Chernobyl disaster

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The **Chernobyl disaster** was a nuclear accident that occurred on 26 April 1986 at the Chernobyl Nuclear Power Plant in the Ukrainian SSR (now Ukraine). It is considered the worst nuclear power plant accident in history, and it is the only one classified as a level 7 event on the International Nuclear Event Scale.

Chernobyl disaster

The nuclear reactor after the disaster. Reactor 4 (center). Turbine building (lower left). Reactor 3 (center right).

Date	26 April 1986
Time	01:23:45 (Moscow Time UTC+3)
Location	Pripyat, Ukrainian SSR, Soviet Union, now Ukraine

The disaster began during a systems test on 26 April 1986 at reactor number four of the Chernobyl plant, which is near the town of Pripyat. There was a sudden power output surge, and when an emergency shutdown was attempted, a more extreme spike in power output occurred, which led to a reactor vessel rupture and a series of explosions. This event exposed the graphite moderator of the reactor to air, causing it to ignite.[1] The resulting fire sent a plume of highly radioactive smoke fallout into the atmosphere and over an extensive geographical area, including Pripyat. The plume drifted over large parts of the western Soviet Union, Eastern Europe, Western Europe, and Northern Europe. Large areas in Ukraine, Belarus, and Russia were evacuated, and over 336,000 people were resettled. According to official post-Soviet data,[2][3] about 60% of the fallout landed in Belarus.

The accident raised concerns about the safety of the Soviet nuclear power industry, as well as nuclear power in general, slowing its expansion for a number of years and forcing the Soviet government to become less secretive about its procedures.[4][notes 1]

The abandoned city of Pripyat with Chernobyl plant in the distance

Russia, Ukraine, and Belarus have been burdened with the continuing and substantial decontamination and health care costs of the Chernobyl accident. Thirty one deaths are directly attributed to the accident, all among the reactor staff and emergency workers. Estimates of the number of deaths potentially resulting from the accident vary enormously; the World Health Organization suggest it could reach 4,000 while a Greenpeace report puts this figure at 200,000 or more.

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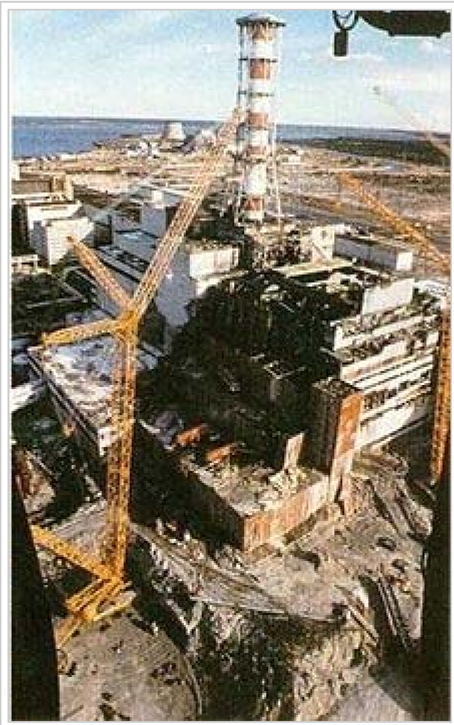
Accident



Chernobyl disaster aftermath, showing extensive damage to the main reactor hall.

On 26 April 1986, at 01:23 (UTC+3), reactor four suffered a catastrophic power increase, leading to explosions in its core. This dispersed large quantities of radioactive fuel and core materials into the atmosphere[5]:73 and ignited the combustible graphite moderator. The burning graphite moderator increased the emission of radioactive particles, carried by the smoke, as the reactor had not been contained by any kind of hard containment vessel. The accident occurred during an experiment scheduled to test a potential safety emergency core cooling feature, which took place during the normal shutdown procedure.

The attempted experiment

Even when not actively generating power, nuclear power reactors require cooling, typically provided by coolant flow, to remove decay heat.[6] Pressurized water reactors use water flow at high pressure to remove waste heat. Following an emergency shutdown (scram), the core still generates a significant amount of residual heat, which is initially about seven percent of the total thermal output of the plant. If not removed by coolant systems, the heat could lead to core damage.[7][8]

Following an emergency shutdown, reactor cooling is still required to keep the temperature in the reactor core low enough to avoid fuel damage. The reactor that exploded in Chernobyl consisted of about 1,600 individual fuel channels, and each operational channel required a flow of 28 metric tons (28,000 liters (7,400 USgal)) of water per hour.[5]:7 There had been concerns that in the event of a power grid failure, external power would not have been immediately available to run the plant's cooling water pumps. Chernobyl's reactors had three backup diesel generators. Each generator required 15 seconds to start up but took 60–75 seconds[5]:15 to attain full speed and reach the capacity of 5.5 MW required to run one main cooling water pump.[5]:30

This one-minute power gap was considered unacceptable, and it had been suggested that the mechanical energy (rotational momentum) of the steam turbine and residual steam pressure (with turbine valves closed) could be used to generate electricity to run the main cooling water pumps while the generator was still at the correct RPM, frequency, and voltage. In theory, analyses indicated that this residual momentum and steam pressure had the potential to provide power for 45 seconds,[5]:16 which would bridge the power gap between the onset of the external power failure and the full availability of electric power from the emergency diesel generators. This capability still needed to be confirmed experimentally, and previous tests had ended unsuccessfully. An initial test carried out in 1982 showed that the excitation voltage of the turbine-generator was insufficient; it did not maintain the desired magnetic field after the turbine trip. The system was modified, and the test was repeated in 1984 but again proved unsuccessful. In 1985, the tests were attempted a third time but also yielded negative results. The test procedure was to be repeated again in 1986, and it was scheduled to take place during the maintenance shutdown of Reactor Four.[9]

The test focused on the switching sequences of the electrical supplies for the reactor. The test procedure was to begin with an automatic emergency shutdown (SCRAM). No detrimental effect on the safety of the reactor was anticipated, so the test program was not formally coordinated with either the chief designer of the reactor (NIKIET) or the scientific manager. Instead, it was approved only by the director of the plant (and even this approval was not consistent with established procedures). According to the test parameters, the thermal output of the reactor should have been *no lower* than 700 MW at the start of the experiment. If test conditions had been as planned, the procedure would almost certainly have been carried out safely; the eventual disaster resulted from attempts to boost the reactor output once the experiment had been started, which was inconsistent with approved procedure.[10]

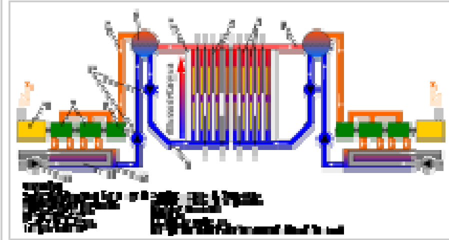
The Chernobyl power plant had been in operation for two years without the capability to ride through the first 60–75 seconds of a total loss of electric power, thus lacking an important safety feature. The station managers presumably wished to correct this at the first opportunity, which may explain why they continued the test even when serious problems arose, and why the requisite approval for the test was not sought from the Soviet nuclear oversight regulator (even though there was a representative at the complex of 4 reactors).[notes 2]:18–20

The experimental procedure was intended to run as follows:

1. The reactor was to be running at a low power level, between >700 MW & 800 MW.
2. The steam turbine was to be run up to full speed.
3. When these conditions were achieved, the steam supply was to be closed off.
4. Generator performance was to be recorded to determine whether it could provide the bridging power for coolant pumps.
5. After the "momentum" was used up at the normal operating RPM, frequency, and voltage the turbine/generator would be allowed to freewheel down.

Conditions prior to the accident

The conditions to run the test were established prior to the day shift of 25 April 1986. The day shift workers had been instructed in advance and were familiar with the established procedures. A special team of electrical engineers was present to test the new voltage regulating system.[11] As planned, a gradual reduction in the output of the power unit was begun at 01:06 on 25 April, and the power level had reached 50% of its nominal 3200 MW thermal level by the beginning of the day shift. At this point, another regional power station unexpectedly went off line, and the Kiev electrical grid controller requested that the further reduction of Chernobyl's output be postponed, as power was needed to satisfy the peak evening demand. The Chernobyl plant director agreed and postponed the test.


