Chernobyl Disaster Report

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DTU/2K16/MC/13

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Introduction

The Chernobyl disaster was a nuclear accident that occurred on 26 April 1986 at the No. 4 nuclear reactor in the Chernobyl Nuclear Power Plant, near the city of Pripyat in the north of the Ukrainian SSR. It is considered the worst nuclear disaster in history and is one of only two nuclear energy disasters rated at seven — the maximum severity — on the International Nuclear Event Scale, the other being the 2011 Fukushima Daiichi nuclear disaster in Japan.

The accident started during a safety test on an RBMK-type nuclear reactor, which was commonly used throughout the Soviet Union. The test was a simulation of an electrical power outage to aid the development of a safety procedure for maintaining cooling water circulation until the back-up generators could provide power. This operating gap was about one minute and had been identified as a potential safety problem that could cause the nuclear reactor core to overheat.

Three such tests had been conducted since 1982, but had failed to provide a solution. On this fourth attempt, the test was delayed by 10 hours, so the operating shift that had been prepared was not present. During the test preparation, the reactor power unexpectedly dropped to a near-zero level. The operators were able to restore the power level, but in doing so they put the reactor in a highly unstable condition. The risks were not made evident in the operating instructions, despite a similar accident occurring years before, and they proceeded with the test even though the power level was still lower than prescribed in the procedure. Upon test completion, they triggered the reactor shutdown, but a combination of reactor design and construction flaws caused an uncontrolled nuclear chain reaction instead.

A large amount of energy was suddenly released, vapourising superheated cooling water and rupturing the reactor core in a highly destructive steam explosion. This was immediately followed by an open-air reactor core fire that released considerable airborne radioactive contamination for about nine days that precipitated onto parts of the USSR and western Europe, before being finally contained on 4 May 1986. The fire gradually released about the same amount of contamination as the initial explosion. As a result of rising ambient radiation levels off-site, a 10-kilometre (6.2 mi) radius exclusion zone was created 36 hours after the accident. About 49,000 people were evacuated from the area, primarily from Pripyat. The exclusion zone was later increased to 30 kilometres (19 mi) radius when a further 68,000 people were evacuated from the wider area.

At a glance

Date 26th April 1986; 33 years ago

Time 01:23:40 MSD (UTC +4:00)

Location Chernobyl Nuclear Power Plant, Pripyat, Ukranian SSR, Soviet Union

Type Nuclear and Radiation Accident

Cause Reactor design flaw and breach of protocol during simulated power outage safety test

Deaths 42 acute and delayed (several months), less than 100 at present, possibly 1000 extra long term cases of cancer (per United Nations)

Background

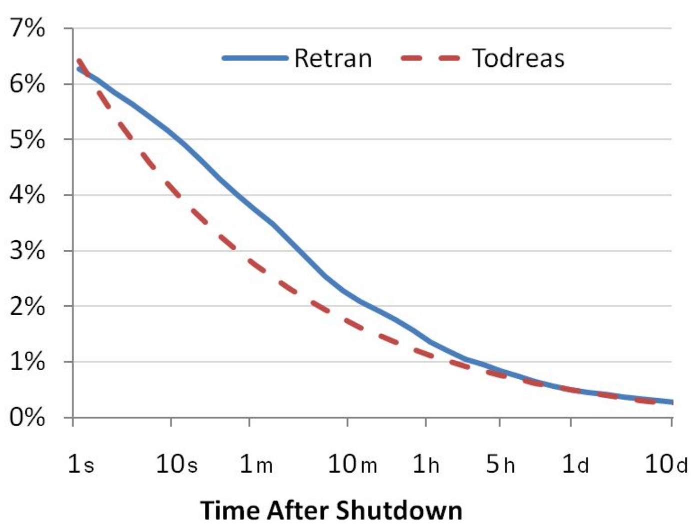
RBMK Reactors

The **RBMK** (Russian: Реактор Большой Мощности Канальный, РБМК; *Reaktor Bolshoy Moshchnosti Kanalnyy*, "High Power Channel-type Reactor") is a class of graphite-moderated nuclear power reactor designed and built by the Soviet Union. The name refers to its unusual design where, instead of a large steel pressure vessel surrounding the entire core, each fuel assembly is enclosed in an individual 8 cm diameter pipe (called a "channel") which allows the flow of cooling water around the fuel.

Reactor Cooling During Power Outage

In steady-state operation, a significant fraction (over 6%) of the power from a nuclear reactor is derived not from fission but from the decay heat of its accumulated fission products. This heating continues for some time after the chain reaction has been stopped (e.g. following an emergency scram) and active cooling is required to prevent core meltdown. RBMK reactors like those at Chernobyl use water as a coolant. Reactor No. 4 at Chernobyl included about 1,600 individual fuel channels, each of which required coolant flow of 28 metric tons (28,000 litres or 7,400 US gallons) per hour.

Since cooling pumps still require electricity and must run for some time after an emergency shutdown in the event of a power grid failure, each of Chernobyl's reactors had three backup diesel generators. The backup generators could start up in 15 seconds, but took 60–75 seconds to attain full speed and generate the 5.5-megawatt output required to run one main pump.



This one-minute delay constituted a significant safety risk. It had been theorized that the stored rotational inertia of the steam turbines and the residual steam pressure could be used to generate the required electrical power to cover this gap. Analysis indicated that this might be sufficient to provide electrical power to run the coolant pumps for 45 seconds, not *quite* bridging the gap between an external power failure and the full availability of the emergency generators.

Safety Test

This capability still needed to be confirmed experimentally, and previous tests had ended unsuccessfully. An initial test carried out in 1982 indicated 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, a test was conducted a third time but also yielded negative results. The test procedure was to be run again in 1986, and scheduled to take place during a maintenance shutdown of reactor No. 4.

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, and thus lacked 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 had not been sought from the Soviet nuclear oversight regulator (even though there was a representative at the complex of four reactors).

The test focused on the switching sequences of the electrical supplies for the reactor. The test procedure was expected to begin with an automatic emergency shutdown. No detrimental effect on the safety of the reactor was anticipated, so the test programme 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).

The experimental procedure was intended to run as follows:

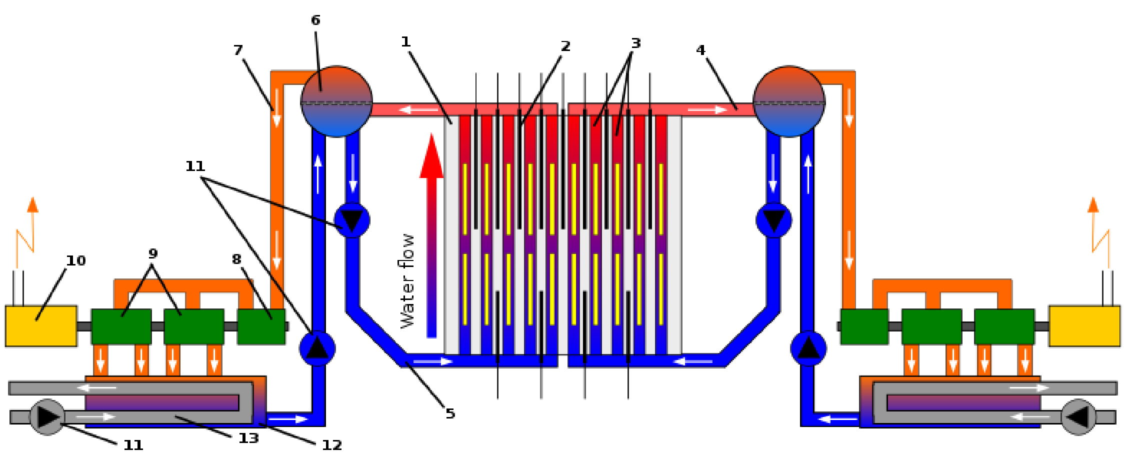
1. The reactor was to be running at a low power level, between 700 MW and 800 MW
2. The steam-turbine generator was to be run up to full speed
3. When these conditions were achieved, the steam supply for the turbine generator was to be closed off
4. Turbine generator performance was to be recorded to determine whether it could provide the bridging power for coolant pumps until the emergency diesel generators were sequenced to start and provide power to the cooling pumps automatically
5. After the emergency generators reached normal operating speed and voltage, the turbine generator would be allowed to continue to freewheel down

Test Delay and Shift Change

The test was to be conducted during the day-shift of 25 April 1986 as part of a scheduled reactor shut down. The day shift crew had been instructed in advance on the reactor operating conditions to run the test and in addition, a special team of electrical engineers was present to conduct the one-minute test of the new voltage regulating system once the correct conditions had been reached. As planned, a gradual reduction in the output of the power unit began at 01:06 on 25 April, and the power level had reached 50% of its nominal 3,200 MW thermal level by the beginning of the day shift.

At this point, another regional power station unexpectedly went offline, 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. Despite this delay, preparations for the test not affecting the reactor's power were carried out, including the disabling of the emergency core cooling system or ECCS, a passive/active system of core cooling intended to provide water to the core in a loss-of-coolant accident. Given the other events that unfolded, the system would have been of limited use, but it's disabling as a "routine" step of the test is indicative of the lack of attention to safety in the test.

