What Happened at That Time?

IMANAKA Tetsuji
Research Reactor Institute, Kyoto University
Kumatori-cho, Osaka, 590-0494 Japan

✧ The eve

On April 25, 1986 (Fri), at the 4th block of the Chernobyl Nuclear Power Plant (NPP) in Ukrainian Republic of the former USSR, the procedure started to stop the reactor for maintenance for the first time since its operation in December 1983. At the Chernobyl NPP, four RBMK-1000 type reactors (1 GW electricity) were in operation and No. 5 and No. 6 blocks were under construction at that time.

It was in 1971 that a large project began to construct a nuclear power station on the bank of Pripyat river, a branch of Dnepr river, located about 100 km north from the Ukrainian capital, Kyiv (Fig. 1). In parallel with the power station, a new town named Pripyat city was constructed for station workers. The first block became in operation in 1977.

"RBMK" is an abbreviation of the Russian term meaning "Channel-type Big Power Reactor". From its structure, it can be called "graphite-moderator, light-water boiling, channel-type reactor" (Fig. 2. Table 1). RBMK was developed from the reactor originally constructed to produce plutonium for making Soviet atomic bombs. Its merits are the followings: refueling is possible while the reactor is in operation, power-upgrading is easy by attaching additional channels, inland construction is easy without difficulty of transporting heavy structures such as pressure vessel of light water reactor and so on. Meanwhile, the followings are its weak points: reactor control is complicated because of a lot of power channels (1,661 in the 4th block), vulnerable reactor characteristics that power will increase in a case of vapor increase at the reactor core (positive void reactivity coefficient), as well as power will surge in an extreme case that all control rods move down together into the core (positive scram). The last two design defects are considered directly related with the Chernobyl accident, but operators did not know such defects [1].

A emergency generator test was planned at the time of the shutdown of the 4th block on April 25. It was a test of a generator aimed to provide electricity to pumps at the time of blackout, using inert energy of free-wheeling turbines [2]. At 01:00 on April 25, the process began to reduce the reactor power from the nominal value (3.2 GW thermal). At 13:05, when the power decreased to 1.6 GWt, one of two turbines was isolated. Although it was planned to continue decreasing the reactor power, because of the order from the Kyiv grid center, the 4th block continued to operate at the power level of 50 %.

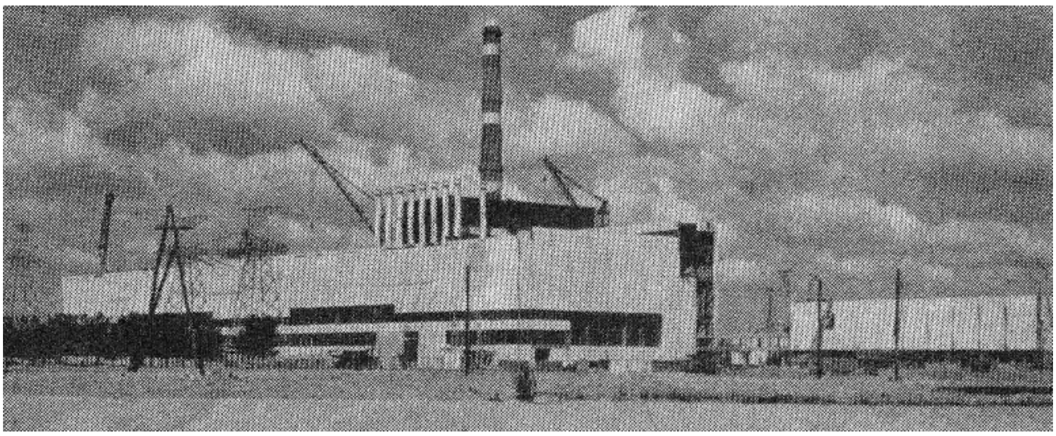

Fig. 1: Construction of No. 1 block at Chernobyl NPP.