Schematic diagram of reactor

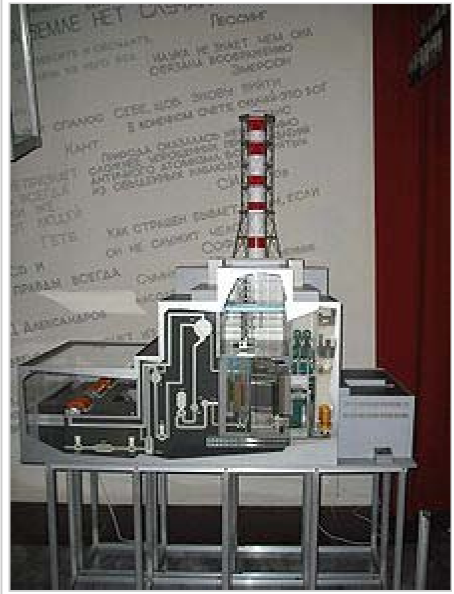
At 23:04, the Kiev grid controller allowed the reactor shut-down to resume. This delay had some serious consequences: the day shift had long since departed, the evening shift was also preparing to leave, and the night shift would not take over until midnight, well into the job. According to plan, the test should have been finalized during the day shift, and the night shift would only have had to maintain decay heat cooling systems in an otherwise shut down plant; the night shift had very limited time to prepare for and carry out the experiment. Further rapid reduction in the power level from 50% was actually executed during the shift change-over. Alexander Akimov was chief of the night shift, and Leonid Toptunov was the operator responsible for the reactor's operational regimen, including the movement of the control rods. Toptunov was a young engineer who had worked independently as a senior engineer for approximately three months.[5]:36–8

The test plan called for the power output of reactor 4 to be gradually reduced to a thermal level of 700–1000 MW.[12] The level established in the test program (700 MW) was achieved at 00:05 on April 26; however, because of the natural production of the neutron absorber xenon-135 in the core, reactor power continued to decrease, even without further operator action. As the power reached approximately 500 MW, Toptunov mistakenly inserted the control rods too far, bringing the reactor to an unintended near-shutdown state. The exact circumstances are hard to know, because both Akimov and Toptunov died from radiation sickness.

The reactor power dropped to 30 MW thermal (or less)—an almost completely shut down power level, which was approximately 5 percent of the minimum initial power level established as safe for the test.[10]:73 Control-room personnel consequently made the decision to restore the power and extracted the reactor control rods,[13] and several minutes elapsed between their extraction and the point that the power output began to increase and subsequently stabilize at 160–200 MW (thermal). This maneuver withdrew the majority of control rods to the rods' upper limits, but the low value of the operational reactivity margin restricted any further rise of reactor power. The rapid reduction in the power during the initial shutdown, and the subsequent operation at a level of less than 200 MW led to increased poisoning of the reactor core by the accumulation of xenon-135. This made it necessary to extract additional control rods from the reactor core in order to counteract the poisoning.

The operation of the reactor at the low power level with a small reactivity margin was accompanied by unstable core temperature and coolant flow, and possibly by instability of neutron flux.[14] Various alarms started going off at this point. The control room received repeated emergency signals regarding the levels in the steam/water separator drums, as well as of relief valves opened to relieve excess steam into a turbine condenser and of large excursions or variations in the flow rate of feed water, and also from the neutron power controller. In the period between 00:35 and 00:45, emergency alarm signals concerning thermal-hydraulic parameters were apparently ignored, apparently to preserve the reactor power level. Emergency signals from the reactor emergency protection system (EPS-5) triggered a trip which turned off both turbine-generators.[15]

After a while, a more or less stable state at a power level of 200 MW was achieved, and preparation for the experiment continued. As part of the test plan, extra water pumps were activated at 01:05 on 26 April, increasing the water flow. The increased coolant flow rate through the reactor produced an increase in the inlet coolant temperature of the reactor core, which now more closely approached the nucleate boiling temperature of water, reducing the safety margin. The flow exceeded the allowed limit at 01:19. At the same time, the extra water flow lowered the overall core temperature and reduced the existing steam voids in the core.[16] Since water also absorbs neutrons (and the higher density of liquid water makes it a better absorber than steam), turning on additional pumps decreased the reactor power further still. This prompted the operators to remove the manual control rods further to maintain power.[17]

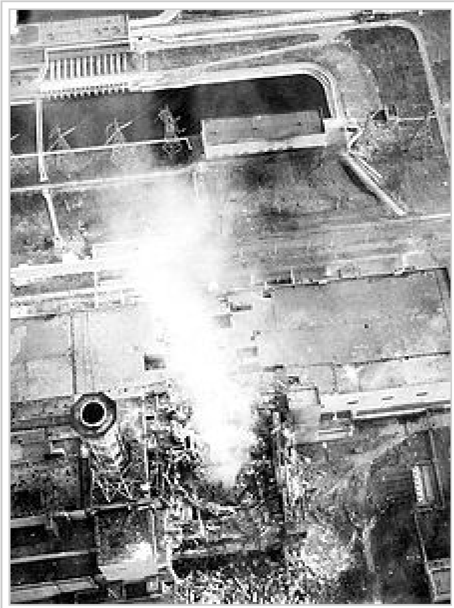


Chernobyl plant model on display at Kiev Ukrainian National Chernobyl Museum

All these actions led to an extremely unstable reactor configuration. Nearly all of the control rods were removed, which would limit the value of the safety rods when initially inserted in a scram condition. Further, the reactor coolant had reduced boiling, but had limited margin to boiling, so any power excursion would produce boiling, reducing neutron absorption by the water. The reactor was in an unstable configuration that was clearly outside the safe operating envelope established by the designers.

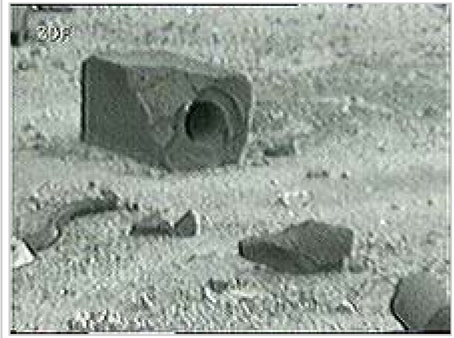
Experiment and explosion

At 1:23:04 a.m. the experiment began. The steam to the turbines was shut off, and a run down of the turbine generator began, together with four (of eight total) Main Circulating Pumps (MCP). The diesel generator started and sequentially picked up loads, which was complete by 01:23:43; during this period the power for these four MCPs was supplied by the coasting down turbine generator. As the momentum of the turbine generator that powered the water pumps decreased, the water flow rate decreased, leading to increased formation of steam voids (bubbles) in the core. Because of the positive void coefficient of the RBMK reactor at low reactor power levels, it was now primed to embark on a positive feedback loop, in which the formation of steam voids reduced the ability of the liquid water coolant to absorb neutrons, which in turn increased the reactor's power output. This caused yet more water to flash into steam, giving yet a further power increase. However, during almost the entire period of the experiment the automatic control system successfully counteracted this positive feedback, continuously inserting control rods into the reactor core to limit the power rise.



Aerial view of the damaged core. Roof of the turbine hall is damaged (image center). Roof of the adjacent reactor 3 (image lower left) shows minor fire damage.

At 1:23:40, as recorded by the SKALA centralized control system, an emergency shutdown or SCRAM of the reactor, which inadvertently triggered the explosion, was initiated. The scram was started when the EPS-5 button (also known as the AZ



Lumps of graphite moderator ejected from the core. The largest lump shows an intact control rod channel.

-5 button) of the reactor emergency protection system was pressed thus fully inserting all control rods, including the manual control rods that had been incautiously withdrawn earlier. The reason the EPS-5 button was pressed is not known, whether it was done as an emergency measure or simply as a routine method of shutting down the reactor upon completion of the experiment. There is a view that the SCRAM may have been ordered as a response to the unexpected rapid power increase, although there is no recorded data convincingly testifying to this. Some have suggested that the button was not pressed but rather that the signal was automatically produced by the emergency protection system; however, the SKALA clearly registered a manual scram signal. In spite of this, the question as to when or even whether the EPS-5 button was pressed was the subject of debate. There are assertions that the pressure was caused by the rapid power acceleration at the start, and allegations that the button was not pressed until the reactor began to self-destruct but others assert that it happened earlier and in calm conditions.[18]:578[19] For whatever reason, the EPS-5 button was pressed, so the insertion of control rods into the reactor core began. The control rod insertion mechanism operated at a relatively slow speed (0.4 m/s) taking 18–20 seconds for the rods to travel the full approximately 7-meter core length (height). A bigger problem was a flawed graphite-tip control rod design, which initially displaced coolant before neutron-absorbing material was inserted and the reaction slowed. As a result, the SCRAM actually increased the reaction rate in the lower half of the core.