At 23:04, the Kiev grid controller allowed the reactor shutdown 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 finished during the day shift, and the night shift would only have had to maintain decay heat cooling systems in an otherwise shut-down plant.



Legend:

1. Graphite moderated reactor core
2. Control rods
3. Pressure channels with fuel rods
4. Water/steam mixture
5. Water
6. Water/steam separator
7. Steam inlet
8. High-pressure steam turbine
9. Low-pressure steam turbine
10. Generator
11. Pump
12. Steam condenser
13. Cooling water (from river, sea, etc.)

The night shift had very limited time to prepare for and carry out the experiment. Anatoly Dyatlov, deputy chief-engineer of the entire Chernobyl Nuclear Power Plant, was present to supervise and direct the experiment; as he out-ranked all other supervisory personnel present, his orders and instructions overrode any objections of other senior personnel present during the test and its preparation. Serving under Dyatlov, Aleksandr 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.

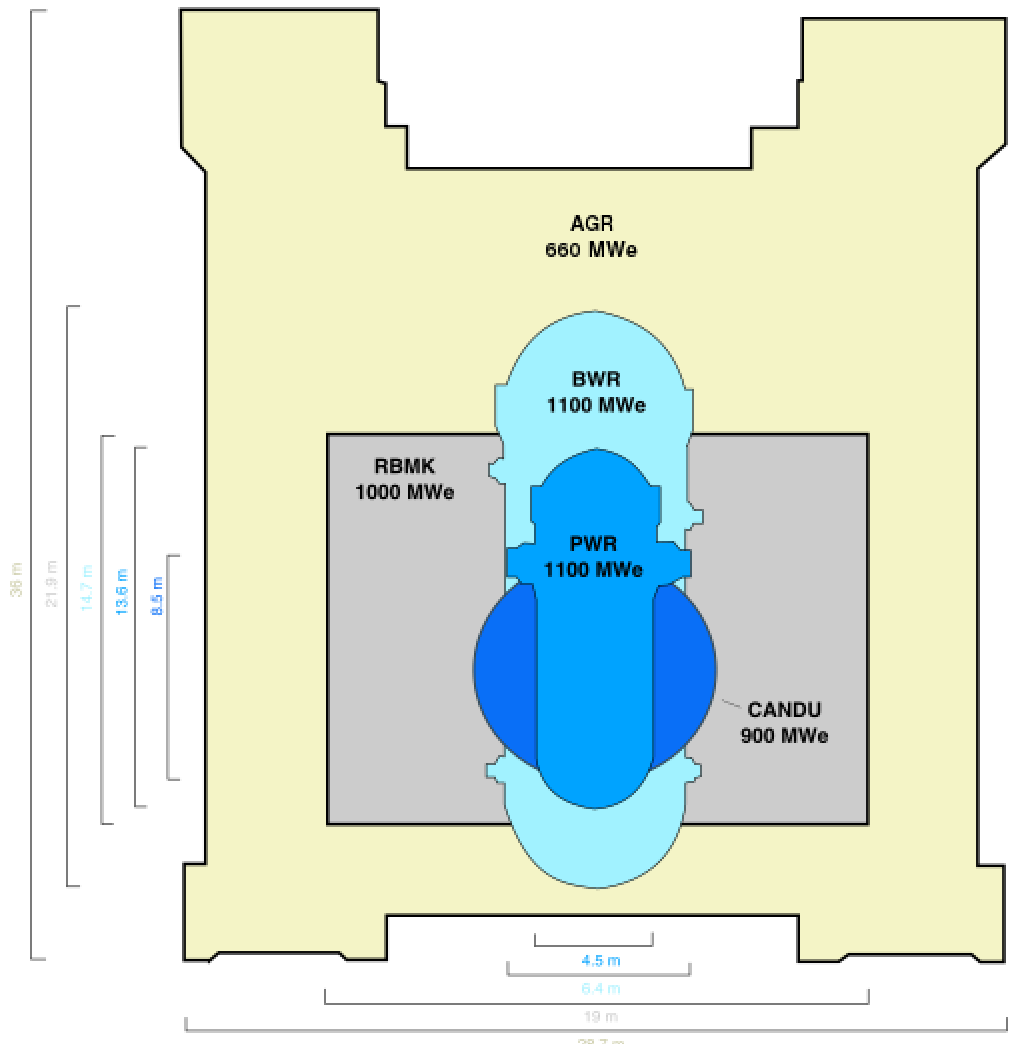
Unexpected drop of the reactor power

The test plan called for a gradual decrease in power output from reactor No. 4 to a thermal level of 700–1000 MW and an output of 720 MW was reached at 00:05 on 26 April. Due to the reactor's production of a fission byproduct, xenon-135, which is a reaction-inhibiting neutron absorber, core power continued to decrease in the absence of further operator action—a process known as reactor poisoning. In steady-state operation, this is avoided because xenon-135 is "burned off" as quickly as it is created from decaying iodine-135 by the absorption of neutrons from the ongoing chain reaction, becoming highly stable xenon-136. With the reactor power reduced, previously produced high quantities of iodine-135 were decaying into the neutron-absorbing xenon-135 faster than the now reduced neutron flux could burn off.

When the reactor power dropped to approximately 500 MW, the reactor control has been switched to a different mode in order to manually maintain the power level. Around that moment, the power suddenly fell into an unintended near-shutdown state, with a power output of 30 MW thermal or less. The exact circumstances that caused the power fall are unknown because Akimov died in hospital on 10 May and Toptunov on 14 May; early reports attributed it to Toptunov's mistake, but it has also been suggested it was due to an equipment failure.

The reactor was now producing 5% of the minimum initial power level prescribed for the test. This led to further heavy poisoning of the reactor core by the accumulation of xenon-135 and hindered the rise of reactor power. Control-room personnel had to raise power by disconnecting most of the reactor control rods from the automatic control rod regulation system and manually extracting the majority of rods to their upper limits in order to counteract the poisoning. Several minutes elapsed between their extraction and the point at which the power output began to increase and subsequently stabilized at 160–200 MW (thermal).

The operation of the reactor at the low power level (and high poisoning level) was accompanied by unstable core temperatures and coolant flow, and possibly by instability of neutron flux, which triggered alarms. The control room received repeated emergency signals regarding the levels in the steam/water separator drums, and large excursions or variations in the flow rate of feed water, as well as from relief valves opened to relieve excess steam into a turbine condenser, and from the neutron power controller. Between 00:35 and 00:45, emergency alarm signals concerning thermal-hydraulic parameters were ignored, apparently to preserve the reactor power level.



Reactor conditions priming the accident

When a power level of 200 MW was reattained, though it was much lower than the prescribed 700 MW, preparation for the experiment continued. As part of the test plan, extra water pumps were activated at 01:05, increasing the water flow. The increased coolant flow rate through the reactor produced an increase in the inlet coolant temperature of the reactor core (the coolant no longer having sufficient time to release its heat in the turbine and cooling towers), which now more closely approached the nucleate boiling temperature of water, reducing the safety margin.

The flow exceeded the allowed limit at 01:19, triggering an alarm of low steam pressure in the steam separators. At the same time, the extra water flow lowered the overall core temperature and reduced the existing steam voids in the core and the steam separators. Since water weakly absorbs neutrons (and the higher density of liquid water makes it a better absorber than steam), the activation of the additional pumps decreased the reactor power. The crew responded by turning off two of the circulation pumps to reduce feedwater flow, in an effort to increase steam pressure, and by removing more manual control rods to maintain power.

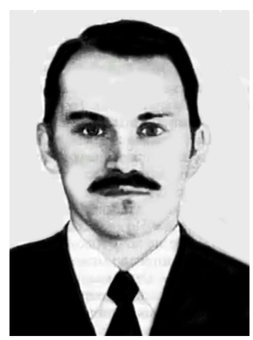
The combined effect of these various actions was an extremely unstable reactor configuration. Nearly all of the 211 control rods had been extracted manually, including all but 18 of the "fail-safe" manually operated rods of the minimum 28 that were supposed to remain fully inserted to control the reactor even in the event of a loss of coolant. While the emergency scram system that would insert all control rods to shut down the reactor could still be activated manually (through the "AZ-5" switch), the automated system that would ordinarily do the same had been mostly disabled to maintain the power level, and many other automated and even passive safety features of the reactor had been bypassed. The reduction of reactor coolant pumping left little safety margin; any power excursion could produce boiling, thereby reducing neutron absorption by the water. The reactor configuration was outside the safe operating envelope prescribed by the designers. If anything pushed it into supercriticality, it would be unable to recover automatically.

People Involved

Anatoly Dyatlov

Anatoly Dyatlov, the deputy chief engineer, supervised the test. At the moment the reactor power slipped to 30 MW, Dyatlov reported that he was out of the control room and inspecting equipment elsewhere in the plant. Dyatlov stated that Akimov and Toptunov were already raising power upon his return, and that had they not done so, he would have ordered them to. In testimony at the trial, several witnesses recalled Dyatlov remaining in the room at this point, but did not report any disagreements or "serious discussions" related to the increase in power or at any other point during the test.

