CHERNOBYL NUCLEAR POWER PLANT ACCIDENT - CASE STUDY

Yu.A. Izrael
Institute of Global Climate and Ecology, Russian Federal Service for Hydrometeorology and Environment Monitoring, Russian Academy of Sciences, Russia

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Summary

Under normal operating regime, nuclear power stations practically do not release aerosol products to the atmosphere leading to essential radioactive fallout. According to studies conducted by scientists from different countries, under the normal operating regime nuclear reactors can release to the atmosphere inert gases (^{41}**Ar**, ^{133}**Xe**, ^{85}**Kr**), in some cases with insignificant admixture of tritium (^{3}**H**) and iodine (^{131}**I**) isotopes. Some other isotopes are also mentioned in gaseous releases (for instance, ^{135}**Xe**, ^{14}**C** and ^{129}**I**).

Under normal operating regime, nuclear power stations can release (2-4) $\cdot$ 10^5 Ci/year in the form of gaseous products (mainly, due to relatively short-lived inert gas isotopes), up to 10 Ci/year of aerosol products, 0.5 Ci/year of radioactive iodine; only very small quantity of aerosol products can fall on the surface, including the Iodine isotopes. When this takes place, only a small quantity of the aerosol products can be felt onto the ground surface. However, accidents at nuclear reactors are an important exception, as well accidents of different type at atomic enterprises.

Among notable accidents occurred at nuclear reactors, it should be noted here (in a chronological order) the following: the Windscale accident (the Great Britain, 1957),

the Three-Mile-Island nuclear power station accident (the USA, 1983), and the greatest all over the world Chernobyl nuclear power station accident (the former USSR, 1986). For comparison, total release of radioactivity under tests of nuclear weapon and largest accidents (PBq per D+3) is as follows:

Isotope	Tests	Chernobyl (former USSR)	Windscale (UK)
^{137}Cs	1500	89	0.044
^{134}Cs		48	0.0011
^{90}Sr	1300	7.4	0.00022
^{131}I	780 000	1300	0.59

(**^{134}Cs** is induced nuclide generated by irradiation with the neutrons from a reactor).