A few seconds after the start of the SCRAM, a massive power spike occurred, the core overheated, and seconds later this overheating resulted in the initial explosion. Some of the fuel rods fractured, blocking the control rod columns and causing the control rods to become stuck after being inserted only one-third of the way. Within three seconds the reactor output rose above 530 MW.[5]:31 The subsequent course of events was not registered by instruments: it is known only as a result of mathematical simulation. Apparently, a great rise in power first caused an increase in fuel temperature and massive steam buildup, leading to a rapid increase in steam pressure. This destroyed fuel elements and ruptured the channels in which these elements were located.[20] Then, according to some estimations, the reactor jumped to around 30 GW thermal, ten times the normal operational output. The last reading on the control panel was 33 GW. It was not possible to reconstruct the precise sequence of the processes that led to the destruction of the reactor and the power unit building, but a steam explosion, like the explosion of a steam boiler from excess vapor pressure, appears to have been the next event. There is a general understanding that it was steam from the wrecked channels entering the reactor inner structure that caused the destruction of the reactor casing, tearing off and lifting by force the 2,000 ton upper plate (to which the entire reactor assembly is fastened). Apparently, this was the first explosion that many heard.[21]:366 This ruptured further fuel channels—as a result the remaining coolant flashed to steam and escaped the reactor core. The total water loss combined with a high positive void coefficient to increase the reactor power.

A second, more powerful explosion occurred about two or three seconds after the first; evidence indicates that the second explosion resulted from a nuclear excursion.[22] The nuclear excursion dispersed the core and effectively terminated that phase of the event. However, a graphite fire was burning by now, greatly contributing to the spread of radioactive material and the contamination of outlying areas.[23] There were initially several hypotheses about the nature of the second explosion. One view was that "the second explosion was caused by the hydrogen which had been produced either by the overheated steam-zirconium reaction or by the reaction of red-hot graphite with steam that produce hydrogen and carbon monoxide." Another hypothesis posits that the second explosion was a thermal explosion of the reactor as a result of the uncontrollable escape of fast neutrons caused by the complete water loss in the reactor core.[24] A third hypothesis was that the explosion was caused, exceptionally, by steam. According to this version, the flow of steam and the steam pressure caused all the destruction following the ejection from the shaft of a substantial part of the graphite and fuel.

> According to observers outside Unit 4, burning lumps of material and sparks shot into the air above the reactor. Some of them fell on to the roof of the machine hall and started a fire. About 25 per cent of the red-hot graphite blocks and overheated material from the fuel channels was ejected. …Parts of the graphite blocks and fuel channels were out of the reactor building. …As a result of the damage to the building an airflow through the core was established by the high temperature of the core. The air ignited the hot graphite and started a graphite fire.[5]:32

However, the ratio of xenon radioisotopes released during the event provides compelling evidence that the second explosion was a nuclear power transient. This nuclear transient released ~0.01 kiloton of TNT equivalent (40 GJ) of energy; the analysis indicates that the nuclear excursion was limited to a small portion of the core.[22]

Contrary to safety regulations, a combustible material (bitumen) had been used in the construction of the roof of the reactor building and the turbine hall. Ejected material ignited at least five fires on the roof of the (still operating) adjacent reactor 3. It was imperative to put those fires out and protect the cooling systems of reactor 3.[5]:42 Inside reactor 3, the chief of the night shift, Yuri Bagdasarov, wanted to shut down the reactor immediately, but chief engineer Nikolai Fomin would not allow this. The operators were given respirators and potassium iodide tablets and told to continue working. At 05:00, however, Bagdasarov made his own decision to shut down the reactor, leaving only those operators there who had to work the emergency cooling systems.[5]:44

Radiation levels

Approximate radiation levels at different locations shortly after the explosion:[25]

Location	Radiation (roentgens per hour)	Sieverts per hour (SI Unit)
Vicinity of the reactor core	30,000	300
Fuel fragments	15,000–20,000	150-200
Debris heap at the place of circulation pumps	10,000	100
Debris near the electrolyzers	5,000–15,000	50-150
Water in the Level +25 feedwater room	5,000	50
Level 0 of the turbine hall	500–15,000	5-150
Area of the affected unit	1,000–1,500	10-15
Water in Room 712	1,000	10
Control room, shortly after explosion	3–5	.03-.05
Gidroelektromontazh depot	30	.3
Nearby concrete mixing unit	10–15	.10-.15

Plant layout

Based on the image of the plant[26]

Level	Objects
49.6	Roof of the reactor building, gallery of the refueling mechanism
39.9	Roof of the deaerator gallery
35.5	Floor of the main reactor hall
31.6	Upper side of the upper biological shield, floor of the space for pipes to steam separators
28.3	Lower side of the turbine hall roof
24.0	Deaerator floor, measurement and control instruments room
16.4	Floor of the pipe aisle in the deaerator gallery
12.0	Main floor of the turbine hall, floor of the main circulation pump motor compartments
10.0	Control room, floor under the reactor lower biological shield, main circulation pumps
6.0	Steam distribution corridor
2.2	Upper pressure suppression pool
0.0	Ground level; house switchgear, turbine hall level
-0.5	Lower pressure suppression pool
-5.2, -4.2	Other turbine hall levels
-6.5	Basement floor of the turbine hall

Individual involvement

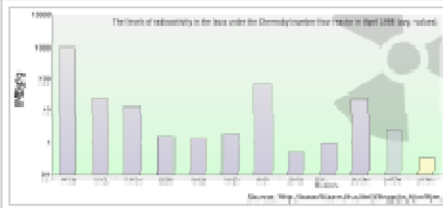
Main article: Individual involvement in the Chernobyl disaster

Deaths and survivors

Main article: Deaths due to the Chernobyl disaster

Immediate crisis management

Radiation levels



Extremely high levels of radioactivity in the lava under the Chernobyl number four reactor in 1986

The radiation levels in the worst-hit areas of the reactor building have been estimated to be 5.6 roentgens per second (R/s) (1.4 milliamperes per kilogram), equivalent to more than 20,000 roentgens per hour. A lethal dose is around 500 roentgens (0.13 coulombs per kilogram) over 5 hours, so in some areas, unprotected workers received fatal doses within minutes. However, a dosimeter capable of measuring up to 1,000 R/s (0.3 A/kg) was inaccessible because of the explosion, and another one failed when turned on. All remaining dosimeters had limits of 0.001 R/s (0.3 μA/kg) and therefore read "off scale." Thus, the reactor crew could ascertain only that the radiation levels were somewhere above 0.001 R/s (3.6 R/h, or 0.3 μA/kg), while the true levels were much, much higher in some areas.[5]:42–50

Because of the inaccurate low readings, the reactor crew chief Alexander Akimov assumed that the reactor was intact. The evidence of pieces of graphite and reactor fuel lying around the building was ignored, and the readings of another dosimeter brought in by 04:30 were dismissed under the assumption that the new dosimeter must have been defective.[5]:42–50 Akimov stayed with his crew in the reactor building until morning, trying to pump water into the reactor. None of them wore any protective gear. Most, including Akimov, died from radiation exposure within three weeks.[27]:247–48

Fire containment

Firefighter Leonid Telyatnikov, being decorated for bravery

Shortly after the accident, firefighters arrived to try to extinguish the fires. First on the scene was a Chernobyl Power Station firefighter brigade under the command of Lieutenant Volodymyr Pravik, who died on 9 May 1986 of acute radiation sickness. They were not told how dangerously radioactive the smoke and the debris were, and may not even have known that the accident was anything more than a regular electrical fire: "We didn't know it was the reactor. No one had told us."[28]

Grigorii Khmel, the driver of one of the fire-engines, later described what happened:

> We arrived there at 10 or 15 minutes to two in the morning… We saw graphite scattered about. Misha asked: "What is graphite?" I kicked it away. But one of the fighters on the other truck picked it up. "It's hot," he said. The pieces of graphite were of different sizes, some big, some small enough to pick up…
>
> We didn't know much about radiation. Even those who worked there had no idea. There was no water left in the trucks. Misha filled the cistern and we aimed the water at the top. Then those boys who died went up to the roof—Vashchik Kolya and others, and Volodya Pravik… They went up the ladder… and I never saw them again.[29]:54

However, Anatoli Zakharov, a fireman stationed in Chernobyl since 1980, offers a different description:

> I remember joking to the others, "There must be an incredible amount of radiation here. We'll be lucky if we're all still alive in the morning."

Twenty years after the disaster, he claimed the firefighters from the Fire Station No. 2 were aware of the risks.

