Chernobyl Accident
(Updated August 2010)

- The Chernobyl accident in 1986 was the result of a flawed reactor design that was operated with inadequately trained personnel.
- The resulting steam explosion and fires released at least 5% of the radioactive reactor core into the atmosphere and downwind.
- Two Chernobyl plant workers died on the night of the accident, and a further 28 people died within a few weeks as a result of acute radiation poisoning.
- Resettlement of areas from which people were relocated is ongoing.

The April 1986 disaster at the Chernobyl nuclear power plant in the Ukraine was the product of a flawed Soviet reactor design coupled with serious mistakes made by the plant operators. It was a direct consequence of Cold War isolation and the resulting lack of any safety culture.

The accident destroyed the Chernobyl 4 reactor, killing 30 operators and firemen within three months and several further deaths later. One person was killed immediately and a second died in hospital soon after as a result of injuries received. Another person is reported to have died at the time from a coronary thrombosis. Acute radiation syndrome (ARS) was originally diagnosed in 237 people on-site and involved with the clean-up and it was later confirmed in 134 cases. Of these, 28 people died as a result of ARS within a few weeks of the accident. Nineteen more subsequently died between 1987 and 2004 but their deaths cannot necessarily be attributed to radiation exposure. Nobody off-site suffered from acute radiation effects although a large proportion of childhood thyroid cancers diagnosed since the accident is likely to be due to intake of...
radioactive iodine fallout. Furthermore, large areas of Belarus, Ukraine, Russia and beyond were contaminated in varying degrees. See also Chernobyl Accident Appendix 2: Health Impacts.

The Chernobyl disaster was a unique event and the only accident in the history of commercial nuclear power where radiation-related fatalities occurred. However, the design of the reactor is unique and the accident is thus of little relevance to the rest of the nuclear industry outside the then Eastern Bloc.

The Chernobyl site and plant

The Chernobyl Power Complex, lying about 130 km north of Kiev, Ukraine, and about 20 km south of the border with Belarus, consisted of four nuclear reactors of the RBMK-1000 design (see information page on RBMK Reactors), units 1 and 2 being constructed between 1970 and 1977, while units 3 and 4 of the same design were completed in 1983. Two more RBMK reactors were under construction at the site at the time of the accident. To the southeast of the plant, an artificial lake of some 22 square kilometres, situated beside the river Pripyat, a tributary of the Dniepr, was constructed to provide cooling water for the reactors.

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

The RBMK-1000 is a Soviet-designed and built graphite moderated pressure tube type reactor, using slightly enriched (2% U-235) uranium dioxide fuel. It is a boiling light water reactor, with two
loops feeding steam directly to the turbines, without an intervening heat exchanger. Water pumped to the bottom of the fuel channels boils as it progresses up the pressure tubes, producing steam which feeds two 500 MWe turbines. The water acts as a coolant and also provides the steam used to drive the turbines. The vertical pressure tubes contain the zirconium alloy clad uranium dioxide fuel around which the cooling water flows. The extensions of the fuel channels penetrate the lower plate and the cover plate of the core and are welded to each. A specially designed refuelling machine allows fuel bundles to be changed without shutting down the reactor.

The moderator, whose function is to slow down neutrons to make them more efficient in producing fission in the fuel, is graphite, surrounding the pressure tubes. A mixture of nitrogen and helium is circulated between the graphite blocks to prevent oxidation of the graphite and to improve the transmission of the heat produced by neutron interactions in the graphite to the fuel channel. The core itself is about 7 m high and about 12 m in diameter. In each of the two loops, there are four main coolant circulating pumps, one of which is always on standby. The reactivity or power of the reactor is controlled by raising or lowering 211 control rods, which, when lowered into the moderator, absorb neutrons and reduce the fission rate. The power output of this reactor is 3200 MW thermal, or 1000 MWe. Various safety systems, such as an emergency core cooling system, were incorporated into the reactor design.

One of the most important characteristics of the RBMK reactor is that it it can possess a 'positive void coefficient', where an increase in steam bubbles (‘voids’) is accompanied by an increase in core reactivity (see information page on RBMK Reactors). As steam production in the fuel channels increases, the neutrons that would have been absorbed by the denser water now produce increased fission in the fuel. There are other components that contribute to the overall power coefficient of reactivity, but the void coefficient is the dominant one in RBMK reactors. The void coefficient depends on the composition of the core – a new RBMK core will have a negative void coefficient. However, at the time of the accident at Chernobyl 4, the reactor's fuel burn-up, control rod configuration and power level led to a positive void coefficient large enough to overwhelm all other influences on the power coefficient.

The 1986 Chernobyl accident

On 25 April, prior to a routine shutdown, the reactor crew at Chernobyl 4 began preparing for a test to determine how long turbines would spin and supply power to the main circulating pumps following a loss of main electrical power supply. This test had been carried out at Chernobyl the previous year, but the power from the turbine ran down too rapidly, so new voltage regulator designs were to be tested.

A series of operator actions, including the disabling of automatic shutdown mechanisms, preceded the attempted test early on 26 April. By the time that the operator moved to shut down the reactor, the reactor was in an extremely unstable condition. A peculiarity of the design of the control rods caused a dramatic power surge as they were inserted into the reactor (see Chernobyl Accident Appendix 1: Sequence of Events).

The interaction of very hot fuel with the cooling water led to fuel fragmentation along with rapid steam production and an increase in pressure. The design characteristics of the reactor were such that substantial damage to even three or four fuel assemblies can – and did – result in the destruction of the reactor. The overpressure caused the 1000 t cover plate of the reactor to become partially detached, rupturing the fuel channels and jamming all the control rods, which by that time were only halfway down. Intense steam generation then spread throughout the whole core (fed by
water dumped into the core due to the rupture of the emergency cooling circuit) causing a steam explosion and releasing fission products to the atmosphere. About two to three seconds later, a second explosion threw out fragments from the fuel channels and hot graphite. There is some dispute among experts about the character of this second explosion, but it is likely to have been caused by the production of hydrogen from zirconium-steam reactions.

Two workers died as a result of these explosions. The graphite (about a quarter of the 1200 tonnes of it was estimated to have been ejected) and fuel became incandescent and started a number of fires, causing the main release of radioactivity into the environment. A total of about 14 EBq (14 x 10^{18} Bq) of radioactivity was released, over half of it being from biologically-inert noble gases.

About 200-300 tonnes of water per hour was injected into the intact half of the reactor using the auxiliary feedwater pumps but this was stopped after half a day owing to the danger of it flowing into and flooding units 1 and 2. From the second to tenth day after the accident, some 5000 tonnes of boron, dolomite, sand, clay and lead were dropped on to the burning core by helicopter in an effort to extinguish the blaze and limit the release of radioactive particles.

The damaged Chernobyl unit 4 reactor building

Immediate impact of the Chernobyl Accident

It is estimated that all of the xenon gas, about half of the iodine and caesium, and at least 5% of the remaining radioactive material in the Chernobyl 4 reactor core (which had 192 tonnes of fuel) was released in the accident. Most of the released material was deposited close by as dust and debris, but the lighter material was carried by wind over the Ukraine, Belarus, Russia and to some extent over Scandinavia and Europe.
The casualties included firefighters who attended the initial fires on the roof of the turbine building. All these were put out in a few hours, but radiation doses on the first day were estimated to range up to 20,000 millisieverts (mSv), causing 28 deaths – six of which were firemen – by the end of July 1986.

The next task was cleaning up the radioactivity at the site so that the remaining three reactors could be restarted, and the damaged reactor shielded more permanently. About 200,000 people (‘liquidators’) from all over the Soviet Union were involved in the recovery and clean-up during 1986 and 1987. They received high doses of radiation, averaging around 100 millisieverts. Some 20,000 of them received about 250 mSv and a few received 500 mSv. Later, the number of liquidators swelled to over 600,000 but most of these received only low radiation doses. The highest doses were received by about 1000 emergency workers and on-site personnel during the first day of the accident.

Initial radiation exposure in contaminated areas was due to short-lived iodine-131; later caesium-137 was the main hazard. (Both are fission products dispersed from the reactor core, with half lives of eight days and 30 years, respectively. 1.8 EBq of I-131 and 0.085 EBq of Cs-137 were released.) About five million people lived in areas contaminated (above 37 kBq/m² Cs-137) and about 400,000 lived in more contaminated areas of strict control by authorities (above 555 kBq/m² Cs-137).

The plant operators’ town of Pripyat was evacuated on 27 April (45,000 residents). By 14 May, some 116,000 people that had been living within a 30 kilometre radius had been evacuated and later relocated. About 1000 of these returned unofficially to live within the contaminated zone. Most of those evacuated received radiation doses of less than 50 mSv, although a few received 100 mSv or more.

In the years following the accident, a further 220,000 people were resettled into less contaminated areas, and the initial 30 km radius exclusion zone (2800 km²) was modified and extended to cover 4300 square kilometres. This resettlement was due to application of a criterion of 350 mSv projected lifetime radiation dose, though in fact radiation in most of the affected area (apart from half a square kilometre) fell rapidly so that average doses were less than 50% above normal background of 2.5 mSv/yr.

Environmental and health effects of the Chernobyl accident

Several organisations have reported on the impacts of the Chernobyl accident, but all have had problems assessing the significance of their observations because of the lack of reliable public health information before 1986.

In 1989, the World Health Organization (WHO) first raised concerns that local medical scientists had incorrectly attributed various biological and health effects to radiation exposure. Following this, the Government of the USSR requested the International Atomic Energy Agency (IAEA) to coordinate an international experts’ assessment of accident’s radiological, environmental and health consequences in selected towns of the most heavily contaminated areas in Belarus, Russia, and Ukraine. Between March 1990 and June 1991, a total of 50 field missions were conducted by 200 experts from 25 countries (including the USSR), seven organisations, and 11 laboratories. In the absence of pre-1986 data, it compared a control population with those exposed to radiation. Significant health disorders were evident in both control and exposed groups, but, at that stage,
none was radiation related.

Subsequent studies in the Ukraine, Russia and Belarus were based on national registers of over one million people possibly affected by radiation. By 2000, about 4000 cases of thyroid cancer had been diagnosed in exposed children. However, the rapid increase in thyroid cancers detected suggests that some of it at least is an artefact of the screening process. Thyroid cancer is usually not fatal if diagnosed and treated early.

In February 2003, the IAEA established the Chernobyl Forum, in cooperation with seven other UN organisations as well as the competent authorities of Belarus, the Russian Federation and Ukraine. In April 2005, the reports prepared by two expert groups – "Environment", coordinated by the IAEA, and "Health", coordinated by WHO – were intensively discussed by the Forum and eventually approved by consensus. The conclusions of this 2005 Chernobyl Forum study (revised version published 2006) are in line with earlier expert studies, notably the UNSCEAR 2000 report which said that "apart from this [thyroid cancer] increase, there is no evidence of a major public health impact attributable to radiation exposure 14 years after the accident. There is no scientific evidence of increases in overall cancer incidence or mortality or in non-malignant disorders that could be related to radiation exposure." As yet there is little evidence of any increase in leukaemia, even among clean-up workers where it might be most expected. However, these workers – where high
doses may have been received – remain at increased risk of cancer in the long term.

