ± 0.09	51%	✓ p < 0.05
newborns + stillborns + spontaneous abortions	2.76 ± 0.26	2.34 ± 0.15	18%	borderline p = 0.165

Yellow column = added by the present report

Although chi-square test criteria confirmed the difference between the birth defect frequencies in clean and polluted territories, a Bayesian analysis did not. The authors stated that endocrinal diseases were an important factor of the origin of birth defects.

It is difficult to properly assess this study as it is in Russian and only limited information is presented in the English abstract. One wonders why the actual % increases were not reported in the abstract, and had to be calculated independently here. However it is probably the largest study of its type which has been published in the West. Statistically significant increases in birth defects **were** found in highly contaminated areas of Russia.

This is similar to the elevated rates of neural tube defects observed by Wertelecki (2010) in north-western Ukraine (Volyn and Rivne provinces); the elevated rates of NTDs, microcephaly, microphthalmia, teratomas, and conjoined twins in Rivne province; and in the Polissia region of Rivne. Population rates of NTD, microcephaly, and microphthalmia in Polissia were observed to be among the highest in Europe. <http://ibis-birthdefects.org/start/pdf/BaltimoreAbstr.pdf>

(c) Down Syndrome

A relatively common birth defect is Down Syndrome⁴⁸ which is closely associated with trisomy, a nondisjunction⁴⁹ defect on chromosome 21 of the human genome. This occurs most often in the female egg cells (oocytes). Animal studies show that radiation causes nondisjunction during oogenesis and spermatogenesis, however these studies cannot be easily extrapolated to humans.

⁴⁸ formerly called "Down's Syndrome" and "mongolism"

⁴⁹ where chromosomes fail to separate properly during meiosis

The link between radiation and Down Syndrome was found by accident four decades ago by Kochupillai *et al* (1976) who observed increased cases of Down Syndrome in populations living in Kerala India, whose beaches have high levels of naturally-occurring radioactive sand.

Many studies have been published on Down Syndrome but unfortunately most are unsatisfactory for the reasons listed previously i.e. lack of diagnostic criteria, insufficient control groups, low statistical power and confounding factors.

Verger (1993) explained that many studies failed to take into account trisomy cases which ended in spontaneous abortions and were therefore unreported: this could result in under-ascertainment of Down Syndrome cases. Verger also stated that oocytes may be exposed to radiation during two periods: before the completion of the first meiosis division and at ovulation. Most epidemiology studies in trisomy and exposure to radiation exposures examined only the former period.

Small trisomy increases were observed in several European countries and areas nine months after Chernobyl but these were indicative rather than conclusive. These included **England** (Bound *et al*, 1995); **Scotland** (Ramsay *et al*, 1991); **Sweden** (Ericson and Kallen, 1994); **Southern Germany** (Sperling *et al*, 1991); **Finland** (Harjulehto-Mervaala *et al*, 1992) and **Hungary** (Czeizel *et al*, 1993). It is noted that the last two studies concluded that no increases were found but they actually found small increases which were not statistically significant.

In a major controversial review, Little (1993) stated that there was "nothing to worry about" as regards increased Down Syndrome cases being found. Later, in an equally famous riposte, Mühlendahl and Muck (1996) replied that indeed there was "something to worry about".

In a more comprehensive study, Sperling *et al* (1994a) observed a large increase in trisomy 21 in West Berlin in January 1987, nine months after the Chernobyl accident. Professor Sperling and his colleagues concluded that the increased prevalence of trisomy 21 was causally related to a short period of exposure to radiation as a result of Chernobyl. This was based on the assumptions (a) that maternal meiosis was an error prone process susceptible to exogenous factors at the time of conception and (b) that owing to the high prevalence of iodine deficiency in Berlin, a large amount of iodine-131 would have been taken up over a short time period.

This controversial report led to considerable correspondence in the British Medical Journal at the time. See

BMJ. 1994 Jul 16; 309(6948):139–40
BMJ. 1994 Jul 16; 309(6948):151–4
BMJ. 1994 Jul 16; 309(6948):154–7
BMJ. 1994 Jul 16; 309(6948):158–62 and
BMJ. 1994 Nov 12; 309(6964):1298–1302

Although several correspondents refuted their findings, Sperling *et al* (1994b) stood by their study. Professor Sperling and his team stated that significant increases in Down Syndrome incidences had also been observed for infants born in January 1987 in Scotland, Sweden and Denmark. They added that the US BEIR V Committee (BEIR, 1990) in their discussion of the effects of low dose radiation on non-disjunction in humans had concluded that nine of the 13 studies they examined had showed a positive effect and only two a negative effect. See <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2541820/pdf/bmj00465-0061d.pdf>.

Mühlendahl and Muck (1996) stated that several of the criticisms of Sperling's article were quite unfair and the result of biased reading⁵⁰. They stated that there were in fact serious doubts about the matter which should not be too readily dismissed.

Burkart *et al* (1997) asserted that the West Berlin trisomy cluster could not have been caused by radiation as their estimated doses were too low in comparison with natural background radiation. Since 1997, many reports have acknowledged that estimates of internal doses can contain many large uncertainties. The issue was unresolved at the time.

In the large study by IARC's EUROCAT Working Group on congenital malformations after Chernobyl, Dolk and Nichols (1999) found a statistically significant 22 % (95 % CI: 13 %-31 %) excess of Down Syndrome in those born **two years after accident**, with no dose-response relationship. However there was no discussion or follow up on this individual finding partly as the findings for other congenital malformation endpoints were negative.

Zatsepin *et al* (2007) observed a large statistically significant peak of Down Syndrome cases in Belarus in January 1987 (26 cases observed and 9.84 expected; observed/expected ratio=2.64; 95 % CI=1.72-3.76), but they observed no long-term trends in contaminated or control areas. They stated that the timing of the Down Syndrome peak, the high dose rates during the Chernobyl plume's passage and cell data showing a radiosensitive phase of oogenesis around conception time in mammals, suggested that the peak may be linked to Chernobyl.

It is concluded that IARC should be funded to review the post-Chernobyl evidence on birth defects including Down Syndrome.

⁵⁰ This, the authors added, was very common – a human trait. To counter this it was necessary to adopt a fundamentally sceptical attitude based on hard evidence, but it was always more easy to recognise the speck of sawdust in a neighbour's eye than the plank of wood in one's own eye.

12

Ill Health among Children

(a) Introduction

A health factor which has received insufficient consideration in epidemiology studies is the general poor health of children still living in highly contaminated areas in Belarus, Ukraine and Russia.

In adults, many commentators have remarked on the marked general deterioration in health indicators in Belarus, Ukraine and Russia. For example, between 1990 and 2005, the average lifespan for a male adults in Russia decreased from 70 to 61 years and in the Ukraine from 67 to 61 years: in western Europe, the average male life span is >75. Some of the complex factors involved in the considerable declines in health indicators in Belarus, Ukraine and Russia are described in the UNDP (2002) report. However without access to government data, it is difficult to assess whether continued exposures to low residual levels of radioactivity are a factor.

But it is not just adult life expectancy: anecdotally many children complain of ill health and many visitors remark on the poor health status of children in badly affected areas (Lomat *et al*, 1997). Western science, of course, demands epidemiological evidence rather than anecdotal reports but this evidence has not been available – often due to the lack of central funding.

However these problems have appeared so acute and clear to thousands of non-medical lay visitors and to medical staff that in the 1990s and 2000s they established charities to bring the children of Chernobyl to their own countries in the West (including US and Canada) for temporary respites from high radioactivity levels. Scores of these NGOs now exist at international, national and local levels and each year they bring thousands of Chernobyl children to their own countries and homes. Without exception, these groups observed improvements in the healths of invited children (Walker, 2015).

In the past, these groups were unfortunately ignored on the grounds that the observed improvements in these children were subjective and due to the improvements in outlook and temperament that everyone experiences on holiday.

Recent authoritative studies have shed much-needed light on this matter: they indicate beyond reasonable doubt that radiation exposures to children living in contaminated areas are implicated in their poor healths. It is therefore unsurprising that their healths improve when they visit abroad.

(b) Impaired Lung Function and Increased Breathing Difficulties

Svendsen *et al* (2010) observed that Ukrainian children in highly contaminated villages were 2.60 (95 % CI: 1.07-6.34) times more likely to suffer serious (up to 80 %) reductions in their forced vital lung capacity and 5.08 (95 % CI: 1.02-25.19) times more likely to have seriously (up to 80 %) reduced expiration rates. They found statistically significant increases in both airway obstruction and subsequent breathing restrictions with increasing Cs-137 levels in soil.

Later, the same team (Svendsen *et al*, 2015) confirmed and strengthened their findings with data from Cs-137 whole-body measurements rather than Cs-137 soil levels. In more detail, they observed that decreases in predicted forced vital lung capacity and increases in bronchodilator responsiveness and restrictive impairment of breathing were associated with increases in weight-adjusted Cs-137 whole-body burdens after adjusting for potential confounders.

The surprising finding was that these serious impairments were associated with very low doses. The median Cs-137 whole body burden was 66 Bq/kg (95 % CI, 15–241 Bq/kg), equivalent to an estimated mean internal dose of 0.165 mSv/yr (95 % CI, 0.037–0.602 mSv/yr) which is well below background radiation levels of about 3 mSv/yr.

The authors concluded

“Children in a region just outside of the closed Chernobyl contamination zone continued to have respiratory health deficits associated with ¹³⁷Cs whole-body burden as recently as 2010.”

(c) Decreased Blood Counts

In children living in a highly contaminated zone in Ukraine near Chernobyl, Stepanova *et al* (2008) found statistically significant reductions in red and white blood cell counts, platelet counts and haemoglobin levels with increasing residential Cs-137 soil contamination. Over a six-year period, some blood markers did improve slightly but not white blood cell counts and no markers declined in the ~700 children born after the accident.