> Of course we knew! If we'd followed regulations, we would never have gone near the reactor. But it was a moral obligation—our duty. We were like kamikaze.[30]

The immediate priority was to extinguish fires on the roof of the station and the area around the building containing Reactor No. 4 to protect No. 3 and keep its core cooling systems intact. The fires were extinguished by 05:00, but many firefighters received high doses of radiation. The fire inside Reactor No. 4 continued to burn until 10 May 1986; it is possible that well over half of the graphite burned out.[5]:73 The fire was extinguished by a combined effort of helicopters dropping over 5,000 metric tons of sand, lead, clay, and boron onto the burning reactor and injection of liquid nitrogen. Ukrainian filmmaker Vladimir Shevchenko captured film footage of an Mi-8 helicopter as it collided with a nearby construction crane, causing the helicopter to fall near the damaged reactor building and kill its four-man crew.[31]

From eyewitness accounts of the firefighters involved before they died (as reported on the CBC television series *Witness*), one described his experience of the radiation as "tasting like metal," and feeling a sensation similar to that of pins and needles all over his face. (This is similar to the description given by Louis Slotin, a Manhattan Project physicist who died days after a fatal radiation overdose from a criticality accident.)[32]

The explosion and fire threw hot particles of the nuclear fuel and also far more dangerous fission products, radioactive isotopes such as caesium-137, iodine-131, strontium-90 and other radionuclides, into the air: the residents of the surrounding area observed the radioactive cloud on the night of the explosion.

Timeline

- 1:26:03 – fire alarm activated
- 1:28 – arrival of local firefighters, Pravik's guard
- 1:35 – arrival of firefighters from Pripyat, Kibenok's guard
- 1:40 – arrival of Telyatnikov
- 2:10 – turbine hall roof fire extinguished
- 2:30 – main reactor hall roof fires suppressed

- 3:30 – arrival of Kiev firefighters[33]
- 4:50 – fires mostly localized
- 6:35 – all fires extinguished‡[34]

‡With the exception of the fire contained inside Reactor 4, which continued to burn for many days.[5]:73

Evacuation of Pripyat

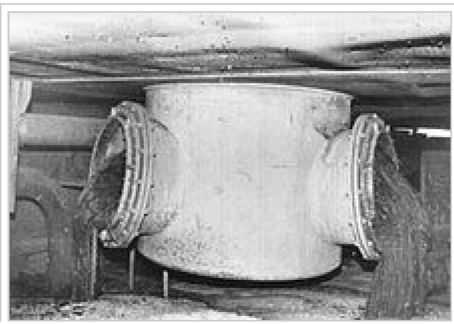
View of Chernobyl taken from Pripyat (city)

The nearby city of Pripyat was not immediately evacuated after the incident. Only after radiation levels set off alarms at the Forsmark Nuclear Power Plant in Sweden,[35] over one thousand kilometers from the Chernobyl Plant, did the Soviet Union admit that an accident had occurred. Nevertheless, authorities attempted to conceal the scale of the disaster. For example, while evacuating the city of Pripyat, the following warning message was read on local radio: "An accident has occurred at the Chernobyl Nuclear Power Plant. One of the atomic reactors has been damaged. Aid will be given to those affected and a committee of government inquiry has been set up."[*citation needed*]

The government committee was eventually formed, and tasked to investigating the accident. It was headed by Valeri Legasov, who arrived at Chernobyl in the evening of 26 April. By the time Legasov arrived, two people had already died and 52 were receiving medical attention in a hospital. By the night of 26–27 April—more than 24 hours after the explosion—Legasov's committee had ample evidence showing extremely high levels of radiation had caused a number of cases of radiation exposure. Based on the evidence at hand, Legasov's committee acknowledged the destruction of the reactor and ordered the evacuation of Pripyat.

The evacuation began at 14:00 on 27 April. In order to expedite the evacuation, the residents were told to bring only what was necessary, as the authorities had said it would only last approximately three days. As a result, most of the residents left their personal belongings, which can still be found today. An exclusion zone of 30 km (19 mi) remains in place today (although its shape has changed and its size has been expanded).

Steam explosion risk



Two floors of bubbler pools beneath the reactor served as a large water reservoir from the emergency cooling pumps and as a pressure suppression system capable of condensing steam from a (small) broken steam pipe; the third floor above them, below the reactor, served as a steam tunnel. The steam released from a broken pipe was supposed to enter the steam tunnel and be led into the pools to bubble through a layer of water. The pools and the basement were flooded because of ruptured cooling water pipes and accumulated fire water. They now constituted a serious steam explosion risk. The smoldering graphite, fuel and other material above, at more than 1200 °C,[37] started to burn through the reactor floor and mixed with molten concrete that had lined the reactor, creating corium, a radioactive semi-liquid material comparable to lava.[36][38] If this mixture had melted through the floor into the pool of water, it would have created a massive steam explosion that would have ejected more radioactive material from the reactor. It became an immediate priority to drain the pool.[39]

Chernobyl Corium lava flows formed by fuel-containing mass in the basement of the plant. Lava flow (1). Concrete (2). Steam pipe (3). Electrical equipment (4).[36]

The bubbler pool could be drained by opening its sluice gates. Volunteers in diving suits entered the radioactive water and managed to open the gates. These were engineers Alexei Ananenko (who knew where the valves were) and Valeri Bezpalov, accompanied by a third man, Boris Baranov, who provided them with light from a lamp, though this lamp failed, leaving them to find the valves by feeling their way along a pipe. All of them returned to the surface and according to Ananenko, their colleagues jumped for joy when they heard they had managed to open the valves. Despite their good condition after completion of the task, all of them suffered from radiation sickness, and at least two—Ananenko and Bezpalov—later died.[*citation needed*] Some sources claim incorrectly that they died in the plant.[40] It is likely that intense alpha radiation hydrolyzed the water, generating a low-pH hydrogen peroxide (H_2O_2) solution akin to an oxidizing acid.[41] Conversion of bubbler pool water to H_2O_2 is confirmed by the presence in the Chernobyl lavas of studtite and metastudtite,[42][43] the only minerals that contain peroxide.[44]

Fire brigade pumps were then used to drain the basement. The operation was not completed until 8 May, after 20,000 metric tons of highly radioactive water were pumped out.

With the bubbler pool gone, a meltdown was less likely to produce a powerful steam explosion. To do so, the molten core would now have to reach the water table below the reactor. To reduce the likelihood of this, it was decided to freeze the earth beneath the reactor, which would also stabilize the foundations. Using oil drilling equipment, injection of liquid nitrogen began on 4 May. It was estimated that 25 metric tons of liquid nitrogen per day would be required to keep the soil frozen at −100 °C.[5]:59 This idea was soon scrapped and the bottom room where the cooling system would have been installed was filled with concrete.

Debris removal

The worst of the radioactive debris was collected inside what was left of the reactor, much of it shoveled in by liquidators wearing heavy protective gear (dubbed "bio-robots" by the military); these workers could only spend a maximum of 40 seconds at a time working on the rooftops of the surrounding buildings because of the extremely high doses of radiation given off by the blocks of graphite and other debris. The reactor itself was covered with bags containing sand, lead, and boric acid dropped from helicopters (some 5,000 metric tons during the week following the accident). By December 1986 a large concrete sarcophagus had been erected, to seal off the reactor and its contents.[45]


Chernobyl power plant in 2003 with the sarcophagus containment structure

Many of the vehicles used by the "liquidators" remain parked in a field in the Chernobyl area.[46]

Causes

Operator error initially faulted

There were two official explanations of the accident: the first, subsequently acknowledged as erroneous, was published in August 1986 and effectively placed the blame on the power plant operators. To investigate the causes of the accident the IAEA created a group known as the International Nuclear Safety Advisory Group (INSAG), which in its report of 1986, INSAG-1, on the whole also supported this view, based on the data provided by the Soviets and the oral statements of specialists.[47] In this view, the catastrophic accident was caused by gross violations of operating rules and regulations. "During preparation and testing of the turbine generator under run-down conditions using the auxiliary load, personnel disconnected a series of technical protection systems and breached the most important operational safety provisions for conducting a technical exercise."[48]:311 The operator error was probably due to their lack of knowledge of nuclear reactor physics and engineering, as well as lack of experience and training. According to these allegations, at the time of the accident the reactor was being operated with many key safety systems turned off, most notably the Emergency Core Cooling System (ECCS), LAR (Local Automatic control system), and AZ (emergency power reduction system). Personnel had an insufficiently detailed understanding of technical procedures involved with the nuclear reactor, and knowingly ignored regulations to speed test completion.[48]

> The developers of the reactor plant considered this combination of events to be impossible and therefore did not allow for the creation of emergency protection systems capable of preventing the combination of events that led to the crisis, namely the intentional disabling of emergency protection equipment plus the violation of operating procedures. Thus the primary cause of the accident was the extremely improbable combination of rule infringement plus the operational routine allowed by the power station staff.[48]:312

In this analysis of the causes of the accident, deficiencies in the reactor design and in the operating regulations that made the accident possible were set aside and mentioned only casually. Serious critical observations covered only general questions and did not address the specific reasons for the accident. The following general picture arose from these observations. Several procedural irregularities also helped to make the accident possible. One was insufficient communication between the safety officers and the operators in charge of the experiment being run that night. The reactor operators disabled safety systems down to the generators, which the test was really about. The main process computer, SKALA, was running in such a way that the main control computer could not shut down the reactor or even reduce power. Normally the reactor would have started to insert all of the control rods. The computer would have also started the "Emergency Core Protection System" that introduces 24 control rods into the active zone within 2.5 seconds, which is still slow by 1986 standards. All control was transferred from the process computer to the human operators.