The Chernobyl Forum report says that people in the area have suffered a paralysing fatalism due to myths and misperceptions about the threat of radiation, which has contributed to a culture of chronic dependency. Some "took on the role of invalids." Mental health coupled with smoking and alcohol abuse is a very much greater problem than radiation, but worst of all at the time was the underlying level of health and nutrition. Apart from the initial 116,000, relocations of people were very traumatic and did little to reduce radiation exposure, which was low anyway. Psycho-social effects among those affected by the accident are similar to those arising from other major disasters such as earthquakes, floods and fires.

According to the most up-to-date estimate of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the average radiation dose due to the accident received by inhabitants of 'strict radiation control' areas (population 216,000) in the years 1986 to 2005 was 61 mSv (over the 20-year period), and in the 'contaminated' areas (population 6.4 million) it averaged 9 mSv, a minor increase over the dose due to background radiation over the same period (50 mSv).

The numbers of deaths resulting from the accident are covered in the Report of the Chernobyl Forum Expert Group "Health", and are summarised in Chernobyl Accident Appendix 2: Health Impacts.

Some exaggerated figures have been published regarding the death toll attributable to the Chernobyl disaster. A publication by the UN Office for the Coordination of Humanitarian Affairs (OCHA) lent support to these. However, the Chairman of UNSCEAR made it clear that "this report is full of unsubstantiated statements that have no support in scientific assessments", and the Chernobyl Forum report also repudiates them.

**Progressive closure of the Chernobyl plant**

In the early 1990s, some US$400 million was spent on improvements to the remaining reactors at Chernobyl, considerably enhancing their safety. Energy shortages necessitated the continued operation of one of them (unit 3) until December 2000. (Unit 2 was shut down after a turbine hall fire in 1991, and unit 1 at the end of 1997.) Almost 6000 people worked at the plant every day, and their radiation dose has been within internationally accepted limits. A small team of scientists works within the wrecked reactor building itself, inside the shelter.

Workers and their families now live in a new town, Slavutich, 30 km from the plant. This was built following the evacuation of Pripyat, which was just 3 km away.

Ukraine depends upon, and is deeply in debt to, Russia for energy supplies, particularly oil and gas, but also nuclear fuel. Although this dependence is gradually being reduced, continued operation of nuclear power stations, which supply half of total electricity, is now even more important than in 1986.

When it was announced in 1995 that the two operating reactors at Chernobyl would be closed by 2000, a memorandum of understanding was signed by Ukraine and G7 nations to progress this, but its implementation was conspicuously delayed. Alternative generating capacity was needed, either gas-fired, which has ongoing fuel cost and supply implications, or nuclear, by completing...
The Chernobyl accident in 1986 was the result of a flawed reactor design that was not emphasised in the Vital Safety Report (VSR).

Two Chernobyl plant workers died on the night of the accident, and a further 28 people were killed in the re-entry rescue mission. The resulting steam explosion and fires released at least 5% of the radioactive reactor core into the atmosphere and downwind.

Effects of Atomic Radiation (UNSCEAR), the average radiation dose due to the accident received by the population of the affected area is estimated to be 20 millisieverts (mSv) per person. This is 20 times the average radiation dose for the population of the rest of the world. Of this, about 10 mSv was from external radiation exposure and the rest from internal exposure to radioactive iodine.

The IAEA/PI/A32E, 1991; Appendix 1: Sequence of Events

The accident occurred on 26 April 1986 during a routine maintenance operation on Reactor 4. The operators did not follow the instructions of the reactor operation manual by maintaining the reactor water inventory. The reactor was placed in a dangerous state by the operators, and the reactor core overheated, causing a pressure release in the steam generators. The steam pressure release was not observed by the operators, who continued to operate the reactor at high power levels. When the pressure relief valves opened, the reactor core and graphite were exposed to a high-temperature environment, leading to a series of events that caused the reactor to become uncontrolled and lose coolant, resulting in a steam explosion.

The Chernobyl Forums: 2003

A New Safe Confinement structure will be built by the end of 2011, and then will be moved into place on rails. It is to be an 18,000 tonne metal arch 105 metres high, 200 metres long and spanning 257 metres, to cover both unit 4 and the hastily-built 1986 structure. The Chernobyl Shelter Fund, set up in 1997, had received €810 million from international donors and projects towards this project and previous work. It and the Nuclear Safety Account, also applied to Chernobyl decommissioning, are managed by the European Bank for Reconstruction and Development (EBRD), which announced a €135 million contribution to the fund in May 2008. The total cost of the new shelter is estimated to be €1.2 billion.

Used fuel from units 1 to 3 is stored in each unit's cooling pond, in a small interim spent fuel storage facility pond (ISF-1), and in the reactor of unit 3.

In 1999, a contract was signed for construction of a radioactive waste management facility to store 25,000 used fuel assemblies from units 1-3 and other operational wastes, as well as material from decommissioning units 1-3 (which will be the first RBMK units decommissioned anywhere). The contract included a processing facility, able to cut the RBMK fuel assemblies and to put the material in canisters, which will be filled with inert gas and welded shut. They will then be transported to the dry storage vaults in which the fuel containers would be enclosed for up to 100 years. This facility, treating 2500 fuel assemblies per year, would be the first of its kind for RBMK fuel. However, after a significant part of the storage structures had been built, technical deficiencies in the concept emerged, and the contract was terminated in 2007. The interim spent fuel storage facility (ISF-2) is now planned to be completed by others by mid-2013.

In April 2009, Nukem handed over a turnkey waste treatment centre for solid radioactive waste (ICSRM, Industrial Complex for Radwaste Management). In May 2010, the State Nuclear Regulatory Committee licensed the commissioning of this facility, where solid low- and intermediate-level wastes accumulated from the power plant operations and the decommissioning of reactor blocks 1 to 3 is conditioned. The wastes are processed in three steps. First, the solid radioactive wastes temporarily stored in bunkers is removed for treatment. In the next step, these wastes, as well as those from decommissioning reactor blocks 1-3, are processed into a form suitable for permanent safe disposal. Low- and intermediate-level wastes are separated into combustible, compactable, and non-compactable categories. These are then subject to incineration, high-force compaction, and cementation respectively. In addition, highly radioactive and long-lived solid waste is sorted out for temporary separate storage. In the third step, the conditioned solid waste materials are transferred to containers suitable for permanent safe storage.
As part of this project, at the end of 2007, Nukem handed over an Engineered Near Surface Disposal Facility for storage of short-lived radioactive waste after prior conditioning. It is 17 km away from the power plant at the Vektor complex within the 30-km zone. The storage area is designed to hold 55,000 m³ of treated waste which will be subject to radiological monitoring for 300 years, by when the radioactivity will have decayed to such an extent that monitoring is no longer required.

Another contract has been let for a Liquid Radioactive Waste Treatment Plant, to handle some 35,000 cubic metres of low- and intermediate-level liquid wastes at the site. This will need to be solidified and eventually buried along with solid wastes on site.

In January 2008, the Ukraine government announced a four-stage decommissioning plan which incorporates the above waste activities and progresses towards a cleared site.

Resettlement of contaminated areas

In the last two decades there has been some resettlement of the areas evacuated in 1986 and subsequently. Recently the main resettlement project has been in Belarus.

In July 2010, the Belarus government announced that it had decided to settle back thousands of people in the ‘contaminated areas’ covered by the Chernobyl fallout, from which 24 years ago they and their forbears were hastily relocated. Compared with the list of contaminated areas in 2005, some 211 villages and hamlets had been reclassified with fewer restrictions on resettlement. The decision by the Belarus Council of Ministers resulted in a new national program over 2011-15 and up to 2020 to alleviate the Chernobyl impact and return the areas to normal use with minimal restrictions. The focus of the project is on the development of economic and industrial potential of the Gomel and Mogilev regions from which 137,000 people were relocated.

The main priority is agriculture and forestry, together with attracting qualified people and housing them. Initial infrastructure requirements will mean the refurbishment of gas, potable water and power supplies, while the use of local wood will be banned. Schools and housing will be provided for specialist workers and their families ahead of wider socio-economic development. Overall, some 21,484 dwellings are slated for connection to gas networks in the period 2011-2015, while about 5600 contaminated or broken down buildings are demolished. Over 1300 kilometres of road will be laid, and ten new sewerage works and 15 pumping stations are planned. The cost of the work was put at BYR 6.6 trillion ($2.2 billion), split fairly evenly across the years 2011 to 2015 inclusive.

The feasibility of agriculture will be examined in areas where the presence of caesium-137 and strontium-90 is low, "to acquire new knowledge in the fields of radiobiology and radioecology in order to clarify the principles of safe life in the contaminated territories." Land found to have too high a concentration of radionuclides will be reforested and managed. A suite of protective measures is to be set up to allow a new forestry industry whose products would meet national and international safety standards. In April 2009, specialists in Belarus stressed that it is safe to eat all foods cultivated in the contaminated territories, though intake of some wild food was restricted.

Protective measures will be put in place for 498 settlements in the contaminated areas where average radiation dose may exceed 1 mSv per year. There are also 1904 villages with annual average effective doses from the pollution between 0.1 mSv and 1 mSv. The goal for these areas is to allow their re-use with minimal restrictions, although already radiation doses there from the caesium are lower than background levels anywhere in the world. The most affected settlements...
are to be tackled first, around 2011-2013, with the rest coming back in around 2014-2015.

What has been learnt from the Chernobyl disaster?

Leaving aside the verdict of history on its role in melting the Soviet 'Iron Curtain', some very tangible practical benefits have resulted from the Chernobyl accident. The main ones concern reactor safety, notably in eastern Europe. (The US Three Mile Island accident in 1979 had a significant effect on Western reactor design and operating procedures. While that reactor was destroyed, all radioactivity was contained—as designed—and there were no deaths or injuries.)

While no-one in the West was under any illusion about the safety of early Soviet reactor designs, some lessons learned have also been applicable to Western plants. Certainly the safety of all Soviet-designed reactors has improved vastly. This is due largely to the development of a culture of safety encouraged by increased collaboration between East and West, and substantial investment in improving the reactors.

Modifications have been made to overcome deficiencies in all the RBMK reactors still operating. In these, originally the nuclear chain reaction and power output could increase if cooling water were lost or turned to steam, in contrast to most Western designs. It was this effect which led to the uncontrolled power surge that led to the destruction of Chernobyl 4 (see Positive void coefficient section in the information page on RBMK Reactors). All of the RBMK reactors have now been modified by changes in the control rods, adding neutron absorbers and consequently increasing the fuel enrichment from 1.8 to 2.4% U-235, making them very much more stable at low power (see Post accident changes to the RBMK section in the information page on RBMK Reactors). Automatic shut-down mechanisms now operate faster, and other safety mechanisms have been improved. Automated inspection equipment has also been installed. A repetition of the 1986 Chernobyl accident is now virtually impossible, according to a German nuclear safety agency report.