Aleksandr Akimov



Aleksandr Akimov, the unit shift chief, was in charge of the test itself. He took over the shift at midnight from Tregub, who stayed on-site. The drop in reactor power from 1,500 MWt to 30 MWt was disconcerting; he wanted to abort the test. He supported Toptunov's decision to shut down the poisoned reactor, but was overridden by Dyatlov and forced to continue.

Nikolai Gorbachenko

Gorbachenko, a radiation monitoring technician began his shift and checked in unit 3; he skipped the check of unit 4 as it was being shut down, so at the moment of the accident he was located in the duty room.

A flat and powerful thud shook the building; he and his assistant Pshenichnikov thought it was a water hammer occurring during a turbine shutdown. Another flat thud followed, accompanied by lights going out, the control panel of unit 4 losing signal, latched double doors being blown apart by the blast, and black and red powder falling from the ventilation; emergency lights then switched on. Telephone connection with unit 4 was cut.

Valery Khodemchuk

The night shift main circulating pump operator, Khodemchuk, was likely killed immediately; he was stationed in the collapsed part of the building, in the far end of the southern main circulating pumps engine room at level +10. His body was never recovered and is entombed in the nuclear reactor's debris.

Vladimir Shashenok

Shashenok, the automatic systems adjuster from *Atomenergonaladka*—the Chernobyl startup and adjustment enterprise—was supposed to be in room 604, the location of the measurement and control instruments, on the upper landing across the turbine room on level +24, under the reactor feedwater unit; he was reporting the states of the pressure

gauges of the profile of the multiple forced circulation circuits to the computer room by telephone.

The communication lines were cut during the explosion. Shashenok received deep thermal and radiation burns over his entire body when the overpressure spike destroyed the isolation membranes and the impulse pipes of the manometers in his instrument room just before the explosion, which then demolished the room itself. The landing was found damaged, covered with ankle-deep water, and there were leaks of boiling water and radioactive steam. Shashenok was found unconscious in room 604, pinned under a fallen beam, with bloody foam coming out of his mouth.

His body was severely contaminated by radioactive water. He was carried out by Gorbachenko and Pyotr Palamarchuk and died at 6 a.m in the Pripyat hospital under the care of the chief physician, Vitaly Leonenko, without regaining consciousness. Gorbachenko suffered a radiation burn on his back where Shashenok's hand was located when he helped carry him out. Khodemchuk and Shashenok were the first two victims of the disaster. A report by the Associated Press at the time, citing Soviet newspaper Pravda, claimed that Shashenok was buried two days later at a village near Chernobyl. His wife Lyudmilla had been evacuated before the burial and was not there. A year later he was exhumed and re-buried beside his 29 fellow workers at Moscow's Mitinskoe Cemetery.

Oleg Genrikh and Anatoly Kurguz

Genrikh, an operator of the control room on level +36, was taking a nap in a windowless room adjacent to the control room. The window in the control room was broken and the lights went out. His colleague Kurguz was in the control room with three open doors between him and the reactor room; at the moment of the explosion, he suffered severe burns from steam entering the control room. Genrikh received less serious burns as he was protected by the windowless room. The stairs on the right side were damaged; he managed to escape by the stairs on the left. On the way back they were joined by Simeonov and Simonenko, the gas loop operators, all four heading to the control room. Kurguz was shortly afterwards evacuated by ambulance; aware of the dangers of radiation contamination, Genrikh took a shower and changed his clothes.

Aleksandr Yuvchenko

Yuvchenko was located in his office between reactors 3 and 4, on level 12.5; he described the event as a shock wave that buckled walls, blew doors in, and brought a cloud of milky grey radioactive dust and steam. The lights went out. He met a badly burned, drenched and shocked pump operator, who asked him to rescue Khodemchuk; that quickly proved impossible as that part of the building did not exist anymore. Yuvchenko, together with the foreman Yuri Tregub, ran out of the building and saw half of the building gone and the

reactor emitting a blue ionized air glow. They returned to the building and met Valeri Perevozchenko and two junior technicians, Kudryavtsev and Proskuryakov, ordered by Dyatlov to manually lower the presumably seized control rods. Tregub went to report the extent of damage to the control room.

The four climbed a stairwell to level 35 to survey the damage; Yuvchenko held open the massive door into the reactor room and the other three proceeded in to locate the control rod mechanism; after no more than a minute in the hallway near the entrance to the reactor hall, all three had sustained fatal doses of radiation.

The three would later die in the Moscow hospital. Yuvchenko meanwhile suffered serious beta burns and gamma burns to his left shoulder, hip and calf as he kept the radioactive-dust-covered door open. It was later estimated he received a dose of 4.1 Sv. At 3 a.m., he began vomiting intensely; by 6 a.m., he could no longer walk. He later spent a year in the Moscow hospital receiving blood and plasma transfusions and received numerous skin grafts.

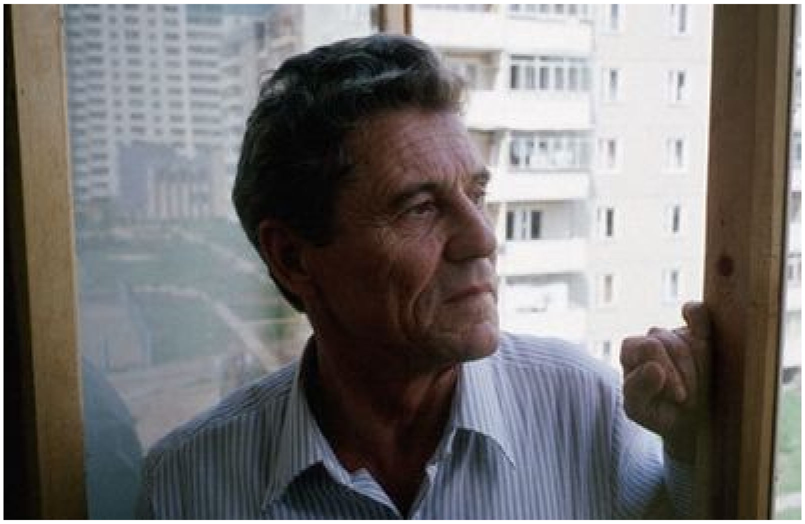
Valery Perevozchenko

Perevozchenko, the reactor section foreman, was in the company of Alexander Yuvchenko shortly before the explosion. While both men were returning from Unit 3, Perevozchenko was called to the Unit 4 control room, arriving shortly after the explosions. He then returned to search for his comrades. He witnessed the destruction of the reactor building from the broken windows of the deaerator gallery.

With his face already tanned by the radiation, he went to the dosimetry room and asked Gorbachenko for radiation levels; Gorbachenko left with Palamarchuk to rescue Shashenok while Perevozchenko went through the graphite and fuel containing radioactive rubble on level 10 to the remains of room 306 in an unsuccessful attempt to locate Khodemchuk, close to debris emitting over 10,000 roentgens per hour (90 μA/kg). He then went to the control room of Genrikh and Kurguz and found it empty; vomiting and losing consciousness, he returned to the control room to report on the situation.

Viktor Bryukhanov

Bryukhanov, the plant manager, arrived at 2:30 a.m. Akimov reported a serious radiation accident but intact reactor, fires in the process of being extinguished, and a second emergency water pump being readied to cool the reactor. Due to limitations of available



instruments, they seriously underestimated the radiation level. At 3 a.m., Bryukhanov called Maryin, the deputy secretary for the nuclear power industry, reporting Akimov's version of the situation.

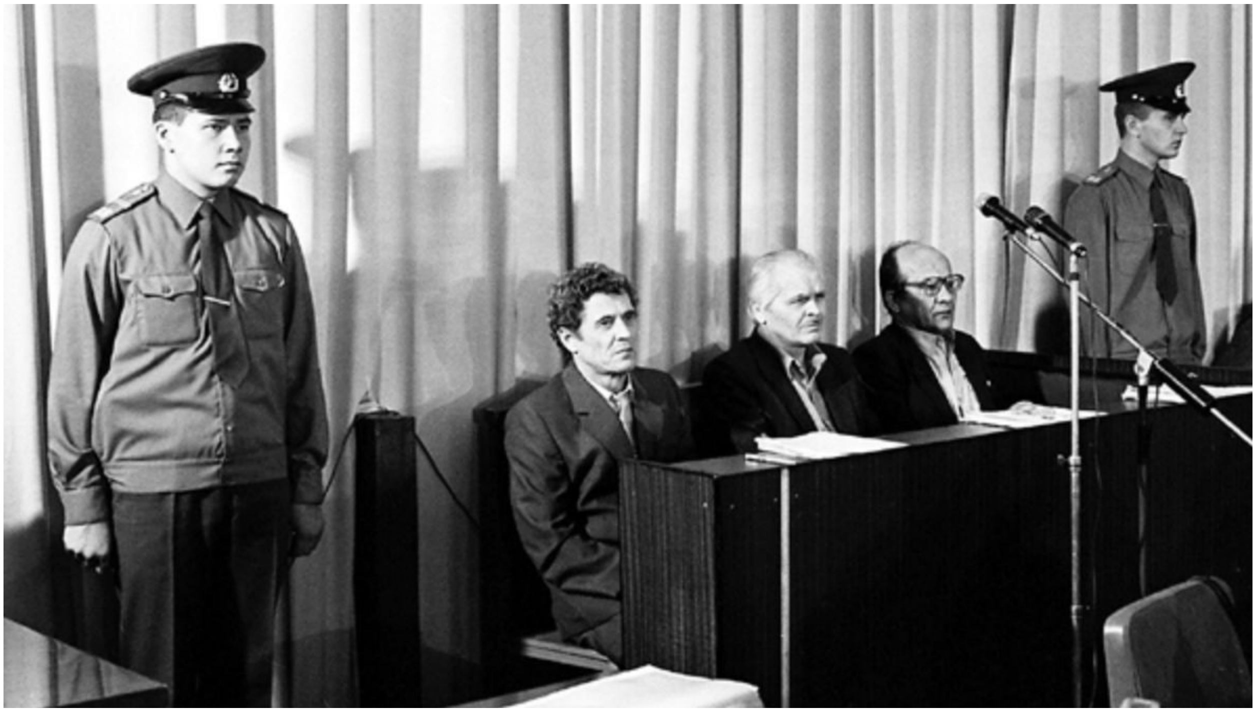
Maryin sent the message further up the chain of command, to Frolyshev, who then called Vladimir Dolgikh. Dolgikh subsequently called General Secretary Mikhail Gorbachev and other members of the Politburo. At 4 a.m., Moscow ordered feeding of water to the reactor. As Director of the Chernobyl site, Bryukhanov was sentenced to ten years imprisonment but only served five years of the sentence.

