WORLD NUCLEAR ASSOCIATION

Chernobyl Accident 1986

(Updated May 2021)

- **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 environment, with the deposition of radioactive materials in many parts of Europe.**
- **Two Chernobyl plant workers died due to the explosion on the night of the accident, and a further 28 people died within a few weeks as a result of acute radiation syndrome.**
- **The United Nations Scientific Committee on the Effects of Atomic Radiation has concluded that, apart from some 5000 thyroid cancers (resulting in 15 fatalities), "there is no evidence of a major public health impact attributable to radiation exposure 20 years after the accident."**
- **Some 350,000 people were evacuated as a result of the accident, but resettlement of areas from which people were relocated is ongoing.**

The April 1986 disaster at the Chernobyl[a] nuclear power plant in Ukraine was the product of a flawed Soviet reactor design coupled with serious mistakes made by the plant operators[b]. 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.

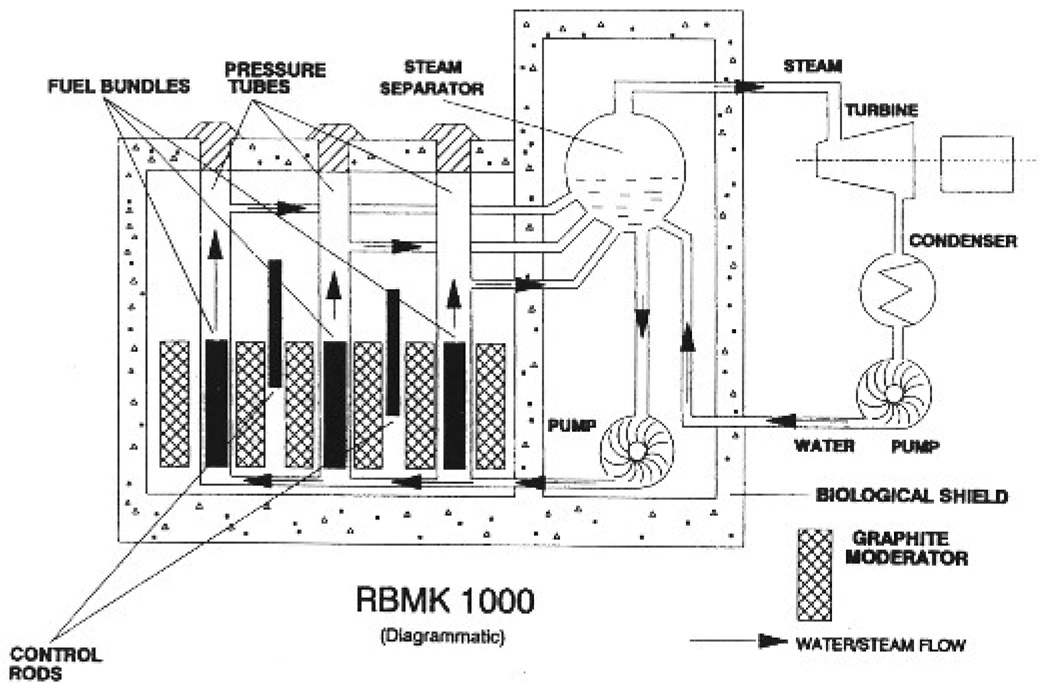
Another person is reported to have died at the time from a coronary thrombosis[c]. Acute radiation syndrome (ARS) was originally diagnosed in 237 people onsite and involved with the clean-up and it was later confirmed in 134 cases. Of these, 28 people died as a result of ARS within a few weeks of the accident. Nineteen more workers subsequently died between 1987 and 2004, but their deaths cannot necessarily be attributed to radiation exposure[d]. Nobody offsite suffered from acute radiation effects although a significant, but uncertain, fraction of the thyroid cancers diagnosed since the accident in patients who were children at the time are likely to be due to intake of radioactive iodine fallout[m,9]. Furthermore, large areas of Belarus, Ukraine, Russia, and beyond were contaminated in varying degrees. See also sections below and 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[e]. The design of the reactor is unique and in that respect the accident is thus of little relevance to the rest of the nuclear industry outside the then Eastern Bloc. However, it led to major changes in safety culture and in industry cooperation, particularly between East and West before the end of the Soviet Union. Former President Gorbachev said that the Chernobyl accident was a more important factor in the fall of the Soviet Union than *Perestroika* – his program of liberal reform.

