Chernobyl – Catastrophe and Consequences

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Figures

Tables

Abbreviations

ACF	aggregated concentration factor
ARS	acute radiation syndrome
BNFL	British Nuclear Fuels Plc.
BAF	bioaccumulation factor
CF	concentration factor
CR	concentration ratio
CEC	cation exchange capacity
CFILs	Council Food Intervention Limits
CLL	Chronic Lymphocytic Leukaemia
CI	confidence interval
d.w.	dry weight
EC	electrical conductivity
ERR	excess relative risk
EAR	excess absolute risk
fSU	former Soviet Union
f.w.	fresh weight
FES	‘Frayed Edge Sites’
GDL	Generalised Derived Limit
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiation Protection
IRG	inert radioactive gases
NPP	Nuclear Power Plant
NWT	nuclear weapons test
RBE	relative biological effectiveness
RN	radionuclide
SEER	US Program Surveillance Epidemiology and Results
TUE	transuranium elements

UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UNDP	United Nations Development Programme
UNICEF	United Nations Children's Fund
UN-OCHA	UN Office for the coordination of Humanitarian Affairs
WHO	World Health Organisation

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Introduction

Jim T. Smith and Nick A. Beresford

The explosion at Unit 4 of the Chernobyl nuclear power station was the worst nuclear accident in history. Radioactive fallout from the accident (directly or indirectly) affected the lives of hundreds of thousands of people in the former Soviet Union and contamination spread throughout Europe. In the 19 years since the accident, thousands of scientific papers have been published on Chernobyl and its consequences. In this book we have tried to summarise this vast literature, focusing particularly on the long-term consequences of the accident to people and the environment.

There are many historical accounts of the Chernobyl accident (e.g., Shcherbak, 1989; IAEA, 1991; UNSCEAR, 2000; Mould, 2000; Kryshev and Ryazantsev, 2000; OECD/NEA, 2002). Whilst this book focuses primarily on the longer term impacts of the accident, here we briefly summarise the history of the accident and its immediate consequences. In particular, we aim to put Chernobyl within the context of other (natural and man-made) sources of radioactivity in the environment. This chapter also introduces some key concepts and units of radiation measurement and risk assessment. Many of these will be familiar to some readers, and are therefore where possible included in boxes separate from the main text.

1.1 HISTORY OF THE ACCIDENT

At the time of the accident in 1986, Chernobyl was one of four nuclear power stations in the Ukraine and was part of a rapid expansion in nuclear generating capacity. The Chernobyl power station consisted of four 'RBMK-1000'-type reactors, the first of which, Unit 1, began electricity generation in 1977. Electricity generation at Unit 4 (the reactor at which the accident occurred) was begun in 1983 and in 1986 two other Units (5 and 6) were being built. Construction of these last units stopped after the accident.

The accounts of the accident and its immediate aftermath (Shcherbak, 1989; IAEA, 1991; Mould, 2000) make truly chilling reading. There are still some uncertainties regarding the exact causes and events leading to the accident, though the key factors are now known. The accident occurred during an experiment to test the behaviour of an electrical system which powered the station in the event of a failure of the main electricity supply. In order to conduct the experiment, the reactor thermal power output had to be reduced to 700–1,000 MegaWatts (MW), about 25% of its maximum power output.

At 13:00 on 25 April, 1986, the plant operators began reduction of the reactor power in preparation for the experiment. At 14:00, however, the operators received a request from Kiev to continue supplying electricity until 23:10 that evening, so the experiment was postponed. At 23:10 reduction of the reactor power output began again and at just after midnight on 26 April, reactor power was 720 MW. Approximately 30 minutes later, however, power output had fallen to just 30 MW. This unexpected fall in the power output is believed to have been due to a problem in the operation of the automatic control rods (which were designed to control the reactor power under low-power conditions).

At 01:00, the operators had stabilised reactor power at 200 MW by removing some of the control rods. During the next 20 minutes the operators varied the flow rate of water in the coolant circuit, leading to a significant variation in temperature of the inlet water. The reactor has been described as being in an unstable condition during this period (UNSCEAR, 2000): the coolant flow was almost completely liquid water with no stream entrained. At 01:22:30 the operator received an automatic printout which indicated that the reactor should be shut down immediately (IAEA, 1986). This warning was ignored. At 01:23 the experiment began, despite the fact that:

- the reactor power output was well below that required by the experimental procedure;
- certain reactor safety systems had been deliberately disabled in order to carry out the experiment; and
- the number of control rods in the reactor was only half the minimum required for its safe operation.

Thirty seconds after the experiment began, the reactor power began to increase rapidly and ten seconds later the operators attempted a full emergency shut down by re-inserting the control rods. The reactor power was now increasing exponentially leading to a failure in the pressurised cooling water system. Eight seconds later, the reactor exploded (an explosion of steam, not a nuclear explosion) scattering burning core debris over the surrounding area. The ruined reactor is shown in Figures 1.1 and 1.2.

Box 1.1. Design flaw in the RBMK reactor.