1. Chernobyl Nuclear Power Plant Accident (Versions of Possible Causes of the Accident)

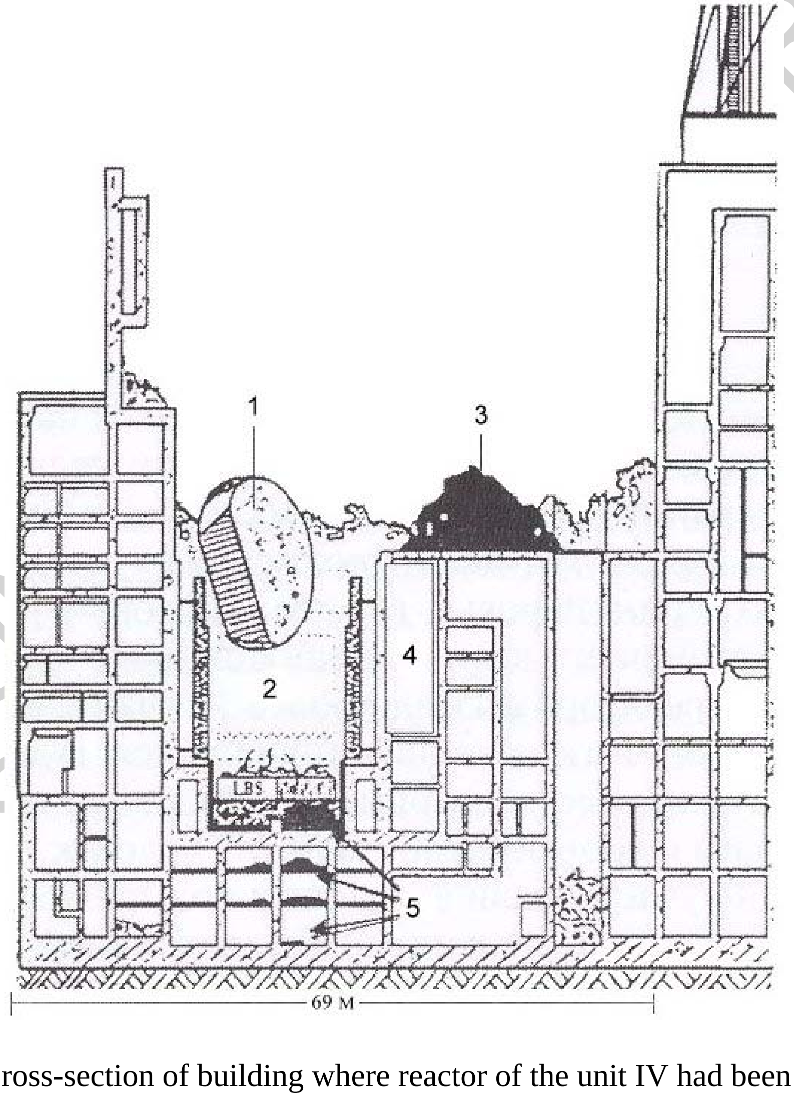

Figure 1. Cross-section of building where reactor of the unit IV had been destroyed. 1 – the reactor cover; 2 – area of the reactor active zone (empty); 3 – materials dumped from the helicopters; 4 – a basin for short storage of exhausted nuclear fuel; 5 – a place of fuel "lava".

This had happened on April 26, 1986. Accident at the Chernobyl Nuclear Power Plant (CNPP) had occurred during technical tests in a regime of small power which were carried out at a reactor of the Unit IV. The safety systems of the reactor were switched off that resulted in its abnormal and unstable working regime that led to sharp and uncontrolled rise of the power.

The enormous power caused a series of vapor explosions which had destroyed the reactor itself and damaged the building. Fragments of the reactor active zone, being thrown out, caused 30 more centers of burning on the roof that was covered by the easily ignitable material tar. A crater had been formed after destruction of the building and the reactor (Figure 1).

Already in five minutes the first group of 14 firemen had arrived at the accident place, and in two hours 250 people were working at the site, and 69 among them were directly involved in the fire suppression. These works were carried out at the 70-meter altitude and under condition of high levels of radiation and strong smoking that had caused heavy defeat of almost half of the participants with further deaths.

Thus, this accident was a result of both, faults of the reactor construction (high positive coefficients of reactivity under certain conditions) and inadmissible erroneous actions of operators who had switched off emergency protective systems.

At the first step of the struggle against the fire and the radionuclide release, huge quantity of special compositions absorbing the neutrons as well material used to put out (extinguish) fires was dropped from helicopters into the crater on the roof. Totally, about 5 000 tons of different materials had been thrown down, and those were as follows: lead, compounds of boron (Br), dolomite, sand, and clay as well as sodium phosphate and liquid polymer materials.

During the first of the total 1 800 flights, the helicopters were hovering above the reactor, but, later on, the doses those were taken by pilots were considered too high, so, the decision had been made to throw the materials down during the moment of their flight over the reactor. This led to inaccurate hits and this caused new destructions and further spread of radioactive contamination.

On the 7-8th day dumping (discharge) of the materials had been decreased, and then stopped totally because of fears that the building structures would not be able to stand. Melted materials of the active zone (corium or lava) flew down to the bottom of the reactor shaft. Here, under graphite that played the role of a peculiar filter for volatile compounds, and a layer of metallized fuel had been formed.

The resulting quick spreading of the corium and its contacting with water had caused the water vapor formation that promoted a sharp increase of intensity of the radioactive releases occurring at the final step of the accident active period. Approximately in 9 days, the corium had quickly solidified and lost capability of reacting with surrounding materials that significantly decreased the heat release, and, as a consequence, reduced the intensity of the radionuclide release by two-three orders of magnitude.

Since this accident was really very large and had rather serious consequences, many people wanted to know the reason why this could happen. There were many different versions of conjectures on the possible cause. Some scientists proposed that this could be caused in response to a distant earthquake, some – that this was a deep fault in the Earth's crust.

We do not think that it is reasonable to present here this discussion. According to the conclusion of the Governmental commission, the official version on the Chernobyl NPP accident is the following: the thermal (non-nuclear) explosion had occurred in a course of tests aimed at examination of a possibility to apply a voltage from the turbo-generator in a regime of de-energizing of the CNPP.

As a matter of fact, this only cause had led to destruction of the unit IV, the fire in the reactor, and the release of significant quantity of radioactivity, accumulated in the reactor by the moment of the explosion, into the ambient environment.

However, the great dimensions of the accident and its consequences make us to ponder over the causes of this accident, and, first of all, over reliability of the reactor type (RBMK) that burst in Chernobyl as well as over a right way of organization of functioning of these reactors and over general state of national nuclear power engineering.