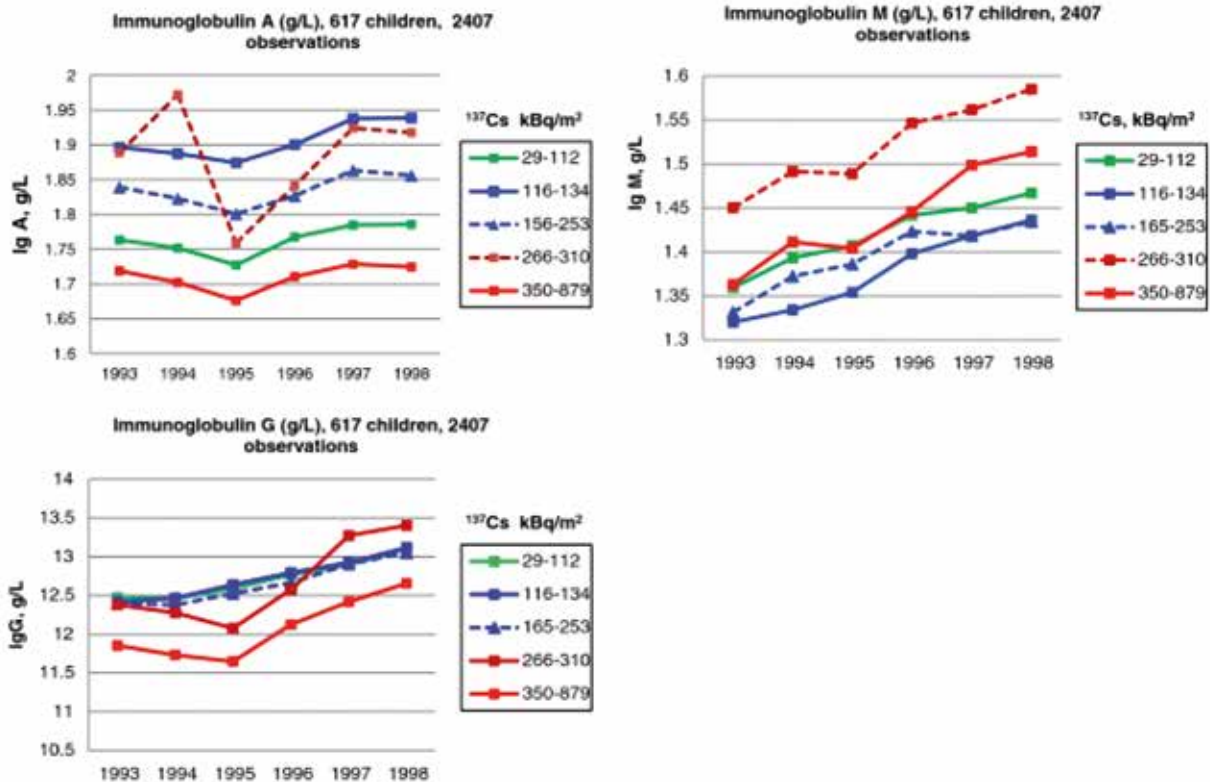
Later, the same team, Lindgren *et al* (2015) used a more accurate exposure assessment, whole-body Cs concentrations. Among 590 children aged 0–18 years, they confirmed their earlier findings that those with higher Cs-137 body burdens had statistically significant decreases in haemoglobin, erythrocyte and thrombocyte counts.

(d) Increased Immunoglobulin Factors

The immune system, with high levels of cell proliferation and gene amplification, transcription and translation, make it highly susceptible to radiation. Titov *et al* (1995) carried out clinical and immunological examinations of more than 6,000 children in highly contaminated areas of Belarus. B-cell levels, blood concentrations of immunoglobulins IgM, IgG, IgA and IgE; IgG levels in serum and saliva; and various antibody levels were investigated. Long-term effects were increased concentrations of IgM and IgG, which were correlated with Cs-137 land contamination levels and Cs-137 levels in children.

Later McMahon *et al* (2014) observed general, but not universal, increases in immunoglobins as shown in figure 12.1

Figure 12.1: **Changes in levels of immunoglobulins A, G, and M between 1993 and 1998 by Cs-137 exposure. Residential Cs-137 soil contamination levels grouped into quintiles.**



source: McMahon *et al* (2014)

The relationship between chronic radiation exposures and immunoglobulin concentrations is poorly understood. However it is generally accepted that raised immunoglobulin concentrations are indicative of increased infections, viruses and raised antibody levels in blood. Inflammatory factors are also likely involved and it is known that these are connected with the non-targeted effects of radiation (Hildebrandt, 2010). A possible explanation is that low levels of radiation cause chronic low level inflammation which in turn causes increased production of immunoglobulins.

(e) Increased Anaemias and Colds

In a recent study, McMahon *et al* (2015) examined the health effects of changed food intervention in approximately 1,000 school children in the contaminated Narodichi district of Zhytomyr region in Ukraine. These children continue to be exposed to low levels of radiation from ingesting locally-produced foods. School children had been receiving three daily meals uncontaminated with man-made radioactivity up to 1995, but in that year these were reduced to two low-level meals per day, presumably because of the costs and difficulties of importing radioactivity-free foodstuffs.

The study first found that, before 1995, improvements were being observed in several blood parameters in school children due to radioactivity-free school meals. Second they observed that these improvements were reversed after

1995 when the number of low level meals was reduced. Between 1995 and 1996, haemoglobin levels decreased slightly from 12.63 g/dL (95 % CI: 12.56–12.71) to 12.46 g/dL (95 % CI: 12.39–12.52). And red blood cell counts decreased slightly from 4.10 (95 % CI: 4.07–4.12) to 4.02 (95 % CI: 4.00–4.04) × 10¹²/ litre. These differences are statistically significant at p =.01.

At the same time, the prevalence ratio (PR) of (previously declining) anaemia⁵¹ increased from 0.57 to 1.31 per year, an increase of 130 % (p <0.0001). After the reduction in clean meals, the PR of common cold and bronchitis increased by 83 %, from 1.27 to 2.32 per year (p=0.01) and by 14 % from 1.09 to 1.24 per year (p =0.43) respectively.

The authors concluded that

“Food supplementation provided by the Ukrainian government likely prevented [the] development of anaemia in many of the children residing in the contaminated district. Food supplementation ... should be considered an effective approach to reduce [the] adverse health effects of radiation.”

(e) Children of Chernobyl

Hundreds of local, national and international voluntary groups have been established to help the children in the radioactively contaminated areas of Belarus, Ukraine and Russia. This help includes visits abroad for tens of thousands of children to provide respites from their radioactively contaminated homelands. Hundreds of doctors from many countries work *pro bono* in contaminated territories, helping to minimize Chernobyl's health consequences. These humanitarian actions constitute a silent rebuke of the disregard shown by some agencies and national authorities towards the continuing plight of affected children in Belarus, Ukraine, and Russia.

(f) Recommendations

It can be seen from the above studies that visits to radioactivity-free countries are very likely to be beneficial to the healths of children in contaminated areas of Ukraine, Belarus and Russia.

Accordingly, it is recommended that Western governments and the EC should adopt a pro-active stance towards humanitarian aid to these children in contaminated areas. This should include helping existing NGOs which provide radioactivity-free visits in the West to the children of Chernobyl. Funding should also be provided to help NGOs deliver health projects and initiatives to develop civil society in these countries.

On addition, it is recommended that financial assistance be offered by Western governments and the EC to the government of Ukraine to enable three radioactivity-free meals per day to be provided to schoolchildren in heavily contaminated areas. Similar arrangements should be encouraged in Belarus and Russia.

⁵¹ a decrease in red blood cell levels in blood leading to its lowered ability to carry oxygen

13

Mental Health and Other Effects

(a) Mental Health and Psycho-social Effects

In 2005, the IAEA/WHO (2005) stated

“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.”

Clearly, the Chernobyl accident has had profound and far-reaching psycho-social effects on the 530,000 clean-up workers, 130,000 evacuees, and 270,000 people who live in the very highly contaminated areas of Belarus, Ukraine and Russia.

In this short report, it is difficult to do justice to the scale of these problems.

The origins of these effects are thought to be related to several factors, including:

- anxiety about the effects of radiation,
- extreme pessimism, depression, apathy and fatalism
- feelings of victimhood, leading to a sense of social exclusion
- stress associated with evacuation and resettlement (UNDP, 2002).

Evacuations

New evidence emerging from Fukushima indicates that nuclear disasters and their necessary evacuations can and do result in the deaths of thousands of people. Official data from Fukushima show that nearly 2,000 people died from the effects of evacuations necessary to avoid high radiation exposures from the disaster, including suicides. [http://www.reconstruction.go.jp/topics/main - cat2/sub - cat2 - 1/20141226_kanrenshi.pdf](http://www.reconstruction.go.jp/topics/main-cat2/sub-cat2-1/20141226_kanrenshi.pdf)

It is clear that the uprooting to unfamiliar areas, cutting of family ties, loss of social support networks, disruption, exhaustion, poor physical conditions and disorientation can and do result in many older people dying. Following the Fukushima evacuations, suicides also occurred among younger and older people, but the trends are unclear, see <http://www.pref.fukushima.lg.jp/uploaded/attachment/62562.docx>. A Japanese Cabinet Office report stated that, between March 2011 and July 2014, 56 suicides in Fukushima Prefecture were linked to the nuclear accident. See <http://www.japantimes.co.jp/news/2014/08/26/national/social-issues/fukushimas-high-number-disaster-related-suicides-likely-due-nuclear-crisis-cabinet-office/#.VqtBaFJovAq>

There appear to be few studies of psychosocial health effects (including deaths and suicides) published in the West following the very large forced evacuations after Chernobyl. This may be because of translation difficulties or because relatively few Ukrainian or Russian periodicals are transmitted to, or are published in the West. It could

also be due to the fact that a more developed sense of social values existed in the former USSR (as opposed to individualistic values in Japan) which resulted in greater solidarity and social cohesion during the crisis.

In future, it is recommended that deaths from evacuation-related trauma, ill-health and suicides should be included in assessments of the fatalities from nuclear disasters.

(b) Cataract Induction

The eye lens is one of the more radiosensitive tissues in humans. Cataracts (cloudiness in the eye lens) can be induced by acute doses of less than 2 Gy, but the radiation mechanisms involved are not known. The latency period for cataract-opacity seems to be inversely proportional to dose, so long follow-up times are necessary to observe the effects of small exposures.

Along with childhood thyroid cancer, this is an area where previous thinking on radiation's effects is being revised as a result of Chernobyl. As stated by the IAEA/WHO (2005)

“... radiation cataracts/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.”

A case-control study (Bebeshko *et al*, 2007) of 14,731 clean-up workers using a non-threshold non-linear model demonstrated a dose-dependent relative risk of radiation cataract induction = 3.451 per Gy (95 % CI:1.347–5.555). This is a much higher risk than was generally accepted previously.

Worgul *et al* (2007) examined 8,607 Chernobyl clean-up workers for eye cataracts 12/14 years after exposure. The dose response relationship was found to be mostly linear, and when cataract end points were analysed for dose thresholds, the upper confidence levels were all below 0.7 Gy. They observed an increased risk of cataracts, compatible with a possible threshold of 0.1–0.25 Gy, much lower than previously thought. The authors stated their findings did not support ICRP Report 60's assumption of a 5 Gy threshold for opacities from protracted exposures. Because cataracts were the dose-limiting effect in current eye risk guidelines, ICRP limits for exposures to the eye should be revised.

Ainsbury *et al* (2009) reviewed the combined results of mechanistic and human studies on cataract induction by radiation and they concluded that the question of the threshold dose, if any, for cataract development was not resolved and was certainly below 0.5 Gy. The authors concluded that although cataracts had been classified as a deterministic effect of radiation they may in fact be more accurately described by a linear, no-threshold model, i.e. a stochastic effect.

(c) Diabetes and Other Endocrine Diseases

In Japan, mass screening between 1971 and 1992 for diabetes in adult survivors of the Hiroshima bomb revealed a 2.1-fold increase in prevalence in males and a 2.0-fold increase in females (Ito, 1994). Kovalenko *et al* (2001) observed increased levels of hyperinsulinaemia in clean-up workers after Chernobyl which they interpreted to be a direct or indirect consequence of irradiation.

