Chernobyl

Zhores Medvedev

On 8 August 2019, a deadly nuclear explosion took place in northern Russia in the vicinity of the Nenoksa weapons testing range. At least five people are said to have died. Subsequently, a Russian state weather agency confirmed release into the atmosphere of strontium, barium and other radioactive isotopes, indicating that a nuclear reactor was involved in the explosion.

Zhores Medvedev died in 2018, before this recent explosion. Back in 2011, he charted a trail of nuclear disasters from Kyshtym in the Cheliabinsk region of Russia, to Chernobyl near Pripyat in Ukraine, and to Fukushima in Japan. Dr Medvedev's warnings then continue to ring true. They were contained in his new preface to the Spokesman edition of his book, The Legacy of Chernobyl*, first published in 1990.*

Photos: Lesley Thacker

On 3 February 1987, during a lecture trip to Japan, I was invited to meet five members of the Japan Atomic Industrial Forum Inc. They wanted to discuss my book, *Nuclear Disaster in the Urals,* which described the consequences of the Kyshtym disaster, an explosion at a nuclear waste site in the Soviet Union in 1957.

The book, published in New York in 1979 and translated into Japanese in 1982, was then still the only published description of this accident. The Kyshtym disaster was not yet included in a list of nuclear accidents prepared by the International Atomic Energy Agency (IAEA). Top of this list, recorded at a top-of-the-scale 7 in severity, was Chernobyl, Three Mile Island was scale 5, and the fire at Windscale in England, in 1957, was scale 3. (The International Nuclear Event Scale was revised several times, subsequently, and the fire at Windscale is now reckoned to be scale 5.)

In 1987, I had already started to study the available information on Chernobyl because I was not satisfied with the Soviet Report to the IAEA, which blamed mainly the power station personnel for gross operational errors. My Japanese hosts were not interested in too many details. 'We do not find Chernobyl relevant to Japan,' one of them told me. 'Such accidents can never happen here.'

Nuclear disaster in the Urals

'Kyshtym', a small industrial town in the Urals, was the code name for correspondence among officials about this accident, which actually happened about 60 km east of Kyshtym in a larger but secret town, the first Soviet military nuclear centre, which was in Cheliabinsk region. It was not marked on maps, although the population was nearly 50,000. For scientists who lived there the address was ‘Post Box 40, Cheliabinsk’. The first Soviet plutonium-producing reactor was built there in 1948. In 1957, there were three plutonium-producing reactors and a reprocessing plant known as ‘Mayak’, which extracted plutonium from spent nuclear fuel. Liquid waste after plutonium extraction was transferred to a storage facility built in 1953 about 10 km east of the town. Before 1953 the waste was dumped into the nearest lake, Karachay, and the Techa River. (Lake Karachay is now the largest storage place of nuclear waste in the world.) The underground storage consisted of many steel tanks, each 250 cubic metres in size. These tanks were mounted on a concrete base and covered by a concrete lid. Cooling by water was necessary because the concentrated liquid nuclear waste is hot and can boil dry. In the United States, at this time, boiling was prevented by diluting with water the waste from plutonium production, so it had to be kept in much larger tanks.

Reprocessing involves dissolving the spent fuel in nitric acid, so the waste contains nitrates and acetates, which can be explosive in a dry state. It also produces radiolytic hydrogen, which can accumulate under the lid. (American storage tanks are not covered.) The cooling system in one of the tanks failed and it lost water. Waste started to boil and became too concentrated. On 29 September 1957, a spark ignited the hydrogen, which in turn detonated nitrates, so that a tank containing about 100 tons of waste exploded. The blast was equivalent to about 100 tons of TNT. This is a reconstruction, made later. Many details of this event were never disclosed. It is still not known what happened to the whole storage facility.

Most of the radioactivity, 20 to 50 million curies, was dispersed around the storage facility, but about 2 million curies of isotopes of caesium and strontium in aerosol form rose up to two kilometres in the air and distributed over a large area in a north-easterly direction. The radioactive cloud covered an area of 23,000 sq.km. of agricultural land. There were 217 villages and settlements here, with a population of 270,000. Early snow and the absence of equipment and personnel complicated the measurement of contamination. During the next two years, about 10,000 villagers from an area of about 1,000 sq.km. were resettled. Nineteen villages were destroyed by fire to prevent people returning. Agricultural production was stopped over a larger area.