Reactor RBMK had been developed in the USSR and had undergone all necessary tests. A decision to build atomic stations (NPPs) and to equip them with this type of reactor had been made only on the basis of all the tests done. The special Interagency Scientific-Technical Council on the nuclear power stations existed in the Ministry of Middle Machine Building headed by academician A.P. Aleksandrov existed in former USSR for solution of technical problems in the field of nuclear power engineering.

All leading scientists and specialists in this field took part in the work of this Council: scientific leaders and main designers of reactors, general designers of nuclear stations and chief specialists. And, no decision made by this Council contained any information allowing any doubts on the safety of these type reactors.

All basic scientific and technical decisions in relation to nuclear stations for different purposes were made in the Ministry of Middle Machine Building of USSR that was responsible for nuclear protective potential of the country, and it had all scientific, research, and designing organizations needed for the works for the nuclear power engineering. But, in middle of the 1960s exploitation of nuclear plants was entrusted to the USSR Ministry of Power Engineering and Electric Power Supply that possessed a great scientific-technical potential in the field of traditional power engineering, but had no means to control and sustain works for the nuclear station exploitation.

In June of 1986, i.e. already after the Chernobyl accident, the problem of improvement of the nuclear power engineering was considered at special meetings of Politbureau of Central Committee of the Communist Party. Different opinions were expressed but only one was prevailing that was necessary to entrust exploitation of NPPs to that ministry where all necessary means and relevant experience were available. One should take into account that in all countries where nuclear power engineering exists it was a new type of industrial activity that was developed on the basis of specific works for creation of nuclear weapons. Different reorganizations and "perestroikas" in this field took place earlier or later everywhere all over the world.

It seems reasonable to consider the reorganization mentioned above as the main mistake that resulted in tragic consequences. New, and still not sufficiently examined (studied) and mastered, this power production was potentially dangerous and at the same time was introduced too early into ordinary framework of civil industry. By the time of the Chernobyl accident, the USSR nuclear power engineering was only 22 years old.

Together with development of the nuclear power engineering the basis for norms and standards for this new type of industry was developed too. The norms and standards were developed and improved together with accumulation of experience of the NPP functioning. This process was rather quick, and, for several years, the operation of nuclear power units did not comply with the improved norms accepted on the basis of their work. But, no reconstruction or modernization of them was carried out.

It seems that functioning of NPP in the system of civil industry was not carefully thought out. It was supposed that regulations and instructions on the nuclear power stations maintenance would be strictly be performed by the personnel. It became clear after the Chernobyl accident how much this is important to take into account the so-called "human factor".

Analysis of many aspects of this event had demonstrated that it was not possible to foresee all circumstances that led to the accident. But, this allows making conclusions and learning lessons for further development and progress of the nuclear power engineering that is the extremely important field of human activity.

Unit IV of the Chernobyl NPP (CNPP) was destroyed, and a short-time outburst (release) to the environment of accumulated radionuclides took place as a result of thermal (non-nuclear) explosion on April 26, 1986. Then, during two weeks (including 6 May) a plume of gaseous and aerosol radioactive products continued to be released into the atmosphere due to high temperature of graphite burning and inner heating. The data on radionuclide release from the reactor and the problem of possibility to reconstruct the radioactivity source as a whole during the CNPP accident are in more detail discussed in Section 5.

Naturally, the mechanism of aerosol particle formation, and, consequently, the structure, composition and other characteristics of aerosol particles, resulting from "nuclear" accidents, considerably differ from those resulting from nuclear explosions. This distinction is determined by quite different physical and chemical conditions of particle generation, difference in the material of which the particles are formed, etc.

The conditions of radioactive particle formation during the Chernobyl accident are discussed below. The following scheme of emergency release has been proposed by Sivintsev and Khrulev (1995). It includes four main stages:

- 1st stage – an outburst (release) caused by an explosion because of positive reactivity input;
- 2nd stage - a release connected with burning of a graphite core of the reactor;
- 3rd stage - a release due to processes running during an increase in fuel temperature and fuel-containing matter due to energy of radioactive decay of accumulated fission products;
- 4th stage - a sharp decrease in the release resulted from stabilization and the following gradual temperature drop.

Different measures taken at the emergency unit could exert effect on the release dynamics. It was supposed that the covering material thrown down (dropped) from helicopters onto the building of the emergency unit, weakened the iodine and cesium release; however, we suppose it could lead to the temperature drop at the 3rd stage.