The RBMK nuclear reactor used at Chernobyl, in contrast to most nuclear reactors, had what is known in the nuclear industry as a 'positive void coefficient'. In an accident situation, should cooling water be lost or turned to steam, most reactors (with 'negative void coefficient') naturally reduce their power output. In the RBMK reactor, loss of cooling water results in an increase in power output and consequent temperature rise in the reactor core. This in turn causes more of the coolant water to turn to steam, leading, potentially, to an uncontrolled rise in power output.

Figure 1.1. The destroyed Unit 4 reactor building at the Chernobyl Nuclear Power Plant (NPP). The edge of the Cooling Pond can be seen top left.

Figure 1.2. Aerial view of the destroyed reactor.

Over 100 firemen were called to the scene and they worked with plant personnel to put out many small fires in the reactor building and on the roofs of Unit 4 and the adjacent Unit 3 building. This work exposed the emergency workers to extremely high doses of radiation. The report of the IAEA International Chernobyl Project (IAEA, 1991) describes the scene:

> By dawn on the Saturday [26 April], more than 100 firemen had succeeded in putting out the roof fires, and by about 05:00 all but the graphite fire in the [reactor] core had been extinguished. These courageous actions by the early firefighters and plant personnel resulted in many injuries, but they were essential to preventing the spread of the fire to the other units and to preventing a hydrogen explosion or fire that might have ignited the oil in the turbines. Many firemen stayed on the alert on the premises for several hours after the fire was out, which resulted in a number of radiation exposures.
>
> Radiation levels were so high in the damaged part of the plant and just outside it that monitoring equipment in the plant could not measure them. Available portable radiation meters went off-scale and systematic monitoring became impossible. It seems that many of those who entered the buildings to rescue others, fight fires, perform critical operations or assess damage did not appreciate the radiation risk.

Although the initial fires had been put out, the destroyed reactor core continued to burn. During the days after the explosion, helicopters were used to dump thousands of tonnes of various materials onto the exposed reactor core. These materials included boron, lead, sand and clay to smother the fire, absorb radiation and reduce nuclear reactions in the molten core material. In total, 1,800 helicopter flights were made at great risk to the pilots (UNSCEAR, 2000). Despite the heroic efforts of firemen, helicopter pilots and many other emergency workers to put out the fire, the reactor continued to burn for 10 days.

Box 1.2. Myths and revelations.

Soon after the accident, an article appeared in the *New York Times* claiming that the Ukrainian word ‘Чорнобиль’ (Chernobyl) translates to English as ‘Wormwood’ (a bitter herb) and quoting a verse from the Book of Revelations:

> The third angel sounded and there fell a great star from heaven, burning, as it were a lamp, and it fell on the third part of the rivers and upon the fountains of water; And the name of the star is Wormwood; and the third part of the waters became Wormwood, and many men died of the waters because they were made bitter.

This has been interpreted by some as giving an apocalyptic dimension to the tragedy, particularly since radioactivity polluted rivers and reservoirs in the Ukraine. In fact, the herb named Chernobyl (‘Чернобыльник’ – Russian, Чорнобиль – Ukrainian) is the Mugwort (*Artemesia vulgaris*). The Wormwood (Полынь горькая, polyn gorkaya – Russian, Полин гіркий’ polyn girkiy – Ukrainian) is a related, but different species, *Artemesia absinthum*.

1.1.1 Emergency response and early health effects

In the early stages of the accident, many power plant operators and emergency workers were exposed to very high doses of radiation. This was a result of external gamma radiation from the exposed reactor core and core debris, as well as exposure to beta radiation from contamination of their skin and clothes (see Box 1.3 for a description of different radiation types). One hundred and thirty four emergency workers were confirmed as suffering from acute radiation sickness (UNSCEAR, 2000), 28 of whom died during the months after the accident (Table 1.1). Internal radiation exposure of these people (mainly from inhalation of radioiodine and radiocaesium) was in general much lower than the external exposure. Chapter 6 presents a fuller discussion of the health consequences of the accident.

Box 1.3. Charateristics of some radioactive emissions.

Radiation type	Description	Stopped by:	Approximate relative biological effectiveness*
Alpha particle	Helium nucleus	Air or outer layers of skin	20
Beta particle	Electron	Few mm of aluminium	1†
Gamma ray	Electromagnetic wave	Few cm of lead	1

* Relative biological effectiveness is used to convert radiation energy absorbed by the human body into a radiation dose: for a given absorbed energy alpha radiation is estimated to be approximately 20 times more biologically damaging than high-energy beta or gamma.
† For beta energies $<10\,keV$ a value of 3 is often used.

Table 1.1. Confirmed cases of acute radiation sickness in emergency workers.
Adapted from UNSCEAR (2000).

Degree of acute radiation sickness	Range of external radiation dose*	Number of people affected	Number of deaths
Mild	0.8–2.1 gray	41	0
Moderate	2.2–4.1 gray	50	1
Severe	4.2–6.4 gray	22	7
Very severe	6.5–16 gray	21	20
Total		*134*	*28*

* See Box 1.4 for a definition of the gray.