Nikolai Fomin

Chief engineer Fomin arrived in the block 4 control room at 4:30 a.m. He ordered continuous feeding of water into the reactor, which was already in progress by emergency pump 2 from the deaerators. Fomin kept pressing the staff to feed water to the reactor and transferred more people to unit 4 to replace those being disabled by radiation.

After Dyatlov left, Fomin ordered Sitnikov, his replacement, to climb to the roof of unit C and survey the reactor. Sitnikov obeyed but was unable to reach the roof due to a padlocked door. Sitnikov then assisted Akimov and Toptunov with feeding water into the reactor; the water, however, flowed through the severed pipes into the lower levels of the plant, carrying radioactive debris and causing short circuits in the cableways common to all four blocks.

Later, before the trial, Fomin suffered a mental breakdown and tried to kill himself by breaking his glasses and slitting his wrists with the shards.



The trial of Anatoly Dyatlov, Viktor Bryukhanov and Nikolai Fomin. Those responsible for the Chernobyl Accident, July 1897

Accident

Test Execution

At 01:23:04, the test began. Four of the main circulating pumps (MCP) were active (of the eight total, six are normally active under regular operation). The steam to the turbines was shut off, beginning a run-down of the turbine generator. The diesel generators started and sequentially picked up loads; the generators were to have completely picked up the MCPs' power needs by 01:23:43. In the interim, the power for the MCPs was to be supplied by the turbine generator as it coasted down. As the momentum of the turbine generator decreased, so did the power it produced for the pumps. The water flow rate decreased, leading to increased formation of steam voids in the coolant flowing up through the fuel pressure tubes.

Unlike western light-water reactors, the RBMK has a positive void coefficient of reactivity at low power levels, meaning that when cooling water boils excessively in the fuel pressure tubes it produces large steam voids in the coolant rather than small bubbles. This intensifies the nuclear chain reaction, as it reduces the relative volume of cooling water available to absorb neutrons. The consequent power increase then produces more voids which further intensifies the chain reaction, and so on. Given this characteristic, reactor No. 4 was now at risk of a runaway increase in its core power with nothing to restrain it.

Throughout most of the experiment the local automatic control system (LAC) successfully counteracted this positive feedback, by inserting control rods into the reactor core to limit the power rise. However, this system had control of only 12 rods, as nearly all the others had been manually retracted by the reactor operators.

Reactor Shutdown and Power Excursion

At 01:23:40, as recorded by the SKALA centralized control system, a Scram (emergency shutdown) of the reactor was initiated as the experiment was wrapping up. The SCRAM was started when the AZ-5 button (also known as the EPS-5 button) of the reactor emergency protection system was pressed: this engaged the drive mechanism on all control rods to fully insert them, including the manual control rods that had been withdrawn earlier.

The mechanism would be used even to routinely shut down the reactor after the experiment for the planned maintenance and the Scram likely preceded the sharp increase in power. However, the precise reason why the button was pressed when it was is not certain, as only the deceased Akimov and Toptunov partook in that decision, though the atmosphere in the control room was calm at that moment. Meanwhile, the RBMK designers claim that the button had to be pressed only after the reactor already began to self-destruct.

When the AZ-5 button was pressed, the insertion of control rods into the reactor core began. The control rod insertion mechanism moved the rods at 0.4 metres per second (1.3 ft/s), so that the rods took 18 to 20 seconds to travel the full height of the core, about 7 metres (23 ft). A bigger problem was the design of the RBMK control rods, each of which had a graphite neutron moderator section attached to its end to boost reactor output by displacing water when the control rod section had been fully withdrawn from the reactor, i.e. when a control rod was at maximum extraction, a neutron-moderating graphite extension was centered in the core with 1.25 metres (4.1 ft) columns of water above and below it.

Consequently, injecting a control rod downward into the reactor in a scram initially displaced (neutron-absorbing) water in the lower portion of the reactor with (neutron-moderating) graphite. Thus, an emergency scram initially increased the reaction rate in the lower part of the core.[4]:4 This behaviour had been discovered when the initial insertion of control rods in another RBMK reactor at the Ignalina Nuclear Power Plant in 1983 induced a power spike. Procedural countermeasures were not implemented in response to Ignalina; INSAG-7 later stated, "Apparently, there was a widespread view that the conditions under which the positive scram effect would be important would never occur. However, they did appear in almost every detail in the course of the actions leading to the (Chernobyl) accident.

A few seconds into the scram, a power spike did occur and the core overheated, causing some of the fuel rods to fracture, blocking the control rod columns and jamming the control rods at one-third insertion, with the graphite water-displacers still in the lower part of the core. Within three seconds the reactor output rose above 530 MW.

The subsequent course of events was not registered by instruments; it has been reconstructed through mathematical simulation. Per the simulation, the power spike would have caused an increase in fuel temperature and steam buildup, leading to a rapid increase in steam pressure. This caused the fuel cladding to fail, releasing the fuel elements into the coolant, and rupturing the channels in which these elements were located.

Steam Explosions

As the scram was starting, the reactor output jumped to around 30,000 MW thermal, 10 times its normal operational output, the indicated last reading on the power meter on the control panel. Some estimate the power spike may have gone 10 times higher than that. 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 vapour pressure, appears to have been the next event. There is a general understanding that it was explosive steam pressure from the damaged fuel channels escaping into the reactor's exterior cooling structure that caused the explosion that destroyed the reactor casing, tearing off and blasting the upper plate called the upper biological shield, to which the entire reactor assembly is fastened, through the roof of the reactor building. This is believed to be the first explosion that many heard.

This explosion ruptured further fuel channels, as well as severing most of the coolant lines feeding the reactor chamber, and as a result, the remaining coolant flashed to steam and escaped the reactor core. The total water loss in combination with a high positive void coefficient further increased the reactor's thermal power.

A second, more powerful explosion occurred about two or three seconds after the first; this explosion dispersed the damaged core and effectively terminated the nuclear chain reaction. This explosion also compromised more of the reactor containment vessel and ejected hot lumps of graphite moderator. The ejected graphite and the demolished channels still in the remains of the reactor vessel caught fire on exposure to air, greatly contributing to the spread of radioactive fallout and the contamination of outlying areas.

According to observers outside Unit 4, burning lumps of material and sparks shot into the air above the reactor. Some of them fell onto the roof of the machine hall and started a fire. About 25% 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.

After the larger explosion, a number of employees at the power station went outside to get a clearer view of the extent of the damage. One such survivor, Alexander Yuvchenko, recounts that once he stepped outside and looked up towards the reactor hall, he saw a "very beautiful" laser-like beam of blue light caused by the ionized-air glow that appeared to "flood up into infinity".

There were initially several hypotheses about the nature of the second explosion. One view was that the second explosion was caused by the combustion of hydrogen, which had been produced either by the overheated steam-zirconium reaction or by the reaction of red-hot graphite with steam that produced hydrogen and carbon monoxide. Another hypothesis, by Checherov, published in 1998, was 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. A third hypothesis was that the second explosion was another steam explosion. According to this version, the first explosion was a more minor steam explosion in the circulating loop, causing a loss of coolant flow and pressure that in turn caused the water still in the core to flash to steam; this second explosion then caused the majority of the damage to the reactor and containment building.

Fizzled nuclear explosion hypothesis

The force of the second explosion and the ratio of xenon radioisotopes released after the accident (a vital tool in nuclear forensics) indicated to Yuri V. Dubasov in a 2009 publication (suggested before him by Checherov in 1998), that the second explosion could have been a nuclear power transient resulting from core material melting in the absence of its water coolant and moderator. Dubasov argues that the reactor did not simply undergo a runaway delayed-supercritical exponential increase in power into the multi-gigawatt power range. That permitted a dangerous "positive feedback" runaway condition, given the lack of passive nuclear safety stops, such as Doppler broadening, when power levels began to increase above the commercial level.