I learnt about this disaster in 1958, when my friend V. M. Klechkovsky, then chairman of the department of agrochemistry of the Moscow Agricultural Academy, was appointed head of the programme for rehabilitation of contaminated agricultural land. Some of my close friends from student years moved to the area to work. The risks were high, but salaries were also very high. Their work, however, was classified as ‘top secret’.

In November 1976, already living and working in London, I briefly mentioned an explosion of the nuclear waste site in the Urals in a British magazine, *New Scientist*. Two days later, the Chairman of the United Kingdom Atomic Energy Authority, Sir John Hill, in an interview with the Press Association, published in many countries, described my story as ‘pure fiction, rubbish and figment of imagination’. American scientists made similar comments. An explosion of nuclear waste was considered impossible. However, in 1977, I published in *New Scientist* more details about the ecological effect of this accident. Then the discussion moved to a different level. In 1978, I was invited to several US National Laboratories (Argonne, Oak Ridge, Brookhaven and Los Alamos). Everywhere I was told that such a serious accident could not happen without American scientists finding out about it.

In Los Alamos in November 1978, Edward Teller, the creator of the American hydrogen bomb, questioned me very aggressively for nearly three hours. He accused me of a deliberate attempt to frighten the western public about the dangers of nuclear power, which was being widely promoted at the time. The report of the Los Alamos National Laboratory, published in 1982 (D. V. Soran, D.V. Stillman, *An Analysis of the Alleged Kyshtym Disaster*) attempted to explain this radioactive contamination by a nuclear weapon test.

The disaster was partially declassified in 1989. The local population started to demand the same financial compensation and medical attention as the victims of Chernobyl. Only in 1990, when the Soviet authorities formally acknowledged this accident, was ‘The Kyshtym Disaster’ included in the list of nuclear accidents by the International Atomic Energy Agency. It was given severity scale 6, between Three Mile Island and Chernobyl. In 1990, as a participant of the Kurchatov Institute of Atomic Energy Conference on Kyshtym, I had an opportunity to visit the site. I also visited the local cemetery to see the graves of two of my friends who had died from leukaemia.

The secrets of Chernobyl

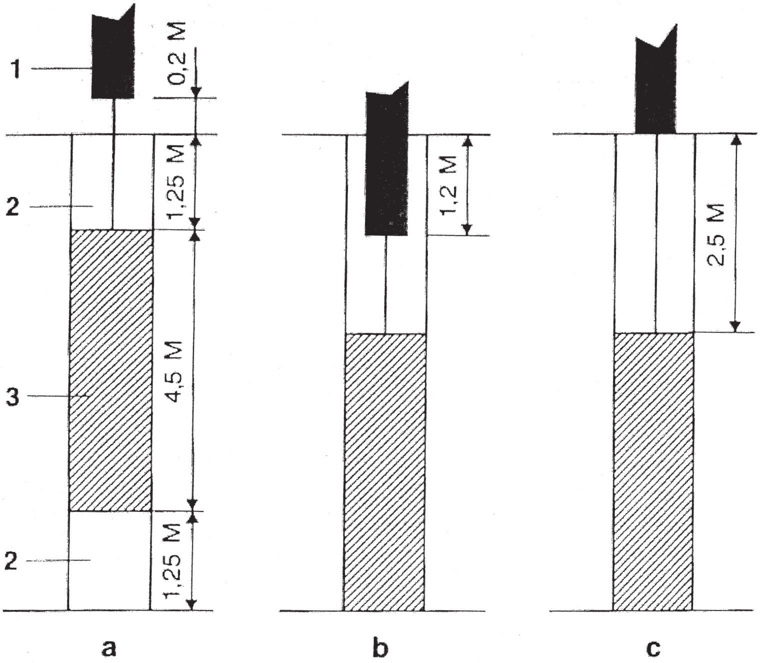
The Chernobyl disaster has been comprehensively studied, but many aspects are not well known.

The Chernobyl reactors are Soviet designed and built, a source of pride at the time. RBMK-1000 is a graphite moderated reactor using slightly enriched uranium (2% U-235). It is a boiling water reactor with two loops feeding steam directly to the turbines. The use of a graphite moderator allows a reduction of reactor pressure, but also makes the reactor core very large, 7m high and about 12m in diameter. That is why no containment vessel was made. Raising or lowering 211 control rods regulated the reactivity. One drawback of the RBMK reactor, well known to the designers and to the IAEA, was the ‘positive void coefficient’, when an increase in steam bubbles (voids) causes an increase in core reactivity. The shutdown procedure was dangerously slow at about 10 seconds.