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 were 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 at the time of the accident.



Source: OECD NEA

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, the function of which 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 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.

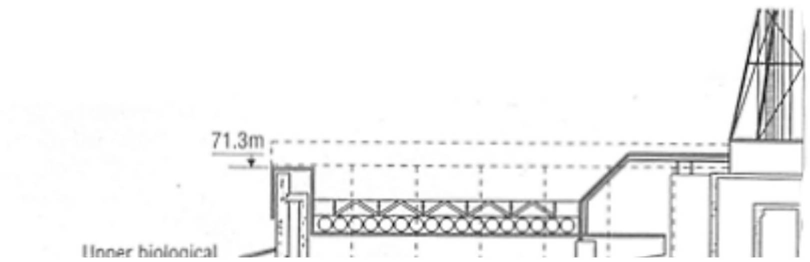
A series of operator actions, including the disabling of automatic shutdown mechanisms, preceded the attempted test early on 26 April. By the time that the operator moved to shut down the reactor, the reactor was in an extremely unstable condition. A peculiarity of the design of the control rods caused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

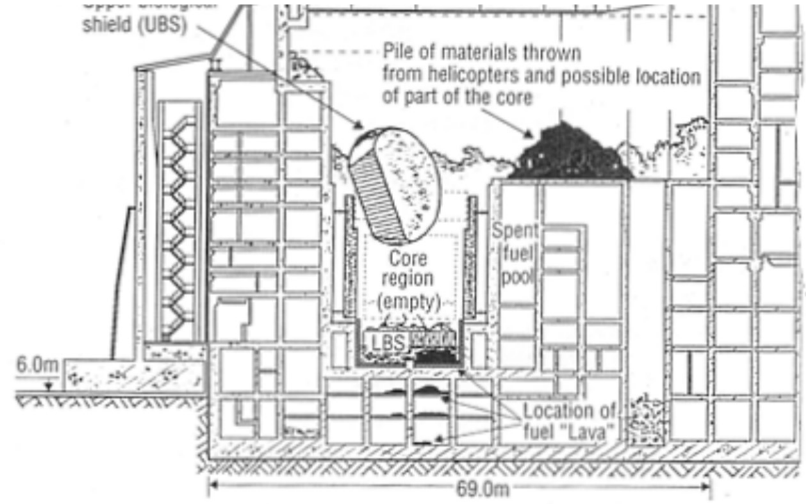
The interaction of very hot fuel with the cooling water led to fuel fragmentation along with rapid steam production and an increase in pressure. The design characteristics of the reactor were such that substantial damage to even three or four fuel assemblies would – and did – result in the destruction 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[f], causing the main release of radioactivity into the environment. A total of about 14 EBq (14×10^{18} Bq) of radioactivity was released, over half of it being from biologically-inert noble gases.*

* The figure of 5.2 EBq is also quoted, this being "iodine-131 equivalent" - 1.8 EBq iodine and 85 PBq Cs-137 multiplied by 40 due its longevity, and ignoring the 6.5 EBq xenon-33 and some minor or short-lived nuclides.

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

The 1991 report by the State Committee on the Supervision of Safety in Industry and Nuclear Power on the root cause of the accident looked past the operator actions. It said that while it was certainly true the operators placed their reactor in a dangerously unstable condition (in fact in a condition which virtually guaranteed an accident) it was also true that in doing so they had not in fact violated a number of vital operating policies and principles, since no such policies and principles had been articulated. Additionally, the operating organization had not been made aware either of the specific vital safety significance of maintaining a minimum operating reactivity margin, or the general reactivity characteristics of the RBMK which made low power operation extremely hazardous.