The evidence for this hypothesis originates at Cherepovets, Vologda Oblast, Russia, 1000 km northeast of Chernobyl. Physicists from the V.G. Khlopin Radium Institute in Leningrad measured anomalous xenon-135 — a short half-life isotope — levels at Cherepovets four days after the explosion, even as the general distribution was spreading the radiation to the north in Scandinavia. It is thought that a nuclear event in the reactor may have raised xenon to higher levels in the atmosphere than the later fire did, which moved the xenon to that location.

That while this positive-feedback power excursion that increased until the reactor disassembled itself by means of its internal energy and external steam explosions is the more accepted explanation for the cause of the explosions, Dubasov argues instead that a runaway prompt criticality occurred, with the internal physics being more similar to the explosion of a fizzled nuclear weapon, and that this failed/fizzle event produced the second explosion.

This nuclear fizzle hypothesis, then mostly defended by Dubasov, was examined further in 2017 by retired physicist Lars-Erik De Geer in an analysis that puts the hypothesized fizzle event as the more probable cause of the first explosion. The more energetic second explosion, which produced the majority of the damage, has been estimated by Dubasov in 2009 as equivalent to 40 billion joules of energy, the equivalent of about 10 tons of TNT. Both the 2009 and 2017 analyses argue that the nuclear fizzle event, whether producing the second or first explosion, consisted of a prompt chain reaction (as opposed to the consensus delayed neutron mediated chain-reaction) that was limited to a small portion of the reactor core, since expected self-disassembly occurs rapidly in fizzle events.

Crisis Management

Fire Containment

Contrary to safety regulations, bitumen, a combustible material, 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 adjacent reactor No. 3, which was still operating. It was imperative to put those fires out and protect the cooling systems of reactor No. 3.[25]:42 Inside reactor No. 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, Bagdasarov made his own decision to shut down the reactor, leaving only those operators there who had to work the emergency cooling systems.

Shortly after the accident, at 01:45, 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. 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: "Is that 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 them 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 a 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.

Anatoli Zakharov, a fireman stationed in Chernobyl since 1980, offers a different description in 2008: "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. He also stated: "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.

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 5:00, 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.

It was thought by some that the core fire was extinguished by a combined effort of helicopters dropping more than 5000 metric tons of sand, lead, clay, and neutron-absorbing boron onto the burning reactor. It is now known that virtually none of the neutron absorbers reached the core. Historians estimate that about 600 Soviet pilots risked dangerous levels of radiation to fly thousands of flights needed to cover reactor No. 4 in this attempt to seal off radiation.

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.)

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.

Equipment assembled included remote-controlled bulldozers and robot-carts that could detect radioactivity and carry hot debris. Valery Legasov, first deputy director of the Kurchatov Institute of Atomic Energy in Moscow, said in 1987: "But we learned that robots are not the great remedy for everything. Where there was a very high radiation, the robot ceased to be a robot—the electronics quit working.

Radiation Levels

The ionizing radiation levels in the worst-hit areas of the reactor building have been estimated to be 5.6 roentgens per second (R/s), equivalent to more than 20,000 roentgens per hour. A lethal dose is around 500 roentgens (~5 Gray (Gy) in modern radiation units) over five hours, so in some areas, unprotected workers received fatal doses in less than a minute. However, a dosimeter capable of measuring up to 1,000 R/s was buried in the rubble of a collapsed part of the building, and another one failed when turned on. All remaining dosimeters had limits of 0.001 R/s 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), while the true levels were much higher in some areas.

Because of the inaccurate low readings, the reactor crew chief Aleksandr 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. Akimov stayed with his crew in the reactor building until morning, sending members of his crew to try to pump water into the reactor. None of them wore any protective gear. Most, including Akimov, died from radiation exposure within three weeks.

Evacuation

The nearby city of Pripyat was not immediately evacuated. The townspeople, in the early hours of the morning, at 01:23 local time, went about their usual business, completely oblivious to what had just happened. However, within a few hours of the explosion, dozens of people fell ill. Later, they reported severe headaches and metallic tastes in their mouths, along with uncontrollable fits of coughing and vomiting. As the plant was run by authorities in Moscow, the government of Ukraine did not receive prompt information on the accident.

Valentyna Shevchenko, then Chairwoman of the Presidium of the Verkhovna Rada Supreme Soviet of the Ukrainian SSR, recalls that Ukraine's acting Minister of Internal Affairs Vasyl Durdynets phoned her at work at 09:00 to report current affairs; only at the end of the conversation did he add that there had been a fire at the Chernobyl nuclear power plant, but it was extinguished and everything was fine. When Shevchenko asked "How are the people?"he replied that there was nothing to be concerned about: "Some are celebrating a wedding, others are gardening, and others are fishing in the Pripyat River".

Shevchenko then spoke over the phone to Volodymyr Shcherbytsky, head of the Central Committee of the Communist Party of Ukraine and *de facto* head of state, who said he anticipated a delegation of the state commission headed by Boris Shcherbina, the deputy chairman of the Council of Ministers of the USSR.

A commission was established later in the day to investigate the accident. It was headed by Valery Legasov, First Deputy Director of the Kurchatov Institute of Atomic Energy, and included leading nuclear specialist Evgeny Velikhov, hydro-meteorologist Yuri Izrael, radiologist Leonid Ilyin, and others. They flew to Boryspil International Airport and arrived at the power plant in the evening of 26 April. By that time two people had already died and 52 were hospitalized. The delegation soon had ample evidence that the reactor was destroyed and extremely high levels of radiation had caused a number of cases of radiation exposure. In the early daylight hours of 27 April, approximately 36 hours after the initial blast, they ordered the evacuation of Pripyat. Initially it was decided to evacuate the population for three days; later this was made permanent.

Delayed Announcement

Evacuation began long before the accident was publicly acknowledged by the Soviet Union. In the morning of 28 April, radiation levels set off alarms at the Forsmark Nuclear Power Plant in Sweden, over 1,000 kilometres (620 mi) from the Chernobyl Plant. Workers at Forsmark reported the case to the Swedish Radiation Safety Authority, which determined that the radiation had originated elsewhere. That day, the Swedish government contacted the Soviet government to inquire about whether there had been a nuclear accident in the Soviet Union. The Soviets initially denied it, and it was only after the Swedish government suggested they were about to file an official alert with the International Atomic Energy Agency, that the Soviet government admitted an accident took place at Chernobyl.

At first, the Soviets only conceded that a minor accident had occurred, but once they began evacuating more than 100,000 people, the full scale of the situation was realized by the global community. At 21:02 the evening of 28 April, a 20-second announcement was read in the TV news programme *Vremya*: "There has been an accident at the Chernobyl Nuclear Power Plant. One of the nuclear reactors was damaged. The effects of the accident are being remedied. Assistance has been provided for any affected people. An investigative commission has been set up." This was the entirety of the announcement of the accident. The Telegraph Agency of the Soviet Union (TASS) then discussed the Three Mile Island accident and other American nuclear accidents, an example of the common Soviet tactic of whataboutism when one occurred in the Soviet Union. The mention of a commission, however, indicated to observers the seriousness of the incident, and subsequent state radio broadcasts were replaced with classical music, which was a common method of preparing the public for an announcement of a tragedy.

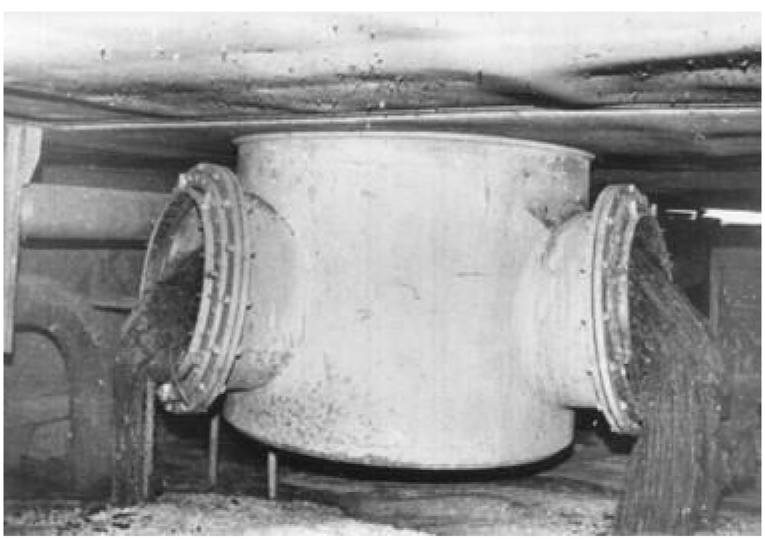
Around the same time, ABC News released its report about the disaster. Shevchenko was the first of the Ukrainian state top officials to arrive at the disaster site early on 28 April. There she spoke with members of medical staff and people, who were calm and hopeful that they could soon return to their homes. Shevchenko returned home near midnight, stopping at a radiological checkpoint in Vilcha, one of the first that were set up soon after the accident.