This view is reflected in numerous publications and also artistic works on the theme of the Chernobyl accident that appeared immediately after the accident,[5] and for a long time remained dominant in the public consciousness and in popular publications.

Operating instructions and design deficiencies found

In 1993 the IAEA Nuclear Safety Advisory Group (INSAG) published an additional report, INSAG-7,[10] which reviewed "that part of the INSAG-1 report in which primary attention is given to the reasons for the accident." In this later report, most of the accusations against staff for breach of regulations were acknowledged to be erroneous, based on incorrect information obtained in August 1986. This report reflected another view of the reasons for the accident, presented in Appendix I. According to this account, the operators' actions in turning off the Emergency Core Cooling System, interfering with the settings on the protection equipment, and blocking the level and pressure in the separator drum did not contribute to the original cause of the accident and its magnitude, though they may have been a breach of regulations. Turning off the emergency system designed to prevent the two turbine generators from stopping was not a violation of regulations.[10]

Human factors contributed to the conditions that led to the disaster. These included operating the reactor at a low power level—less than 700 MW—a level documented in the run-down test program, and operating with a small operational reactivity margin (ORM). Operating the reactor at this low power level was not forbidden by regulations, contradicting what Soviet experts asserted in 1986.[10]:18 However, regulations did forbid operating the reactor with a small margin of reactivity. However, "... post-accident studies have shown that the way in which the real role of the ORM is reflected in the Operating Procedures and design documentation for the RBMK-1000 is extremely contradictory," and furthermore, "ORM was not treated as an operational safety limit, violation of which could lead to an accident.",[10]:34-25).

According to the INSAG-7 Report, the chief reasons for the accident lie in the peculiarities of physics and in the construction of the reactor. There are two such reasons:[10]:18

- The reactor had a dangerously large positive void coefficient. The void coefficient is a measurement of how a reactor responds to increased steam formation in the water coolant. Most other reactor designs have a negative coefficient, i.e. the nuclear reaction rate slows when steam bubbles form in the coolant, since as the vapor phase in the reactor increases, fewer neutrons are slowed down. Faster neutrons are less likely to split uranium atoms, so the reactor produces less power (a negative feed-back). Chernobyl's RBMK reactor, however, used solid graphite as a neutron moderator to slow down the neutrons, and the water in it, on the contrary, acts like a harmful neutron absorber. Thus neutrons are slowed down even if steam bubbles form in the water. Furthermore, because steam absorbs neutrons much less readily than water, increasing the intensity of vaporization means that more neutrons are able to split uranium atoms, increasing the reactor's power output. This makes the RBMK design very unstable at low power levels, and prone to suddenly increasing energy production to a dangerous level. This behavior is counter-intuitive, and this property of the reactor was unknown to the crew.

- A more significant flaw was in the design of the control rods that are inserted into the reactor to slow down the reaction. In the RBMK reactor design, the lower part of each control rod was made of graphite and was 1.3 meters shorter than necessary, and in the space beneath the rods were hollow channels filled with water. The upper part of the rod—the truly functional part that absorbs the neutrons and thereby halts the reaction—was made of boron carbide. With this design, when the rods are inserted into the reactor from the uppermost position, the graphite parts initially displace some water (which absorbs neutrons, as mentioned above), effectively causing less neutrons to be absorbed initially. Thus for the first few seconds of control rod activation, reactor power output is increased, rather than reduced as desired. This behavior is counter-intuitive and was not known to the reactor operators.

- Other deficiencies besides these were noted in the RBMK-1000 reactor design, as were its non-compliance with accepted standards and with the requirements of nuclear reactor safety.

Both views were heavily lobbied by different groups, including the reactor's designers, power plant personnel, and the Soviet and Ukrainian governments. According to the IAEA's 1986 analysis, the main cause of the accident was the operators' actions. But according to the IAEA's 1993 revised analysis the main cause was the reactor's design.[49] One reason there were such contradictory viewpoints and so much debate about the causes of the Chernobyl accident was that the primary data covering the disaster, as registered by the instruments and sensors, were not completely published in the official sources.

Once again, the human factor had to be considered as a major element in causing the accident. INSAG notes that both the operating regulations and staff handled the disabling of the reactor protection easily enough: witness the length of time for which the ECCS was out of service while the reactor was operated at half power. INSAG's view is that it was the operating crew's deviation from the test program that was mostly to blame. "Most reprehensibly, unapproved changes in the test procedure were deliberately made on the spot, although the plant was known to be in a very different condition from that intended for the test." [10]:24

As in the previously released report INSAG-1, close attention is paid in report INSAG-7 to the inadequate (at the moment of the accident) "culture of safety" at all levels. Deficiency in the safety culture was inherent not only at the operational stage but also, and to no lesser extent, during activities at other stages in the lifetime of nuclear power plants (including design, engineering, construction, manufacture and regulation). The poor quality of operating procedures and instructions, and their conflicting character, put a heavy burden on the operating crew, including the Chief Engineer. "The accident can be said to have flowed from a deficient safety culture, not only at the Chernobyl plant, but throughout the Soviet design, operating and regulatory organizations for nuclear power that existed at that time." [10]:24

Effects

Main article: Chernobyl disaster effects

International spread of radioactive substances

Four hundred times more radioactive material was released than had been by the atomic bombing of Hiroshima. However, compared to the total amount released by nuclear weapons testing during the 1950s and 1960s, the Chernobyl disaster released 1/100 to 1/1000 the radioactivity.[51] The fallout was detected over all of Europe except for the Iberian Peninsula.[52][53][54]

An exhibit at the Ukrainian National Chernobyl Museum. Mutations in both humans and other animals may have increased as a result of the disaster.[50]

The initial evidence that a major release of radioactive material was affecting other countries came not from Soviet sources, but from Sweden, where on the morning of 28 April[55] workers at the Forsmark Nuclear Power Plant (approximately 1,100 km (680 mi) from the Chernobyl site) were found to have radioactive particles on their clothes.[56] It was Sweden's search for the source of radioactivity, after they had determined there was no leak at the Swedish plant, that at noon on April 28 led to the first hint of a serious nuclear problem in the western Soviet Union.

Hence the evacuation of Pripyat on April 27, 36 hours after the initial explosions, was silently completed before the disaster became known outside the Soviet Union. The rise in radiation levels had at that time already been measured in Finland, but a civil service strike delayed the response and publication.[57]

Areas of Europe contaminated with Cs^{137}[58]

Country	37-185 kBq/m^2	185-555 kBq/m^2	555-1480 kBq/m^2	+1480 kBq/m^2
Russia	49 800	5 700	2 100	3000
Belarus	29 900	10 200	4200	2200
Ukraine	37 200	3 200	900	600
Sweden	12 000	-	-	-
Finland	11 500	-	-	-
Austria	8 600	-	-	-
Norway	5 200	-	-	-
Bulgaria	4 800	-	-	-
Switzerland	1 300	-	-	-
Greece	1 200	-	-	-
Slovenia	300	-	-	-
Italy	300	-	-	-
Moldavia	60	-	-	-

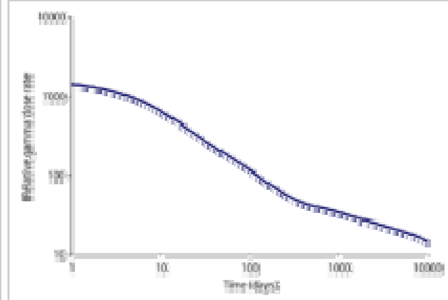
Contamination from the Chernobyl accident was scattered irregularly depending on weather conditions. Reports from Soviet and Western scientists indicate that Belarus received about 60% of the contamination that fell on the former Soviet Union. However, the 2006 TORCH report stated that half of the volatile particles had landed outside Ukraine, Belarus, and Russia. A large area in Russia south of Bryansk was also contaminated, as were parts of northwestern Ukraine. Studies in surrounding countries indicate that over one million people could have been affected by radiation.[59]

Recently published data from a long-term monitoring program (The Korma Report)[60] show a decrease in internal radiation exposure of the inhabitants of a region in Belarus close to Gomel. Resettlement may even be possible in prohibited areas provided that people comply with appropriate dietary rules.