Immediate impact of the Chernobyl accident

The accident caused the largest uncontrolled radioactive release into the environment ever recorded for any civilian operation, and large quantities of radioactive substances were released into the air for about 10 days. This caused serious social and economic disruption for large populations in Belarus, Russia, and Ukraine. Two radionuclides, the short-lived iodine-131 and the long-lived caesium-137, were particularly significant for the radiation dose they delivered to members of the public.

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 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 caused 28 deaths – six of which were firemen – by the end of July 1986. The doses received by the firefighters and power plant workers were high enough to result in acute radiation syndrome (ARS), which occurs if a person is exposed to more than 700 milligrays (mGy) within a short time frame (usually minutes). Common ARS symptoms include gastrointestinal problems (*e.g.* nausea, vomiting), headaches, burns and fever. Whole body doses between 4000 mGy and 5000 mGv within a short time frame would kill 50% of those exposed, with 8000-10,000 mGy universally fatal. The doses received by the firefighters who died were estimated to range up to 20,000 mGy.

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 (mSv). Some 20,000 liquidators received about 250 mSv, with a few receiving approximately 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 onsite personnel during the first day of the accident.

According to the most up-to-date estimate provided by 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 31 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 (about 50 mSv)[4].

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 8 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 of Belarus, Russia and Ukraine contaminated (above 37 kBq/m^2 Cs-137 in soil) and about 400,000 lived in more contaminated areas of strict control by authorities (above 555 kBq/m^2 Cs-137). A total of 29,400 km^2 was contaminated above 180 kBq/m^2.

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.

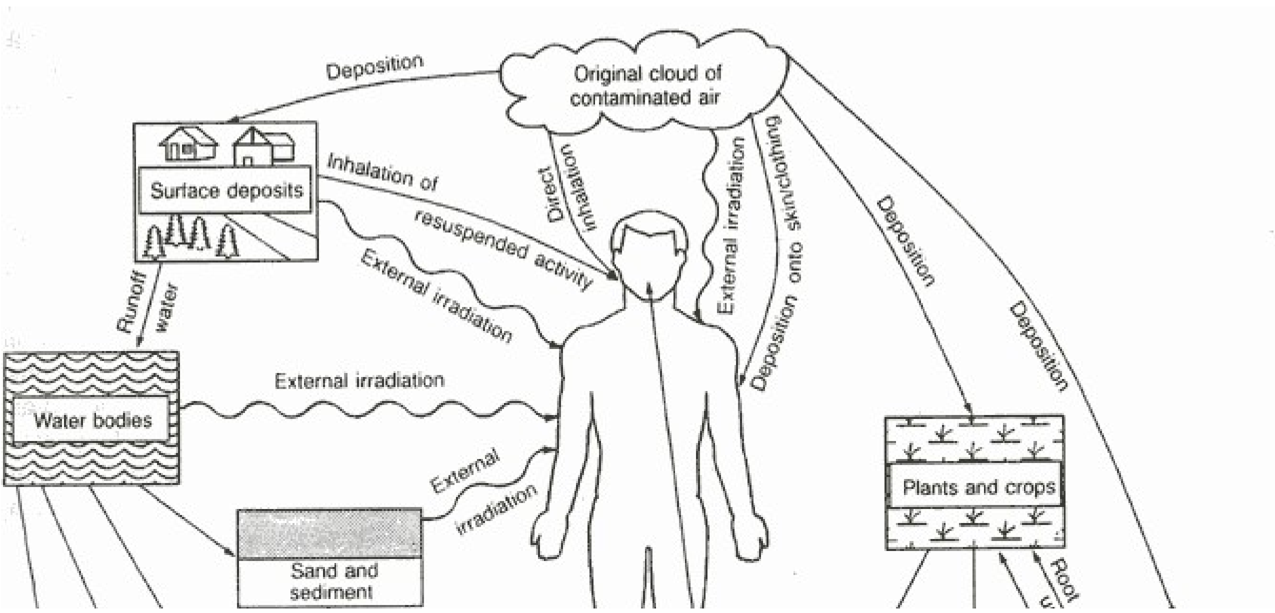
In the years following the accident, a further 220,000 people were resettled into less contaminated areas, and the initial 30 km radius exclusion zone (2800 km^2) was modified and extended to cover 4300 square kilometres. This resettlement was due to application of a criterion of 350 mSv projected lifetime radiation dose, though in fact radiation in most of the affected area (apart from half a square kilometre close to the reactor) fell rapidly so that average doses were less than 50% above normal background of 2.5 mSv/yr. See also following section on Resettlement of contaminated areas.