Since 1989, over 1000 nuclear engineers from the former Soviet Union have visited Western nuclear power plants and there have been many reciprocal visits. Over 50 twinning arrangements between East and West nuclear plants have been put in place. Most of this has been under the auspices of the World Association of Nuclear Operators (WANO), a body formed in 1989 which links 130 operators of nuclear power plants in more than 30 countries (see also information page on Cooperation in the Nuclear Power Industry).

Many other international programmes were initiated following Chernobyl. The International Atomic Energy Agency (IAEA) safety review projects for each particular type of Soviet reactor are noteworthy, bringing together operators and Western engineers to focus on safety improvements. These initiatives are backed by funding arrangements. The Nuclear Safety Assistance Coordination Centre database lists Western aid totalling almost US$1 billion for more than 700 safety-related projects in former Eastern Bloc countries. The Convention on Nuclear Safety adopted in Vienna in June 1994 is another outcome.

The Chernobyl Forum report said that some seven million people are now receiving or eligible for benefits as 'Chernobyl victims', which means that resources are not targeting the needy few percent of them. Remedying this presents daunting political problems however.
The Chernobyl accident in 1986 was the result of a flawed reactor design that was…

Notes

a. Chernobyl is the well-known Russian name for the site; Chornobyl is preferred by Ukraine. [Back]

b. Much has been made of the role of the operators in the Chernobyl accident. The 1986 Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident (INSAG-1) of the International Atomic Energy Agency's (IAEA's) International Nuclear Safety Advisory Group accepted the view of the Soviet experts that "the accident was caused by a remarkable range of human errors and violations of operating rules in combination with specific reactor features which compounded and amplified the effects of the errors and led to the reactivity excursion." In particular, according to the INSAG-1 report: "The operators deliberately and in violation of rules withdrew most control and safety rods from the core and switched off some important safety systems."

However, the IAEA's 1992 INSAG-7 report, The Chernobyl Accident: Updating of INSAG-1, was less critical of the operators, with the emphasis shifted towards "the contributions of particular design features, including the design of the control rods and safety systems, and arrangements for presenting important safety information to the operators. The accident is now seen to have been the result of the concurrence of the following major factors: specific physical characteristics of the reactor; specific design features of the reactor control elements; and the fact that the reactor was brought to a state not specified by procedures or investigated by an independent safety body. Most importantly, the physical characteristics of the reactor made possible its unstable behaviour." But the report goes on to say that the International Nuclear Safety Advisory Group "remains of the opinion that critical actions of the operators were most ill judged. As pointed out in INSAG-1, the human factor has still to be considered as a major element in causing the accident."

It is certainly true that the operators placed the reactor in a dangerous condition, in particular by removing too many of the control rods, resulting in the lowering of the reactor's operating reactivity margin (ORM, see information page on RBMK Reactors). However, the operating procedures did not emphasise the vital safety significance of the ORM but rather treated the ORM as a way of controlling reactor power. It could therefore be argued that the actions of the operators were more a symptom of the prevailing safety culture of the Soviet era rather than the result of recklessness or a lack of competence on the part of the operators (see Appendix to information page on Nuclear Power in Russia, Soviet Nuclear Culture).

In what is referred to as his Testament – which was published soon after his suicide two years after the accident – Valery Legasov, who had led the Soviet delegation to the IAEA Post-Accident Review Meeting, wrote: "After I had visited Chernobyl NPP I came to the conclusion that the accident was the inevitable apotheosis of the economic system which had been developed in the USSR over many decades. Neglect by the scientific management and the designers was everywhere with no attention being paid to the condition of instruments or of equipment... When one considers the chain of events leading up to the Chernobyl accident, why one person behaved in such a way and why another person behaved in another etc, it is impossible to find a single culprit, a single initiator of events, because it was like a closed circle." [Back]

c. The initial death toll was officially given as two initial deaths plus 28 from acute radiation syndrome. One further victim, due to coronary thrombosis, is widely reported, but does not appear on official lists of the initial deaths. The 2006 report of the UN Chernobyl Forum Expert Group "Health", Health Effects of the Chernobyl Accident and Special Health Care Programmes, states:
The Chernobyl accident caused the deaths of 30 power plant employees and firemen within a few days or weeks (including 28 deaths that were due to radiation exposure)." [Back]

d. Apart from the initial 31 deaths (two from the explosions, one reportedly from coronary thrombosis – see Note c above – and 28 firemen and plant personnel from acute radiation syndrome), the number of deaths resulting from the accident is unclear and a subject of considerable controversy. According to the 2006 report of the UN Chernobyl Forum's 'Health' Expert Group¹: "The actual number of deaths caused by this accident is unlikely ever to be precisely known."

On the number of deaths due to acute radiation syndrome (ARS), the Expert Group report states: "Among the 134 emergency workers involved in the immediate mitigation of the Chernobyl accident, severely exposed workers and fireman during the first days, 28 persons died in 1986 due to ARS, and 19 more persons died in 1987-2004 from different causes. Among the general population affected by the Chernobyl radioactive fallout, the much lower exposures meant that ARS cases did not occur."

According to the report: "With the exception of thyroid cancer, direct radiation-epidemiological studies performed in Belarus, Russia and Ukraine since 1986 have not revealed any statistically significant increase in either cancer morbidity or mortality induced by radiation." The report does however attribute a large proportion of child thyroid cancer fatalities to radiation, with nine deaths being recorded during 1986-2002 as a result of progression of thyroid cancer.

A summary of the estimates by the Expert Group of the total number of deaths can be found in Chernobyl Accident Appendix 2: Health Impacts. [Back]

e. There have been fatalities in military and research reactor contexts, e.g. Tokai-mura. [Back]

f. Although most reports on the Chernobyl accident refer to a number of graphite fires, it is highly unlikely that the graphite itself burned. According to the General Atomics website (http://gt-mhr.ga.com/safety.php): "It is often incorrectly assumed that the combustion behavior of graphite is similar to that of charcoal and coal. Numerous tests and calculations have shown that it is virtually impossible to burn high-purity, nuclear-grade graphites." On Chernobyl, the same source states: "Graphite played little or no role in the progression or consequences of the accident. The red glow observed during the Chernobyl accident was the expected color of luminescence for graphite at 700°C and not a large-scale graphite fire, as some have incorrectly assumed."

A 2006 Electric Power Research Institute Technical Report² states that the International Atomic Energy Agency's INSAG-1 report is...
potentially misleading through the use of imprecise words in relation to graphite behaviour. The report discusses the fire-fighting activities and repeatedly refers to "burning graphite blocks" and "the graphite fire". Most of the actual fires involving graphite which were approached by fire-fighters involved ejected material on bitumen-covered roofs, and the fires also involved the bitumen. It is stated: "The fire teams experienced no unusual problems in using their fire-fighting techniques, except that it took a considerable time to extinguish the graphite fire." These descriptions are not consistent with the later considered opinions of senior Russian specialists... There is however no question that extremely hot graphite was ejected from the core and at a temperature sufficient to ignite adjacent combustible materials.

There are also several referrals to a graphite fire occurring during the October 1957 accident at Windscale Pile No. 1 in the UK. However, images obtained from inside the Pile several decades after the accident showed that the graphite was relatively undamaged. [Back]

g. The International Chernobyl Project, 1990-91 - Assessment of Radiological Consequences and Evaluation of Protective Measures, Summary Brochure, published by the International Atomic

http://www.world-nuclear.org/info/chernobyl/inf07.html
Energy Agency, reports that, in June 1989, the World Health Organization (WHO) sent a team of experts to help address the health impacts of radioactive contamination resulting from the accident. One of the conclusions from this mission was that "scientists who are not well versed in radiation effects have attributed various biological and health effects to radiation exposure. These changes cannot be attributed to radiation exposure, especially when the normal incidence is unknown, and are much more likely to be due to psychological factors and stress. Attributing these effects to radiation not only increases the psychological pressure in the population and provokes additional stress-related health problems, it also undermines confidence in the competence of the radiation specialists." [Back]


k. The quoted comment comes from a 6 June 2000 letter from Lars-Erik Holm, Chairman of UNSCEAR and Director-General of the Swedish Radiation Protection Institute, to Kofi Annan, Secretary-General of the United Nations. The letter is available on the website of Radiation, Science, and Health (www.radscihealth.org/rsh/) [Back]

l. A reinforced concrete casing was built around the ruined reactor building over the seven months following the accident. This shelter – often referred to as the sarcophagus – was intended to contain the remaining fuel and act as a radiation shield. As it was designed for a lifetime of around 20 to 30 years, as well as being hastily constructed, a second shelter – known as the New Safe Confinement – with a 100-year design lifetime is planned to be placed over the existing structure. See also ASE keeps the lid on Chernobyl, World Nuclear News (19 August 2008). [Back]

References

The Chernobyl accident in 1986 was the result of a flawed reactor design that was...
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General of the United Nations. The letter is available on the website of Radiation,
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GreenFacts webpage on Scientific Facts on the Chernobyl Nuclear Accident
(www.greenfacts.org/en/chernobyl)

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Chernobyl Legacy website (www.chernobyllegacy.com)
Sequence of Events

Chernobyl Accident Appendix 1

(Updated November 2009)

During the course of a safety system test being carried out just before a routine maintenance outage, Chernobyl 4 was destroyed as a result of a power transient on 26 April 1986.

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

The accident

The unit 4 reactor was to be shut down for routine maintenance on 25 April 1986. It was decided to take advantage of this shutdown to determine whether, in the event of a loss of station power, the slowing turbine could provide enough electrical power to operate the main core cooling water circulating pumps, until the diesel emergency power supply became operative. The aim of this test was to determine whether cooling of the core could continue to be ensured in the event of a loss of power. (Adequate coolant circulation following completion of the test was ensured by arranging power supplies to four of the eight pumps from station service power; the other four pumps were supplied by unit service power.)

This type of test had been run the previous year, but the power delivered from the running down turbine fell off too rapidly, so it was decided to repeat the test using the new voltage regulators that had been developed. Unfortunately, this test, which was considered essentially to concern the non-nuclear part of the power plant, was carried out without a proper exchange of information and coordination between the team in charge of the test and the personnel in charge of the safety of the nuclear reactor. Therefore, inadequate safety precautions were included in the test programme and the operating personnel were not alerted to the nuclear safety implications of the electrical test and its potential danger.

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

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

For this test, the reactor should have been stabilised at about 700-1000 MWt prior to shutdown, but
possibly due to operational error the power fell to about 30 MW\textsuperscript{b} at 00:28 on 26 April. Efforts to increase the power to the level originally planned for the test were frustrated by a combination of xenon poisoning\textsuperscript{c}, reduced coolant void and graphite cooldown. Many of the control rods were withdrawn to compensate for these effects, resulting in a violation of the minimum operating reactivity margin\textsuperscript{d} (ORM, see \textit{Positive void coefficient} section in the information page on RBMK Reactors) by 01:00 - although the operators may not have known this. At 01:03, the reactor was stabilised at about 200 MWt and it was decided that the test would be carried out at this power level.