Marinucci *et al* (2002) observed an increased risk of type 1 diabetes in Gomel, Belarus, after the accident compared with before it. Later a more detailed study (Zalutskaya *et al*, 2004) also found a significant increase in children and adolescents, this time comparing Gomel with a less exposed area. The authors stated that the increase was continuing and had not yet reached its peak. On the other hand, a similar analysis from Poland (Bandurska-Stankiewicz and Rutkowska 2004) did not show an increased risk of diabetes among those exposed to higher radiation levels.

However Taskinen *et al* (2000) and Lorini *et al* (2005) observed that children exposed to high levels of radiation for medical reasons developed a state of insulin resistance. Indeed the latter authors recommended that all subjects, particularly children, exposed to irradiation for medical reasons should be regularly investigated for early risk markers for diabetes.

Kaminskiy *et al* (2014) examined the health records of over 10,000 Ukrainian clean-up workers and observed statistically significant (2 to 10-fold) and reliable ($p < 0.01$) increases in the incidences of non-cancer endocrine diseases. In particular they observed a 11.9 % average (16.3 % in recent years) increase of type 2 diabetes mellitus.

In addition, they found a 23.2 % increase in nodular goitre, a 13.4 % increase in autoimmune thyroiditis; a 41.7 % increase of pre-obesity; and a 38.1 % in obesity compared to the population. The authors noted a trend to further increases.

It is recommended that further research be carried out on diabetes and other endocrine diseases among children in the populations exposed after Chernobyl.

(d) Schizophrenia

Two psychiatrists (Loganovsky and Loganovskaja, 2000) examined 100 Russian patients with acute radiation sickness (ARS) and 100 Russian clean-up workers for 5 or more years since 1986. Beginning in 1990, they observed a statistically significant ~5 fold increase in schizophrenia⁵² incidence in clean-up workers in comparison with the general population (5.4 versus 1.1 per 10,000). Those exposed to high doses (>0.30 Sv) had considerably more schizophrenic syndromes. The authors hypothesized that radiation may be a trigger that predisposes to or causes schizophrenia-like disorders.

⁵² Schizophrenia is a mental disorder usually characterized by abnormal social behaviour and failure to recognize reality.

14

Collective Doses

(a) Introduction

Radiation exposures are 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, country or indeed the world. This may appear straightforward, but within some 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, none exists for collective doses: currently no legal sanctions exist against high collective doses.

Despite this reluctance, a strong scientific case exists for using collective doses. This arises from the widely accepted use of the linear-no-threshold (LNT) model for radiation's effects. This model predicts that radiation 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, apart from zero dose. A corollary of the LNT is that, scientifically-speaking, it is correct to estimate collective doses even where individual doses are extremely low, for example below background levels. However some previous reports by IAEA/WHO (2005) have not endorsed collective doses particularly when individual doses are low.

This chapter briefly discusses official collective dose estimates for Belarus, Ukraine and Russia; and the rest of Europe. The 2006 TORCH report contains a more detailed discussion of collective doses which remains relevant and to which readers are referred.

Collective doses are estimated by assessing the average doses to exposed populations. These 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
- conversion factors from Gy to Sv (from organ doses to whole body doses) and
- doses for a lifetime, i.e. 80 years

(b) Collective Dose Estimates in European countries

Table 14.1 sets out collective doses in European countries estimated by the OECD/NEA (1996) ranked by average dose to each person in the countries surveyed. The OECD study was prepared by an NEA committee of national experts and is considered relatively reliable. Nevertheless, it only presented an estimate for the first year after Chernobyl, during which about 30 % of the collective dose occurs. Therefore it was necessary to increase the total 3.34 fold to extend the doses for 80 years until 2056. This would result in a European collective dose of about 230,000 person Sv, adding the smaller collective doses to other countries not shown.

This table also shows that the Austrian people received the highest per capita dose in 1986 from Chernobyl, i.e. in countries outside Belarus, Ukraine and Russia. 2.2 mSv is roughly the same dose received by most people in Europe

Table 14.1: Collective doses in OECD European countries to 2065

Country	1986 population millions	OECD/NEA, 1996 (first year x 3.3) person Sv	Average dose received in 1986 mSv
Austria	7.4	16,000	2.2
Finland	4.9	8,250	1.7
Italy	56.6	92,400	1.6
Greece	9.8	12,000	1.2
United Kingdom	56.6	2,100	1.2
West Germany	61	61,000	1.0
France	55	4,300	0.8
Sweden	8.3	5,600	0.7
Switzerland	6.5	4,600	0.7
Belgium	10	1,300	0.13
Total		~230,000	

source: OECD/NEA (1996)

from background radiation. It will be seen that countries such as Italy and West Germany received relatively high collective doses, influenced mainly by their high populations.

(c) Collective Dose Estimates

Various populations were exposed to different average doses. These can be multiplied by their numbers to obtain their collective doses. Table 14.2 sets out the total collective doses to 2065 to various populations from UNSCEAR (2008).

Table 14.2: Collective Doses from Chernobyl

Population	Number	Average dose mSv	Collective dose Man Sv
Clean-up workers	530,000	117	62,000
Evacuees	115,000	31	3,600
Inhabitants of contaminated areas of Belarus, Russia and Ukraine	6,400,000	9	58,900
Inhabitants of Belarus, Russia and Ukraine	98,000,000	1.3	125,000
Inhabitants of Western Europe	500,000,000	0.3	150,000
Total	605,000,000		400,000

source: UNSCEAR (2008)

(d) Comparison with other Nuclear Accidents

Bennett (1995, 1996) compared the collective dose from Chernobyl's fallout with the collective doses from previous nuclear accidents releases. These are set out in table 14.3 together with the estimate by this report for Chernobyl and the latest UNSCEAR (2008) estimate for the Fukushima accident. It can be seen from this table that the Chernobyl accident remains, by some margin, the most serious nuclear accident.

Table 14.3: **Collective Doses from Nuclear Power Accidents – person Sv**

Nuclear Accident	Collective Dose
Chernobyl accident USSR 1986	400,000
Fukushima accident Japan 2011*	48,000
Kyshtym accident USSR 1957**	2,500
Windscale accident UK 1957**	2,000

sources: this report, *UNSCEAR (2013), **Bennett (1995, 1996)

(e) Future Cancer cases and deaths

Assuming the risk of cancer is directly proportional to dose with no threshold (i.e. LNT), it follows that the number of future cancer deaths can be estimated as the simple product of the collective dose x the accepted risk factor which is widely observed – currently this is 10 % per sievert for fatal cancer, as DDREFs are no longer applied (see Box B on page 61).

Therefore this report estimates that $400,000 \times 0.1 = 40,000$ fatal cancers will arise in Europe between now and 2065. This is similar to but lower than the figure estimated in TORCH 2006 report but that was for the world not just Europe.(TORCH (2006) had estimated up to 60,000 fatal cancers.)

This report's central estimate of 40,000 fatal cancers in Europe is slightly higher than the upper bound in the recent 16,000 (6,700 to 38,000) estimate by Professor Cardis (2015).

It is also not too different from the estimate of 23,000 fatal cancers for OECD countries in Europe which can be derived from the data in table 14.1. These estimates for excess fatal cancers are set out in table 14.4.

Table 14.4: **Predicted excess fatal cancers in Europe to 2065**

	Fatal Cancers
Cardis (2015)	16,000 (6,700–38,000)
OECD (1995)	23,000
UNSCEAR (2008)	40,000

NB – numbers in yellow cells derived by this report from data in the relevant reports

Given the inevitable uncertainties involved in such future predictions, these estimates are not dissimilar. They are also similar to Cardis' central estimate of 41,000 excess cancer **cases** (i.e. not deaths) in Europe up to 2065. See table 14.5.

Table 14.5: Predicted excess cancer cases in Europe to 2065

Region	Belarus, Ukraine and Russia	Other European Countries	Totals (uncertainty range)
thyroid cancer	~11,000	~5,000	16,000 (3,500–72,000)
all other cancers	~12,500	~12,500	25,000 (11,000–59,000)
total cancer cases	~23,500	~17,500	41,000

source: Cardis (2015)

NB – numbers in yellow cells derived by this report from data in Cardis (2015)

15

Conclusions and Recommendations

(a) Main Findings

It is estimated that, between now and 2065, about 40,000 **fatal cancers** will occur in Europe. This is similar to the TORCH estimate in 2006 and to other independent estimates. Cardis (2015) estimated 16,000 cancer deaths in Europe alone (range 6,700–38,000) by 2065.

For **thyroid cancer**, 6,000 cases have already arisen (UNSCEAR, 2008) and the most recent estimates (Cardis, 2015) suggest an excess of 16,000 cases in Europe to 2065 with 2/3rds in Belarus, Russia and Ukraine.

Over 6 million people still live in the countries with **high levels of radioactive contamination** (>40 kBq/m²): Belarus (18,000 km²), Ukraine (12,000 km²) and European Russia (16,000 km²). Also 100 million people in these countries continue to live in areas contaminated with lower levels of radioactivity.

Western Europe (defined as all European countries excluding Russia, Ukraine and Belarus) received more than half of Chernobyl's fallout: this was spread over 42 % of its land area accounting for about 40 % of Chernobyl's collective dose to the world.

Outside Belarus Russia and Ukraine, the most highly contaminated⁵³ countries were **Austria and the Balkan and Slavic countries**, particularly Slovakia, Slovenia and Moldova. Apart from Belarus, Russia and Ukraine, more attention should be paid to Austria which had the highest average Cs-137 deposition density and the highest average Cs-137 integrated activity in diet in 1986–1987. Austria also experienced the second highest average deposition density of I-131, and fifth highest average integrated activity in air of I-131, all at times of main deposition.

Since the 2006 TORCH report, **thyroid cancer** (TC) incidence rates have continued to mount especially among adult women in Belarus and Ukraine. Thyroid cancers are now increasing among those exposed as adults, not just children and adolescents. UNSCEAR (2008) estimated that a substantial fraction of the 6,000 thyroid cancer cases which had arisen so far in the former USSR republics were due to Chernobyl.

The estimated relative risks⁵⁴ (RRs) in the most contaminated areas of these countries are very high, ~8 at the level of one gray. This translates to 700 % increases over background rates in these areas. These are extraordinarily high, perhaps the largest increases in risk ever measured after exposures to toxic substances. The incidence rates for adults are expected to peak in the near future in Belarus but will continue above the pre-accident rates for many years.

Increasing TC incidence rates after Chernobyl have also been reported in Austria, Slovakia, Czech Republic, and Poland. These countries were not as heavily contaminated as the severely contaminated areas of Belarus, Ukraine and Russia but their contamination levels matched or exceeded the levels in the less contaminated areas of Belarus, Ukraine and Russia. Raised TC levels were even observed as far away (~2,500 km) as Northern England.

⁵³ Both in terms of deposition density of Cs-137 and of the fraction of the country highly contaminated

⁵⁴ Relative to background risks

Small but significant fractions of observed TC cases in Austria and in other European countries since 1990 are likely to have been caused by the Chernobyl plumes. It is difficult to be precise about the fraction but this report estimates between 8 % and 41 % in the Vienna region of Austria.