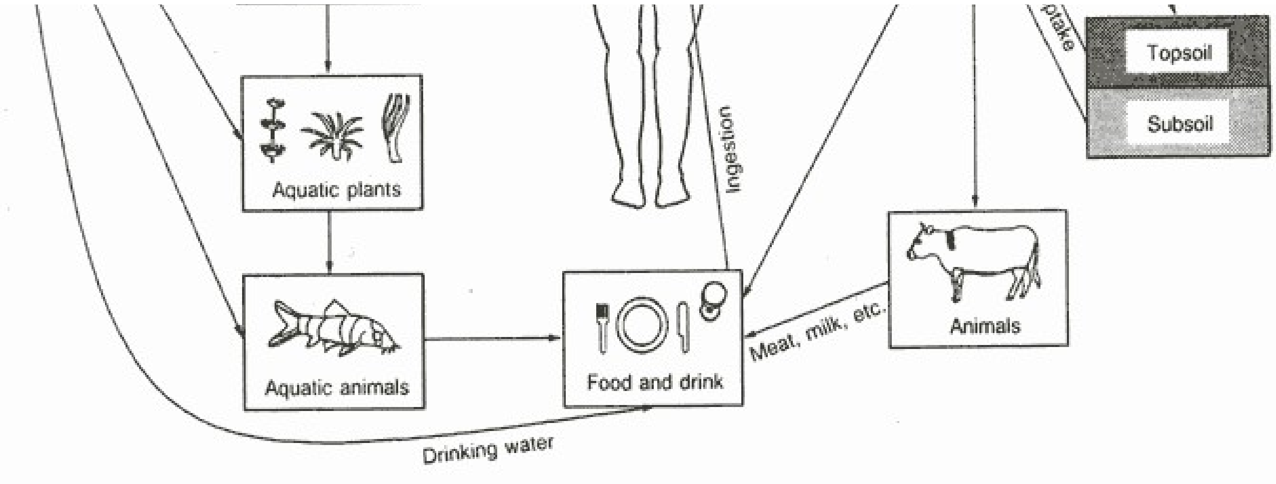
Long-term health effects of the Chernobyl accident

Video: Experts talk about the health effects of Chernobyl (Recorded 2011)

Several organizations 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[9]. 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 organizations, and 11 laboratories[3]. 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.





Main environmental pathways of human radiation exposure
[Source : IAEA technical report ISBN 92-0-129191-4 Vienna 1991]

Paths of radiation exposure[h]

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[i]) are in line with earlier expert studies, notably the UNSCEAR 2000 report[j] 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." There is little evidence of any increase in leukaemia, even among clean-up workers where it might be most expected. Radiation-induced leukemia has a latency period of 5-7 years, so any potential leukemia cases due to the accident would already have developed. A low number of the clean-up workers, who received the highest doses, may have a slightly increased risk of developing solid cancers in the long term. To date, however, there is no evidence of any such cancers having developed. Apart from these, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) said: "The great majority of the population is not likely to experience serious health consequences as a result of radiation from the Chernobyl accident. Many other health problems have been noted in the populations that are not related to radiation exposure."

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.

A particularly sad effect of the misconceptions surrounding the accident was that some physicians in Europe advised pregnant women to undergo abortions on account of radiation exposure, even though the levels concerned were vastly below those likely to have teratogenic effects. Robert Gale, a hematologist who treated radiation victims after the accident, estimated that more than 1 million abortions were undertaken in the Soviet Union and Europe as a result of incorrect advice from their doctors about radiation exposure and birth defects following the accident.