Calculations performed after the accident showed that the ORM at 01:22:30 was equal to eight manual control rods. The minimum permissible ORM stipulated in the operating procedures was 15 rods. The test commenced at 01:23:04; the turbine stop valves were closed and the four pumps powered by the slowing turbine started to run down. The slower flowrate, together with the entry to the core of slightly warmer feedwater, may have caused boiling (void formation) at the bottom of the core. This, along with xenon burnout, could have resulted in a runaway increase in power. An alternative view is that the power excursion was triggered by the insertion of the control rods\textsuperscript{e} after the scram button was pressed (at 01:23:40)\textsuperscript{f}.

At 01:23:43, the power excursion rate emergency protection system signals came on and power exceeded 530 MWt and continued to rise. Fuel elements ruptured, leading to increased steam generation, which in turn further increased power owing to the large positive void coefficient. Damage to even three or four fuel assemblies would have been enough to lead to the destruction of the reactor. The rupture of several fuel channels increased the pressure in the reactor to the extent that the 1000 t reactor support plate became detached, consequently jamming the control rods, which were only halfway down by that time. As the channel pipes began to rupture, mass steam generation occurred as a result of depressurisation of the reactor cooling circuit. A note in the operating log of the Chief Reactor Control Engineer reads: "01:24: Severe shocks; the RCPS rods stopped moving before they reached the lower limit stop switches; power switch of clutch mechanisms is off."

Two explosions were reported, the first being the initial steam explosion, followed two or three seconds later by a second explosion, possibly from the build-up of hydrogen due to zirconium-steam reactions. Fuel, moderator, and structural materials were ejected, starting a number of fires, and the destroyed core was exposed to the atmosphere. One worker, whose body was never recovered, was killed in the explosions, and a second worker died in hospital a few hours later as a result of injuries received in the explosions.

Some media had reported a seismic origin of the accident, however the scientific credibility of the paper at the origin of this rumour has been discarded.

\textbf{Consequences of the accident}

The plume of smoke, radioactive fission products and debris from the core and the building rose up to about 1 km into the air. The heavier debris in the plume was deposited close to the site, but lighter components, including fission products and virtually all of the noble gas inventory were blown by the prevailing wind to the northwest of the plant.

Fires started in what remained of the unit 4 building, giving rise to clouds of steam and dust, and fires also broke out on the adjacent turbine hall roof (bitumen, a flammable material, had been used
The scheduled shutdown of the reactor started. Gradual lowering of the power level began.

INSAG-1 report suggests: "The fires on the roofs of units 3 and 4 were localized at 02:10 and 02:20 respectively, and the fire was quenched at 05:00." Unit 3, which had continued to operate, was shut down at this time, and units 1 and 2 were shut down in the morning of 27 April.

"The main challenges were to prevent the fire from spreading to unit 3, to localize the fire on the roof of the common machine hall of units 3 and 4, to protect the undamaged parts of unit 4 (the control room, inside the machine room, the main circulating pump compartments the cable trays), and to protect the flammable materials stored on-site, such as diesel oil, stored gas and chemicals.

Initially, attempts to introduce water into the reactor core were unsuccessful. Water fed in by the emergency feedwater pumps injected at a rate of 200-300 tonnes/hr went to other parts of the damaged primary circuit. When it was realised that this water flowed in the direction of units 1 and 2, water injection was stopped after half a day. Steam and white smoke from the reactor well were observed on the first day of the accident, but no steam was seen on the second day.

On 28 April, a massive accident management operation began. This involved involved dropping large amounts of different materials, each one designed to combat a different feature of the fire and the radioactive release. The first measures taken to control fire and the radionuclides releases consisted of dumping neutron-absorbing compounds and fire-control material into the crater that resulted from the destruction of the reactor. The total amount of materials dumped on the reactor was about 5000 t including about 40t of boron carbide, 2400 t of lead, 1800 t of sand and clay, and 800 t of dolomite. About 1800 helicopter flights were carried out to dump materials onto the reactor.

During the first flights, the helicopter remained stationary over the reactor while dumping materials. As the dose rates received by the helicopter pilots during this procedure were too high, it was decide that the materials should be dumped while the helicopters travelled over the reactor. This procedure caused additional destruction of the standing structures and spread the contamination. Boron carbide was dumped in large quantities from helicopters to act as a neutron absorber and prevent any renewed chain reaction. Dolomite was also added to act as heat sink and a source of carbon dioxide to smother the fire. Lead was included as a radiation absorber, as well as sand and clay which it was hoped would prevent the release of particulates. While it was later discovered that many of these compounds were not actually dropped on the target, they may have acted as thermal insulators and precipitated an increase in the temperature of the damaged core leading to a further release of radionuclides a week later.

A system was installed by 5 May to feed cold nitrogen to the reactor space, to provide cooling and to blanket against oxygen. By 6 May the core temperature had fallen and there was sharp reduction in the rate of radionuclide release. In addition, work began on a massive reinforced concrete slab...
with a built-in cooling system beneath the reactor. This involved digging a tunnel from underneath unit 3. About 400 people worked on this tunnel which was completed in 15 days, allowing the installation of the concrete slab. This slab would not only be of use to cool the core if necessary, it would also act as a barrier to prevent penetration of melted radioactive material into the groundwater.

In addition to the two workers that had died from the explosions on the day of the accident, by the end of July, six firemen and a further 22 plant staff (including one person that was at the site on business) had died of acute radiation poisoning as a result of the accident.

**Accident timeline**

*The sequence of events which follows has been compiled following a review of a large number of reports and it represents what is considered the most likely sequence of events, but there remain some uncertainties.*

<table>
<thead>
<tr>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>April 25</strong></td>
<td></td>
</tr>
<tr>
<td>01:06</td>
<td>The scheduled shutdown of the reactor started. Gradual lowering of the power level began.</td>
</tr>
<tr>
<td>03:47</td>
<td>Lowering of reactor power halted at 1600 MW(thermal).</td>
</tr>
<tr>
<td>14:00</td>
<td>The emergency core cooling system (ECCS) was isolated (part of the test procedure) to prevent it from interrupting the test later. The fact that the ECCS was isolated did not contribute to the accident; however, had it been available it might have reduced the impact slightly.</td>
</tr>
<tr>
<td>23:10</td>
<td>Power reduction recommenced.</td>
</tr>
<tr>
<td>24:00</td>
<td>Shift change.</td>
</tr>
<tr>
<td><strong>April 26</strong></td>
<td></td>
</tr>
<tr>
<td>00:05</td>
<td>Power level had been decreased to 720 MWt and continued to be reduced. Although INSAG-1 stated that operation below 700 MWt was forbidden, sustained operation of the reactor below this level was not proscribed.</td>
</tr>
<tr>
<td>00:28</td>
<td>With the power level at about 500 MWt, control was transferred from the local to the automatic regulating system. The operator might have failed to give the 'hold power at required level' signal or the regulating system failed to respond to this signal. This led to an unexpected fall in power, which rapidly dropped to 30 MWt.</td>
</tr>
<tr>
<td>00:43:27</td>
<td>Turbogenerator trip signal blocked in accordance with operational and test procedures. INSAG-1 incorrectly reported this event occurring at 01:23:04 and stated: &quot;This trip would have saved the reactor.&quot; However, it is more likely that disabling this trip only delayed the onset of the accident by 39 seconds.</td>
</tr>
<tr>
<td>01:00</td>
<td>The reactor power had risen to 200 MWt and stabilised. Although the operators may not have known it, the required operating reactivity margin (ORM) of 15 rods had been violated. The decision was made to carry out the turbogenerator rundown tests at a power level of about 200 MWt.</td>
</tr>
<tr>
<td>01:03</td>
<td>A standby main circulation pump was switched into the left hand cooling circuit in order to increase the water flow to the core (part of the test procedure).</td>
</tr>
<tr>
<td>01:07</td>
<td>An additional cooling pump was switched into the right hand cooling circuit (part of the test procedure). Operation of additional pumps removed heat from the core more quickly leading to decreased reactivity, necessitating further absorber rod removal to prevent power levels falling. The pumps delivered excessive flow to the point where they exceeded their allowed limits. Increased core flow led to problems with the level in the steam drum.</td>
</tr>
<tr>
<td>01:19</td>
<td>The steam drum level was still near the emergency level. To compensate, the operator increased feedwater flow. This raised the drum level, but further reduced reactivity to the system. The automatic control rods went up to the upper tie plate to compensate but further withdrawal of manual rods was required to maintain the reactivity balance. System pressure began to fall and, to stabilise pressure, the steam turbine bypass valve was shut off. Since the operators were having trouble with the pressure and level control, they deactivated the automatic trip systems to the steam drum around this time.</td>
</tr>
<tr>
<td>01:22:30</td>
<td>Calculations performed after the accident found that the ORM at this point proved to be equal to eight control rods. Operating policy required that a minimum ORM of 15 control rods be inserted in the reactor at all times.</td>
</tr>
</tbody>
</table>
| 01:23   | Reactor parameters stabilised. The unit shift supervisors considered that preparations for the tests had
Turbine feed valves closed to start turbine coasting. This was the beginning of the actual test. According to Annex I of INSAG-7, for the following approximately 30 seconds of rundown of the four coolant pumps, "the parameters of the unit were controlled, remained within the limits expected for the operating conditions concerned, and did not require any intervention on the part of the personnel."

The emergency button (AZ 5) was pressed by the operator. Control rods started to enter the core, increasing the reactivity at the bottom of the core.

Power excursion rate emergency protection system signals on; power exceeded 530 MWt.

Disconnection of the first pair of main circulating pumps (MCPs) being 'run down', followed immediately by disconnection of the second pair.

Sharp reduction in the flow rates of the MCPs not involved in the rundown test and unreliable readings in the MCPs involved in the test; sharp increase in pressure in the steam separator drums; sharp increase in the water level in the steam separator drums.

Restoration of flow rates of MCPs not involved in the rundown test to values close to the initial ones; restoration of flow rates to 15% below the initial rate for the MCPs on the left side which were being run down; restoration of flow rates to 10% below the initial rate for one of the other MCPs involved in the test and unreliable readings for the other one; further increase of pressure in the steam separator drums and of water level in the steam separator drums; triggering of fast acting systems for dumping of steam to condensers.

Emergency protection signal 'Pressure increase in reactor space (rupture of a fuel channel)'; 'No voltage - 48 V' signal (no power supply to the servodrive mechanisms of the EPS); 'Failure of the actuators of automatic power controllers Nos 1 and 2' signals.

From a note in the chief reactor control engineer's operating log: "01:24: Severe shocks; the RCPS rods stopped moving before they reached the lower limit stop switches; power switch of clutch mechanisms is off."