In Western Europe, precautionary measures taken in response to the radiation included seemingly arbitrary regulations banning the importation of certain foods but not others. In France some officials stated that the Chernobyl accident had no adverse effects.[61] Official figures in southern Bavaria in Germany indicated that some wild plant species contained substantial levels of caesium, which were believed to have been passed onto them by wild boars, a significant number of which had already contained radioactive particles above the allowed level, consuming them.[62]

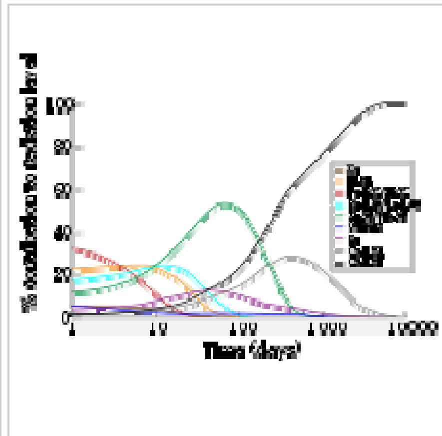
Radioactive release

Like many other releases of radioactivity into the environment, the Chernobyl release was controlled by the physical and chemical properties of the radioactive elements in the core. While the general population often perceives plutonium as a particularly dangerous nuclear fuel, its effects are almost eclipsed by those of its fission products. Particularly dangerous are highly radioactive compounds that accumulate in the food chain, such as some isotopes of iodine and strontium.



The external gamma dose for a person in the open near the Chernobyl site.

Two reports on the release of radioisotopes from the site were made available, one by the OSTI and a more detailed report by the OECD, both in 1998.[63][64] At different times after the accident, different isotopes were responsible for the majority of the external dose. The dose that was calculated is that received from external gamma irradiation for a person standing in the open. The dose to a person in a shelter or the internal dose is harder to estimate.



Contributions of the various isotopes to the (atmospheric) dose in the contaminated area soon after the accident.

The release of radioisotopes from the nuclear fuel was largely controlled by their boiling points, and the majority of the radioactivity present in the core was retained in the reactor.

- All of the noble gases, including krypton and xenon, contained within the reactor were released immediately into the atmosphere by the first steam explosion.
- About 1760 PBq of I-131, 55% of the radioactive iodine in the reactor, was released, as a mixture of vapor, solid particles, and organic iodine compounds.
- Caesium and tellurium were released in aerosol form.
- An early estimate for fuel material released to the environment was 3 t ± 1.5%; this was later revised to 3.5 t ± 0.5%. This corresponds to the atmospheric emission of 6 t of fragmented fuel.[64]

Two sizes of particles were released: small particles of 0.3 to 1.5 micrometers (aerodynamic diameter) and large particles of 10 micrometers. The large particles contained about 80% to 90% of the released nonvolatile radioisotopes zirconium-95, niobium-95, lanthanum-140, cerium-144 and the transuranic elements, including neptunium, plutonium and the minor actinides, embedded in a uranium oxide matrix.

Health of plant workers and local people

In the aftermath of the accident, 237 people suffered from acute radiation sickness, of whom 31 died within the first three months.[65][66] Most of these were fire and rescue workers trying to bring the accident under control, who were not fully aware of how dangerous exposure to the radiation in the smoke was. Whereas, in the World Health Organization's 2006 report of the Chernobyl Forum expert group on the 237 emergency workers who were diagnosed with ARS, ARS was identified as the cause of death for 28 of these people within the first few months after the disaster. There were no further deaths identified, in the general population affected by the disaster, as being caused by ARS. Of the 72,000 Russian Emergency Workers being studied, 216 non-cancer deaths are attributed to the disaster, between 1991 and 1998. The latency period for solid cancers caused by excess radiation exposure is 10 or more years; thus at the time of the WHO report being undertaken, the rates of solid cancer deaths were no greater than the general population. Some 135,000 people were evacuated from the area, including 50,000 from Pripyat.

Residual radioactivity in the environment

Rivers, lakes and reservoirs


Earth Observing-1 image of the reactor and surrounding area in April 2009

The Chernobyl nuclear power plant is located next to the Pripyat River, which feeds into the Dnipro River reservoir system, one of the largest surface water systems in Europe. The radioactive contamination of aquatic systems therefore became a major problem in the immediate aftermath of the accident.[67] In the most affected areas of Ukraine, levels of radioactivity (particularly radioiodine: I-131, radiocaesium: Cs-137 and radiostrontium: Sr-90) in drinking water caused concern during the weeks and months after the accident. After this initial period, however, radioactivity in rivers and reservoirs was generally below guideline limits for safe drinking water.[67]

Bio-accumulation of radioactivity in fish[68] resulted in concentrations (both in western Europe and in the former Soviet Union) that in many cases were significantly above guideline maximum levels for consumption.[67] Guideline maximum levels for radiocaesium in fish vary from country to country but are approximately 1,000 Bq/kg in the European Union.[69] In the Kiev Reservoir in Ukraine, concentrations in fish were several thousand Bq/kg during the years after the accident.[68] In small "closed" lakes in Belarus and the Bryansk region of Russia, concentrations in a number of fish species varied from 0.1 to 60 kBq/kg during the period 1990–92.[70] The contamination of fish caused short-term concern in parts of the UK and Germany and in the long term (years rather than months) in the affected areas of Ukraine, Belarus, and Russia as well as in parts of Scandinavia.[67]

Groundwater

Groundwater was not badly affected by the Chernobyl accident since radionuclides with short half-lives decayed away long before they could affect groundwater supplies, and longer-lived radionuclides such as radiocaesium and radiostrontium were adsorbed to surface soils before they could transfer to groundwater.[71] However, significant transfers of radionuclides to groundwater have occurred from waste disposal sites in the 30 km (19 mi) exclusion zone around Chernobyl. Although there is a potential for transfer of radionuclides from these disposal sites off-site (i.e. out of the 30 km (19 mi) exclusion zone), the IAEA Chernobyl Report[71] argues that this is not significant in comparison to current levels of washout of surface-deposited radioactivity.

Flora and fauna

Map of radiation levels in 1996 around Chernobyl.

After the disaster, four square kilometers of pine forest in the immediate vicinity of the reactor turned reddish-brown and died, earning the name of the "Red Forest".[72] Some animals in the worst-hit areas also died or stopped reproducing. Most domestic animals were removed from the exclusion zone, but horses left on an island in the Pripyat River 6 km (4 mi) from the power plant died when their thyroid glands were destroyed by radiation doses of 150–200 Sv.[73] Some cattle on the same island died and those that survived were stunted because of thyroid damage. The next generation appeared to be normal.[73]

The major plume of radiation released by the Chernobyl disaster was carried directly over what is now called the Red Forest. Radioactive particles settled on trees, killing areas of pine forest.

A robot sent into the reactor itself has returned with samples of black, melanin-rich radiotrophic fungi that are growing on the reactor's walls.[74]

Of the 440,350 wild boar killed in the 2010 hunting season in Germany, over 1,000 were found to be contaminated with levels of radiation above the permitted limit of 600 bequerels, due to residual radioactivity from Chernobyl.[75]

The Norwegian Agricultural Authority reported that in 2009 a total of 18,000 livestock in Norway needed to be given uncontaminated feed for a period of time before slaughter in order to ensure that their meat was safe for human consumption. This was due to residual radioactivity from Chernobyl in the plants they graze on in the wild during the summer. The after-effects of Chernobyl were expected to be seen for a further 100 years, although the severity of the effects would decline over that period.[76]

Chernobyl after the disaster

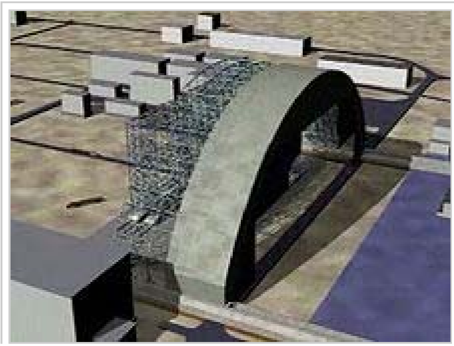
Main article: Chernobyl after the disaster

Recovery process

Recovery projects

The Chernobyl Shelter Fund

The Chernobyl Shelter Fund was established in 1997 at the Denver 23rd G8 summit to finance the Shelter Implementation Plan (SIP). The plan calls for transforming the site into an ecologically safe condition by means of stabilization of the sarcophagus followed by construction of a New Safe Confinement (NSC). While the original cost estimate for the SIP was US$768 million, the 2006 estimate was $1.2 billion. The SIP is being managed by a consortium of Bechtel, Battelle, and Electricité de France, and conceptual design for the NSC consists



of a movable arch, constructed away from the shelter to avoid high radiation, to be slid over the sarcophagus. The NSC is expected to be completed in 2013, and will be the largest movable structure ever built.