Some exaggerated figures have been published regarding the death toll attributable to the Chernobyl disaster, including a publication by the UN Office for the Coordination of Humanitarian Affairs (OCHA)[6]. However, the Chairman of UNSCEAR made it clear that "this report is full of unsubstantiated statements that have no support in scientific assessments"[k], and the Chernobyl Forum report also repudiates these claims.

The number of deaths resulting from the accident are covered most fully in the account of health effects provided by an annex to the UNSCEAR 2008 report, released in 2011. The report concluded: "In summary, the effects of the Chernobyl accident are many and varied. Early deterministic effects can be attributed to radiation with a high degree of certainty, while for other medical conditions, radiation almost certainly was not the cause. In between, there was a wide spectrum of conditions. It is necessary to evaluate carefully each specific condition and the surrounding circumstances before attributing a cause."[5]

According to an UNSCEAR report in 2018, about 20,000 cases of thyroid cancer were diagnosed 1991-2015 in patients who were 18 and under at the time of the accident. The report states that a quarter of the cases (5000 cases) were "probably" due to high doses of radiation, and that this fraction was likely to have been higher in earlier years, and lower in later years. However, it also states that the uncertainty around the attributed fraction is very significant – at least 0.07 to 0.5 – and that the influence of annual screenings and active follow-up make comparisons with the general population problematic. Thyroid cancer is usually not fatal if diagnosed and treated early; the report states that of the diagnoses made between 1991 and 2005, 15 proved to be fatal[9].

Progressive closure of the Chernobyl plant

In the early 1990s, some $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[l].

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 Khmelnitski unit 2 and Rovno unit 4 ('K2R4') in Ukraine. Construction of these was halted in 1989 but then resumed, and both reactors came online late in 2004, financed by Ukraine rather than international grants as expected on the basis of Chernobyl's closure.

Chernobyl today

See Chernobyl website for details.

Unit 4 containment

Chernobyl unit 4 was enclosed in a large concrete shelter which was erected quickly (by October 1986) to allow continuing operation of the other reactors at the plant. However, the structure is neither strong nor durable. The international Shelter Implementation Plan in the 1990s involved raising money for remedial work including removal of the fuel-containing materials. Some major work on the shelter was carried out in 1998 and 1999. About 200 tonnes of highly radioactive material remains deep within it, and this poses an environmental hazard until it is better contained.

The New Safe Confinement (NSC) structure was completed in 2017, having been built adjacent and then moved into place on rails. It is an arch 110 metres high, 165 metres long and spanning 260 metres, covering both unit 4 and the hastily-built 1986 structure. The arch frame is a lattice construction of tubular steel members, equipped with internal cranes. The design and construction contract for this was signed in 2007 with the Novarka consortium and preparatory work onsite was completed in 2010. Construction started in April 2012. The first half, weighing 12,800 tonnes, was moved 112 metres to a holding area in front of unit 4 in April 2014. The second half was completed by the end of 2014 and was joined to the first in July 2015. Cladding, cranes, and remote handling equipment were fitted in 2015. The entire 36,000 tonne structure was pushed 327 metres into position over the reactor building in November 2016, over two weeks, and the end walls completed. The NSC is the largest moveable land-based structure ever built.

The hermetically sealed building will allow engineers to remotely dismantle the 1986 structure that has shielded the remains of the reactor from the weather since the weeks after the accident. It will enable the eventual removal of the fuel-containing materials (FCM) in the bottom of the reactor building and accommodate their characterization, compaction, and packing for disposal. This task represents the most important step in eliminating nuclear hazard at the site – and the real start of dismantling. The NSC will facilitate remote handling of these dangerous materials, using as few personnel as possible. During peak construction of the NSC some 1200 workers were onsite.

The Chernobyl Shelter Fund, set up in 1997, had received €864 million from international donors by early 2011 towards this project and previous work. It and the Nuclear Safety Account (NSA), set up in 1993, are managed by the European Bank for Reconstruction and Development (EBRD). The total cost of the new shelter was in 2011 estimated to be €1.5

billion. In November 2014 the EBRD said the overall €2.15 billion Shelter Implementation Plan including the NSC had received contributions from 43 governments but still had a funding shortfall of €615 million. The following month the EBRD made an additional contribution of €350 million in anticipation of a €165 million contribution by the G7/European Commission, which was confirmed in April 2015. This left a balance of €100 million to come from non-G7 donors, and €15 million of this was confirmed in April 2015.