Further Information

Notes

a. Much of the account in this Appendix is based on the International Atomic Energy Agency's INSAG-7 report (see Reference 1 below), which maintains that the operating rules were violated by the operators. However, there remains considerable uncertainty over whether or not they did comply with procedures, since the operating procedures themselves were ambiguous. The plant's Deputy Chief Engineer at that time, Anatoly Dyatlov, acknowledged that he took the decision to run the test at a lower power level than he had originally planned, but argued that the lower power level was permitted by the regulations. [Back]

b. The drop in power occurred at 00:28 on 26 April during transfer from local to global power control. The INSAG-7 report (see Reference 1 below) states: "The INSAG-1 report describes the precipitous fall in power to 30 MW(th) as being due to an operator error. Recent reports suggest that there was no operator error as such; the SCSSINP Commission report (Annex I, Sections 1-4.6, 1-4.7) refers to an unknown cause and inability to control the power, and A.S. Dyatlov, former Deputy Chief Engineer for Operations at the Chernobyl plant, in a private communication refers to the system not working properly." [Back]

c. Xenon poisoning was a significant contributor to the Chernobyl accident. Xenon-135 is produced in the reactor by the decay of the fission product iodine-135 (I-135). As I-135 has a half-life of 6.7 hours, Xe-135 will continue to build up after a reactor has been shut down. (Xe-135 itself has a half-life of 9.2 hours, so will eventually decay.) Xe-135 is a very strong neutron absorber and is 'burned' in the process of absorbing neutrons. During normal operation, the production of Xe-135 is
balanced by the reaction rate. When the power of the Chernobyl 4 reactor dropped at 00:28 on 26 April, Xe-135 would have built up making it difficult to raise the reactor power. Attempts to raise the reactor power at this point led to so many control rods being withdrawn that the emergency protection system was brought to a state where termination of the nuclear reaction could not be guaranteed. [Back]

d. The operating reactivity margin (ORM) is simply the number of equivalent control rods remaining in the core. According to the INSAG-7 report (see Reference 1 below): "The definition is not precise, and the importance of the quantity for the safety of the plant seems to have been poorly understood by the operators... The magnitude of the ORM was not conveniently available to the operator, nor was it incorporated into the reactor's protection system." [Back]

e. It is possible that the design of the RBMK emergency protection system control rods was responsible for triggering the power surge that initiated the accident. A lower graphite 'displacer' is attached to the ends of the boron carbide absorber rods to prevent coolant water from entering the space vacated as the rod is withdrawn, thereby adding to the reactivity worth of the rod. As a fully withdrawn rod is inserted, an area at the bottom of the core that initially contains water (neutron absorbing) is replaced by the graphite displacer, adding to the reactivity in this region. According to the INSAG-7 report (see Reference 1 below): "The dimensions of rod and displacer were such that when the rod was fully extracted the displacer sat centrally within the fuelled region of the core with 1.25 m of water at either end. On receipt of a scram signal causing a fully withdrawn rod to fall, the displacement of water from the lower part of the channel as the rod moved downwards from its upper limit stop position caused a local insertion of positive reactivity in the lower part of the core. The magnitude of this 'positive scram' effect depended on the spatial distribution of the power density and the operating regime of the reactor." This effect had been identified at the Ignalina plant in 1983 and restrictions on the complete withdrawal of control and safety rods were intended to be imposed. However, "such restrictions were never imposed and apparently the matter was forgotten." See also see Post accident changes to the RBMK section in the information page on RBMK Reactors.

The Report by a Commission to the USSR State Committee for the Supervision of Safety in Industry and Nuclear Power (SCSSINP), Annex I of INSAG-7, states: "The event which initiated the accident was the pressing of the EPS-5 [scram] button when the RBMK-1000 reactor was operating at low power with a greater than permissible number of manual control rods withdrawn from the reactor." [Back]

f. It has not been established why the scram button (EPS-5, also referred to as AZ-5) was pressed at 1:23:40. Annex I of the INSAG-7 report (see Reference 1 below), Report by a Commission to the USSR State Committee for the Supervision of Safety in Industry and Nuclear Power (SCSSINP), states: "Neither the reactor power nor the other parameters (pressure and water level in the steam separator drums, coolant and feedwater flow rates, etc.) required any intervention by the personnel or by the engineered safety features from the beginning of the tests until the EPS-5 button was pressed." The report adds: "The Commission was unable to establish why the button was pressed." However, according to Anatoly Diatlov, the plant's Deputy Chief Engineer at that time: "There was actually one reason for dropping the protection rods: a wish to shut down the reactor when work was finished". [Back]

g. Most reports refer to a graphite fire. However, it is highly unlikely that the graphite itself burned. According to the General Atomics website (http://gt-mhr.ga.com/safety.php): "It is often incorrectly assumed that the combustion behavior of graphite is similar to that of charcoal and coal. Numerous
tests and calculations have shown that it is virtually impossible to burn high-purity, nuclear-grade graphites." On Chernobyl, the same source states: "Graphite played little or no role in the progression or consequences of the accident. The red glow observed during the Chernobyl accident was the expected color of luminescence for graphite at 700°C and not a large-scale graphite fire, as some have incorrectly assumed."

While *INSAG-1* states that the fires were extinguished at 05:00 on the day of the accident, many accounts report that the 'graphite fire' burned for nine days before being extinguished. [Back]

References


Health Impacts

Chernobyl Accident Appendix 2

(Updated November 2009)

The health effects of the Chernobyl accident have been the subject of unprecedented study by health professionals and unprecedented speculation and exaggeration by parts of the media. This Appendix summarises the following authoritative and expert assessments of the situation:

- The 2006 report of the World Health Organization (WHO), Health Effects of the Chernobyl Accident and Special Health Care Programmes.
- Estimated Long Term Health Effects of the Chernobyl Accident, Background Paper 3 of the April 1996 conference in Vienna, One Decade After Chernobyl.

Number of deaths

Apart from the initial 31 deaths (two from the explosions, one reportedly from coronary thrombosis (heart attack), and 28 firemen and plant personnel from acute radiation syndrome), the number of deaths resulting from the accident is unclear and a subject of considerable controversy. According to the 2006 report of the UN Chernobyl Forum's 'Health' Expert Group: "The actual number of deaths caused by this accident is unlikely ever to be precisely known."

On the number of deaths due to acute radiation syndrome (ARS), the Expert Group report states: "Among the 134 emergency workers involved in the immediate mitigation of the Chernobyl accident, severely exposed workers and fireman during the first days, 28 persons died in 1986 due to ARS, and 19 more persons died in 1987-2004 from different causes. Among the general population affected by the Chernobyl radioactive fallout, the much lower exposures meant that ARS cases did not occur.

Studies have been carried out to estimate the number of other fatalities amongst the emergency workers as well as the population of the contaminated areas.

Regarding the emergency workers with doses lower than those causing ARS symptoms, the Expert Group report referred to studies carried out on 61,000 emergency Russian workers where a total of 4995 deaths from this group were recorded during 1991-1998. "The number of deaths in Russian emergency workers attributable to radiation caused by solid neoplasms and circulatory system diseases can be estimated to be about 116 and 100 cases respectively." Furthermore, "the number of leukaemia cases attributable to radiation in this cohort can be estimated to be about 30." Thus, 4.6% of the number of deaths in this group are attributable to radiation-induced diseases. (The estimated average external dose for this group was 107 mSv.) From this study, it could be possible to arrive at an estimate of the mortality rate attributable to Chernobyl radiation for the rest of the Russian emergency workers (192,000 persons), as well as for the Belarusian and Ukrainian emergency workers (74,000 and 291,000 persons, respectively). Such estimates, however, have not yet been made and would depend on several assumptions, including that the
age, gender and dose distributions are similar in these groups.

The picture is even more unclear for the populations of the areas affected by the Chernobyl fallout. However, the report does link the accident to an increase in thyroid cancer in children: "During 1992-2000, in Belarus, Russia and Ukraine, about 4000 cases of thyroid cancer were diagnosed in children and adolescents (0–18 years), of which about 3000 occurred in the age group of 0–14 years. For 1152 thyroid cancer patient cases diagnosed among Chernobyl children in Belarus during 1986-2002, the survival rate is 98.8%. Eight patients died due to progression of their thyroid cancer and six children died from other causes. One patient with thyroid cancer died in Russia." It is from this that several reports give a figure of around nine thyroid cancer deaths resulting from the accident. It should also be noted that other statistics quoted in the Expert Group report give the total number of thyroid cancer cases among those exposed under the age of 18 as over 4800, though this does not affect the general point that "a large proportion of the thyroid cancer fatalities can be attributed to radiation."

Regarding other effects, the Expert Group report states: "There is little peer-reviewed scientific evidence showing an increase above the spontaneous levels from cancer, leukaemia, or non-cancer mortality in populations of the areas affected by the Chernobyl fallout." It does point out a study that reports an annual death rate of 18.5 per 1000 persons for the population living in Ukrainian areas contaminated with radionuclides, compared with 16.5 per 1000 for the 50 million population of Ukraine. "The reason for the difference is not clear, and without specific knowledge of the age and sex distributions of the two populations, no conclusion can be drawn."

Current risk models are derived from studies of atomic bomb survivors, without adjustments for the protracted dose rates or allowances for differing background cancer incidence rates and demographics in the Chernobyl exposed populations. Based on these models, "a radiation related increase of total cancer morbidity and mortality above the spontaneous level by about 1-1.5% for the whole district and by about 4-6% in its most contaminated villages" can be estimated. The report continues: "The predicted lifetime excess cancer and leukaemia deaths for 200,000 liquidators, 135,000 evacuees from the 30 km zone, 270,000 residents of the SCZs ['strict control zones'] were 2200 for liquidators, 160 for evacuees, and 1600 among residents of the SCZs. This total, about 4000 deaths projected over the lifetimes of the some 600,000 persons most affected by the accident, is a small proportion of the total cancer deaths from all causes that can be expected to occur in this population. It must be stressed that this estimate is bounded by large uncertainties."

Beyond this, "for the further population of more than 6,000,000 persons in other contaminated areas, the projected number of deaths was about 5000. This latter estimate is particularly uncertain, as it is based on an average dose of just 7 mSv, which differs very little from natural background radiation levels." There is good reason to be sceptical of such a projection on the basis of the known or assumed doses.

The report emphasises that considerable uncertainty surrounds such projections. "Because of the uncertainty of epidemiological model parameters, predictions of future mortality or morbidity based on the recent post-Chernobyl studies should be made with special caution. Significant non-radiation related reduction in the average lifespan in the three countries over the past 15 years remains a significant impediment to detecting any effect of radiation on both general and cancer morbidity and mortality."

Exposures and Effects of the Chernobyl Accident

http://www.world-nuclear.org/info/chernobyl/inf07.html
The conclusions of the Annex J report by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) are reproduced here. The full report is available from UNSCEAR\(^2\).

Conclusions

402. The accident of 26 April 1986 at the Chernobyl nuclear power plant, located in Ukraine about 20 km south of the border with Belarus, was the most serious ever to have occurred in the nuclear industry. It caused the deaths, within a few days or weeks, of 30 power plant employees and firemen (including 28 with acute radiation syndrome) and brough about the evacuation, in 1986, of about 116,000 people from areas surrounding the reactor and the relocation, after 1986, of about 220,000 people from Belarus, the Russian Federation and Ukraine. Vast territories of those three countries (at that time republics of the Soviet Union) were contaminated, and trace deposition of released radionuclides was measurable in all countries of the northern hemisphere. In this Annex, the radiation exposures of the population groups most closely involved in the accident have been reviewed in detail and the health consequences that are or could be associated with these radiation exposures have been considered.