Computer impression of the New Safe Confinement to cover the No. 4 Reactor at Chernobyl

Dimensions:

- Span: 270 m (886 ft)
- Height: 100 m (330 ft)
- Length: 150 m (492 ft)

The United Nations Development Programme

The United Nations Development Programme has launched in 2003 a specific project called the Chernobyl Recovery and Development Programme (CRDP) for the recovery of the affected areas.[77] The programme was initiated in February 2002 based on the recommendations in the report on Human Consequences of the Chernobyl Nuclear Accident. The main goal of the CRDP’s activities is supporting the Government of Ukraine in mitigating long-term social, economic, and ecological consequences of the Chernobyl catastrophe. CRDP works in the four most Chernobyl-affected areas in Ukraine: Kyivska, Zhytomyrska, Chernihivska and Rivnenska.

The International Project on the Health Effects of the Chernobyl Accident

The International Project on the Health Effects of the Chernobyl Accident (IPEHCA) was created and received US $20 million, mainly from Japan, in hopes of discovering the main cause of health problems due to ^{131}I radiation. These funds were divided between Ukraine, Belarus, and Russia, the three main affected countries, for further investigation of health effects. As there was significant corruption in former Soviet countries, most of the foreign aid was given to Russia, and no positive outcome from this money has been demonstrated.

Assessing the disaster's effects on human health

An international assessment of the health effects of the Chernobyl accident is contained in a series of reports by the United Nations Scientific Committee of the Effects of Atomic Radiation (UNSCEAR).[78] UNSCEAR was set up as a collaboration between various UN bodies, including the World Health Organisation, after the atomic bomb attacks on Hiroshima and Nagasaki, to assess the long-term effects of radiation on human health.

Demonstration on Chernobyl day near WHO in Geneva

UNSCEAR has conducted 20 years of detailed scientific and epidemiological research on the effects of the Chernobyl accident. Apart from the 57 direct deaths in the accident itself, UNSCEAR originally predicted up to 4,000 additional cancer cases due to the accident.[79]

UNSCEAR now states:

> Among the residents of Belarus, the Russian Federation and Ukraine, there had been up to the year 2005 more than 6,000 cases of thyroid cancer reported in children and adolescents who were exposed at the time of the accident, and more cases can be expected during the next decades. Notwithstanding the influence of enhanced screening regimes, many of those cancers were most likely caused by radiation exposures shortly after the accident. Apart from this increase, there is no evidence of a major public health impact attributable to radiation exposure two decades after the accident. There is no scientific evidence of increases in overall cancer incidence or mortality rates or in rates of non-malignant disorders that could be related to radiation exposure. The incidence of leukaemia in the general population, one of the main concerns owing to the shorter time expected between exposure and its occurrence compared with solid cancers, does not appear to be elevated. Although those most highly exposed individuals are at an increased risk of radiation-associated effects, 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.[80]

However, thyroid cancer is generally treatable.[81] With proper treatment, the five-year survival rate of thyroid cancer is 96%, and 92% after 30 years,[82] suggesting there may be up to 500 early deaths from this cause.

In addition, the IAEA states that there has been no increase in the rate of birth defects or abnormalities, or solid cancers (such as lung cancer) corroborating UNSCEAR's assessments.[83] UNSCEAR does also raise the possibility of long term genetic defects, pointing to a doubling of radiation-induced minisatellite mutations among children born in 1994.[84] There is some dispute over the control groups in this study and the long term effects are not clear.

The Chernobyl Forum is a regular meeting of IAEA, other United Nations organizations (FAO, UN-OCHA, UNDP, UNEP, UNSCEAR, WHO, and the World Bank), and the governments of Belarus, Russia, and Ukraine that issues regular scientific assessments of the evidence for health effects of the Chernobyl accident.[85] The Chernobyl Forum concluded that twenty-eight emergency workers died from acute radiation syndrome including beta burns and 15 patients died from thyroid cancer, and it roughly estimated that cancer deaths caused by Chernobyl may reach a total of about 4,000 among the 600,000 people having received the greatest exposures. It also concluded that a greater risk than the long-term effects of radiation exposure is the risk to mental health of exaggerated fears about the effects of radiation:[83]

> The designation of the affected population as “victims” rather than “survivors” has led them to perceive themselves as helpless, weak and lacking control over their future. This, in turn, has led either to over cautious behavior and exaggerated health concerns, or to reckless conduct, such as consumption of mushrooms, berries and game from areas still designated as highly contaminated, overuse of alcohol and tobacco, and unprotected promiscuous sexual activity.[86]

Fred Mettler commented that 20 years later:[87]

> The population remains largely unsure of what the effects of radiation actually are and retain a sense of foreboding. A number of adolescents and young adults who have been exposed to modest or small amounts of radiation feel that they are somehow fatally flawed and there is no downside to using illicit drugs or having unprotected sex. To reverse such

attitudes and behaviors will likely take years although some youth groups have begun programs that have promise.

In addition, disadvantaged children around Chernobyl suffer from health problems that are attributable not only to the Chernobyl accident, but also to the poor state of post-Soviet health systems.[88]

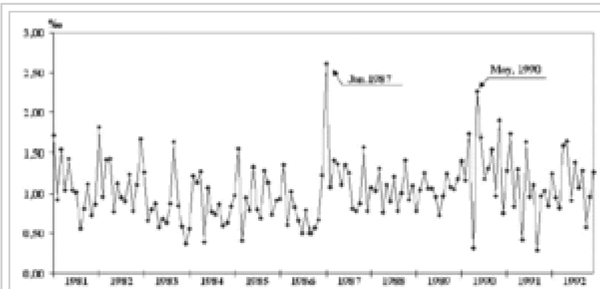
Another study critical of the Chernobyl Forum report was commissioned by Greenpeace, which asserts that "the most recently published figures indicate that in Belarus, Russia and Ukraine alone the accident could have resulted in an estimated 200,000 additional deaths in the period between 1990 and 2004."[89] The Scientific Secretary of the Chernobyl Forum questioned the choice by the report authors to selectively use non-peer reviewed papers and only those non-peer reviewed papers as their source material while Gregory Härtl (spokesman for the WHO) expressed concern that the conclusions were motivated by ideology.[90]

The German affiliate of the International Physicians for the Prevention of Nuclear War (IPPNW) argued that more than 10,000 people are today affected by thyroid cancer and 50,000 cases are expected in the future.[91]

Chernobyl: Consequences of the Catastrophe for People and the Environment is an English translation of the 2007 Russian publication *Chernobyl*. It was published online in 2009 by the New York Academy of Sciences in their *Annals of the New York Academy of Sciences*. It presents an analysis of scientific literature and concludes that medical records between 1986, the year of the accident, and 2004 reflect 985,000 deaths as a result of the radioactivity released. The authors suggest that most of the deaths were in Russia, Belarus and Ukraine, but others were spread through the many other countries the radiation from Chernobyl struck.[92] The literature analysis draws on over 1,000 published titles and over 5,000 internet and printed publications discussing the consequences of the Chernobyl disaster. The authors contend that those publications and papers were written by leading Eastern European authorities and have largely been downplayed or ignored by the IAEA and UNSCEAR.[93] Author Alexy V. Yablokov was also one of the general editors on the Greenpeace commissioned report also criticizing the Chernobyl Forum finds published one year prior to the Russian language version of this report.[89]

Other health problems linked with the Chernobyl disaster include

- Down syndrome (trisomy 21). In West Berlin, Germany, prevalence of Down syndrome (trisomy 21) peaked 9 months following the main fallout.[11, 12][*citation needed*] Between 1980 and 1986, the birth prevalence of Down syndrome was quite stable (i.e., 1.35–1.59 per 1,000 live births [27–31 cases]).[*citation needed*] In 1987, 46 cases were diagnosed (prevalence = 2.11 per 1,000 live births). Most of the excess resulted from a cluster of 12 cases among children born in January 1987.[*citation needed*] The prevalence of Down syndrome in 1988 was 1.77, and in 1989, it reached pre-Chernobyl values. The authors[*citation needed*] noted that the isolated geographical position of West Berlin prior to reunification, the free genetic counseling, and complete coverage of the population through one central cytogenetic laboratory support completeness of case ascertainment; in addition, constant culture preparation and analysis protocols ensure a high quality of data.[*citation needed*]