The State Commission created by the government to study the accident prepared a detailed Report in August 1986, which was presented to the IAEA and discussed there at a special international conference. The accident was blamed on incredible errors and the incompetence of the operating personnel. The director of the Chernobyl plant, chief engineer, his deputy and several operators of Reactor 4 were arrested, tried by the Supreme Court of the USSR, and sentenced to ten years in prison for criminal neglect in operation of a potentially explosive system. Research into the causes of the explosion continued. The main puzzle was that the explosion happened a few seconds after an operator, L.Toptunov, pressed the red ‘panic button’ for emergency shutdown, and the control rods started to move down. Neither Toptunov, nor his supervisor who gave the order, survived to stand trial.

In January 1988, the Soviet journal *Atomnaja Energia* published a paper by the physicist E. Adamov and others on the first phase of the Chernobyl accident.[1] They concluded that the real cause of the explosion was a design fault of the control rods which were inserted into the reactor core to slow down the fission reaction. To gain some extra power the lower part of each control rod was graphite, and beneath the rods channels were filled with water. The upper part of the rod was made of boron carbide, which absorbs neutrons. With this design, during the first seconds after the ‘panic button’ was pressed, 170 rods started to move down at once, slowed by having to displace water, not absorbing neutrons, but instead producing a surge of reactivity in the lower part of the reactor core, resulting in the explosion due to the increase in criticality and reactivity. The operators did not know about this possibility, and it was the first time in Toptunov’s short life that he had used the emergency button. The conclusion of the paper in *Atomnaja Energia* was that the dramatic increase in reactivity (nearly 100 fold) was a direct result of the design error.

Figure: Scheme of the position of graphite ends of the control rods of the RBMK-1000 reactor



1. Boron parts of the control rods position in working reactor
2. Connection between rod and graphite end supplement
3. Graphite end
   a. Before Chernobyl accident
   b. After Chernobyl accident in other RBMK reactors
   c. After redesign in 1987

(From Adamov et al)

The Commission did not report this fault to the International Atomic Energy Agency in August 1986. But it was known to the designers of the RBMK model. All the other 15 RBMK reactors in the USSR[2] were instructed to continue operating, but with the control rods descended down into the core by 25% of their length. This reduced generation of electricity to 70% of projected power. Billions of kilowatts of electricity were lost. Later the control rods were redesigned (see Figure).

The official acknowledgement of the design fault of the RBMK reactors was slow. A special amendment to the 1986 Government Report was sent to the IAEA in Vienna only in 1991. It made clear that the RBMK-1000 reactor did not correspond to safety norms and had some potentially dangerous features. 'The operators did not violate any rules and their actions did not contribute to the development of the accident …’ This conclusion appeared in the IAEA papers only in 1993, when the USSR had already disappeared. The general press in the Russian Federation, and in Ukraine and Belarus, reported nothing about the rehabilitation of the management and personnel of the Chernobyl plant.

The Chernobyl disaster contributed heavily to the economic, political and social crisis that developed into the collapse of the Soviet Union. Between 1987 and 1991 nearly 60 nuclear reactors of different types, including thermal and experimental, were either closed down or frozen in the construction or project stage. The programme of thermal nuclear stations to heat some cities (Gorky, Odessa, Voronezh, Rostov-Don) was cancelled, although they had already been built and tested. The Armenian nuclear power station was stopped after the earthquake in 1988. A shortage of electric power resulted in the cancellation of many industrial projects. Because Ukraine and Belorussia were mainly affected by radioactive fallout from Chernobyl, local nationalist movements, which were embryonic before 1986, became major political forces. When I was in Ukraine in 1991 for the International Conference on the Ecological and Medical Consequences of the Chernobyl Accident, there was a demonstration in Kiev on 26 April with placards that said ‘Stop the Radiation Genocide of the Ukrainian People’.