Increased incidences of **leukemia** are now well established among the clean-up workers in Ukraine and Russia with very high risk factors similar to those observed for thyroid cancer. Slightly lower leukemia risks were observed among residents of seriously contaminated areas in Ukraine and Belarus. Indications of increased leukemia risks among infants have been observed in Slovakia, Germany, Greece, Italy and Belarus. However International Agency for Research on Cancer's (IARC's) ECLIS project which would clarify the matter has been stalled mainly by lack of central funding. It is recommended that this be provided to finish the project.

Increases in **solid cancers** were observed among clean-up workers in Belarus and Ukraine but their relative risks (20 % to 50 %) were considerably lower than the 700 % increases observed for thyroid cancer, and the 200 % to 500 % increases observed for leukemia. It is recommended that IARC should be funded to carry out a study of the incidences of breast and other solid cancers in European countries post 1986.

Several new studies have confirmed increased risks of **cardiovascular disease** and **stroke** after Chernobyl. It is recommended that further studies be funded and carried out on radiogenic cardiovascular diseases, in particular the Low Dose Research towards Multidisciplinary Integration (DoReMi) project to estimate radiation-induced circulatory disease at low doses <https://ec.europa.eu/programmes/horizon2020/en/news/how-protect-against-low-level-radiation>.

It is also recommended that IARC's remit (presently cancers) should be expanded to include CVD and stroke. As current radiation dose limits around the world are based on cancer risks alone, it is recommended that they should be tightened to take into account CVD and stroke risks as well.

A recent very large study observed statistically significant increases in **nervous system birth defects** in highly contaminated areas in Russia, similar to the elevated rates of such birth defects observed in highly contaminated areas in Ukraine. IARC should be funded to carry out an up-to-date comprehensive study of birth defects, particularly nervous system defects and **Down Syndrome** after Chernobyl.

Recent studies provide strong evidence of **decreased health indicators among children** living in contaminated areas in Belarus and Ukraine, including

- (a) impaired lung function and increased breathing difficulties (Svendsen *et al*, 2015)
- (b) lowered blood counts (Lindgren *et al*, 2015)
- (c) high anaemia levels and more colds (McMahon *et al*, 2015)
- (d) raised levels of immunoglobulin fluctuation (McMahon *et al*, 2014)

It is therefore unsurprising that visits to radiation-free countries by children living in contaminated areas of Ukraine, Belarus and Russia have been observed to be highly beneficial to their healths. Accordingly, it is recommended that Western governments and the EC should seek to help existing charities and non-government organisations (NGOs) which provide **radioactivity-free visits in the West** to the children of Chernobyl. Funding should also be provided to help NGOs deliver health projects and initiatives to develop civil society to these countries.

In particular it is recommended that financial assistance be offered by Western governments and the EC to the government of Ukraine to re-instate **three radioactivity-free meals per day** to schoolchildren in areas heavily

contaminated by Chernobyl fallout. These had been shown to be of considerable benefit to children, and when the number was reduced to two per day, declines in health resulted. Similar improved arrangements should be encouraged in Belarus and Russia.

There appear to be few studies of **psychosocial health effects** (including deaths and suicides) published in the West following the very large forced evacuations after Chernobyl. However these are considered to be important. In future, it is recommended that deaths from evacuation-related trauma, ill-health and suicides should be included in assessments of the fatalities from nuclear disasters.

(b) Lessons from the Chernobyl and Fukushima Accidents

It is vital that governments and international agencies learn from these accidents. Regrettably, future nuclear accidents could occur as many nuclear power stations are now approaching the ends of their lives – the most dangerous time for reactors. In addition, several governments have decided to ignore the disastrous effects of nuclear accidents and are planning or constructing more nuclear power stations.

In 2005, the IAEA/WHO (2005) stated

“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.”

While this is undoubtedly correct, it raises the vexed question of **trust** in governments and international agencies which does not exist after Chernobyl and Fukushima. To re-establish that trust will be difficult. At a minimum, it will require the following to happen.

First, for concerned governments to make clear to their citizens that they will consider safer energy options that do not have the potential for another Chernobyl or Fukushima.

Second, for a dialogue to be created between agencies such as IARC, IAEA, WHO and national governments on the one hand and various NGOs/health charities on the other for exchanges of views on radiation risks and energy policies. Unfortunately, no such dialogue exists at present.

Third, WHO should no longer be required to have its reports on radiation matters vetted by the IAEA, as presently required under the 1959 agreement between the two UN agencies. <http://independentwho.org/en/who-and-iaea-agreement/>

Fourth, UN agencies in this area, IARC, WHO, UNSCEAR, IAEA should be required to have independent scientists from NGOs and health charities as members of their main Committees. This does not occur at present. Also these agencies should be required to consult on their draft reports, including the convening of meetings with environment NGOs and independent health charities. This also does not occur at present.

In addition to providing timely and accurate information, government health authorities and disaster planners need to **improve their preparedness** for future accidents by means of the following:

- providing stable iodine to all citizens within at least 30 km of all nuclear reactors
- stocking emergency levels of radioactivity-free water supplies, long-life milk and dried food supplies
- distributing information leaflets to the public explaining what to do in the event of an emergency and explaining why precautionary measures are necessary
- planning evacuations
- constructing and staffing permanent emergency evacuation centres
- carrying out emergency evacuation drills
- planning subsequent support of evacuated populations
- planning how to help those who choose to remain in contaminated areas
- increasing the mental health training of primary physicians and nurses
- moving the site of care to primary care settings, and
- informing citizens that these measures have been taken

It may be argued that these measures are unnecessary and/or too expensive. However this report shows that they are indeed necessary. Governments which choose to promote potentially dangerous energy policies should also fund the necessary precautions in case of accidents.

(c) Future Research

Many research needs have been identified throughout this report. They were also identified in IARC's health research initiative on Chernobyl – Action of Research on Chernobyl (ARCH) http://arch.iarc.fr/documents/ARCH_SRA.pdf.

The ARCH project was set up in 2008 and its proposed research agenda was published in 2012. http://arch.iarc.fr/documents/ARCH_SRA.pdf. Its main recommendation was the establishment of a Chernobyl Health Effects Research Foundation (CHERF) which would coordinate and fund studies to assess the overall long-term health effects of the disaster. <http://www.iarc.fr/en/publications/pdfs-online/epi/sp95/SP95.pdf>.

The key question is whether sufficient central funding will be obtained from the European Commission. Recently a liaison group between the Commission and IARC called CO-CHER <http://co-cher.iarc.fr/> was established to identify further steps and, presumably, possible funding.

A conference **Scientific Symposium: 30 years after Chernobyl** is to be held on 11 June, 2016 at IARC's offices in Lyon, France.

Possible funding could also be received from the Open Project for the European Radiation Research Area (OPERRA) <http://www.melodi-online.eu/operra.html> – a loose grouping of national research agencies on radiation health issues. It is recommended that this funding is provided as soon as possible.

(d) Humanitarian Aid

More research is needed but, more important, more help is needed especially for the children in the most affected countries. Unfortunately some international nuclear agencies and national authorities remain in denial about the scale of the health disaster caused by Chernobyl. This is shown by their continuing refusal to devote resources to humanitarian aid, rehabilitation and disaster management.

This is regrettable: however there is one silver lining.

Many thousands of concerned citizens throughout the world have mobilised to help stricken people in the three countries most seriously affected. Hundreds of local, national and international voluntary groups have been established especially to help the children in these areas. This help includes visits abroad for tens of thousands of children to provide respites from their radioactively contaminated homelands. This report provides strong epidemiological evidence that such visits are indeed helpful. Hundreds of doctors from many countries also work *pro bono* in contaminated territories, helping to minimize Chernobyl's health consequences.

These humanitarian actions are sorely needed and welcome. They constitute a silent rebuke of the disregard shown by some international nuclear agencies and national authorities towards the continuing plight of affected children in Belarus, Ukraine, and Russia.

References

Ahlsvede J, Simon Hebel, J. Ole Ross, Robert Schoetter, Martin B. Kalinowski. Update and Improvement of the Global Krypton-85 Emission Inventory. (2013) *Journal of Environmental Radioactivity*, Volume 115, January 2013, 34–42.

Ainsbury EA, Bouffler SD, Dörr W, Graw J, Muirhead CR, Edwards AA, Cooper J (2007) Radiation cataractogenesis: a review of recent studies. *Radiat Res.* 2009 Jul;172(1):1–9.

AIRT Working Group. Italian cancer figures-report 2006: incidence, mortality and estimates 2006. *Epidemiol Prev.* 2006; 30 (1 suppl 2): 80–81.

Akiba S, Lubin J, Ezaki H, Ron E, Ishimaru T, Asano M, *et al* (1991) Thyroid Cancer Incidence among Atomic Bomb Survivors in Hiroshima and Nagasaki 1958–79. Technical Report TR 5–91. Hiroshima, Japan: Radiation Effects Research Foundation.

Altman DG and Bland JM (1995) Absence of evidence is not evidence of absence. *BMJ* 1995; 311, pp 485–7.

Auvinen A, Hakama M, Arvela H, Hakulinen T, Rahola T, Suomela M *et al* (1994) Fallout from Chernobyl and incidence of childhood leukemia in Finland, 1976–92. *BMJ* 1994; 309:151.

Auvinen A, Vahteristo M, Arvela H, *et al* (2001) Chernobyl fallout and outcome of pregnancy in Finland. (2001) *Environmental Health Perspectives.* 2001;109(2):179–185.

Bandurska-Stankiewicz E and Rutkowska J (2004) Letter to Zalutskaya *et al.* *Diabetologia.* Nov;47(11): 2049–50.

Baverstock K, Egloff B, Pinchera A, Ruchti C, Williams D (1992) Thyroid cancer after Chernobyl. *Nature* 1992; 359 : 21–2.

Bebeshko VG, Dimitry A. Bazyka, Volodymyr Buzunov (2007) Chernobyl: Current situation of non-cancer diseases International Congress Series Volume 1299, February 2007, Pages 54–59.

Beck HL (1980) Exposure rate conversion factors for radionuclides deposited on the ground. EML-378. July 1980.

BEIR V (1990) US Committee on the Biological Effects of Ionising Radiation, US National Academy of Sciences, 'Health Risks from Exposure to Low Levels of Ionizing Radiation'.

BEIR VII (2006) US Committee on the Biological Effects of Ionising Radiation, US National Academy of Sciences, 'Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2', www.nap.edu/books/030909156X/html

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.

Bishop PA (1966) Teratogenic Effects Of Radiation. *Clinical Obstetrics & Gynaecology*: September 1966 – Volume 9 – Issue 3 – pp. 631–640 Symposium on Teratology.

Bobovnikova TI and Konoplev AV (1991) Comparative analysis of chemical forms of long-lived radionuclides and their migration and transformation in the environment following the Kyshtym and Chernobyl accidents.

Bossew P *et al* (1996): Cäsiumbelastung der Böden Österreichs (Contamination of Austrian soils with ¹³⁷Cs). Austrian Federal Environmental Agency, Monographien Band 60, March 1996. (In German, English abstract); www.umweltbundesamt.at/fileadmin/site/publikationen/M060.pdf

Bound JP *et al* (1995) Down's syndrome: prevalence and ionising radiation in an area of north west England 1957–91. *J Epidemiol Community Health* 1995;49:164–170

Boyle P, Ferlay J. Cancer incidence and mortality in Europe, 2004. *Ann Oncol*. 2005; 16: 481–488.