There was a notification from Moscow that there was no reason to postpone the 1 May International Workers' Day celebrations in Kiev (including the annual parade), but on 30 April a meeting of the Political bureau of the Central Committee of the CPSU took place to discuss the plan for the upcoming celebration. Scientists were reporting that the radiological background level in Kiev was normal. At the meeting, which was finished at 18:00, it was decided to shorten celebrations from the regular three and a half to four hours to under two hours. Several buildings in Pripyat were officially kept open after the disaster to be used by workers still involved with the plant. These included the Jupiter factory which closed in 1996 and the Azure Swimming Pool, used by the Chernobyl liquidators for recreation during the clean-up, which closed in 1998.

Explosion Risk

Two floors of bubbler pools beneath the reactor served as a large water reservoir for the emergency cooling pumps and as a pressure suppression system capable of condensing steam in case of a small broken steam pipe; the third floor above them, below the reactor, served as a steam tunnel. The steam released by a broken pipe was supposed to enter the steam tunnel and be led into the pools to bubble through a layer of water. After the disaster, the pools and the basement were flooded because of ruptured cooling water pipes and accumulated firefighting water, and constituted a serious steam explosion risk.

The smoldering graphite, fuel and other material above, at more than 1,200 °C (2,190 °F), started to burn through the reactor floor and mixed with molten concrete from the reactor lining, creating corium, a radioactive semi-liquid material comparable to lava. If this mixture had melted through the floor into the pool of water, it was feared it could have created a serious steam explosion that would have ejected more radioactive material from the reactor. It became necessary to drain the pool.



The bubbler pool could be drained by opening its sluice gates. However, the valves controlling it were underwater, located in a flooded corridor in the basement. Volunteers in wetsuits and respirators (for protection against radioactive aerosols) and equipped with dosimeters, entered the knee-deep radioactive water and managed to open the valves. These were the engineers Alexei Ananenko and Valeri Bezpalov (who knew where the valves were), accompanied by the shift supervisor Boris Baranov. Upon succeeding, all risk of a further steam explosion was eliminated. All three men were awarded the Order For Courage by Ukrainian President Petro Poroshenko in May 2018.

Research by Andrew Leatherbarrow, author of *Chernobyl 01:23:40*, determined that the frequently recounted story that suggests that all three men died just days after the incident is false. Alexei Ananenko continues to work in the nuclear energy industry, and rebuffs the growth of the Chernobyl media sensationalism surrounding him. While Valeri Bezpalov was found to still be alive by Leatherbarrow, the 65-year-old Baranov had lived until 2005 and had died of heart failure. Once the bubbler pool gates were opened by the Ananenko team, fire brigade pumps were then used to drain the basement. The operation was not completed until 8 May, after 20,000 metric tons (20,000 long tons; 22,000 short tons) of 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 well drilling equipment, the 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 (−148 °F). This idea was soon scrapped.

As an alternative, coal miners were deployed to excavate a tunnel below the reactor to make room for a cooling system. The final makeshift design for the cooling system was to incorporate a coiled formation of pipes cooled with water and covered on top with a thin thermally conductive graphite layer. The graphite layer as a natural refractory material would rapidly cool the suspected molten uranium oxide without burn through. This graphite cooling plate layer was to be encapsulated between two concrete layers, each one meter thick for stabilisation. This system was designed by Bolshov, the director of the Institute for Nuclear Safety and Development formed in 1988. Bolshov's graphite-concrete "sandwich" would be similar in concept to later core catchers that are now part of many nuclear reactor designs.

Bolshov's graphite cooling plate, alongside the prior nitrogen injection proposal, were not used following the drop in aerial temperatures and indicative reports that the fuel melt had stopped. It was later determined that the fuel had passed through three storeys before coming to rest in one of a number of basement rooms. The precautionary underground channel with its active cooling was therefore deemed redundant, as the fuel was self-cooling. The excavation was then simply filled with concrete to strengthen the foundation below the reactor.

It is likely that intense alpha radiation hydrolysed the water, generating a low-pH hydrogen peroxide (H_2O_2) solution akin to an oxidizing acid. Conversion of water from an unknown source, to H_2O_2 is confirmed by the presence in the Chernobyl lavas of studtite and metastudtite, the only minerals that contain peroxide.

Debris Removal

In the months after the explosion, attention turned to removing the radioactive debris from the roof. The worst of the radioactive debris was collected inside what was left of the reactor, however, it was estimated that there were approximately 100 tons of debris on that roof that resulted from the explosion and which had to be removed to enable the safe construction of the 'sarcophagus' – a concrete structure that would entomb the reactor and reduce radioactive dust being released into the atmosphere. The initial plan was to use robots to clear the debris off the roof. The Soviets used approximately 60 remote-controlled robots, most of them built in the Soviet Union, although many failed due to the effect of high levels of radiation on their electronic controls.

Consequently, the most highly radioactive materials were shoveled by Chernobyl liquidators from the military wearing heavy protective gear (dubbed "bio-robots" by the military); these soldiers could only spend a maximum of 40-90 seconds 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.

Though the soldiers were only supposed to perform the role of the "bio-robot" a maximum of once, some soldiers reported having done this task five or six times. Only 10% of the debris cleared from the roof was performed by robots with the other 90% removed by approximately 5,000 men who absorbed, on average, an estimated dose of 25 rem (250 mSv) of radiation each.

At the time there was still fear that the reactor could re-enter a self-sustaining nuclear chain-reaction and explode again, and a new containment structure was planned to prevent rain entering and triggering such an explosion, and to prevent further release of radioactive material. This was the largest civil engineering task in history, involving a quarter of a million construction workers who all reached their official lifetime limits of radiation. Ukrainian filmmaker Vladimir Shevchenko captured film footage of an Mi-8 helicopter as its main rotor collided with a nearby construction crane cable, causing the helicopter to fall near the damaged reactor building and killing its four-man crew on 2 October 1986.

By December 1986, a large concrete sarcophagus had been erected to seal off the reactor and its contents. Environmental and the greater urban decontamination liquidators, similarly first washed buildings and roads with "Bourda", a sticky polymerizing fluid DeconGel, designed to entrain radioactive dust and when dry, could then be peeled off and compacted into configurations, akin to carpet rolls, in preparation for burial. A unique "clean up" medal was given to the workers.

Although many of the radioactive emergency vehicles were buried in trenches, many of the vehicles used by the liquidators, including the helicopters, still remain parked in a field in the Chernobyl area. Scavengers have since removed many functioning, but highly radioactive, parts. Liquidators worked under deplorable conditions, poorly informed and with poor protection. Many, if not most of them, exceeded radiation safety limits.

During the construction of the sarcophagus, a scientific team re-entered the reactor as part of an investigation dubbed "Complex Expedition,'' to locate and contain nuclear fuel in a way that could not lead to another explosion. These scientists manually collected cold fuel rods, but great heat was still emanating from the core. Rates of radiation in different parts of the building were monitored by drilling holes into the reactor and inserting long metal detector tubes. The scientists were exposed to high levels of radiation and radioactive dust.

After six months of investigation, in December 1986, they discovered with the help of a remote camera an intensely radioactive mass in the basement of Unit Four, more than two metres wide, which they called "the elephant's foot" for its wrinkled appearance. The mass was composed of melted sand, concrete and a large amount of nuclear fuel that had escaped from the reactor. The concrete beneath the reactor was steaming hot, and was breached by now-solidified lava and spectacular unknown crystalline forms termed chernobylite. It was concluded that there was no further risk of explosion.

The official contaminated zones became stage to a massive clean-up effort lasting seven months. The official reason for such early (and dangerous) decontamination efforts, rather than allowing time for natural decay, was that the land must be repopulated and brought back into cultivation. Indeed, within fifteen months 75% of the land was under cultivation, even though only a third of the evacuated villages were resettled. Defence forces must have done much of the work. Yet this land was of marginal agricultural value. According to historian David Marples, the administration had a psychological purpose for the clean-up: they wished to forestall panic regarding nuclear energy, and even to restart the Chernobyl power station.