The other three Chernobyl reactors continued to work for many years. The last of them was shut down in 2000 under pressure from the European Union. (The EU promised compensation which never materialised.) Work on cooling the spent fuel storages and the nuclear reactor cores, and servicing and sealing the damaged reactor, continues today with thousands of workers in round-the-clock shifts. The whole site is expected to be dismantled by 2065, after two periods of decay half-lives of caesium-137 and strontium-90. However, the dismantling cannot be carried out without a new, much larger protective structure, which has to cover the original sarcophagus and the whole site. This structure is designed to prevent the release of radioactive debris and dust from the destroyed reactor into the environment. The technology for this dismantling will be developed later. The new project, which is known as the ‘New Safe Confinement’, with an estimated cost of $600 million, is expected to last 100 years or more. Because Ukraine is unable to finance the project, the United Nations has been collecting donations since 2006. Nearly 50 governments have promised to contribute. But the French company, which was awarded the contract in 2007, still performs only preparatory work. It may take a decade before the actual dismantling of the destroyed reactor will start.

Fukushima: The improbable can happen

The first nuclear reactor for the Fukushima I plant was designed in the early 1960s, ordered in 1966, and put into operation in 1971 for the Tokyo Electric Power Company (TEPCO) by General Electric. It was modest in terms of power; a 460 MW boiling water reactor (BWR). The second reactor of the same type was more powerful (784 MW), and the last (the sixth reactor), which came into operation in 1979, was 1100 MW. The design was expected to withstand seismic events of magnitude 7,5. This was the force of the California earthquake of 1952. The San Francisco earthquake of 1906 was 7,8. The Great Tokyo Earthquake of 1923 was magnitude 8,3. The earthquake on 11 March 2011 was magnitude 9.

The Fukushima I nuclear accident is now considered the second largest after Chernobyl. But it is still developing, and might yet take the lead in the IAEA list of nuclear accidents. It is much more complex because it involves several reactors and the spent fuel storage tanks, with about 25 times more radioactivity than there was in the Chernobyl reactor. The picture of the accident grows darker and darker almost daily: partial meltdowns in reactors 1, 2 and 3; hydrogen explosions which destroyed the upper parts of buildings housing the reactors; damage to the containment inside reactor 2; fires and leaks. The amount of radioactivity released into the environment has already reached the Chernobyl level. However, in Chernobyl the release was gases and aerosol into the air. In Japan, there are mostly radioactive solutions which contaminate soil and sea. (In Japan, there is also much more plutonium.)

Igor Ostretsov, a nuclear engineer of Soviet pressurised water reactor (PWR) models, whom I consulted, wrote that the location of the emergency power generators so close to the sea and at sea level, just facing the great tectonic fracture, was a serious mistake. He also considers unfortunate and unsafe the location of very heavy spent fuel storage tanks filled with water in the same building above the reactor. Such a location made it easier to load the fuel rods from the reactor into the storage pool, but it also made ‘suspended’ storage tanks very vulnerable to any earthquake.

The earthquake damaged these tanks, causing them to leak. Their location made it difficult to refill them with cooling water. Helicopters and fire engines were used out of desperation.

Another design fault identified by Ostretsov was the absence of a ventilation system for radiolytic and zirconium-steam reaction produced hydrogen gas. This resulted in accumulation of the gas in the reactor building, and caused explosions which destroyed the building and many critical systems, particularly the cooling loops. The use of seawater was another desperate measure, as the water evaporates, leaving salt, which further damages the fuel rods in the core and in storage pools.

The boiling water reactor (BWR) system has one more problem. The same water, which functions as a neutron moderator and is part of the fission control, is also feeding steam directly to the turbines without an intervening heat exchanger. This purified and deionised water is pumped to the bottom of the fuel channels and boils, producing steam used to drive the turbines. This water accumulates fission radionuclides.

Heavily contaminated water, particularly with iodine-131 and caesium-137, is the main problem. Reactors do not produce carbon dioxide, which is an advantage. But they produce an enormous amount of heat. Working reactors therefore consume a huge amount of cooling water; 21,000 tons per hour in Fukushima I-1, 33,300 tons per hour in Fukushima I-3, and 48,300 tons per hour in Fukushima I-6. Even after shutdown, residual heat from accumulated radionuclides constitutes up to five per cent of project power (depending on the fuel cycle), enough to cause meltdown. Partial meltdowns were reported at Fukushima after the emergency shutdown. Thus, several thousand tons of water per hour are still needed to cool the residual heat of the cores and the spent fuel in storage. With the circulating systems damaged, this water has to be dumped in the sea. There is no project provision to store this amount of radioactive water. Temporary storage was possible only for the reduction of iodine-135 (half-life 6,7 hours) and iodine-131 (half-life 8 days). The iodine isotopes were produced in working reactors. (Nearly 80 million curies of radioactive iodine were released into the air in Chernobyl.)