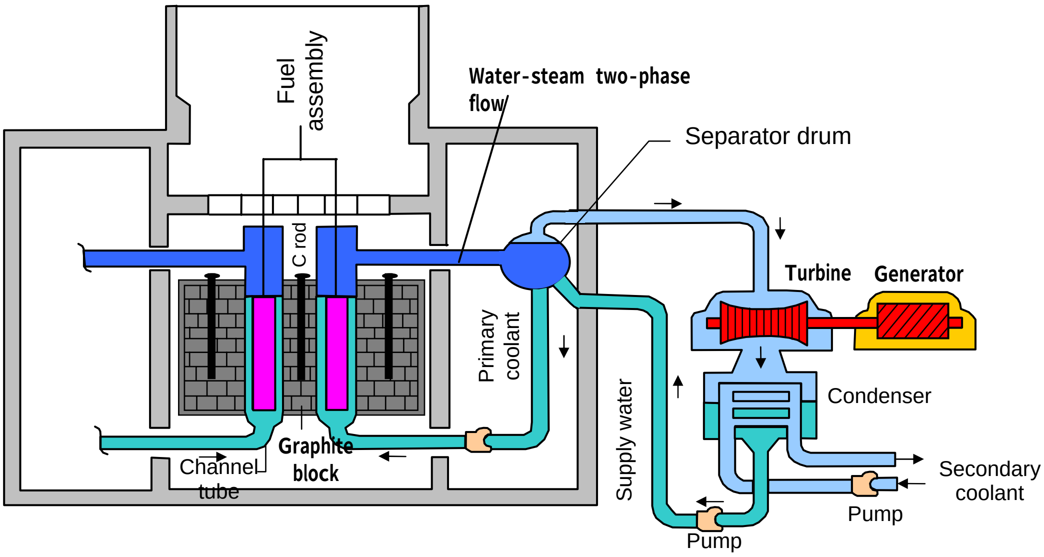

Fig. 2: Basic scheme of RBMK

Table 1: Basic parameters of RBMK1000

Item	Contents
Power	1 GW electricity, 3.2 GW thermal (Efficiency 31.3%)
Turbine	500 MW×2
Reactor core size	Cylinder diameter: 11.8 m, height: 7.0 m ・ Primary structure is a pile of graphite moderator block. ・ Each block has a vertical hole in its center to penetrate a channel tube.
Graphite block	A square box of 25cm×25cm×60cm. Density:1.65 g/cm^2. ・ Diameter of the hole for channel tube: 11.4cm ・ Total weight of graphite block: 1,700 ton
Reactor space size	Cylindrical diameter: 14.52 m, height 9.75m. ・ Graphite reflector blocks are surrounding the reactor core. The metal shroud confines the reactor space, making it airtight. ・ Design pressure of the core space: 0.8kg/cm^3. ・ Outside the shroud, annulus water tank of 2.4 m width, a layer of sand and then concrete shield. ・ The upper core plate (diameter: 17m, height: 3m) and the lower core plate (diameter: 14.5m, height: 2m) have holes like a honeycomb for channels to penetrate.
Fuel channel	Number of fuel channel: 1,661 ・ Outer diameter: 88 mm, inner diameter: 80 mm. ・ Tube material: zirconium ally for the position corresponding to reactor core, welded with stainless steal tubes at upper and lower sides. ・ A fuel assembly is inserted in each fuel channel. ・ Coolant water goes up inside the fuel channel, boiling to steam. ・ Refueling is performed while operating reactor, by isolating channel tube one by one from the coolant loop.
Control rod channel	211 channel ・ Neutron absorber: boron carbide ・ Automatic rod: 12, local automatic rod: 12, manual rod: 115, emergency rod: 24, local emergency rod: 24, shortened rod: 24.
Fuel	Uranium dioxide (UO2). Enrichment: 2 %. ・ Fuel pellet size: diameter 11.5 mm, height 15 mm. ・ Fuel rod: outer diameter 13.6 mm, length 3.5 m. Tube material: zirconium alloy, thickness 0.9 mm. ・ Amount of uranium in the core: 194 ton. Designed burnup: 20 MWD/kg
Fuel bundle	Bundle length 7 m. ・ Two sub-bundles (3.5 m) are connected up and down. ・ Sub-bundle: length 3.5 m, 18 fuel rods are fixed around the central supporting rod. ・ Uranium amount per fuel bundle: 114.7 kg
Coolant loop	Two loops. Coolant: light water ・Inlet temperature of fuel channel: 270°C. ・ Out let: 284°C, pressure 70kg/cm^2, steam quality 14.5 %. ・ 4 circulation pumps per loop (including one reserve). Totally 8 pumps. ・ Coolant flow rate: 37,600 ton/h. Steam supply: 5,800 ton/h.

The above information is mainly based on the 1986 USSR report [2].

At 23:10 on April 25, the shutdown procedure was restarted. Then 00:00 on April 26, the shift of the control room changed from Tregub's team to Akymov's team (each constitutes 4 staff). Soon after the shift change, when the power control system was replaced from local automatic control to automatic control, the reactor power suddenly fell down almost to zero. The generator test was planned to be performed at power level of 700 – 1,000 MW. If it could not be done, the next chance would be several years later.