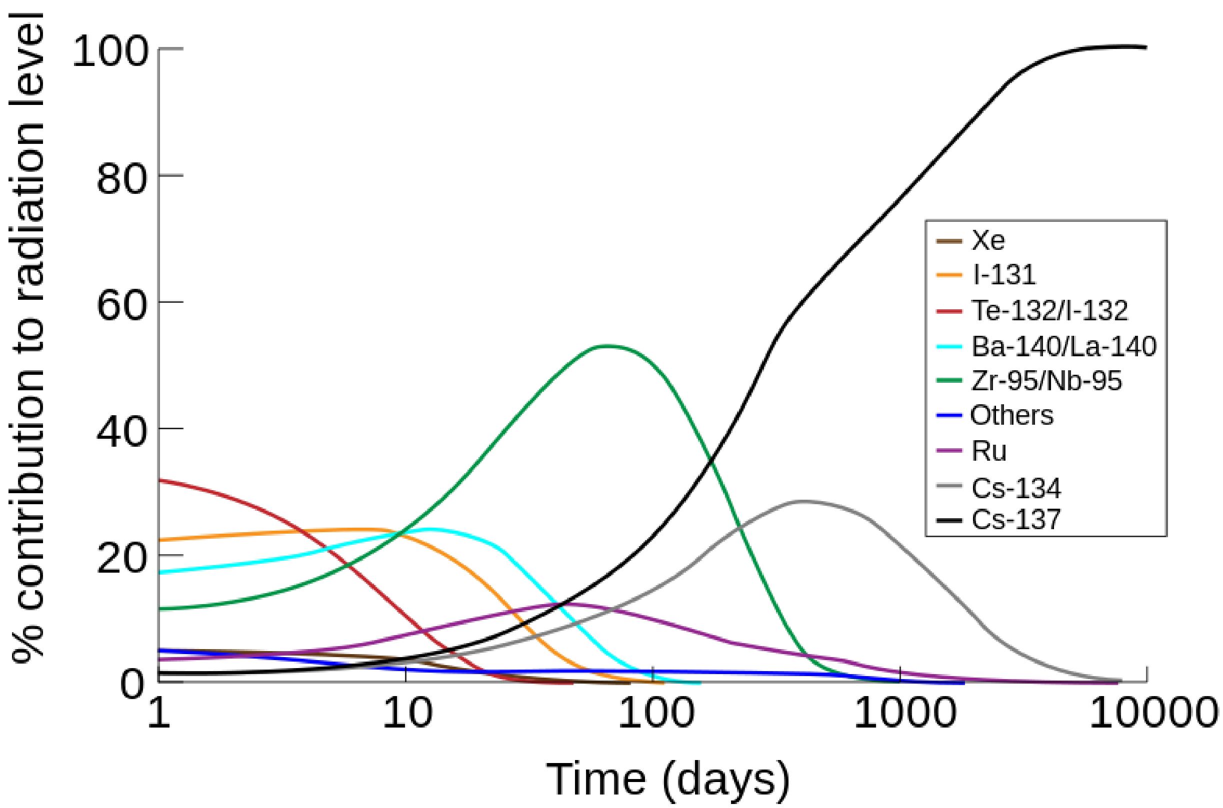
Impact

Environmental

Piglet with dipygus - Kiev - Ukrainian National Chernobyl Museum. "Каліцво порося" visible in the display's caption translates as "mutated piglet".

Although no informing comparisons can be made between the accident and a strictly air burst-fuzed nuclear detonation, it has still been approximated that about four hundred times more radioactive material was released from Chernobyl than by the atomic bombing of Hiroshima and Nagasaki. By contrast the Chernobyl accident released about one hundredth to one thousandth of the total amount of radioactivity released during the era of nuclear weapons testing at the height of the Cold War, 1950–1960s, with the 1/100 to 1/1000 variance due to trying to make comparisons with different spectrums of isotopes released. Approximately 100,000 square kilometres (39,000 sq mi) of land was significantly contaminated with fallout, with the worst hit regions being in Belarus, Ukraine and Russia. Slighter levels of contamination were detected over all of Europe except for the Iberian Peninsula.

The initial evidence that a major release of radioactive material was affecting other countries came not from Soviet sources, but from Sweden. On the morning of 28 April, 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.

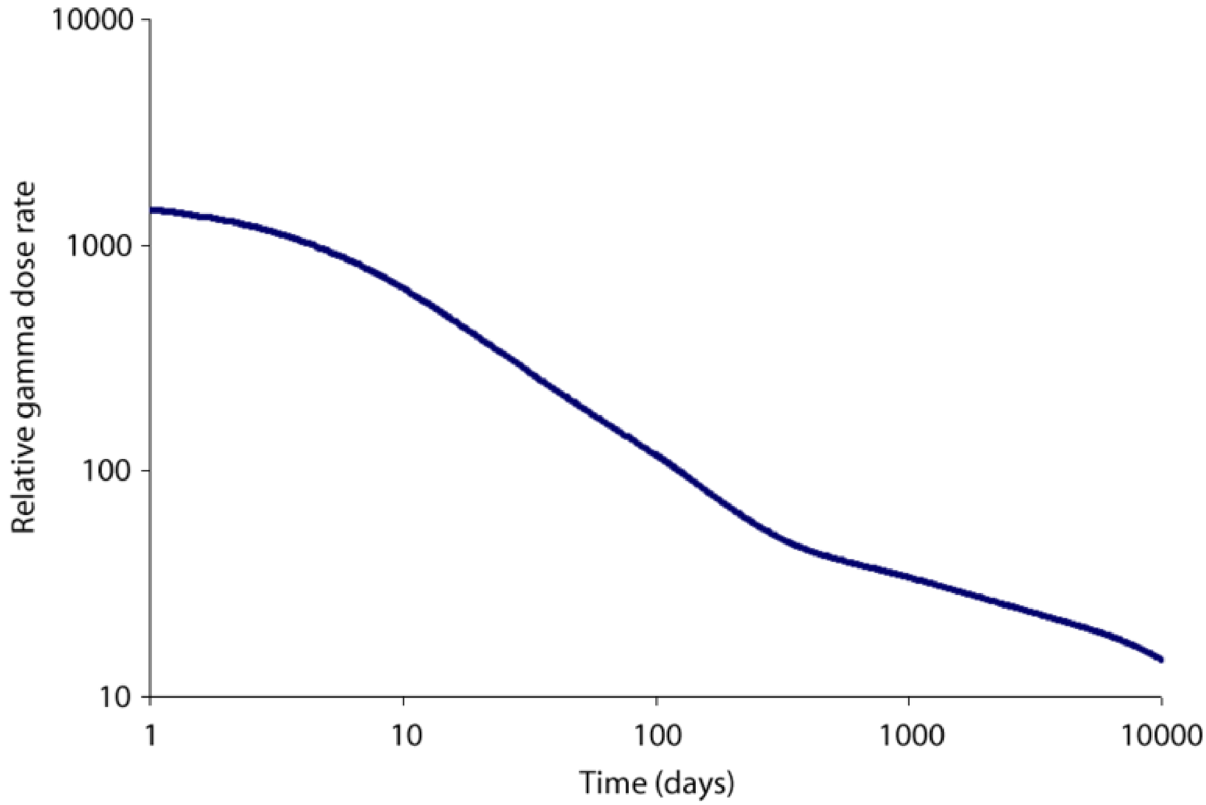


It was Sweden's search for the source of radioactivity, after they had determined there was no leak at the Swedish plant, that at noon on 28 April, led to the first hint of a serious nuclear problem in the western Soviet Union. Hence the evacuation of Pripyat on 27 April 36 hours after the initial explosions, 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.

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. Particularly dangerous are the highly radioactive fission products, those with high nuclear decay rates that accumulate in the food chain, such as some of the isotopes of iodine, caesium and strontium. Iodine-131 was and caesium-137 remains the two most responsible for the radiation exposure received by the general population.

Detailed reports on the release of radioisotopes from the site were published in 1989 and 1995, with the latter report updated in 2002.

At different times after the accident, different isotopes were responsible for the majority of the external dose. The remaining quantity of any radioisotope, and therefore the activity of that isotope, after 7 decay half-lives have passed, is less than 1% of its initial magnitude, and it continues to reduce beyond 0.78% after 7 half-lives to 0.10% remaining after 10 half-lives have passed and so on. Some radionuclides have decay products that are likewise radioactive, which is not accounted for here. 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.



The Chernobyl nuclear power plant is located next to the Pripyat River, which feeds into the Dnieper reservoir system, one of the largest surface water systems in Europe, which at the time supplied water to Kiev's 2.4 million residents, and was still in spring flood when the accident occurred.[71]:60 The radioactive contamination of aquatic systems therefore became a major problem in the immediate aftermath of the accident.

In the most affected areas of Ukraine, levels of radioactivity (particularly from radionuclides ^{131}I, ^{137}Cs and ^{90}Sr) in drinking water caused concern during the weeks and months after the accident,[136] Guidelines for levels of radioiodine in drinking water were temporarily raised to 3,700 Bq/L, allowing most water to be reported as safe, Officially it was stated that all contaminants had settled to the bottom "in an insoluble phase" and would not dissolve for 800–1000 years. A year after the accident it was announced that even the water of the

Chernobyl plant's cooling pond was within acceptable norms. Despite this, two months after the disaster the Kiev water supply was switched from the Dnieper to the Desna River. Meanwhile, massive silt traps were constructed, along with an enormous 30-metre (98 ft) deep underground barrier to prevent groundwater from the destroyed reactor entering the Pripyat River.

After the disaster, four square kilometres (1.5 sq mi) of pine forest directly downwind of the reactor turned reddish-brown and died, earning the name of the "Red Forest". 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. Some cattle on the same island died and those that survived were stunted because of thyroid damage. The next generation appeared to be normal.

On farms in Narodychi Raion of Ukraine it is claimed that from 1986-1990 nearly 350 animals were born with gross deformities such as missing or extra limbs, missing eyes, heads or ribs, or deformed skulls; in comparison, only three abnormal births had been registered in the five years prior.

With radiocaesium binding less with humic acid, peaty soils than the known binding "fixation" that occurs on kaolinite rich clay soils, many marshy areas of Ukraine had the highest soil to dairy-milk transfer coefficients, of soil activity in ~ 200 kBq/m^2 to dairy milk activity in Bq/L, that had ever been reported, with the transfer, from initial land activity into milk activity, ranging from 0.3^{-2} to 20^{-2} times that which was on the soil, a variance depending on the natural acidicity-conditioning of the pasture.