403. The populations considered in this Annex are (a) the workers involved in the mitigation of the accident, either during the accident itself (emergency workers) or after the accident (recovery operation workers) and (b) members of the general public who either were evacuated to aver excessive radiation exposures or who still reside in contaminated areas. The contaminated areas, which are defined in this Annex as being those where the average \(^{137}\text{Cs}\) ground deposition density exceeded 37 kBq m\(^{-2}\) (1 Ci km\(^{-2}\)), are found mainly in Belarus, in the Russian Federation and in Ukraine. A large number of radiation measurements (film badges, TLDs, whole-body counts, thyroid counts, etc.) were made to evaluate the exposures of the population groups that are considered.

404. The approximately 600 emergency workers who were on the site of the Chernobyl power plant during the night of the accident received the highest doses. The most important exposures were due to external irradiation (relatively uniform whole-body gamma irradiation and beta irradiation of extensive body surfaces), as the intake of radionuclides through inhalation was relatively small (except in two cases). Acute radiation sickness was confirmed in 134 of those emergency workers. Forty-one of these patients received whole-body doses from external irradiation of less than 2.1 Gy. Ninety-three patients received higher doses and had more severe acute radiation sickness: 50 persons with doses between 2.2 and 4.1 Gy, 22 between 4.2 and 6.4 Gy, and 21 between 6.5 and 16 Gy. The skin doses from beta exposures, evaluated for eight patients with acute radiation sickness, were in the range of 400-500 Gy.

405. About 600,000 persons (civilian and military) have received special certificates confirming their status as liquidators (recovery operation workers), according to laws promulgated in Belarus, the Russian Federation and Ukraine. Of those, about 240,000 were military servicemen. The principal tasks carried out by the recovery operation workers included decontamination of the reactor block, reactor site and roads, as well as construction of the sarcophagus and of a town for reactor personnel. These tasks were completed by 1990.

406. A registry of recovery operation workers was established in 1986. This registry includes estimates of effective doses from external irradiation, which was the predominant pathway of exposure for the recovery operation workers. The registry data show that the average recorded doses decreased from year to year, being about 170 mSv in 1986, 130 mSv in 1987, 30 mSv in 1988, and 15 mSv in 1989. It is, however, difficult to assess the validity of the results that have been reported because (a) different dosimeters were used by different organizations without any intercalibration; (b) a large number of recorded doses were very close to the dose limit; and (c) there were a large number of rounded values such as 0.1, 0.2, or 0.5 Sv. Nevertheless, it seems reasonable to assume that the average effective dose from external gamma irradiation to recovery operation workers in the years 1986-1987 was about 100 mSv.

407. Doses received by the general public came from the radionuclide releases from the damaged reactor, which led to the ground contamination of large areas. The radionuclide releases occurred mainly over a 10-day period, with varying release rates. From the radiological point of view, the releases of \(^{131}\text{I}\) and \(^{137}\text{Cs}\), estimated to have been 1,760 and 85 PBq, respectively, are the most important. Iodine-131 was the main contributor to the thyroid doses, received mainly via internal irradiation within a few weeks after the accident, while \(^{137}\text{Cs}\) was, and is, the main contributor to the doses to organs and tissues other than the thyroid, from either internal or external irradiation, which will continue to be received, at low dose rates, during several decades.
408. The three main contaminated areas, defined as those with $^{137}$Cs deposition density greater than 37 kBq m$^{-2}$ (1 Ci km$^{-2}$), are in Belarus, the Russian Federation and Ukraine; they have been designated the Central, Gomel-Mogiliv-Bryansk and Kaluga-Tula-Orel areas. The Central area is within about 100 km of the reactor, predominantly to the west and northwest. The Gomel-Mogiliv-Bryansk contaminated area is centred 200 km north-northeast of the reactor at the boundary of the Gomel and Mogiliev regions of Belarus and of the Bryansk region of the Russian Federation. The Kaluga-Tula-Orel area is in the Russian Federation, about 500 km to the northeast of the reactor. All together, territories from the former Soviet Union with an area of about 150,000 km$^2$ were contaminated with $^{137}$Cs deposition density greater than 37 kBq m$^{-2}$. About five million people reside in those territories.

409. Within a few weeks after the accident, more than 100,000 persons were evacuated from the most contaminated areas of Ukraine and of Belarus. The thyroid doses received by the evacuees varied according to their age, place of residence, dietary habits and date of evacuation. For example, for the residents of Pripyat, who were evacuated essentially within 48 hours after the accident, the population-weighted average thyroid dose is estimated to be 0.17 Gy and to range from 0.07 Gy for adults to 2 Gy for infants. For the entire population of evacuees, the population-weighted average thyroid dose is estimated to be 0.47 Gy. Doses to organs and tissues other than the thyroid were, on average, much smaller.

410. Thyroid doses also have been estimated for the residents of the contaminated areas who were not evacuated. In each of the three republics, thyroid doses are estimated to have exceeded 1 Gy for the most exposed infants. For residents of a given locality, thyroid doses to adults were smaller than those to infants by a factor of about 10. The average thyroid dose was approximately 0.2 Gy; the variability of the thyroid dose was two orders of magnitude, both above and below the average.

411. Following the first few weeks after the accident, when $^{131}I$ was the main contributor to the radiation exposures, doses were delivered at much lower dose rates by radionuclides with much longer half-lives. Since 1987, the doses received by the populations of the contaminated areas came essentially from external exposure from $^{134}$Cs and $^{137}$Cs deposited on the ground and internal exposure due to the contamination of foodstuffs by $^{134}$Cs and $^{137}$Cs. Other, usually minor, contributions to the long-term radiation exposures include the consumption of foodstuffs contaminated with $^{90}$Sr and the inhalation of aerosols containing plutonium isotopes. Both external irradiation and internal irradiation due to $^{134}$Cs and $^{137}$Cs result in relatively uniform doses in all organs and tissues of the body. The average effective doses from $^{134}$Cs and $^{137}$Cs that were received during the first 10 years after the accident by the residents of contaminated areas are estimated to be about 10 mSv.

412. The papers available for review by the Committee to date regarding the evaluation of health effects of the Chernobyl accident have in many instances suffered from methodological weaknesses that make them difficult to interpret. The weaknesses include inadequate diagnoses and classification of diseases, selection of inadequate control or reference groups (in particular, control groups with a different level of disease ascertainment than the exposed groups), inadequate estimation of radiation doses or lack of individual data and failure to take screening and increased medical surveillance into consideration. The interpretation of the studies is complicated, and particular attention must be paid to the design and performance of epidemiological studies. These issues are discussed in more detail in Annex I, "Epidemiological evaluation of radiation-induced cancer".

413. Apart from the substantial increase in thyroid cancer after childhood exposure observed in Belarus, in the Russian Federation and in Ukraine, there is no evidence of a major public health impact related to ionizing radiation 14 years after the Chernobyl accident. No increases in overall cancer incidence or mortality that could be associated with radiation exposure have been observed. For some cancers no increase would have been anticipated as yet, given the latency period of around 10 years for solid tumours. The risk of leukaemia, one of the most sensitive indicators of radiation exposure, has not been found to be elevated even in the accident recovery operation workers or in children. There is no scientific proof of an increase in other non-malignant disorders related to ionizing radiation.

414. The large number of thyroid cancers in individuals exposed in childhood, particularly in the severely contaminated areas of the three affected countries, and the short induction period are considerably different from previous experience in other accidents or exposure situations. Other factors, e.g. iodine deficiency and screening, are almost certainly influencing the risk. Few studies have addressed these problems, but those that have still find a significant influence o
radiation after taking confounding influences into consideration. The most recent findings indicate that the thyroid cancer risk for those older than 10 years at the time of the accident is leveling off, the risk seems to decrease since 1995 for those 5-9 years old at the time of the accident, while the increase continues for those younger than 5 years in 1986.

415. There is a tendency to attribute increases in cancer rates (other than thyroid) over time to the Chernobyl accident, but it should be noted that increases were also observed before the accident in the affected areas. Moreover, a general increase in mortality has been reported in recent years in most areas of the former USSR, and this must also be taken into account in interpreting the results of the Chernobyl-related studies. Because of these and other uncertainties, there is a need for well designed, sound analytical studies, especially of recovery operation workers from Belarus, the Russian Federation, Ukraine and the Baltic countries, in which particular attention is given to individual dose reconstruction and the effect of screening and other possible confounding factors.

416. Increases of a number of non-specific detrimental health effects other than cancer in accident recovery workers have been reported, e.g., increased suicide rates and deaths due to violent causes. It is difficult to interpret these findings without reference to a known baseline or background incidence. The exposed populations undergo much more intensive and active health follow-up than the general population. As a result, using the general population as a comparison group, as has been done so far in most studies, is inadequate.

417. Adding iodine to the diet of populations living in iodine-deficient areas and screening the high-risk groups could limit the radiological consequences. Most data suggest that the youngest age group, i.e., those who were less than five years old at the time of the accident, continues to have an increased risk of developing thyroid cancer and should be closely monitored. In spite of the fact that many thyroid cancers in childhood are presented at a more advanced stage in terms of local aggressiveness and distant metastases than in adulthood, they have a good prognosis. Continued follow-up is necessary to allow planning of public health actions, to gain a better understanding of influencing factors, to predict the outcomes of any future accidents, and to ensure adequate radiation protection measures.

418. Present knowledge of the late effects of protracted exposure to ionizing radiation is limited, since the dose-response assessments rely heavily on high-dose exposure studies and animal experiments. The Chernobyl accident could, however, shed light on the late effects of protracted exposure, but given the low doses received by the majority of exposed individuals, albeit with uncertainties in the dose estimates, any increase in cancer incidence or mortality will most certainly be difficult to detect in epidemiological studies. The main goal is to differentiate the effects of the ionizing radiation and effects that arise from many other causes in exposed populations.

419. Apart from the radiation-associated thyroid cancers among those exposed in childhood, the only group that received doses high enough to possibly incur statistically detectable increased risks is the recovery operation workers. Studies of these populations have the potential to contribute to the scientific knowledge of the late effects of ionizing radiation. Many of these individuals receive annual medical examinations, providing a sound basis for future studies of the cohort. It is, however, notable that no increased risk of leukaeemia, an entity known to appear within 2-3 years after exposure, has been identified more than 10 years after the accident.

420. The future challenge is to provide reliable individual dose estimates for the subjects enrolled in epidemiological studies and to evaluate the effects of doses accumulated over protracted time (days to weeks for thyroid exposures of children, minutes to months for bone-marrow exposures of emergency and recovery operation workers, and months to years for whole-body exposures of those living in contaminated areas). In doing this, many difficulties must be taken into consideration, such as (a) the role played by different radionuclides, especially the short-lived radiiodines; (b) the accuracy of direct thyroid measurements; (c) the relationship between ground contamination and thyroid doses; and (d) the reliability of the recorded or reconstructed doses for the emergency and recovery operation workers.