✧ The 4th block exploded

Fourteen people were at the control room of the 4th block. Dyatlov, Deputy Chief Engineer was in responsibility to carry out the test. By the order of Dyatlov, the operators tried to revive the reactor power, by pulling out almost all control rods from the reactor core. As is shown in Table 2, around 01:00, the rector was somehow stabilized at the power level of 200 MWt. Then, it was decided to carry out the generator test at the power less than the planned.

At 01:23:04, by closing the steam valve to No.8 turbine, the generator test started using inert energy of the free-rotating turbine. According to Dyatlov's testimony, the reactor power was stable during the test and there was no sign requiring operator's attention or alarms.

The emergent event started just at 01:23:40 when the operator turned on the AZ-5 button to shut down the reactor by inserting all control rods into the core. On the contrary to the intension of the operator, a positive scram phenomenon happened, which led a power surge at the lower part of the core, damaging several nuclear fuels and channel tubes. Then, following the rupture of channel tubes, a large amount of vapor appeared at the core. A bigger-scale power surge was caused by the effect of positive void

Table 2: Event chronology (April 25 – 26, 1986)

01:00 April 25	Shutdown procedures began by reducing the power from the nominal value (3.2 GWt).
03:47	Power decreased to 1.6 MW.
04:13 -12:36	At power level of 1.6 GW, control systems and vibration characteristics were checked of No. 7 and No. 8 turbine-generators.
13:05	One (No. 7) of two turbines was detached.
14:00	ECCS system was detached. Owing to the request from the Kyiv electric center, the power was kept at 1.6 GWt.
23:10	Shutdown procedure restarted.
00:00 April 26	The control room shit was replaced from Tregub team to Akymov team.
00:28	At 500 MWt, power control system was switched from local automatic control to average automatic control. When switching, abrupt power decrease occurred to almost zero power.
00:41-01:16	No. 8 turbine was detached. Its vibration characteristics were measured during inert rotation.
About 01:00	After the efforts to increase the power, the reactor somehow became stable at 200 MW. The decision was made to perform the emergency generator test at the level below the planned power.
01:03 and 01:07	Two main circular pumps (MCP) were added in operation. All eight MCP began operating.
01:23	According to the analysis after the accident, at this time the reactor was under the extremely unstable condition because of the increase of positive void reactivity coefficient due to withdrawal of almost all control rods as well as reactor operation at the low power level. The operators, however, did not know such situation.
01:23:04	The test was started by closing the steam valve to No. 8 turbine. Coolant flow rate of 4 MCP that were connected to the test generator decreased to some extent, which in turn increased steam generation a little at the core. The effect of this increase was compensated by a small increase of the pressure as well as by gradual insertion of automatic control rods. The reactor power was kept stable during the test, without any extraordinary symptom prompting operator action or alarming signal.
01:23:40	Chief operator Akymov turned on the scram button (AZ-5).
01:23:43	Alarm of "rapid power increase" and "over power".
01:23:46-47	Loss of electricity for MCP. Flow rate decreased. High pressure and high water level in steam separator tank. "Control system failure" alarm.
01:23:49	"High pressure in the reactor space", "Loss of electricity for control rod", "Failure of driving automatic control rods" signals
01:24	The operator wrote in the log note, "01:24 strong explosion. Control rods stopped halfway before reaching the bottom of the core. Loss of driving electricity for control rods." According to eyewitnesses who were outside the reactor building, there were two sequential explosions, blowing up something like fireworks into the night sky.

・The above sequences are mainly cited from the Steinberg report [3].

coefficient of reactivity, which led to explode the reactor and destroyed the building. According to the analysis after the accident, the explosion occurred 6-7 seconds after pushing AZ-5. Eyewitnesses outside the reactor building told that there were a series of explosions like fireworks up into the night sky. Concerning the accident sequence, there are several versions. The above is based on the Steinberg report in 1991 that reinvestigated the cause of the accident by the request of the USSR parliament [3].

It was 3 am when the first information on the accident reached the responsible person of the Soviet Communist Party in Moscow. At 9 am in the morning, the first expert team flew from Moscow and arrived at the scene of the accident in the afternoon. A special medical team from Moscow also arrived in the evening. They have checked patients of workers and firefighters being cared at the Pripyat hospital because of acute radiation syndrome. They selected persons to be sent to Moscow for special treatment. Mr. Shcherbina, Deputy Ministry of USSR, nominated as the chairman of the governmental committee for the Chernobyl accident also arrive at Pripyat in the evening of April 26. The first tasks of the government committee meeting held in the night of April 26 were the followings:

- ✧ To determine the method how to extinguish the graphite fire that continued in the destroyed core, discharging a large amount of radioactivity into the environment,
- ✧ Decision whether or not residents in Pripyat should be evacuated.