Graph of Down syndrome cases in Belarus around the time of Chernobyl

- Chromosomal aberrations. Reports of structural chromosome aberrations in people exposed to fallout in Belarus and other parts of the former Soviet Union, Austria, and Germany argue against a simple dose-response relationship between degree of exposure and incidence of aberrations.[*citation needed*] These findings are relevant because a close relationship exists between chromosome changes and congenital malformations. Inasmuch as some types of aberrations are almost specific for ionizing radiation, researchers use aberrations to assess exposure dose. On the basis of current coefficients, however, one cannot assume that calculation of individual exposure doses resulting from fallout would not induce measurable rates of chromosome aberrations.[*citation needed*]
- Neural tube defects (NTDs) in Turkey. During the embryonic phase of fetal development, the neural tube differentiates into the brain and spinal cord (i.e., collectively forming the central nervous system). Chemical or physical interactions with this process can cause NTDs. Common features of this class of malformations are more or less extended fissures, often accompanied by consecutive dislocation of central nervous system (CNS) tissue. NTDs include spina bifida occulta and aperta, encephalocele, and—in the extreme case—anencephaly. The first evidence in support of a possible association between CNS malformations and fallout from Chernobyl was published by Akar *et al.*. in 1988.[*citation needed*] The Mustafakemalpasa State Hospital, Bursa region, covers a population of approximately 90,000. Investigators have documented the prevalence of malformations since 1983.[*citation needed*] The prevalence of NTDs was 1.7 to 9.2 per 1,000 births, but during the first 6 months of 1987 increased to 20 per 1,000 (12 cases). The excess was most pronounced for the subgroup of anencephalics, in which prevalence increased 5-fold (i.e., 10 per 1,000 [6 cases]). In the consecutive months that followed (i.e., July–December 1987), the prevalence decreased again (1.3 per 1,000 for all NTDs, 0.6 per 1,000 for anencephaly), and it reached pre-Chernobyl levels during the first half of 1988 (all NTDs: 0.6 per 1,000; anencephaly: 0.2 per 1,000). This initial report was supported by several similar findings in observational studies from different regions of Turkey.[*citation needed*]

In popular culture

See also: Chernobyl disaster in popular culture and Nuclear power debate

The Chernobyl accident attracted a great deal of interest. Because of the distrust that many people (both within and outside the USSR) had in the Soviet authorities, a great deal of debate about the situation at the site occurred in the first world during the early days of the event. Because of defective intelligence based on photographs taken from space, it was thought that unit number three had also suffered a dire accident.

Journalists mistrusted many professionals (such as the spokesman from the UK NRPB), and in turn encouraged the public to mistrust them.[94]

In Italy, the Chernobyl accident was reflected in the outcome of the 1987 referendum. As a result of that referendum, Italy began phasing out its nuclear power plants in 1988, a decision that was effectively reversed in 2008.

In 1995 Japanese animator Hayao Miyazaki wrote and directed "On Your Mark", a music video for Japanese pop duo Chage & Aska. This was essentially an animated music video lasting almost seven minutes. The opening scene shows a clean, old-fashioned and apparently deserted small village which is dominated by a huge, asymmetrical version of the Chernobyl "sarcophagus." In an interview in "Animage" magazine in 1995, Miyazaki compared the sarcophagus in the video to Chernobyl, noting the survival of plant life.[95]

The video game *Call of Duty 4: Modern Warfare* features a mission taking place in Pripyat.[96] The "S.T.A.L.K.E.R" series of video games is set in the Chernobyl Exclusion Zone.[97]

Commemoration of the disaster

The Front Veranda (1986) (http://www.susandwhite.com.au/drawings_prints/1986frontver.html) , a lithograph by Susan Dorothea White in the National Gallery of Australia, exemplifies worldwide awareness of the event. *Heavy Water: A film for Chernobyl* was released by Seventh Art in 2006 to commemorate the disaster through poetry and first-hand accounts.[98] The film secured the Cinequest Award as well as the Rhode Island "best score" award [99] along with a screening at Tate Modern.[100]

Chernobyl 20

This exhibit presents the stories of 20 people who have each been affected by the disaster, and each person's account is written on a panel. The 20 individuals whose stories are related in the exhibition are from Belarus, France, Latvia, Russia, Sweden, Ukraine, and the United Kingdom.

Developed by Danish photo-journalist Mads Eskesen, the exhibition is prepared in multiple languages including English, German, Danish, Dutch, Russian, and Ukrainian.

In Kiev, Ukraine, the exhibition was launched at the "Chernobyl 20 Remembrance for the Future" conference on 23 April 2006. It was then exhibited during 2006 in the United States, Australia, Denmark, the Netherlands, Switzerland, Ukraine, and the United Kingdom.

See also

- Chernobyl compared to other radioactivity releases
- Chernobyl disaster effects
- Chernobyl Shelter Fund
- Liquidator (Chernobyl)
- List of Chernobyl-related articles
- Red Forest
- Threat of the Dnieper reservoirs
- Zone of alienation
- Ukrainian National Chernobyl Museum
- Children Of Chernobyl Benefit Concert (C.O.C.B.C)

Other

- National Geographic *Seconds From Disaster* episodes
- *Zero Hour* episode, showing the inside of the power plant with remarkable accuracy
- Fukushima Nuclear Leak

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Documents

The source documents, which relate to the emergency, published in the unofficial sources:

- Technological Regulations on operation of 3 and 4 power units of Chernobyl NPP (http://accidont.ru/archive/Reglament.pdf) (in force at the moment of emergency)
- Tables and graphs of some parameters variation of the unit before the emergency (http://accidont.ru/datas.html)

Notes

1. ^ "No one believed the first newspaper reports, which patently understated the scale of the catastrophe and often contradicted one another. The confidence of readers was re-established only after the press was allowed to examine the events in detail without the original censorship restrictions. The policy of openness (glasnost) and 'uncompromising criticism' of outmoded arrangements had been proclaimed back at the 27th Congress, but it was only in the tragic days following the Chernobyl disaster that glasnost began to change from an official slogan into an everyday practice. The truth about Chernobyl which eventually hit the newspapers opened the way to a more truthful examination of other social problems. More and more articles were written about drug abuse, crime, corruption and the mistakes of leaders of various ranks. A wave of 'bad news' swept over the readers in 1986-87, shaking the consciousness of society. Many were horrified to find out about the numerous calamities of which they had previously had no idea. It often seemed to people that there were many more outrages in the epoch of perestroika than before although, in fact, they had simply not been informed about them previously." -Kagarlitsky pp 333–334
2. ^ "The mere fact that the operators were carrying out an experiment that had not been approved by higher officials indicates that something was wrong with the chain of command. The State Committee on Safety in the Atomic Power Industry is permanently represented at the Chernobyl station. Yet the engineers and experts in that office were not informed about the program. In part, the tragedy was the product of administrative anarchy or the attempt to keep everything secret." Medvedev, Z., pp. 18–20

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External links

- Official UN Chernobyl site (http://chernobyl.undp.org/)
- International Chernobyl Portal chernobyl.info, UN Inter-Agency Project ICRIN (http://chernobyl.info/)
- Frequently Asked Chernobyl Questions (http://www.iaea.or.at/NewsCenter/Features/Chernobyl-15/cherno-faq.shtml) , by the IAEA
- Chernobyl's Legacy (http://www.iaea.org/Publications/Booklets/Chernobyl/chernobyl.pdf) PDF (902KB), by the Chernobyl Forum (UN), updated in 2006
- Chernobyl Recovery and Development Programme (United Nations Development Programme) (http://www.crdp.org.ua/en/)
- Photographs from inside the zone of alienation and City of Prypyat (2010) (http://www.rapik.com/photo/thumbnails.php?album=38)
- Photographs from inside the Chernobyl Reactor and City of Prypyat (http://gerdludwig.com/html/chernobyl_zone.htm)

- Photographs of those affected by the Chernobyl Disaster (http://gerdludwig.com/html/chernobyl_victims.htm)
- EnglishRussia Photos of a RBMK-based power plant (http://englishrussia.com/index.php/2009/04/29/at-the-nuclear-power-plant/) , showing details of the reactor hall, pumps, and the control room

Coordinates: 51°23′22″N 30°05′56″E

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Categories: Chernobyl disaster | 1986 in the Soviet Union | 20th-century explosions | Disasters in the Soviet Union | Energy in Ukraine | Health in Ukraine | History of Belarus (1945–1990) | History of the Soviet Union and Soviet Russia | Industrial accidents and incidents | Industrial fires and explosions | Civilian nuclear power accidents