Measures to protect both the people on the site, and the population of the surrounding areas were, in the very early stages of the accident, inadequate. Firemen had not been trained in radiation protection and had no dosimeters to control their radiation exposure. Although potassium iodide tablets (to block radioiodine uptake by the

Figure 1.3. The abandoned town of Pripyat with the Chernobyl Nuclear Power Station in the background.

thyroid) were distributed to power plant workers within half an hour of the accident (UNSCEAR, 2000), there was 'no systematic distribution' (IAEA, 1991) of tablets to the population of Pripyat, a town approximately 3 km from the plant (Figures 1.3 and 1.4). Face masks to protect from inhalation of radioactivity were not available to the population and there were no official warnings for people to stay indoors, out of the contaminated air. Many children in Pripyat were playing outdoors on 26 April (the accident occurred in the early hours of 26 April), unaware of the potential danger.

At 14:00 on Sunday 27 April, the 44,000 population of Pripyat were evacuated in 1,200 buses. On 2 May it was decided to evacuate people and cattle from an area of approximately 30 km radius around the plant (the '30-km zone'), the boundary being based on a map of radiation dose rate. By 6 May, the entire 30-km zone had been evacuated. Subsequent mapping of contamination later led to more evacuations, including areas in Belarus and the Bryansk region of Russia around 150 km to the northwest of the reactor. In total, approximately 116,000 people (Belyaev *et al.*, 1996) and 60,000 cattle (UNSCEAR, 2000) were initially evacuated from an area of approximately 3,500 km^2. In subsequent years many more people were evacuated, reaching approximately 350,000 (UNDP/UNICEF, 2002). At present, many of the evacuated areas remain uninhabited, though some small areas have been re-settled.

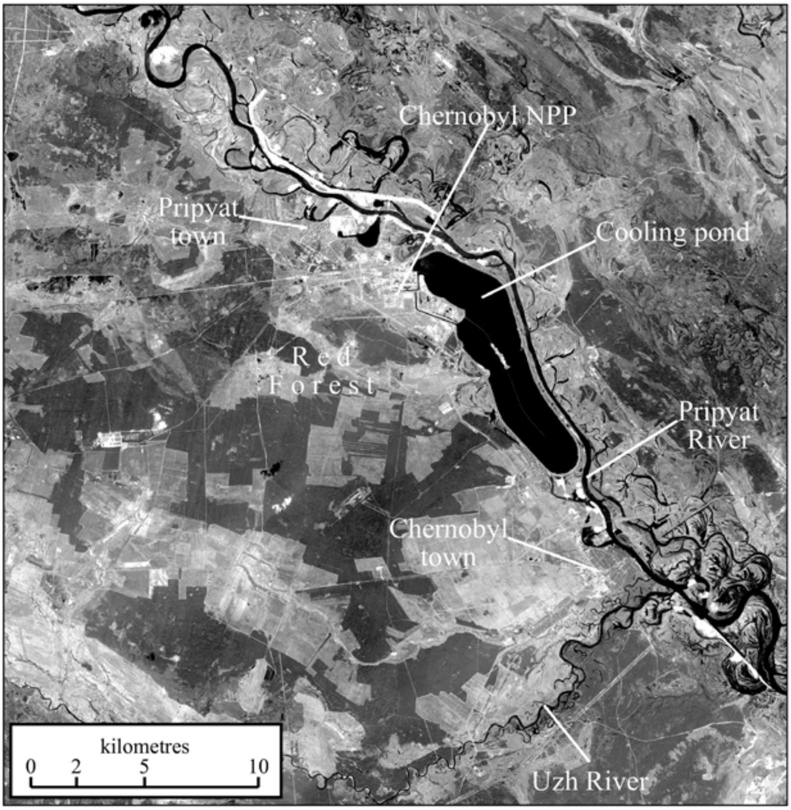

Figure 1.4. Satellite photo of the area around Chernobyl NPP. Note that the town of Chernobyl is about 15 km south of the plant: it had much lower radioactive fallout than many other areas. In this book 'Chernobyl' refers to the nuclear reactor rather than the town unless otherwise stated.
Photo adapted by Simon Wright from the original with the kind permission of Valery Kashparov of the Ukrainian Institute of Agricultural Radiology (UIAR, 2001).

1.1.2 Emergency clean up and waste disposal

A concrete structure (the 'shelter' or 'sarcophagus') was built around the destroyed reactor building in order to prevent further releases of radioactive material (Figures 1.5 and 1.6). The sarcophagus was built rapidly under extremely difficult conditions; work was completed in November 1986 (Belyaev *et al.*, 1996). Since its construction, there have been concerns about the structural integrity of this temporary building. The sarcophagus was (necessarily) built using existing parts of the reactor building as support and the stability of these existing structures is not precisely known.

There has been particular concern that the sarcophagus could collapse in the event of an earthquake, for example (though seismic activity in this area is not high).