Brenner AV, Tronko MD, Hatch M *et al* (2011) I-131 dose response for incident thyroid cancers in Ukraine related to the Chernobyl accident. *Environ Health Perspect*. 2011 Jul;119(7): 933–9.

Brenner D *et al* (2003) Cancer risks attributable to low doses of ionizing radiation: Assessing what we really know. *Proceedings of the National Academy of Sciences*, November 25, 2003, vol.100, no.24, pp.13761–13766, www.ncbi.nlm.nih.gov/pubmed/14610281

Brent RL. 2004. Environmental causes of human congenital malformations: The pediatrician's role in dealing with these complex clinical problems caused by a multiplicity of environmental and genetic factors. *Pediatrics* 113: 957–968.

Bruno RM, Rosa Sicari, Anca Irina Corciu, Elisabetta Bianchini, Francesco Faita, Rossella Di Stefano, Alessandro Antonelli, Lorenzo Ghiadoni, Eugenio Picano (2013) Non-cancer atherosclerotic effects associated with environmental and therapeutic radiation doses: The Chernobyl thyroid cancer children study. *International Journal of Cardiology*, Volume 168, Issue 4, 9 October 2013, Pages 4255–4257.

Burgess JR, Tucker P. Incidence trends for papillary thyroid carcinoma and their correlation with thyroid surgery and thyroid fine-needle aspirate cytology. *Thyroid*. 2006; 16: 47–53.

Burkart W, Grosche B, Schoetzau A (1997) Down syndrome clusters in Germany after the Chernobyl accident. *Radiat Res* 1997 Mar;147(3): 321–8.

Buzunov VO, Prikaschikova KY, Gubina IG, Kostyuk GV, Tereschenko SO (2013) Radiation dose- and sex-dependent cardiovascular mortality in residents of contaminated areas after the Chernobyl NPP accident, 1988–2010 observation period. *Probl Radiac Med Radiobiol*. 2013;(18): 50–8. [Article in English and Ukrainian]

Cardis E (2015) Chernobyl ...29 years later (2015) Lecture to Fukushima Medical University, Japan. May 2015. <http://fmu-global.jp/?wpdmdl=682>

Cardis E *et al* (2006b) Estimates of the cancer burden in Europe from radioactive fallout from the Chernobyl accident. *Int. J. Cancer* 119, 1224–1235.

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, Prysazhnyuk 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.

Cardis E, Hall J, Tavtigian SV (2007) Identification of women with an increased risk of developing radiation-induced breast cancer. *Breast Cancer Res.* 2007;9(3): 106 [PubMed]

Cardis E, Howe G, Ron E *et al* (2006) Consequences of the Chernobyl accident: 20 years on. *J. Radiol. Prot.* 26 (2006) pp 127–140. <http://iopscience.iop.org/article/10.1088/0952-4746/26/2/001/meta;jsessionid=3A900A49AF-D7730A75104B4AC603F6CD.c3.iopscience.cld.iop.org>

Cardis E, Kesminiene A, Ivanov V *et al* (2005b) Risk of thyroid cancer after exposure to ¹³¹I in childhood. *J Natl Cancer Inst* 97: 724–732.

Cardis E, Kesminiene A, Williams D *et al* (2005) Risk of Thyroid Cancer After Exposure to I-131. *J Natl Cancer Inst* 97: 724–732.

Ceresini G, Corcione L, Michiara M, Sgargi P, Teresi G, Gilli A, *et al* (2012) Thyroid cancer incidence by histological type and related variants in a mildly iodine-deficient area of Northern Italy, 1998 to 2009. *Cancer*. 2012;118: 5473.

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

Chen AY, Jemal A, Ward EM (2009) Increasing incidence of differentiated thyroid cancer in the United States, 1988–2005. *Cancer*. 2009; 115: 3801–3807.

Chino M, Hiromasa Nakayama, Haruyasu Nagai, Hiroaki Terada, Genki Katata and Hiromi Yamazawa (2011) Preliminary Estimation of Release Amounts of I-131 and Cs-Accidentally Discharged from the Fukushima Daiichi Nuclear Power Plant into the Atmosphere, *Journal of Nuclear Science and Technology*, 48:7, 1129–1134.

Colonna M, Guizard AV, Schvartz C, *et al*. A time trend analysis of papillary and follicular cancers as a function of tumour size: a study of data from six cancer registries in France (1983–2000). *Eur J Cancer*. 2007; 43: 891–900.

Commission of the European Communities Report EUR–13574(V.1) (Luxembourg); 606 p; 1991; pages 371–396; Seminar on comparative assessment of the environmental impact of radionuclides released during three major nuclear accidents: Kyshtym, Windscale, Chernobyl. (1–5 Oct 1990).

Czeizel AE *et al* (1993) Environmental trichlorfon and cluster of congenital abnormalities. *Lancet*. 1993 Feb 27; 341(8844): 539–42

Davies L, Welch HG. Increasing incidence of thyroid cancer in the United States, 1973–2002. *JAMA*. 2006; 295: 2164–2167.

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.

Demidchik YE, Saenko VA, Yamashita S (2007) Childhood Thyroid Cancer in Belarus, Russia, and Ukraine after Chernobyl and at Present. *Arq Bras Endocrinol Metab* 2007;51/5. <http://www.ncbi.nlm.nih.gov/pubmed/17891238>

Dolk H, Nichols R (1999) Evaluation of the impact of Chernobyl on the prevalence of congenital anomalies in 16 regions of Europe. EUROCAT Working Group. *Int J Epidemiol* 28: 941–8.

Drozdovitch V *et al* (2007) Radiation exposure to the population of Europe following the Chernobyl accident. *Radiation Protection Dosimetry* Volume 123, Issue 4 pp 515–528.

Ericson A and Kallen B (1994) Pregnancy outcome in Sweden after the Chernobyl accident. *Environ Res* 67: 149–59.

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

Fairlie I (2007) Dispersal, deposition and collective doses after the Chernobyl disaster. *Med. Confl. Surviv.* 23(1) 10–30.

Fairlie I and Sumner D (2006) The Other Report on Chernobyl. www.chernobylreport.org

Ferlay J, Bray F, Pisani P, Parkin DM, eds. (2001) GLOBOCAN 2000: Cancer Incidence and Mortality Worldwide. Lyon: IARC Cancer Base No 5; 2001.

Finch, SC, Dyagil I, Reiss RF, Gudzenko, N, Babkina N, Lyubarets T, Bebesheko V, Romanenko A, Chumak VV, Bouville A, Hatch M, Little MP, Bazyka D and Zablotska LB (2016) Clinical characteristics of chronic lymphocytic leukemia occurring in Chornobyl clean-up workers. *Hematol Oncol*, doi: 10.1002/hon.2278. In press.

Furukawa K, Preston D *et al* (2013), Long-term trend of thyroid cancer risk among Japanese atomic-bomb survivors: 60 years after exposure. *Int. J. Cancer*, 132: 1222–1226.

Fuzik M, Prysyazhnyuk A *et al* Thyroid cancer incidence in Ukraine: trends with reference to the Chernobyl accident. *Radiation and Environmental Biophysics* Mar 2011, Volume 50, Issue 1, pp 47–55

Fuzik M, Prysyazhnyuk AY *et al.* (2013) Age and gender patterns of thyroid cancer incidence in Ukraine depending on thyroid radiation doses from radioactive iodine exposure after the Chornobyl NPP accident. *Probl Radiac Med Radiobiol.* 2013;(18): 144–55.

Haeusler MC, Berghold A, Schoell W, Hofer P, Schaffer M. (1992) The influence of the post-Chernobyl fallout on abortion rates in Austria. *Am J Obstet Gynecol* Oct;167 (4 Pt 1): 1025–31.

Harjulehto-Mervaala T, Salonen R, Aro T, Saxen L (1992) The accident at Chernobyl and trisomy 21 in Finland. *Mutat Res.* 1992 Mar;275(2): 8–6.

Heidenreich PA and Kapoor JR (2009) JR Radiation induced heart disease. *Heart* 2009;95: 252–258.

- Hildebrandt G (2010) Non-cancer diseases and non-targeted effects. *Mutat Res.* 2010 May 1;687(1–2): 73–7.
- Hilton J, Cambray RS, Green N (1992) Fractionation of radioactive caesium 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 leukemia in Europe? A commentary on the epidemiologic evidence. *Eur J Public Health*, 12, 72–6.
- Hölggye Z and Malátová I (2012) Estimation of intakes of ¹³¹I, ¹³⁷Cs and ¹³⁴Cs after the Chernobyl accident. *Radiat Prot Dosimetry*150 (4): 504–507.
- Howe HL, Wingo PA, Thun MJ, *et al.* Annual report to the nation on the status of cancer (1973 through 1998), featuring cancers with recent increasing trends. *J Natl Cancer Inst.* 2001; 93: 824–842.
- IAEA/WHO (2005) 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/EC (1996) One Decade After Chernobyl: Summing up the Consequences of the Accident. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1001_web.pdf
- Icsó J, Szöllősová M (1998) Leukemia and Thyroid Tumour in an East-Slovakian District after Chernobyl. *Radiation Protection Dosimetry* 77: 129–131.
- 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.
- Incidence and mortality of solid cancer among emergency workers of the Chernobyl accident: assessment of radiation risks for the follow-up period of 1992–2009.
- Islamova AR (2004) Malignant tumours incidence in women participated in recovery operation works at the Chernobyl accident. [dissertation abstract]. Obninsk (RU): Medical Radiological Research Centre; 2004–19 p. [in Russian].
- Ito C (1994) Trends in the prevalence of diabetes mellitus among Hiroshima atomic bomb survivors. *Diabetes Res Clin Pract* 24: S29–S35
- Ivanov VK *et al* (1997) Case-control analysis of leukemia among Chernobyl accident emergency workers residing in the Federation, 1986–1993. *J. Radiol. Prot.* 17: 137–157
- Ivanov VK *et al* (2008) Risk of thyroid cancer among Chernobyl emergency workers of Russia. *Radiat Environ Biophys.* 2008 Nov;47(4): 463–7
- Ivanov VK, Tsyb AF, Khait SE, Kashcheev VV, Chekin SY, Maksoutov MA, Tumanov KA (2012) Leukemia incidence in the Russian cohort of Chernobyl emergency workers. *Radiat Environ Biophys.* May;51(2): 143–9
- Jacob P, Bogdanova TI *et al* (2006) Thyroid cancer risk in areas of Ukraine and Belarus affected by the Chernobyl accident. *Radiat Res.* 165(1) 1–8