Chernobyl New Safe Confinement under construction and before being moved into place (Image: EBRD)

Funding other Chernobyl work

The Nuclear Safety Account (NSA), had received €321 million by early 2011 for Chernobyl decommissioning and also for projects in other ex-Soviet countries. At Chernobyl it funds the construction of used fuel and waste storage (notably ISF-2, see below) and decommissioning units 1-3. In April 2016 the European Commission pledged €20 million to the NSA, the largest part of €45 million expected from the G7 and the European Commission. A further €40 million was expected from the EBRD in May 2016.

In total, the European Commission has committed around €730 million so far to Chernobyl projects in four ways. First, €550 million for assistance projects, out of which €470 million were channelled through international funds, and €80 million implemented directly by the European Commission. Secondly, power generation support of €65 million. Thirdly, €15 million for social projects. And finally, €100 million for research projects.

Chernobyl used fuel: ISF-1 & ISF-2

Used fuel from units 1-3 was stored in each unit's cooling pond, and in an interim spent fuel storage facility pond (ISF-1). A few damaged assemblies remained in units 1&2 in 2013, with the last of these removed in June 2016. ISF-1 now holds most of the spent fuel from units 1-3, allowing those reactors to be decommissioned under less restrictive licence conditions. Most of the fuel assemblies were straightforward to handle, but about 50 are damaged and required special handling.

In 1999, a contract was signed with Framatome (now Areva) for construction of the ISF-2 radioactive waste management facility to store 25,000 used fuel assemblies from units 1-3 and other operational waste long-term, as well as material from decommissioning units 1-3 (which are the first RBMK units decommissioned anywhere). However, after a significant part of the dry storage facility had been built, technical deficiencies in the concept emerged in 2003, and the contract was terminated amicably in 2007.

Holtec International became the contractor in September 2007 for the new interim spent nuclear fuel storage facility (ISF-2 or SNF SF-2) for the state-owned Chernobyl NPP. Design approval and funding from the NSA was confirmed in October 2010, and the final €87.5 million of €400 million cost was pledged in April 2016. Construction was completed in January 2020. Hot and cold tests took place during 2020, and the facility received an operating licence in April 2021.

ISF-2 is the world's largest dry used fuel storage facility, accommodating 21,217 RBMK fuel assemblies in dry storage for at least a 100-year service life.

The project includes a processing facility, able to cut the RBMK fuel assemblies* and to put the material in double-walled canisters, which are then filled with inert gas and welded shut. They will then be transported to concrete dry storage vaults in which the fuel containers will be enclosed for up to 100 years. This facility, treating 2500 fuel assemblies per year, is the first of its kind for RBMK fuel.

* According to Holtec: "Unique features of the Chernobyl dry storage facility include the world's largest 'hot cell' for dismembering the conjugated RBMK fuel assembly and a (Holtec patented) forced gas dehydrator designed to run on nitrogen."

Other Chernobyl radwastes

Industrial Complex for Radwaste Management (ICSRM): In April 2009, Nukem handed over this turnkey waste treatment centre for solid radioactive waste. 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 m^3 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 (LRTP), to handle some 35,000 cubic metres of low- and intermediate-level liquid wastes at the site. This will be solidified and eventually buried along with solid wastes on site. Construction of the plant has been completed and the start of operations was due late in 2015. LRTP is also funded through EBRD's Nuclear Safety Account (NSA).

Non-Chernobyl used fuel

The Central Spent Fuel Storage Facility (CSFSF) Project for Ukraine's VVER reactors is being built by Holtec International within the Chernobyl exclusion area, between the resettled villages Staraya Krasnitsa, Buryakovka, Chistogalovka, and Stechanka, southeast of Chernobyl and not far from ISF-2. This will not take any Chernobyl fuel, though it will become a part of the common spent nuclear fuel management complex of the state-owned company Chernobyl NPP.