In 1987, Soviet medical teams conducted some 16,000 whole-body count examinations in these otherwise comparatively lightly contaminated regions deemed good prospects for recovery, to determine the completeness of banning local food and subsisting on food imports on the internal body burden of inhabitants, while concurrent agricultural countermeasures were fielded when cultivation did occur to further reduce the soil to human transfer as much as possible. The expected highest body activity was in the first few years, were the unabated ingestion of local food, primarily milk consumption, resulted in the transfer of activity from soil to body, after the dissolution of the USSR, the now-reduced scale initiative to monitor the human body activity in these regions of Ukraine, recorded a small and gradual half-decadal-long rise, in internal committed dose, before returning to the previous trend of observing ever lower body counts each year.

Human

In the accident's aftermath, 237 people suffered from acute radiation sickness, of whom 31 died within the first three months. In 2005, the Chernobyl Forum, composed of the International Atomic Energy Agency, other UN organizations, and the governments of Belarus, Russia and Ukraine, published a report on the radiological environmental and health consequences of the Chernobyl accident. In September 1987, the I.A.E.A. held an Advisory Group Meeting at the Curie Institute in Paris on the medical handling of the skin lesions relating to the acute deaths.

The only known, causal deaths from the accident involved workers in the plant and firefighters. In reporter Grigori Medvedev's book on the accident, there were a number of fishermen on the reservoir a half-kilometer from the reactor to the east. Of these, two shore fishermen, Protosov and Pustavoit, are said to have sustained doses estimated at 400 roentgens, vomited, but survived. The vast majority of Pripyat residents slept through the distant sound of the explosion, including station engineer Breus, who only became aware at 6am, the beginning of his next work shift. He would later be taken to hospital and, while there, made the acquaintance of one teen who had ventured out alone by bicycle to watch the roof fires during the night, stopping for a time and viewing the scene at the fictitious "Bridge of Death" 51.3949°N 30.0695°E, however contrary to this sensationalist label, the youthful night biker was treated and released from hospital, remaining in touch with Breus as of 2019.

With the exception of plant employee Shashenock, who having been struck by injuries compounded by the blast and never fully regaining consciousness, upon the arrival of the world specialist, all serious cases of ARS were treated by Dr. Robert Peter Gale, who documented a first of its kind treatment. In 2019, Gale would write a letter to correct the popularised, though egregious, portrayal of his patients as dangerous to visitors. All those who died were station operators and firefighters, over half of which from the continued wearing of dusty soaked uniforms, causing beta burns to cover large areas of skin. In the first few minutes to days, (largely due to Np-239, a 2.4-day half-life) the beta-to-gamma energy ratio is 30:1, though while adding to the dose, no proximate deaths would be from the gamma fraction of exposure. Instead, owing to the large area of burned skin, bacterial infection was and remains the overarching concern to those afflicted with ARS, as a leading cause of death, quarantine from the *outside* environment is a part of the normal treatment protocol. Many of the surviving firefighters, continue to have skin that is atrophied, spider veined with underlying fibrosis due to experiencing extensive beta burns.

Aftermath

Following the accident, questions arose about the future of the plant and its eventual fate. All work on the unfinished reactors No. 5 and No. 6 was halted three years later. However, the trouble at the Chernobyl plant did not end with the disaster in reactor No. 4. The damaged reactor was sealed off and 200 cubic meters (260 cu yd) of concrete was placed between the disaster site and the operational buildings. The work was managed by Grigoriy Mihaylovich Naginskiy, the deputy chief engineer of Installation and Construction Directorate – 90. The Ukrainian government allowed the three remaining reactors to continue operating because of an energy shortage in the country.

Decommissioning

In October 1991, a fire broke out in the turbine building of reactor No. 2; the authorities subsequently declared the reactor damaged beyond repair, and it was taken offline. Reactor No. 1 was decommissioned in November 1996 as part of a deal between the Ukrainian government and international organizations such as the IAEA to end operations at the plant. On 15 December 2000, then-President Leonid Kuchma personally turned off reactor No. 3 in an official ceremony, shutting down the entire site.

Confinement

Soon after the accident, the reactor building was quickly encased by a mammoth concrete sarcophagus in a notable feat of construction under severe conditions. Crane operators worked blindly from inside lead-lined cabins taking instructions from distant radio observers, while gargantuan-sized pieces of concrete were moved to the site on custom-made vehicles. The purpose of the sarcophagus was to stop any further release of radioactive particles into the atmosphere, mitigate damage should the core go critical and explode, and provide safety for the continued operations of adjacent reactors one through three.

The concrete sarcophagus was never intended to last very long, with a lifespan of only 30 years. On 12 February 2013, a 600 m^2 (6,500 sq ft) section of the roof of the turbine-building collapsed, adjacent to the sarcophagus, causing a new release of radioactivity and temporary evacuation of the area. At first it was assumed that the roof collapsed because of the weight of snow, however the amount of snow was not exceptional, and the report of a Ukrainian fact-finding panel concluded that the collapse was the result of sloppy repair work and aging of the structure. Experts warned the sarcophagus itself was on the verge of collapse.

In 1997, the international Chernobyl Shelter Fund was founded to design and build a more permanent cover for the unstable and short-lived sarcophagus. It received more than €810 million and was managed by the European Bank for Reconstruction and Development (EBRD). The new shelter was named the New Safe Confinement and construction began in 2010. It is a metal arch 105 metres (344 ft) high and spanning 257 metres (843 ft) built on rails adjacent to the reactor No. 4 building so that it could be slid over top the existing sarcophagus. The New Safe Confinement was completed in 2016 and slid into place over top the sarcophagus on 29 November. The huge steel arch was moved into place over several weeks. Unlike the original sarcophagus, the New Safe Confinement is designed to allow the reactor to be safely dismantled using remotely operated equipment.

Waste Management

Used fuel from units 1–3 was stored in the units' cooling ponds, and in an interim spent fuel storage facility pond, ISF-1, which now holds most of the spent fuel from units 1–3, allowing those reactors to be decommissioned under less restrictive conditions. Approximately 50 of the fuel assemblies from units 1 and 2 were damaged and required special handling. Moving fuel to ISF-1 was thus carried out in three stages: fuel from unit 3 was moved first, then all undamaged fuel from units 1 and 2, and finally the damaged fuel from units 1 and 2. Fuel transfers to ISF-1 were completed in June 2016.

A need for larger, longer-term radioactive waste management at the Chernobyl site is to be fulfilled by a new facility designated ISF-2. This facility is to serve as dry storage for used fuel assemblies from units 1–3 and other operational wastes, as well as material from decommissioning units 1–3 (which will be the first RBMK units decommissioned anywhere).

A contract was signed in 1999 with Areva NP (now Framatome) for construction of ISF-2. In 2003, after a significant part of the storage structures had been built, technical deficiencies in the design concept became apparent. In 2007, Areva withdrew and Holtec International was contracted for a new design and construction of ISF-2. The new design was approved in 2010, work started in 2011, and construction was completed in August 2017.

ISF-2 is the world's largest nuclear fuel storage facility, expected to hold more than 21,000 fuel assemblies for at least 100 years. The project includes a processing facility able to cut the RBMK fuel assemblies and to place the material in canisters, to be filled with inert gas and welded shut. The canisters are then to be transported to dry storage vaults, where the fuel containers would be enclosed for up to 100 years. Expected processing capacity is 2,500 fuel assemblies per year.

Exclusion Zone

An area originally extending 30 kilometres (19 mi) in all directions from the plant is officially called the "zone of alienation." It is largely uninhabited, except for about 300 residents who have refused to leave. The area has largely reverted to forest, and has been overrun by wildlife because of a lack of competition with humans for space and resources. Even today, radiation levels are so high that the workers responsible for rebuilding the sarcophagus are only allowed to work five hours a day for one month before taking 15 days of rest. As of 2016, 187 locals had returned and were living permanently in the zone.

In 2011 Ukraine opened up the sealed zone around the Chernobyl reactor to tourists who wish to learn more about the tragedy that occurred in 1986. Sergii Mirnyi, a radiation reconnaissance officer at the time of the accident, and now an academic at the National University of Kyiv-Mohyla Academy, has written about the psychological and physical effects on survivors and visitors, and worked as an advisor to Chernobyl tourism groups.

Recovery Projects

The Chernobyl Trust Fund was created in 1991 by the United Nations to help victims of the Chernobyl accident. It is administered by the United Nations Office for the Coordination of Humanitarian Affairs, which also manages strategy formulation, resource mobilization, and advocacy efforts. Beginning 2002, under the United Nations Development Programme, the fund shifted its focus from emergency assistance to long-term development.

New confinement built in 2017

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 Électricité 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 was moved into position in November 2016 and is expected to be completed in late-2017.

In 2003, the United Nations Development Programme launched the Chernobyl Recovery and Development Programme (CRDP) for the recovery of the affected areas. 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.

More than 18,000 Ukrainian children affected by the disaster have been treated at Cuba's Tarará resort town since 1990.

The International Project on the Health Effects of the Chernobyl Accident 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 among 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.

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