- 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.
- 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, 72 S.; mit Anhang.
- Kadhim M, Salomaa S, Wright E, Hildebrandt G, Belyakov OV, Prise KM, Little MP (2013) Non-targeted effects of ionising radiation--implications for low dose risk. *Mutat Res.* 2013 Apr Jun;752(2): 84–98.
- Kaminskiy OV, Proni, OV and Afanasyev DE (2014) Morbidity pattern of non-cancer endocrine disease in Chernobyl accident emergency workers. (1992–2013) *Problemy Radiatsiinoi Medytsyny ta Radiobiologii*. Vol 19 Sept 2014, 267–276. <http://europepmc.org/abstract/MED/25536564>
- Kashcheev VV, Chekin SY *et al* (2015) *Radiat Environ Biophys.* 54(1): 13–23.
- Kazakov VS, Demidchik EP, Astakhova LN (1992) Thyroid Cancer after Chernobyl. *Nature* 1992; 359: 21.
- Kesminiene K, Anne-Sophie Evrard, Viktor K. Ivanov, Irina V. Malakhova, Juozas Kurtinaitise, Aivars Stengrevics, Mare Tekkel, Sergei Chekin, Vladimir Drozdovitch, Yuri Gavrilin, Ivan Golovanov, Viktor P. Kryuchkov, Evaldas Maceika, Anatoly K. Mirkhaidarov, Semion Polyakov, Vanessa Tenet, Aleksandr R. Tukov, Graham Byrnes, and Elisabeth Cardis (2012) Risk of Thyroid Cancer among Chernobyl Liquidators. *Radiation Research* 178:5, 425–436.
- Kirchner G, Bossew P, De Cort M (2012) Radioactivity from Fukushima Dai-ichi in air over Europe; part 2: what can it tell us about the accident? *Journal of Environmental Radioactivity*, Volume 114, December 2012, P 35–40.
- Kiuru A *et al* (2003) Hereditary minisatellite mutations among the offspring of Estonian Chernobyl clean-up workers. *Radiat. Res.* 159, 651–655
- Kochupillai, N, I. C. Verma, M. S. Grewal & V. Ramalingaswami (1976) Down's syndrome and related abnormalities in an area of high background radiation in coastal Kerala. *Nature* 262, 60–61 (01 July 1976).
- Körblein A (2015) Personal Communication.
- Körblein A, Küchenhoff H (1997) Perinatal mortality in Germany following the Chernobyl accident. *Radiat Environ Biophys* 1997 Feb;36(1): 3–7.
- Kovalenko AN, Zueva NA, Gerasimenko TI, Efimov AS (2001) Hyperinsulinemia as a factor preceding body mass increase in liquidators of the Chernobyl nuclear accident *Lik Sprava* 5–6:10–12. [Article in Russian].
- Krasnikova LI and Buzunov VO (2014) Role of radiation and non-radiation factors on the development of coronary heart disease in the Chornobyl clean-up workers: epidemiological study results. *Probl Radiac Med Radiobiol.* 2014 Sep;19: 67–79.
- Krestinina LY, Preston DL, Ostroumova EV, Degteva MO, Ron E, Vyushkova OV, *et al* (2005) Protracted radiation exposure and cancer mortality in the Tcha River Cohort. *Radiat Res* 164(5): 602–611.
- Kreuzer M, Auvinen A, Cardis E, Hall J, Jourdain JR, Laurier D, Little MP, Peters A, Raj K, Russell NS, Tapio S, Zhang W, Gomolka M (2015) Low-dose ionising radiation and cardiovascular diseases – Strategies for molecular epidemiological studies in Europe. *Mutat Res Rev Mutat Res.* 2015 Apr–Jun;764: 90–100.

Leenhardt L, Bernier MO, Boin-Pineau MH, *et al* (2004) Advances in diagnostic practices affect thyroid cancer incidence in France. *Eur J Endocrinol.* 2004; 150: 133–139.

Leenhardt L, Grosclaude P, Cherie-Challine L (2004) Thyroid Cancer Committee. Increased incidence of thyroid carcinoma in France: a true epidemic or thyroid nodule management effects? Report from the French Thyroid Cancer Committee. *Thyroid.* 2004; 14: 1056–1060.

Leuraud, Klervi *et al* (2015) Ionising radiation and risk of death from leukemia and lymphoma in radiation-monitored workers (INWORKS): an international cohort study. *The Lancet Haematology* Volume 2 , Issue 7, e276 e281. <http://www.thelancet.com/journals/lanhae/article/PIIS2352-3026%2815%2900094-0/fulltext>

Likhtarov I, Kovgan L, Masiuk S, Talerko M, Chepurny M, Ivanova O, *et al.* Thyroid cancer study among Ukrainian children exposed to radiation after the Chernobyl accident: Improved estimates of the thyroid doses to the cohort members. *Health Phys.* 2014;106: 370–396.

Likhtarov I, L. Kovgan, S. Vavilov, M. Chepurny, E. Ron, J. Lubin, A. Bouville, N. Tronko, T. Bogdanova, L. Gulak, L. Zablotska, and G. Howe (2006) Post-Chernobyl Thyroid Cancers in Ukraine. Report 2: Risk Analysis. *Radiation Research: August 2006, Vol. 166, No. 2, pp 375–386.*

Lindgren A, Eugenia Stepanova, Vitaliy Vdovenko, Daria McMahon, Oksana Litvinetz, Elena Leonovich and Wilfried Karmaus (2015) Individual whole-body concentration of ¹³⁷Caesium is associated with decreased blood counts in children in the Chernobyl-contaminated areas, Ukraine, 2008–2010. *Journal of Exposure Science and Environmental Epidemiology* (2015) 25, 334–342.

Little J (1993) The Chernobyl accident, congenital anomalies and other reproductive outcomes. *Paediatric and Perinatal Epidemiology* Volume 7, Issue 2, pp 121–151, April 1993.

Little MP, Tawn EJ, Tzoulaki I, Wakeford R, Hildebrandt G, Paris F, Tapio S and Elliott P (2008) A Systematic Review of Epidemiological Associations Between Low and Moderate Doses of Ionizing Radiation and Late Cardiovascular Effects, and Their Possible Mechanisms. *Radiat. Res.* 169, 99–109.

Liu S, Semenciw R, Ugnat AM, Mao Y. Increasing thyroid cancer incidence in Canada, 1970–1996: time trends and age-period-cohort effects. *Br J Cancer.* 2001; 85: 1335–1339.

Livshits LA, Malyarchuk SG, Lukyanova EM, Antipkin YG, Arabskaya LP, Kravchenko 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. *Radiat Research* 155, 74–80.

Loganovsky KN and Loganovskaja TK (2000) Schizophrenia Spectrum Disorders in Persons Exposed to Ionizing Radiation as a Result of the Chernobyl Accident. *Schizophr Bull* (2000) 26 (4): 751–773.

Lomat L, Galburt G, Quastel MR, Polyakov S, Okeanov A, Rozin S (1997) Incidence of childhood disease in Belarus associated with the Chernobyl accident. *Environmental Health Perspectives.* 1997;105(Suppl 6): 1529–1532.

Lorini R and d'Annunzio G (2005) Letter re Zalutskaya *et al.* *Diabetologia* October 2005, Volume 48, Issue 10, pp 2193–2194

- Magnani C, Dalmaso P, Pastore G, Terracini B, Martuzzi M, Mosso ML, Merletti F (2003) Increasing incidence of childhood leukemia in Northwest Italy 1975–98. *International Journal of Cancer* Volume 105, Issue 4, pp 552–557. 17 Mar 2003.
- Malatova I and Skrkal J (2006) Re-evaluation of internal exposure from the Chernobyl accident to the Czech population. https://www.researchgate.net/profile/Irena_Malatova/publication/228479830_Re-evaluation_of_internal_exposure_from_the_Chernobyl_accident_to_the_Czech_population/links/0912f51101989e5f5a000000.pdf
- Malko MV (1998) 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>
- Malko MV, Ivano EP, Terechovich TI, Ivano VE (2011) Infant Leukemia In Belarus Before And After Chernobyl Medico-biological foundations of life UDC 616–006. <http://elib.bsu.by/bitstream/123456789/16949/1/Malko%20M.V.,%20Ivanov%20E.P.,%20Terechovich%20T.I.,%20Ivanov%20V.E..pdf>
- Martinucci *et al* (2002) Incidence of childhood type 1 diabetes mellitus in Gomel, Belarus. *Pediatr Endocrinol Metab*. 2002 Jan;15(1): 53–7.
- McKenna MT, Michaud CM, Murray CJL, Marks JS. (2005) Assessing the burden of disease in the United States using disability-adjusted life years. *Am J Prev Med* 28: 415–423.
- McMahon DM, Vdovenko V, Stepanova Y, Karmaus W, Zhang H, Irving E, Svendsen E (2015) Dietary supplementation with radionuclide free food improves children's health following community exposure to 137 Caesium: a prospective study. *Environmental Health* 2015, 14:94 (22 December 2015).
- McMahon DM, Vdovenko VY, Karmaus W, *et al*. (2014) Effects of long-term low-level radiation exposure after the Chernobyl catastrophe on immunoglobulins in children residing in contaminated areas: prospective and cross-sectional studies. *Environmental Health*. 2014; 13:36.
- Mitchell I, Livingston EH, Chang AY, *et al* (2007) Trends in thyroid cancer demographics and surgical therapy in the United States. *Surgery*. 2007; 142: 823–828.
- Morris JM, MJ Gardner MJ (1988) *Statistics in Medicine: Calculating confidence intervals for relative risks (odds ratios) and standardised ratios and rates*. *Br Med J (Clin Res Ed)* 1988; 296, 1312.
- Moshhammer H (2015) Personal communication.
- Mühlendahl KE, Muck K (1996) Chernobyl, low-dose radiation and trisomy 21: possibly something to worry about. *Eur J Pediatr*. 1996 Jul;155(7): 612–4 .
- Mürbeth 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*. 2004 Jul; 10(7): CR300–6.
- Noshchenko AG, Bondar OY, and Drozdova VD (2010) Radiation-induced leukemia among children aged 0–5 years at the time of the Chernobyl accident. *Int J Cancer*.2010 Jul 15;127(2): 412–26.

Noshchenko AG, Zamostyan PV, Bondar O Yu and Drozdova VD (2002) Radiation-induced leukemia 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.

OECD/NEA (1996) *The Radiological Impact of the Chernobyl Accident in OECD Countries in Western Europe*. Paris, Organisation of Economic Co-operation and Development.

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>

Ogrodnik A, Hudon TW, Nadkarni PM, Chandawarkar RY (2013) Radiation exposure and breast cancer: lessons from Chernobyl. *Connecticut Medicine*, 77(4): 227–234.

O'Kane P, Evgeniy Shelkovoy, Robert J. McConnell, Victor Shpak, Laurence Parker, Alina Brenner, Lydia Zablotska, Mykola Tronko, and Maureen Hatch. (2010) Frequency of Undetected Thyroid Nodules in a Large I-131-Exposed Population Repeatedly Screened by Ultrasonography: Results from the Ukrainian-American Cohort Study of Thyroid Cancer and Other Thyroid Diseases Following the Chernobyl Accident. *Thyroid*. September 2010, 20(9): 959–964.