According investigations performed, at the 1st stage the temperature rises up to 1800-2000 K took place. At the beginning of the 1st stage, heat-producing rods were destroyed, and fuel was dispersed because of thermal tensions resulting from fuel heating, as well from fission products expansion in closed porosity of fuel (a gaseous "explosion"). Almost immediately after it the second, vaporous explosion occurred under the influence, in particular, of penetration of heated dispersed fuel into heat-transfer agent.

At the 2nd stage, caused by the graphite burning, it was supposed that along with burning products, fine-dispersed fuel particles incorporated in graphite, were released, as well as fission products incorporated in graphite and sorbed by it, into the explosion of the reactor core.

At the 3rd stage (2-5 May, 1986) the increase in the radionuclides release was caused mainly by overheating of fuel due to the radioactive decay of fission products (we suppose also due to formation of "a blanket" from the covering material) up to $T \approx$ 2500-2800^{o}K. By the end of this stage, in addition to the mass release of volatile products, leakage of non-volatile (refractory) **Zr**, **Nb**, **Ce** could occur (together with fuel).

Presumably, aerosol contamination of the atmospheric air can be conditionally subdivided into two main phases: the first one is the particles release from the destroyed reactor at the first moment after the explosion (or explosions) (partially fused (glassy) particles could be also presented here), the second one - outgoing of particles during graphite burning and radioactive particles formation in the zone of the destroyed reactor as a result of condensation of gaseous volatile radioactive products, released or outgoing from the destroyed reactor as a gas-forming plume mainly during the first two weeks after the accident (including 6 May, 1986) right up to the stabilization and considerable temperature drop.

Among the radioactive particles, partially fused ones were found, analogous to the particles formed in nuclear explosions. However, considerable amount of the particles was fragile, consisting of different materials. Sometimes they were particles of "graphite ash" covered by radioactive products, which were caused in a great part by thermodynamic processes in the reactor after the accident.

So, the conditions of the radioactive particles formation are of primary importance. According to an analysis of the real situation, at the moment of explosion (explosions), the fuel was heated up to the temperature of 1000–1800K. Graphite burning and radioactive decay of fission products accelerated the warming-up of the reactor core. Then, the fuel temperature dropped due to heat loss to the graphite stack and reactor structure.

The throwing-down of material from helicopters (about 5000 *t*) for the period from 28 April to 2 May led to additional cooling down to 900 K due to reactions of dolomite de-carbonization, clay dehydration, and melting and evaporation of lead. However, further on, a considerable temperature rise took place (up to 2300 K) because of the worsening in penetrability of the barrier reduction and heat removal under intensive decay of radioactive products.

Since 5 May the temperature began to drop, and the effluent of the intensive flow (stream) of radioactive products from the destroyed reactor was practically stopped on 9 May (although, later, radioactive product releases and outflow were recorded, but their values were significantly smaller).

The following estimations of the fuel temperature were obtained. For release of the volatile elements (**Cs**, **I**) the temperature increased from 1200 to 1400 K between April 26 and May5; for the elements of mean volatility (**Ba**, **Ce**) - from 1800 to 2300 K, and for the refractory ones (**Zr**) - from 2500 to 3000 K. But, such way of approach is proper only in the case when the aerosol particles are entirely condensation products, which is not obvious.

The aerosol particles could largely result from a mechanical release of dispersed fuel and other transformations. So, as the temperature increased, and boron carbide (B_4C), lead, dolomite ($CaMg(CO_3)_2$), sand and clay were thrown down onto the reactor from helicopters, a violent reaction of fuel carbidization took place accompanied by formation of uranium carbides and those of other elements (**Pu**, **Zr**, **Fe**, etc.), the oxides could be completely transformed into carbides for some days at the temperature of 2300 K. During the reaction between PuO_2 and graphite, Pu_2O_3 was formed as an intermediate compound ($T_{\text{melt.}}$ = 2353 K), its volatility being nearly one order of magnitude higher than that of PuO_2.

It seems likely that this led to increased concentrations of $^{\mathbf{239+240}}\mathbf{Pu}$ during the deposition of radioactive products of the accident outside boundaries of 30-km zone southward (from the 5-th to 8-th day after the accident). Besides, carbon black (soot) was formed in the zone of graphite burning under the conditions of oxygen lack, which could sorb (collect) considerable amount of radioactivity on its surface.