The committee decided to extinguish the fire by dropping the material such as sand, lead, boron etc. onto the core using military helicopters. After the long discussion, by the decision of Shcherbina, the evacuation of Pripyat was scheduled on the next day.

✧ 120 thousand evacuees

The weather was fine in Pripyat on April 26. Most residents (population 50,000) did know that something serious event happened at the NPP. They spent, however, that day as usual Saturday. A lot of people were at shops and even a wedding was celebrated. Some people watched the smoking 4th block from the roof of the apartment while sunbathing (Fig. 3-4). Only few people were afraid of radiation and stayed inside their flats closing windows.

Fig. 3. The 4-th reactor on the day of the accident. Photo by Igor Kostine.

Fig. 4. View of Sarcophagus from the roof of an apartment in Pripyat. Photo by Imanaka, October 2005.

It was lucky for the people in Pripyat that the first “hot” radioactive plume released from the destroyed 4th block did not hit directly on the city. It flowed to the west from the destroyed reactor, where pine trees within 5 km died in several days because of strong radiation (Fig 5).

On April 27, because of the change of wind direction, radiation dose rate in Pripyat began to increase. At 07:00, dose rate of 2 - 6 mSv/h was recorded inside Pripyat. Around noon, the following was announced through the local radio: “Dear citizens! Evacuation was ordered in relation with the accident at NPP. Please take passport, indispensable materials and food for three days. Evacuation will begin at 14:00”. 1,200 buses were mobilized from Kyiv to evacuate Pripyat. 45,000 people were evacuated in two hours. Panic that the authority was afraid of did not happen. Many evacuees thought that they could come back home in three days, but they could not restore their life in Pripyat again.

The region surrounding Chernobyl NPP was traditional rural area except Pripyat city. Although Pripyat city were evacuated quickly on the second day, the people within the 30 km zone were left uninformed for a while. It was on May 2, one week after the accident that the evacuation was decided of the people who were living in the 30 km zone other than Pripyat. Their evacuation began on May 3. In a week about 71,000 people left their home. Compared with the case of Pripyat, the evacuation of rural towns/villages was far more difficult. Several hundred thousands of livestock were evacuated together with their owners. Many people reminded their experience at the time of the Nazi invasion. But, different from the previous experience, they could not return home this time. In total 116,000 people were evacuated from the 30 km zone around the Chernobyl NPP in two weeks after the accident.

Figure 6 indicates radiation monitoring data in settlements within the 30-km zone on May 1, 1986 [4]. The maximum of 3,306 μGy/h is seen in Krasnoe village about 6 km north from the ChNPP. The main contamination in this direction was considered to occur on April 27-28 and Krasnoe village was evacuated on May 3. This situation makes us easily suppose serious radiation exposure of residents staying there. Imanaka previously estimated that some fraction of the residents in Krasnoe could receive more than 1 Gy of external dose, a criterion of acute radiation syndrome [5].

Meanwhile, according to the Chernobyl Forum report [6] that was released at a conference held by IAEA and other organizations in September 2005 as a summary of 20-year investigation on the consequences of the accident, the average dose of evacuees was evaluated to be about 30 mSv and their maximum was several hundreds of mSv.

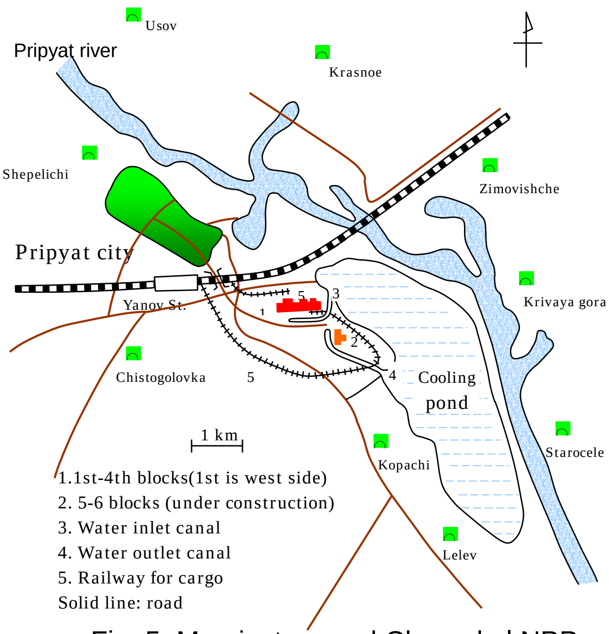

Fig. 5: Map just around Chernobyl NPP.