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

Ozasa Kotaro, Yukiko Shimizu, Akihiko Suyama, Fumiyoshi Kasagi, Midori Soda, Eric J. Grant, Ritsu Sakata, Hiromi Sugiyama and Kazunori Kodama (2012) Studies of the Mortality of Atomic Bomb Survivors, Report 14, 1950–2003: An Overview of Cancer and Non-cancer Diseases. *Radiation Research* 177, 229–243.

Parker SE, Mai CT, Canfield MA, Rickard R, Wang Y, Meyer RE *et al* (2010) Updated national birth prevalence estimates for selected birth defects in the United States, 2004–2006. *Birth Defects Res A Clin Mol Teratol* 88: 1008–1016.

Parkin DM, Cardis E, Masuyer E, Friedl HP, Hansluwka H, Bobev D, Ivanov E, Sinnaeve J, Augustin J, Plesko I (1993) Childhood leukemia following the Chernobyl accident: the European Childhood Leukemia-Lymphoma Incidence Study (ECLIS). *Eur J Cancer* 29A(1): 87–95.

Parkin DM, Clayton D, Black RJ, *et al* (1996) Childhood leukemia in Europe after Chernobyl: 5 year follow-up. *British Journal of Cancer*. 1996;73(8): 1006–1012.

Pellegriti G, Francesco Frasca, Concetto Regalbuto, Sebastiano Squatrito, and Riccardo Vigneri (2013), Worldwide Increasing Incidence of Thyroid Cancer: Update on Epidemiology and Risk Factors. *Journal of Cancer Epidemiology* Volume 2013 Article ID 965212, 10 pages. <http://www.hindawi.com/journals/jce/2013/965212/>

Petralia *et al* (1999) Risk of premenopausal breast cancer in association with occupational exposure to polycyclic aromatic hydrocarbons and benzene. *Scandin J Work Envir Health* 1999;25(3): 215–221.

Pryszazhnyuk A, Gristchenko V, Fedorenko Z, Gulak L, Fuzik M, Slipeniuk Y *et al* (2007) Twenty years after the Chernobyl accident: solid cancer incidence in various groups of the Ukrainian population. *Radiat Environ Biophys*. 2007;46: 43–51.

Pryszazhnyuk AY (2011) Response to "thyroid cancer after Chernobyl: mechanisms of overestimation". *Radiation and Environmental Biophysics* Volume 50, Issue 4, pp 605–606.

Pryszazhnyuk AY *et al* (2014) Quarter of century since the Chernobyl accident: Cancer risks in affected groups of population. *Probl Radiac Med Radiobiol*. 2014 Sep;19: 147–169.

Pryszazhnyuk AY, Ludmila O Gulak, Vladimir G. Gristchenko, Zoya P. Fedorenko (2002) Cancer incidence in Ukraine after the Chernobyl accident, *International Congress Series, Volume 1234, May 2002, pp 281–291*. <http://www.sciencedirect.com/science/article/pii/S0531513101006173>

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

Pukkala E, Kesminiene A, Poliakov S, Ryzhov A, Drozdovitch V, Kovgan L and Cardis E. Breast cancer in Belarus and Ukraine after the Chernobyl accident. (2006) *Int J Cancer*;119(3): 651–8.

Rahu Kaja, Timo Hakulinen, Giedre Smailyte, Aivars Stengrevics, Anssi Auvinen, Peter D. Inskip, John D. Boice Jr., Mati Rahu, Site-specific cancer risk in the Baltic cohort of Chernobyl clean-up workers, 1986–2007, *European Journal of Cancer, Volume 49, Issue 13, September 2013, pp 2926–2933*, <http://www.sciencedirect.com/science/article/pii/S0959804913003262>

Ramsay CN *et al* (1991) Down's syndrome in the Lothian region in Scotland – 1978–1989. *Biomed. Pharmacother.* 45: 267–272.

Reynolds RM, Weir J, Stockton DL, Brewster DH, Sandeep TC, Strachan MW. Changing trends in incidence and mortality of thyroid cancer in Scotland. *Clin Endocrinol (Oxf)*. 2005; 62: 156–162.

Richardson DB (2009) Exposure to ionizing radiation in adulthood and thyroid cancer incidence. *Epidemiology*. 2009 March; 20(2): 181–187.

Richardson David B, Cardis Elisabeth, Daniels Robert D, Gillies Michael, O'Hagan Jacqueline A, Hamra Ghassan B *et al*. Risk of cancer from occupational exposure to ionising radiation: retrospective cohort study of workers in France, the United Kingdom, and the United States (INWORKS) (2015) *BMJ* 2015; 351: h5359 <http://www.bmj.com/content/351/bmj.h5359>

Ries LAG, Melbert D, Krapcho M, *et al*, eds. *SEER Cancer Statistics Review, 1975–2005*. Bethesda, MD: National Cancer Institute; 2008.

Ron E (2009) Response to Jargin. *Health Physics* Vol 96/2 pp 186–187.

Ron E, 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.

Ronckers CM, Erdmann CA, Land CE. (2005) Radiation and breast cancer: a review of current evidence. *Breast Cancer Res*. 2005;7: 21–32. [PubMed]

Roszkowska H, Gorynski P (2004) Thyroid cancer in Poland in 1980–2000. *Przegl Epidemiol*. 2004;58(2) 369–376.

Rothmann K, Greenland S (1998) *Modern epidemiology*. Lippincott-Raven, Philadelphia US.

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.

Schneider AB, Ron E, Lubin J, Stovall M, Gierlowski TC (1993) Dose-response relationships for radiation-induced thyroid cancer and thyroid nodules: evidence for the prolonged effects of radiation on the thyroid. *J Clin Endocrinol Metab* 77(2): 362–369.

Seidel C, Maringer F-J, Baumgartner A, Waldhör T, Bossew P (2012) Health consequences in Upper Austria 25 years after Chernobyl – new considerations regarding the inhalation and ingestion dose by ¹³¹I and ⁹⁰Sr. Report to the Office of the Upper Austrian Provincial Government, Environmental Protection Department. http://www.atomfreie.eu/fileadmin/Daten/Studiathek/2012_03_15_Tschernobylstudie_Kurzfassung_2012.pdf (in German)

Sherman S and Fagin J (2005) Why thyroid cancer? *Thyroid*. 2005; 15: 303–304.

Shimizu Y, Kodama K, Shore RE *et al* (2010) Radiation exposure and circulatory disease risk: Hiroshima and Nagasaki atomic bomb survivor data, 1950–2003. *BMJ*. 2010;340: b5349.

Shore RE (2009) Low-dose radiation epidemiology studies: status and issues. *Health Phys*. 2009 Nov; 97(5): 481–6.

Smailyte G, Miseikyte-Kaubriene E, Kurtinaitis J. Increasing thyroid cancer incidence in Lithuania in 1978–2003. *BMC Cancer*. 2006; 6: 284

Sperling K *et al* (1991) Frequency of Trisomy 21 in Germany before and after the Chernobyl Accident. *Biomed and Pharmacother* 45, 255–262.

Sperling K *et al* (1994a) Significant increase in trisomy 21 in Berlin nine months after the Chernobyl reactor accident: temporal correlation or causal relation? *BMJ* 1994;309:158. <http://www.bmj.com/content/309/6948/158.full>

Sperling K, Pelz J, Wegner RD, Dorries A, Gruters A, Mikkelsen M (1994b) Fallout from Chernobyl. Authors stand by study that Chernobyl increased trisomy 21 in Berlin. *BMJ*. 1994 Jul 16;309(6948): 139–40.

Steinhauser G, Brandl A, Johnson TE (2014) Comparison of the Chernobyl and Fukushima nuclear accidents: A review of the environmental impacts, *Science of The Total Environment*, Volumes 470–471, 1 February 2014, pp 800–817. <http://dx.doi.org/10.1016/j.scitotenv.2013.10.029>

Stepanova E, Karmaus W, Naboka M, *et al* (2008) Exposure from the Chernobyl accident had adverse effects on erythrocytes, leukocytes, and, platelets in children in the Narodichesky region, Ukraine: A 6-year follow-up study. *Environmental Health*. 2008;7:21.

Stohl A *et al* (2012) Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition. *Atmospheric Chemistry and Physics*. Volume 12, Number 5, 2313–2343 <http://www.atmos-chem-phys.net/12/2313/2012/>

Straume T (1991) Health Risks from Exposure to Tritium. Lawrence Livermore Laboratory Report UCRL-LR- 105088. University of California, Livermore, CA, US.

Straume T (1993) Tritium Risk Assessment. *Health Physics* Vol 65. No 6, 673–682 December 1993.

Svendsen ER, Ighor E, Kolpakov, Wilfried J. J. Karmaus, Lawrence C. Mohr, Vitaliy Y. Vdovenko, Daria M. McMahon, Benjamin A. Jelin, and Yevgenia I. Stepanova (2015) Reduced Lung Function in Children Associated with Caesium 137 Body Burden. (2015) *Annals of the American Thoracic Society*, Vol. 12, No. 7 (2015), pp 1050–1057. <http://www.atsjournals.org/doi/10.1513/AnnalsATS.201409-432OC#.Vq98r1JovAo>

Svendsen ER, Kolpakov IE, Stepanova YI, Vdovenko VY, Naboka MV, Mousseau TA, Mohr LC, Hoel DG, Karmaus WJ (2010) ¹³⁷Cesium exposure and spirometry measures in Ukrainian children affected by the Chernobyl nuclear incident. *Environ Health Perspect.* 2010 May;118(5): 720–5.

Taskinen M, Saarinen-Pihkala UM, Hovi L, Lipsanen-Nyman M (2000) Impaired glucose tolerance and dyslipidaemia as late effects after bone marrow transplantation in childhood. *Lancet* 356: 993–997.

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

Timchenko OI, Linchak OV, Protsiuk OV, Pol'ka EA, Benedichuk IuV, Marinich AV (2014) Birth defects on Chernobyl radionuclide polluted territories. *Radiats Biol Radioecol.* 2014 Sep–Oct;54(5): 507–521 [Article in Russian] <http://www.ncbi.nlm.nih.gov/pubmed/25775843>

Titov, Leonid P.; Kharitonic, Galina D.; Gourmanchuk, Irina E.; Ignatenko, Svetlana I (1995) Effects of Radiation on the Production of Immunoglobulins in Children Subsequent to the Chernobyl Disaster. *Allergy and Asthma Proceedings*, Volume 16, Number 4, July–August 1995, pp 185–193(9).

Tokunaga M, Land CE, Tokuoka S, Nishimori I, Soda M, Akiba S (1994) Incidence of female breast cancer among atomic bombing survivors, 1950–1985. *Radiat Res.* 1994 May;138(2): 209–223

Tronko ND, Epstein Y, Oleinik V *et al* (1994) Thyroid gland in children after the Chernobyl accident (yesterday and today). In: Nagataki S, ed. *Nagasaki Symposium on Chernobyl: Update and Future*. Elsevier Science, B.V. Amsterdam (The Netherlands); 1994: 3–46.

Tsyb AF, Parshkov EM, Ivanov VK, Stepanenko VF, Matveenko EG, Skoropad YD. Disease indices of thyroid and their dose dependence in children and adolescents affected as a result of the Chernobyl accident. In: Nagataki S, ed. *Nagasaki Symposium on Chernobyl: Update and Future*. Elsevier Science, B.V. Amsterdam (The Netherlands); 1994: 9–19.