Now, nearly three months after the Japan earthquake, the danger from iodine has diminished. The main problems are strontium-90, caesium-137, plutonium and a few more long-lived radionuclides. The danger of new meltdowns is not yet over. The main problem for years to come will be managing more than 500 tons of spent fuel in the reactors and in storage pools, more than 4 tons of which is plutonium. The cooling systems of the reactors and spent fuel tanks were found beyond repair and the current methods of cooling continue to wash out the radioactivity into the environment. The project to dismantle the whole nuclear plant with its six reactors might take many years.

The legacy, the lessons, the future

It is clear that all the stages of nuclear generation of electricity and all models of reactor design are susceptible to malfunction and human error. Human errors were made not only in the design, engineering and operation, but also in planning oversights, such as not taking into consideration the possible force of earthquakes and tsunamis. Earthquakes with magnitude 9 are not unprecedented in Asia.

The Three Mile Island accident in 1979, the most frightening meltdown of a pressurized water reactor (PWR), resulted from trivial failures in the non-nuclear secondary system and human errors. Melting of nuclear fuel rods and zirconium-steam reaction, with the release of large amounts of hydrogen gas, developed from residual heat after the reactor was shut down. The zirconium oxidation itself releases a lot of heat. It is self-sustaining, like a fire. Overheating with the generation of hydrogen is also possible in spent fuel storage tanks if some of the rods are exposed due to the loss of cooling water.

There have been many reactor accidents below severity level 4 which were very close to becoming disasters: the Leningrad Atomic Electro Station (AES) RBMK-1000 reactor in 1975; a fire at the Armenian AES in 1982; and several reactor accidents on nuclear submarines and icebreakers which were not reported to the International Atomic Energy Agency. The first Soviet nuclear icebreaker, *Lenin,* built in 1957, suffered partial reactor fuel meltdowns twice, in 1965 and in 1967. Reactors made for ships and submarines are more prone to accidents because they operate at much higher levels of uranium-235 enrichment. Soviet designed naval reactors were fuelled with U-235 enriched to 21-45 per cent. After decommissioning, spent fuel in such reactors contains too high concentrations of radioactive isotopes so that it is more ‘hot’ and difficult to handle.

Nuclear power is consumed as electricity without the accumulation of carbon dioxide. However, it constantly accumulates spent fuel rods, which generate intense heat and dangerous radiation for years. Fresh spent fuel rods which are removed from any reactor every 12 to 18 months are the most dangerous due to short-lived isotopes, such as iodine-131, and these are kept close to the reactor under intensive cooling. Without water the spent fuel can suffer meltdown. The duration of this danger of ‘criticality’ depends on the level of enrichment of uranium-235. The quality of cooling water is tightly controlled to prevent the fuel or its cladding from degrading. The use of sea water for cooling nuclear storage pools certainly produces damage, which will complicate the removal of these rods for permanent storage or reprocessing. Spent fuel rods need water cooling for many years. The system also requires removal of radiolytic gases, hydrogen and oxygen.

It is clear now that spent fuel pools as well as reactor cores should be equipped with back-up water circulation systems and separate back-up generators for water circulation. The Three Mile Island accident resulted in nearly one hundred new safety requirements in nuclear power station design and operation. The Fukushima accident will probably generate even more. We might have safer reactors in the future, but they will be more expensive and take more time to build. The nuclear generation of electricity will for many years, if not decades, continue to use old and immature technology. In 2011, there are 178 nuclear reactors, out of a total of 444 that are generating electricity worldwide, which are more than 30 years old and obsolete.

Zhores Medvedev, London, May 2011

References

1. Adamov E.A. et al., *Atomnaja Energija* Vol.64, No 1, pp 24-29, 1988.
2. Information about reactors of different types is taken from *Directory of nuclear power plants in the world 1994,* edited by Haruo Fujii and Atsuyoshi Morishima, Japan Nuclear Energy Information Center Co., Tokyo, Japan

Chernobyl, 2019