421. Finally, it should be emphasized that although those exposed as children and the emergency and recovery operation workers are at increased risk of radiation-induced effects, the vast majority of the population need not live in fear of serious health consequences from the Chernobyl accident. For the most part, they were exposed to radiation levels comparable to or a few times higher than the natural background levels, and future exposures are diminishing as the deposited radionuclides decay. Lives have been disrupted by the Chernobyl accident, but from the radiological point of view and based on the assessments of this Annex, generally positive prospects for the future health of most
Estimated Long Term Health Effects of the Chernobyl Accident

Background Paper 3 from the One Decade after Chernobyl - Summing up the Consequences of the Accident conference held in Vienna in April 1996 attempted to estimate the total lifetime numbers of excess cancers in those exposed to radiation due to the Chernobyl accident. The paper was cited in the above-mentioned 2006 report of the UN Chernobyl Forum's 'Health' Expert Group, which stated: "This assessment involved direct application of available risk factors, derived mainly from the atomic-bomb survivor study, without adjustments for the protracted dose rates or allowances for differing background cancer incidence rates and demographics in the Chernobyl exposed populations. Such estimates are thus intended to be order-of-magnitude or rough scoping estimates to be used for public health planning rather than as an accurate projection of actual cases." The abstract is reproduced below and the full paper is in the One Decade after Chernobyl conference proceedings, available from the IAEA.

Abstract

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Apart from the dramatic increase in thyroid cancer in those exposed as children, there is no evidence to date (1996) of a major public health impact as a result of radiation exposure due to the Chernobyl accident in the three most affected countries (Belarus, Russia and Ukraine).

Although some increases in the frequency of cancer in exposed populations have been reported, these results are difficult to interpret, mainly because of differences in the intensity and method of follow-up between exposed populations and the general population with which they are compared. If the experience of the survivors of the atomic bombing of Japan and of other exposed populations is applicable, the major radiological impact of the accident will be cases of cancer. The total lifetime numbers of excess cancers will be greatest among the 'liquidators' (emergency and recovery workers) and among the residents of 'contaminated' territories, of the order of 2000 to 4600 among each group (the size of the exposed populations is 200,000 liquidators and 6,800,000 residents of 'contaminated' areas). These increases would be difficult to detect epidemiologically against an expected background number of 41,500 and 800,000 cases of cancer respectively among the two groups.

However, the exposures for populations due to the Chernobyl accident are different (in type and pattern) from those of the survivors of the atomic bombing of Japan (and doses received early after the accident are not well known). Predictions derived from studies of these populations are therefore uncertain. Indeed, although an increase in the incidence of thyroid cancer in persons exposed as children as a result of the Chernobyl accident was envisaged, the extent of the increase was not foreseen.

Only ten years have passed since the accident. It is essential, therefore, that monitoring of the health of the population be continued in order to assess the public health impact of the accident, even if any increase in the incidence of cancers as a result of radiation exposure due to the Chernobyl accident, except for leukaemia among liquidators and thyroid cancer, is expected to be difficult to detect. Studies of selected populations and diseases are also needed in order to study observed or predicted effects; careful studies may in particular provide important information on the effect of exposure rate and exposure type in the low to medium dose range and on factors which may modify radiation effects. As such, they may have important consequences for the radiation protection of patients and the general population in the event of any future accidental exposure.

Lessons of Chernobyl - with particular reference to thyroid cancer

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The Chernobyl catastrophe was a dramatic personal experience for me - a difficult exam, which I am not sure that I passed. For many people engaged in radiological protection, though not all, it was a watershed that changed their view on the paradigm on which the present safety regulations are based, the holy mantra of LNT - the linear no-threshold assumption, according to which even the lowest, near-zero doses of radiation may cause cancer and genetic harm. For everybody it might serve as a yardstick for comparison of radiation risks from natural and man-made sources. It also sheds light on how easily the global community may leave the realm of rationality when facing an imaginary emergency.

The LNT assumption is in direct contradiction to a vast sea of data on the beneficial effects of low doses of radiation. When in 1980, as a chairman of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), I tried to convince its members that we should not ignore but rather peruse and assess these data, published in the scientific literature since the end of 19th century, everybody in the Committee was against it. In each of the next seven years I repeated the proposal, to no avail. Finally, the accident at Chernobyl appeared to be an eye opener: two years after the accident, in 1988, the Committee saw the light and decided to study radiation hormesis, i.e. the adaptive and beneficial effects of low levels of radiation. Six years of the Committee's work and hot discussions later, Annex B "Adaptive responses to radiation in cells and organisms" appeared in the UNSCEAR 1994 Report, fourteen years after my original proposal. The Annex started a virtual revolution in research related to radiation protection but, because of many vested interests and conservatism to change the international and national regulations, there is still a long way to go.

The LNT/hormesis controversy is not limited to radiation. It poses questions for practically all noxious physical, chemical and biological agents which we meet in life [1]. Ionizing radiation was discovered rather lately - at the end of the 19th century - but, like these other agents, it has been with us since time immemorial.

The Chernobyl accident was a radiation event unique in human history, but not in the history of the biosphere. There is evidence of a number of episodes of greater radiation levels during the evolution of life on earth, e.g. due to supernovae. In terms of human losses it was a minor event as compared with many other man-made catastrophes but, in political, economic, social and psychological terms, its impact was enormous. Let's have a look at what happened.

About 9 a.m. on Monday 28 April 1986 at the entrance of CLOR in Warsaw I was greeted by my assistant with a statement: "Look, at 7:00 we received a telex from Mikolajki monitoring station saying that the radioactivity of air is there 550 000 times higher than a day before. A similar increase I found in the air filter from our station in the backyard, and the pavement in front of the institute is highly radioactive". Soon, to our relief, we found that the isotopic composition of radioactive dust was not from a nuclear explosion, but rather from a nuclear reactor. Reports inflowing successively from our 140 monitoring stations suggested that a radioactive cloud over Poland traveled westwards and that it arrived from the Soviet Union, but it was only about 6 p.m. that we learned from BBC radio that its source was in Chernobyl.

This was a terrible psychological shock. The air over the whole country was filled with the radioactive material, at levels hundreds of thousands times higher than anything we experienced in the past, even in 1963 - a record year for fallout from nuclear test explosions. It is curious that all my attention was concentrated on this enormous increase in air radioactivity, although I knew that on this first day of "Chernobyl in Poland", the dose rate of external radiation penetrating our bodies reached 30 µR per hour, or 2.6 mSv per year, i.e. only by a factor of 3 higher than a day before.
dose rate was four times lower than I would experience visiting places in Norway, where the natural external radiation (up to 11.3 mSv/year) from the rocks is higher than over the Central European plane. It was also some 100 times lower than in an Iranian resort Ramsar, where the annual dose reaches about 250 mSv per year, or more than 300 times lower than at the Brazilian beaches (790 mSv per year) or in South-West France (up to 870 mSv per year). No adverse health effects have ever been reported among the people living in these areas with high natural background radiation.

But, in 1986, the impact of a dramatic increase in atmospheric radioactivity dominated the thinking of myself and of everybody. This state of mind led to immediate serious consequences in Poland, in the Soviet Union, throughout the Europe, and later all over the globe. First, there were different hectic actions, such as ad hoc coining of different principles and emergency countermeasures, the sense and quality of which lagged far behind the excellent measuring techniques and monitoring systems. An example of this was the radionuclide concentration limits (derived intervention levels) implemented a few days after the accident by various countries and international organizations, which varied by a factor of up to 50,000. The base of some of these limits was not scientific, but reflected the emotional state of the decision makers, and also political and mercantile factors. For example, Sweden allowed for 30 times more activity in imported vegetables than in the domestic ones, and Israel imposed lower limits for radioactivity in food imported from Eastern than from Western Europe. The limit of cesium-137 concentration in meat of 6 Bq/kg was accepted in the Philippines and 6000 Bq/kg in Norway.

The monetary costs of such restrictions were estimated in Norway. At first, the cesium-137 limit for meat was accepted there as 600 Bq/kg, which from a health physics point of view is meaningless, as consumption of 1 kg of such a meat would correspond to a dose of 0.0078 mSv. If somebody would eat 0.25 kg of this meat each day for 1 year the internal radiation dose would reach 0.7 mSv. This limit was often surpassed in mutton, and the farmers received compensation for destroying the meat, and for special fodder they were forced to feed the sheep for months before slaughtering. Such a low limit could have destroyed the living of Lapps whose economy depends on reindeer, an animal having a special food chain based on lichens. Due to this chain the reindeer meat contained in 1986 high concentrations of cesium-137, reaching up to 40,000 Bq/kg. In November 1986, Norwegian authorities introduced a limit of 6000 Bq/kg of reindeer meat and game. Ordinary Norwegian diet includes only about 0.6 kg of reindeer meat per year, thus this limit was aimed to protect Norwegians against a radiation dose of 0.047 mSv/year. In 1994, the costs of this "protection" were evaluated: they reached over $51 million.

Sweden was not better. When the farmers near Stockholm discovered that the Chernobyl accident contaminated the milk of their cows with cesium-137 above the limit of 300 Bq per liter imposed by Swedish authorities, they wrote to them and asked if their milk could not be diluted with uncontaminated milk from other regions, until the limit were attained, for instance by mixing 1 liter of contaminated milk with 10 liters of clean milk. To the farmers’ surprise the answer was "no", and the milk was to be discarded. This was strange, as it always was possible to do so for other pollutants in foodstuffs, and we also dilute the fumes from fireplaces or ovens with the atmospheric air. Authorities explained that even though one could reduce the individual risk by diluting the milk, at the same time, one would increase the number of consumers, and thus the risk would remain the same, although now spread over a larger population. This was a dogmatic application of the LNT assumption, and of its offspring, the concept of "collective dose" (i.e. reaching terrifyingly great numbers of "man-sieverts", by multiplying tiny innocuous individual radiation doses by large number of exposed people). I believe that, in an earlier paper, I demonstrated clearly the lack of sense and negative consequences both of the LNT assumption and of the population dose concept. Their dogmatic application may quite probably have caused the costs of the Chernobyl accident to
The 2006 report of the World Health Organization (WHO), Hall, P., A. Mattsson, and J.D. Boice Jr., Health Impacts of the Chernobyl Accident Appendix 2 (Updated November 2009) describes the health effects of the Chernobyl accident, which occurred in 1986. The report states that the evacuation of 336,000 people from the regions of the former Soviet Union, where the accident took place, increased the average natural radiation dose to about 2.5 mSv per year by 0.8 to 1.4 mSv per year, i.e. by about 30% to 50% [6]. The evacuation was based on radiation limits recommended by the International Commission for Radiological Protection (ICRP) for "the event of major radiation accidents" and on recommendations for protection of the general population, which were tens to hundreds of times lower than natural doses in many countries. In the asphalt paved streets of the "ghost town" of Pripyat, from which about 50,000 people were relocated, and where nobody can enter without special permission, the total external gamma dose rate measured by a Polish team in May 2001 was 0.9 mSv per year, i.e. the same as in Warsaw, and five times lower than at the Grand Central Station in New York. The evacuation led to development of mass psychosomatic disturbances, great economical losses, and traumatic social consequences. Obviously, ICRP will never accept responsibility for the disastrous effects of this dogmatic application of its armchair luctations which has caused the present system of "radiation protection [to] become a health hazard"[3].