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 (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.

UNSCEAR (2008) *United Nations Scientific Committee on the Effects of Atomic Radiation, 2008 Report to the General Assembly, with scientific annexes. Annex D Health Effects Due to the Chernobyl Nuclear Accident*. United Nations, New York.

UNSCEAR (2013) *Volume I (United Nations Scientific Committee on the Effects of Atomic Radiation) Scientific Annex A: Levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami*. http://www.unscear.org/docs/reports/2013/13-85418_Report_2013_Annex_A.pdf

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.

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

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

Vasylenko VV, Tsigankov MY, Nechaev SY, Pikta VO, Zadorozhna GM, Bilonyk AB (2013) Peculiarities of internal radiation doses due to ¹³⁷Cs and ⁹⁰Sr intake in population from Zhytomyr oblast in a late period after the Chornobyl NPP accident. *Probl Radiac Med Radiobiol.* 2013;(18): 59–69.

Verger P (1997) Down syndrome and ionizing radiation. *Health Phys.* 1997 Dec;73(6): 882–93.

Verger P, Catelinois O, Tirmarche M, Chérié-Challine L, Pirard P, Colonna M, Hubert P (2003) Thyroid cancers in France and the Chernobyl accident: risk assessment and recommendations for improving epidemiological knowledge. *Health Phys.* 2003 Sep;85(3): 32–9.

Walker L (2015) Personal Communication. <http://www.chernobyl-children.org.uk/>

Wertelecki W (2010) Malformations in a Chornobyl-Impacted Region. *Pediatrics.* April 2010, Volume 125 / Issue 4.

WHO (2012) Preliminary dose estimation from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami. World Health Organisation. Geneva. http://www.who.int/ionizing_radiation/pub_meet/fukushima_dose_assessment/en/

Williams D (1994) Fallout from Chernobyl. Thyroid cancer in children increased dramatically in Belarus. *BMJ* 1994 ;309:1298; author reply p 1300.

Williams D (2002) Cancer after nuclear fallout: lessons from the Chernobyl accident. *Nat Rev Cancer* ; 2: 543–549.

Williams D (2007) Chernobyl, radiation and thyroid cancer. *International Congress Series.* Vol 1299; p 212

Worgul BV, Shore RE *et al* (2007) Cataracts among Chernobyl clean-up workers: implications regarding permissible eye exposures. *Radiat Res.* 2007 Feb;167(2): 233–43.

Yablokov AV, Nesterenko VB, Nesterenko AV (2009) Consequences of the Chernobyl catastrophe for public health and the environment 23 years later. *Annals of the New York Academy of Sciences* [2009, 1181: 318–326].

Zablotska LB *et al* (2015) Analysis of thyroid malignant pathologic findings identified during 3 rounds of screening (1997–2008) of a cohort of children and adolescents from Belarus exposed to radioiodines after the Chernobyl accident *Cancer* vol 121 issue 3. <http://onlinelibrary.wiley.com/doi/10.1002/cncr.29073/full>

Zablotska LB, Bazyka D, Lubin JH, Gudzenko N, Little MP, Hatch M, Finch S, Dyagil I, Reiss RF, Chumak VV, Bouville A, Drozdovitch V, Kryuchkov VP, Golovanov I, Bakhanova E, Babkina N, Lubarets T, Bebesko V, Romanenko A, Mabuchi K (2013) Radiation and the risk of chronic lymphocytic and other leukemias among Chornobyl clean-up workers. *Environ Health Perspect.* Jan; 121(1): 59–65.

Zablotska LB, Ron E, Rozhko AV, *et al* (2011) Thyroid cancer risk in Belarus among children and adolescents exposed to radioiodine after the Chornobyl accident. *Br J Cancer.*;104: 181–187.

Zalutskaya A, Bornstein SR, Mokhort T, Garmaev D (2004) Did the Chernobyl incident cause an increase in Type 1 diabetes mellitus incidence in children and adolescents? *Diabetologia.* 2004 Jan;47(1): 147–8.

Zatsepin I, Verger P, Robert-Gnansia E, Gredgnière B, Tirmarche M, Khmel R, Babicheva I, Lazjuk G (2007) Down syndrome time-clustering in January 1987 in Belarus: link with the Chernobyl accident? *Reprod Toxicol.* 2007 Nov–Dec; 24(3-4):289–95.

Zimmermann MB and Galetti V (2015) Iodine intake as a risk factor for thyroid cancer: a comprehensive review of animal and human studies. *Thyroid Research* (2015) 8:8.

ANNEX A: Acronyms and Abbreviations

ARCH	Action for Research on Chernobyl (IARC)
BEIR	US Committee on the Biological Effects of Ionizing Radiation
Bq	becquerel (unit of radioactivity)
CERRIE	former UK Committee Examining the Radiation Risks of Internal Emitters
Ci	curie (unit of radioactivity)
DDREF	dose and dose rate effectiveness factor
DG TREN	Directorate-General for Transport and Energy of the EC
DNA	deoxyribose nucleic acid
EC	European Commission
ECLIS	IARC European Childhood Leukemia-Lymphoma Incidence Study
EPA	US Environmental Protection Agency
EAR	excess absolute risk
ERR	excess relative risk
EU	European Union
Gy	gray (unit of absorbed radiation dose)
HPA	former UK Health Protection Agency
IAEA	International Atomic Energy Agency
IARC	International Agency for Research on Cancer
ICP	International Chernobyl Project
ICRP	International Commission on Radiological Protection
IPHECA	former International Project on the Health Effects of the Chernobyl Accident
IRSN	Institut de Radioprotection et de la Sûreté Nucléaire
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
OCHA	UN Office for the Coordination of Humanitarian Affairs
OECD	Organisation for Economic Cooperation and Development
RERF	Japanese Radiation Effects Research Foundation
RR	relative risk
SCPRI	former Service Central de Protection contre les Rayonnements Ionisants
SD	standard deviation
SIR	standardised incidence ratio
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

ANNEX B: Glossary of Common Radiation Terms

Absorbed dose – Quantity of energy imparted by ionising radiation to unit mass of matter such as tissue.
1 Gy = 1 joule per kilogram.

Activity – rate at which radioactive substances decay. Unit – the becquerel (Bq).
1 Bq = 1 disintegration per second.

Beta particle – An electron emitted by the nucleus of a radionuclide.

Decay – The process of spontaneous transformation of a radionuclide. The decrease in the activity of a radioactive substance.

Decay product – A nuclide or radionuclide produced by decay. It may be formed directly from a radionuclide or as a result of a series of successive decays through several radionuclides.

Dose – General term for quantity of radiation. See absorbed dose, effective dose, equivalent dose.

Dose factor – committed effective dose resulting from the inhalation or ingestion of 1 Bq of a given radionuclide.
Unit – sievert per becquerel, symbol – Sv/Bq.

Effective dose – The quantity obtained by multiplying the equivalent doses to various tissues and organs by the tissue weighting factor appropriate to each and summing the products. Unit sievert, symbol Sv.

Equivalent dose – The quantity obtained by multiplying the absorbed dose by the appropriate radiation weighting factor to allow for the different effectiveness of the various ionizing radiations in causing harm to tissue. Unit sievert, symbol Sv.

Gamma ray – A discrete quantity of electromagnetic energy, without mass or charge.

Half-life – The time taken for the activity of a radionuclide to lose half its value by decay.

Ionisation – The process by which a neutral atom or molecule acquires or loses an electric charge.
The production of ions.

Ionising radiation – Radiation that produces ionised atoms in matter.

Nuclear fission – The process in which a nucleus splits into two or more nuclei and energy is released.

Radionuclide – An unstable nuclide that emits ionizing radiation when it decays.

Risk factor – The probability of fatal cancer or leukemia per unit effective dose.

Sievert – See effective dose.

ANNEX C: 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 LET⁵⁵ 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 $\times w_R$

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:

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
μ Sv = microsievert (one millionth of a sievert)	= 10^{-6} Sv
nSv = nanosievert (one billionth of a sievert)	= 10^{-9} Sv

⁵⁵ LET= linear energy transfer, i.e. the energy transferred per unit length of the radiation track

ANNEX D: Major Reports in 2006

In 2005 and 2006, many conferences were held throughout the world to mark the 20th anniversary of the Chernobyl catastrophe including in Austria, Germany, Switzerland, UK, Ukraine, Russia, Belarus and United States. Many major reports were published at that time including (in alphabetical order)

Blokov I, Sadownichik T, Labunska I and Volkov I (Eds.) (2007) *The Health Effects of the Human Victims of the Chernobyl Catastrophe: Collection of Scientific Articles*. Greenpeace, Amsterdam, 2007, 235 pp
<http://www.greenpeace.to/publications.asp#2007>

Centre of Independent Ecological Assessment, Russian Academy of Science, and Russian Greenpeace Council (2006) *Chernobyl Accident's Consequences: An Estimation and the Forecast of Additional General Mortality and Malignant Diseases*. Moscow, 24 pp

Ecopolicy (2006) *Twenty Years of Chernobyl Catastrophe: Ecological and Sociological Lessons. Materials of the International Scientific and Practical Conference. June 5, 2006, Moscow, 305 pp*
www.ecopolicy.ru/upload/File/conferencebook_2006.pdf (in Russian)

Fairlie I and Sumner D (2006) *TORCH – The Other Report on Chernobyl*. www.chernobylreport.org
90 pp (in English, Ukrainian and Russian languages)

HOLTEH (2006) *Twenty Years after the Chernobyl Accident: Future Outlook [Contributed Papers to International Conference. April 24–26, 2006. Kiev, Ukraine, vol. 1–3, Kiev, www.tesec-int.org/T1.pdf*

IAEA/WHO (2005) *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 (2005) *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*

National Belarussian Report (2006) *Twenty Years after the Chernobyl Catastrophe: Consequences in Belarus and Overcoming the Obstacles*. Shevchyuk VE & Gurachevsky VL (Eds.), Belarus Publishers, Minsk, 112 pp (in Russian).

National Russian Report (2006) *Twenty Years of Chernobyl Catastrophe: Results and Perspective on Efforts to Overcome Its Consequences in Russia, 1986–2006*. Shoigu SK & Bol'shov LA (Eds) Ministry of Emergencies, Moscow, 92 pp (in Russian).

National Ukrainian Report (2006) *Twenty Years of Chernobyl Catastrophe: Future Outlook*. Kiev, www.mns.gov.ua/news/show.php?news_id=614&p=1

Pflugbeil S *et al* (2006) *Health Effects of Chernobyl: 20 Years after the Reactor Catastrophe*. German IPPNW, Berlin, 76 pp

Yablokov A, Labunska I and Blokov I (Eds) (2006) *The Chernobyl Catastrophe – Consequences on Human Health*. Greenpeace, Amsterdam, 137 pp, www.greenpeace.org/international/press/reports/chernobylhealthreport

Yablokov A, Braun R and Watermann U (Eds.) (2006) *Chernobyl. 20 Years After. Myth and Truth*. Agenda Verlag, Münster, 217 pp



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