Thus, the radioactive aerosols could be formed as a result of both mechanical break-off of graphite and fuel debris by a flow of uprising gases, and condensation of volatile compounds of radionuclides from the gaseous phase. For example, a particular character of size-distribution of $^{\mathbf{103}}\mathbf{Ru}$ and $^{\mathbf{106}}\mathbf{Ru}$ particles can be explained by existence of highly volatile compound of this element – ruthenium tetraoxide. This compound was sorbed from a gaseous phase at sub-micron inert particles about 0.2 µm in diameter (an analogous effect was observed for isotopes ^{137}**Cs** and ^{134}**Cs**).

Apparently, certain zones were formed in the reactor characterized by considerably different oxidation-reduction conditions and forms of existence in the solid and gaseous phases. Under the complete consumption of oxygen and intensive carbidization of fuel, such oxygen-containing compounds as **Pu**, **Ba**, **Ce** were restored, and their volatility increased.

In contrast, on coming in contact with oxygen of the air, gaseous oxides of **U**, **Ru**, etc. could be formed along with aerosols resulted from condensation of **Cs**, **Ba**-**La**, **Ce**, etc. vapors. It was suggested that the radioactive aerosol outburst was significantly decreased by dumping of materials onto the destroyed reactor from helicopters.

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Biographical sketch

Yuri A. Izrael, academician, professor, Director of Institute of Global Climate and Ecology of the Russian Academy of Sciences and Roshydromet (Russian Federal Service for Hydrometeorology and Environmental Monitoring) is one of Russia's and indeed the world's top names in the Earth sciences. He was born on 15 May 1930 in Tashkent, USSR (Uzbekistan). He had been graduated in Physics and Mathematics in 1953 at the Central Asian State University in Tashkent.

The scientific career of Yuri A. Izrael, Doctor of Sciences (Physics and Mathematics), Professor and Member of the Russian Academy of Sciences has been devoted to nuclear and environmental sciences, meteorology and, in particular, climatology. Since 1953, he worked, at first, in Geophysical Institute, and then in the Institute of Applied Geophysics of the USSR Academy of Sciences, where he progressed from junior scientist to the Institute Director (1969-1973). In 1978, Yu.A. Izrael had created Laboratory of the environment monitoring and climate which, in 1990, had been transformed into the Institute of global climate and ecology. In 1974, he became a head of the Central Administration on Hydrometeorology under council of Ministers of the USSR (GUGMS) which was reformed in 1978 into State USSR Committee for Hydrometeorology and Environmental Monitoring (Goscomgidromet), and Yu.A. Izrael directed this Committee as a Minister until 1991, concurrently serving as Secretary and then' First vice President: of the World Meteorological Organization from 1975 until 1987. Beginning in 1989, Professor Izrael worked actively in the new scientific organization, the International Panel of the Climate Change (IPCC), which, in accordance with a UN proposal, was organized by WMO and UNEP to investigate climate change and its effect upon the environment, economics and human health. He is now its Vice-chairman.

In April 1986, in the former USSR, the largest nuclear accident ever, at the Chernobyl atomic power station, occurred, and it was Professor Yu.A. Izrael who directed the work of helicopters and airplanes which carried out dosimeter and gamma-spectrometer surveys as well as, in general, overseeing the whole scientific programme for estimating radiation conditions around round the site.

As an author Pr. Izrael has contributed over 200 scientific publications as well as 23 monographs and books including: "Peaceful Nuclear Explosions and the Environment" (1974); "Ecology and Control of the Environment" (1979); "Acid Rains" (co-author, 1983); "Global Climatic Catastrophes" (1986); "Antropogenic Climate Change" (1987); "Anthropogenic Ecology of the ocean" (1989); "Chernobyl: Radioactive Contamination or the Environment" (1990); "Earth's Ozone Shield and it's Changes" (1992); and "Radioactive Fallout After Nuclear Explosions and Accidents" (1996, 2002). In 1998 he was the editor-in-chief and scientific head of the "Atlas of Radioactive Contamination of Russia's European Part, Belarus and Ukraine". He is also Chief Editor of the Russian «Meteorology and Hydrology» Journal which was the unique scientific meteorological journal in the Soviet Union and is so now in the Russian Federation. Pr. Izrael is a member of the International Academy of Astronautics and holds a honorary membership of both the Hungarian Meteorological Society. In 1999, Yu.A. Izrael was elected a member of International Union of Radioecologists. He is President of the Russian Academy of Ecology.