In Poland, to save the population from effects of exposure to iodine-131, the government, upon my instigation, administered during three days a single dose of stable iodine to about 18.5 million people, the greatest prophylactic action in the history of medicine performed in so short a time. My medical colleagues and the Ministry of Health were rightly proud of the ingenious and innovative way they implemented this countermeasure. Recently several countries, including the USA, planned to follow in our flight. However, now I see this action as nonsensical. We endeavored to save Polish children from developing thyroid cancers by protecting them from a radiation dose of 50 mSv to the thyroid gland [7]. At this dose ICRP recommended implementation of stable iodine prophylaxis. But in studies of more than 34,000 Swedish patients whose thyroid glands received radiation doses reaching up to 40,000 mSv from iodine-131, there was no statistically significant increase in thyroid cancers in adults or children, who had not already been thought to have cancer before treatment with iodine-131. In fact, an opposite effect was observed: there was a 38% decrease in thyroid cancer incidence as compared with the non-irradiated population [8, 9]. In a much smaller British study of 7417 adult hyperthyroid patients whose thyroids received average radiation doses from iodine-131 reaching 300,000 mSv, a 17% deficit in incidence of all studied cancers was found [10]. Without the stable iodine prophylaxis and milk restrictions, the maximum thyroid dose would have reached about 1000 mSv in about 5% of Polish children [7]. All that I would now expect from this dose is a zero effect.

Fourteen years after the Chernobyl accident in the officially termed “highly contaminated” areas of the former Soviet Union, except for thyroid cancers, no increase in incidence in solid cancers and leukemia was reported. In its 2000 Report, UNSCEAR stated that the “population need not live in fear of serious health consequences”, and “generally positive prospects for the future health of most individuals should prevail” [6]. No epidemics of cancers in the Northern Hemisphere, directly predicted from the LNT assumption to reach tens and hundreds of thousands, or even millions of cases, has ever occurred.

The number of 1800 new thyroid cancers registered among the children from Belarus, Russia and Ukraine should be viewed in respect to extremely high occurrence of the "occult" thyroid cancers in normal populations [11-14]. These cancers, not presenting adverse clinical effects, are detected at post mortem, or by ultrasonography examinations. Their incidence ranges from 5% in Colombia, to 9% in Poland, 13% in the USA, and 35% in Finland [12]. In Finland occult thyroid cancers appear in 2.4% of children 0 to 15 year old [11]. In Minsk, Belarus the normal incidence of occult thyroid...
cancers is 9.3% [15]. The greatest incidence of "Chernobyl" thyroid cancers in children under 15 years old, of 0.0277%, was registered in 1994 in the Bryansk region of Russia, which was less by a factor of about 90 than the normal incidence of occult thyroid cancers among the Finnish children. The "Chernobyl" thyroid cancers are of the same type and similarly invasive as the occult cancers [13]. The first increase of these cancers was registered in 1987 in the Bryansk region, Russia, one year after the accident. Since 1995, the number of registered cancers tends to decline. This is not in agreement with what we know about radiation induced thyroid cancers, the latency time for which is about 5 years after irradiation, and the risk of which increases until 15 - 29 years after exposure [6]. In the United States the incidence rate of thyroid tumors detected between 1974 and 1979 during a screening program was 21 times higher than before the screening [16], an increase similar to that observed in three former Soviet countries. I believe that the increased registration of thyroid cancers in contaminated parts of these countries is a classical screening effect.

There were 28 fatalities caused by very high doses of radiation to rescue workers and employees of the power station, and 3 deaths in this group due to other reasons. Among 237 members of the reactor staff and emergency workers, initially examined for signs of acute radiation sickness, this diagnosis was confirmed in 134 patients. From among these patients, 11 died up to 1998. The causes of death were as follows: 3 cases of coronary heart disease, 2 cases of myelodysplastic syndrome, two cases of liver cirrhosis, and one death each of lung gangrene, lung tuberculosis and fat embolism. One patient, who was classified with Grade II acute radiation sickness (acute radiation dose of 2.2 - 4.1 Gy) died from acute myeloid leukemia. A substantial increase in the incidence of leukemia among recovery operation workers was predicted, but the evidence for a measurable radiation effect on this incidence is somewhat mixed. The average standardized incidence ratio (SIR) for leukemia ranged among these workers for Belarus, Russia and Ukraine from 0.94 to 7.76, but the problem is that similar increase was found for chronic lymphatic leukemia a subtype deemed not to be induced by radiation exposure. Contribution of a screening or diagnostic bias to these excesses cannot be excluded. The SIR for all cancers combined in the recovery operation workers ranged from 0.70 to 1.02 in Belarus, from 0.91 to 1.01 in Russia, and from 1.05 to 1.11 in Ukraine.

In the general population of the contaminated regions of Belarus, the SIR for leukemia was 0.46 to 0.62 (i.e. 46% to 62% of the normal incidence in Belarus), 0.93 to 0.99 in Russia and 1.05 to 1.43 in Ukraine. The SIR for all cancers combined ranged from 0.30 to 0.69 in Belarus, from 0.89 to 0.98 in Russia, and from 0.80 to 0.82 in Ukraine. Hence, the incidence of all cancers appears to have been lower than it would have been in a similar but unirradiated group. The only real adverse health consequence of the Chernobyl catastrophe among about five million people living in the contaminated regions is the epidemics of psychosomatic diseases [6]. These diseases were not due to irradiation with Chernobyl fallout, but were caused by radiophobia, induced by years of propaganda before and after the accident, and aggravated by improper administrative decisions. As a result of these decisions, several million people in three countries have "been labeled as, and perceive themselves as, actual or potential victims of Chernobyl"[17]. This was the main factor behind the economic losses caused by the Chernobyl catastrophe, estimated for Ukraine to reach $148 billion until 2000, and $235 billion until 2016 for Belarus [17].

In 1986 most of my professional colleagues and I, the authorities, and the public in Poland and elsewhere, were pre-conditioned for irrational reactions. Victims of the LNT dogma, we all wished to protect people even against the lowest, near zero doses of ionizing radiation. The dogma influenced behavior of everybody, leading to a mass psychosis, in fact to the greatest psychological catastrophe in history [2], into which the accident in Chernobyl, with the efficient help of media and national and international authorities, quickly evolved. It seems that professionals, international and
The following main lessons can be deduced from this accident:

1. Ionizing radiation killed only a few occupationally exposed people. Due to rapid decay of short-lived radionuclides, the Chernobyl fallout did not expose the general population to harmful radiation doses. Near the burning reactor, the area covered by the dangerous radioactive fallout where, on April 26 1986, the radiation dose rate reached 1 Gy per hour (after one year it had decreased by a factor of about 3000), was limited to two patches totaling together about 0.5 km² in an uninhabited location, and reaching a distance of 1.8 km from the burning nuclear reactor. Several hundred meters outside the 1 Gy isoline the dose rate dropped by two orders of magnitude, to a level of 0.01 to 0.001 Gy per hour. This is a completely different situation than after a surface explosion of a 10 Mt nuclear bomb, when the 1 Gy per hour isoline can reach a distance of 440 km, and the lethal fallout can cover tens of thousands km², and endanger the life of millions of people.

2. The reported excess of thyroid cancers in children and in adults exposed to Chernobyl fallout is not consistent with the knowledge on effects of medical use of iodine-131. The report of an "excess" appears to be an effect of screening, and is only a small fraction of the normal occult thyroid cancers incidence occurring in populations unexposed to iodine-131.

3. Radionuclides were injected high into the stratosphere, at least up to 15 km altitude, which made possible its long distance migration in the whole Northern Hemisphere, and a penetration over the Equator down to the South Pole [18]. With unique, extremely sophisticated radiation monitoring systems, implemented in all developed countries, even the most tiny debris from the Chernobyl reactor was easily detected all over the world. No such system exists for any other potentially harmful environmental agent. Ironically, this excellence of radiological protection ignited the mass anxiety, with its disastrous consequences in the former Soviet Union, and strangulation of nuclear energy development elsewhere.

4. Psychosomatic disorders and the screening effects were the only detectable health consequences among the general population. Fighting the panic and mass hysteria could be regarded as the most important countermeasure to protect the public against the effects of a similar accident should it occur again.

5. This was the worst possible catastrophe of a badly constructed nuclear reactor, with a complete meltdown of the reactor core, followed by the ten-days long completely free emission of radionuclides into the atmosphere. Nothing worse could happen. It resulted in a comparatively small occupational death toll, amounting to about half of that of each weekend's traffic in Poland, and tens or hundreds of times lower than that of many other industrial catastrophes, and it is unlikely that any fatalities were caused by radiation among the public. In the centuries to come, the Chernobyl catastrophe will be seen as a proof that nuclear power is a safe means of energy production.

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Estimated Long Term Health Effects of the Chernobyl Accident


17. UNDP and UNICEF, The Human Consequences of the Chernobyl Nuclear Accident: A strategy for Recovery. 2002, United Nations Development Programme (UNDP) and the UN Children's Fund (UNICEF) with the support of the UN Office for Co-ordination of Humanitarian Affairs (OCHA) and WHO. p. 1-75.


Further Information

http://www.world-nuclear.org/info/chernobyl/inf07.html
Notes


c. *Estimated Long Term Health Effects of the Chernobyl Accident*, Background Paper 3 from the 8-12 April 1996 conference *One Decade after Chernobyl* held in Vienna is available in the conference proceedings from the International Atomic Energy Agency. [Back]

d. *Lessons of Chernobyl with particular reference to thyroid cancer* by Zbigniew Jaworowski was published in April 2004 Newsletter No. 30 of the Australasian Radiation Protection Society (ARPS). The same article appeared in *Executive Intelligence Review (EIR)*, Volume 31, Number 18 (7 May 2004). A version of the ARPS article in Word format and a PDF file of the EIR article can be downloaded from the Environmentalists For Nuclear Energy website (www.ecolo.org). An extended version of this paper was published as *Radiation folly*, Chapter 4 of *Environment & Health: Myths & Realities*, Edited by Kendra Okonski and Julian Morris, International Policy Press (a division of International Policy Network), June 2004 (ISBN 1905041004). [Back]

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3. *Estimated Long Term Health Effects of the Chernobyl Accident* by Elizabeth Cardis *et al.* is in the conference proceedings as Background Paper 3 of the *One Decade after Chernobyl - Summing up the Consequences of the Accident* conference, cosponsored by the International Atomic Energy Agency (IAEA), the World Health Organization (WHO) and the European Commission, held at the IAEA headquarters in Vienna on 8-12 April 1996. [Back]