Decommissioning units 1-3

After the last Chernobyl reactor shut down in December 2000, in mid-2001 a new enterprise, SSE ChNPP was set up to take over management of the site and decommissioning from Energoatom. (Its remit includes eventual decommissioning of all Ukraine nuclear plants.)

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

In February 2014 a new stage of this was approved for units 1-3, involving dismantling some equipment and putting them into safstor condition by 2028. Then, to 2046, further equipment will be removed, and by 2064 they will be demolished.

See also official website.

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 was 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 were 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 Belarus government decision was an important political landmark in an ongoing process. Studies reviewed by UNSCEAR show that the Chernobyl disaster caused little risk for the general population. A UN Development Program report in 2002 said that much of the aid and effort applied to mitigate the effects of the Chernobyl accident did more harm than good, and it seems that this, along with the Chernobyl Forum report, finally persuaded the Belarus authorities. In 2004 President Lukashenko announced a priority to repopulate much of the Chernobyl-affected regions of Belarus, and then in 2009 he said that he “wants to repopulate Chernobyl’s zone quickly”.

In 2011 Chernobyl was officially declared a tourist attraction, with many visitors.

In 2015 the published results of a major scientific study showed that the mammal population of the exclusion zone (including the 2162 sq km Polessian State Radiation-Ecological Reserve – PSRER in Belarus) was thriving, despite land contamination. The “long-term empirical data showed no evidence of a negative influence of radiation on mammal abundance.” The data “represent unique evidence of wildlife's resilience in the face of chronic radiation stress.” (*Current Biology*, Elsevier[8]) . Other studies have concluded that the net environmental effect of the accident has been much greater biodiversity and abundance of species, with the exclusion zone having become a unique sanctuary for wildlife due to the absence of humans.

What has been learned 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[7].

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 those most in need. Remedying this presents daunting political problems however.

Notes & references

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 emphasize 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.

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 Group[1]: "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. [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. Information on the General Atomics website (but now deleted) stated: "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 stated: "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 Report 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 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]

h. Image taken from page 31 of *The International Chernobyl Project Technical Report, Assessment of Radiological Consequences and Evaluation of Protective Measures, Report by an International Advisory Committee*, IAEA, 1991 (ISBN: 9201291914) [Back]

i. A 55-page summary version the revised report, *Chernobyl's Legacy: Health, Environmental and Socio-Economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine, The Chernobyl Forum: 2003–2005, Second revised version*, as well as the Report of the UN Chernobyl Forum Expert Group "Environment" and the Report of the UN Chernobyl Forum Expert Group "Health" are available from the IAEA's webpage for the Chernobyl Forum (http://www-ns.iaea.org/meetings/rw-summaries/chernobyl_forum.htm) [Back]

j. The United Nations Scientific Commission on the Effects of Atomic Radiation (UNSCEAR) is the UN body with a mandate from the General Assembly to assess and report levels and health effects of exposure to ionizing radiation.

Exposures and effects of the Chernobyl accident, Annex J to Volume II of the 2000 United Nations Scientific Committee on the Effects of Atomic Radiation Report to the General Assembly, is available at the UNSCEAR 2000 Report Vol. II webpage (www.unscear.org/unscear/en/publications/2000_2.html). It is also available (along with other reports) on the webpage for UNSCEAR's assessments of the radiation effects of The Chernobyl accident (www.unscear.org/unscear/en/chernobyl.html). The conclusions from Annex J of the UNSCEAR 2000 report are in Chernobyl Accident Appendix: Health Impacts [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. [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]

m. The UNSCEAR committee in 2018[9] estimated that the fraction of the incidence of thyroid cancer attributable to radiation exposure among non-evacuated residents of Belarus, Ukraine and the four most contaminated oblasts of the Russian Federation, who were under 18 at the time of the accident, is in the order of 0.25. The committee states that the uncertainty range of the fraction is large, at least from 0.07 to 0.5. [Back]

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