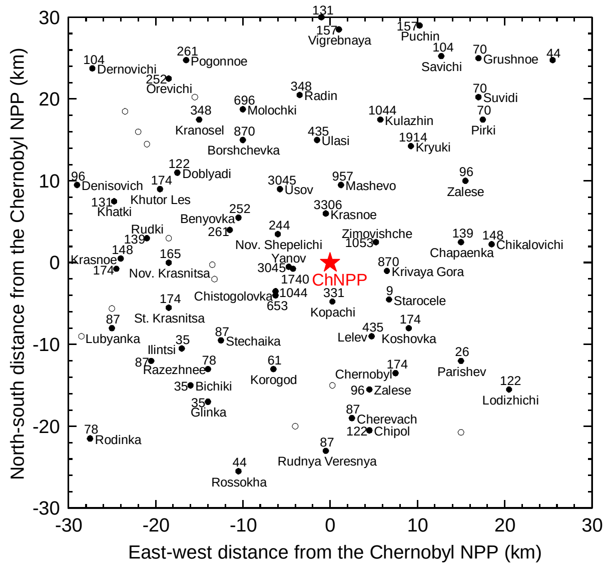

Fig 6. Dose rate in air at settlements within the 30-km zone around Chernobyl NPP on May 1, 1986 [4], unit: μGy/h.

✧ Accident liquidation and construction of Sarcophagus

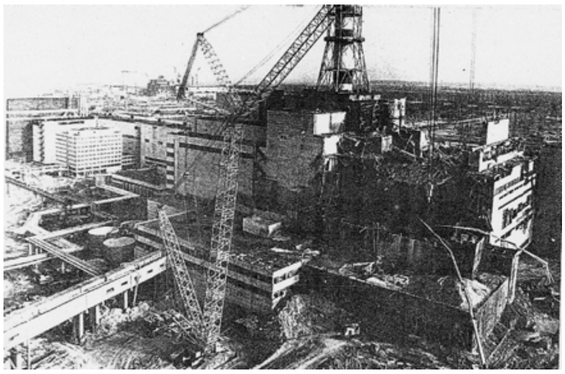

Fig. 7: Construction of Sarcophagus

Five minutes after the explosion at the 4th block, the first firefighter team arrived at the scene. It was firemen of the power station led by lieutenant Pravik. Five minutes later another firemen team led by lieutenant Kybenok arrived from Pripyat city. Pravik's team started extinguishing the fire on the roof of the turbine building in order to prevent the spread of the fire. The Kybenok's team fought the fire at the central hall of the destroyed 4th reactor. Nobody hesitated at the fight being afraid of radiation. Rather, they were not taught about danger of radiation. They became feel sick one after another, and were carried to the hospital in Pripyat.

When the explosion happened, operators at the control room of the 4th block could not understand what happened at the reactor. As shown in Table 2, operator wrote in a log note, "At 1:24, a strong explosion, control rods stopped halfway before reaching the bottom of the core". The first priority for operators was to prevent the reactor from destruction. Therefore, they tried to insert control rods to the full position and keep the core cooling by continuing pumping the coolant. In reality, however, the reactor core was completely destroyed by the first explosions. The operators and other workers should quickly evacuate and go to the shelter. On the contrary, as a result of useless efforts and unreasonable orders to tackle the situation, radiation symptom also appeared in operators.

According to the reports from the USSR authorities, about 300 people was hospitalized, 28 out of which died because of acute radiation syndrome. In addition, one worker became missing under the debris, another died of severe burn on the day of the accident. Adding one more death of other reason, it was reported that 31 people died in total by the Chernobyl accident.

The chemical detachment of the USSR army that was being trained to prepare nuclear wars arrived at the scene on the second day, April 27. It is certain that the first step to liquidate the accident consequences was carried out by this regular army. But, details of their works and radiation dose were yet unknown. During three weeks of their stay, debris such as fuel rods, graphite block etc. thrown from the core and scattered on the ground around the 4th block building were cleared in order to begin the construction of "Sarcophagus" (Fig. 7).

In June, the construction began of "Sarcophagus" that would confine the whole destroyed block by the concrete structure. "Patriotic workers" gathered to Chernobyl from all over USSR. They did heroic works under the condition of strong radiation.

Fig. 8: Working scene of liquidators. From DVD movie "Sacrifice" [7].

A large scale mobilization of reserves was also taken place for the works of decontamination of the territory within the Chernobyl station as well as settlements within the 30 km zone. Their age was 30 – 40 years old and called “liquidators”. The right photo in Fig. 8 shows a scene of clean-up work of radioactive debris that had scattered on the roof of 3rd block. It was done by human-wave tactics at the final stage of the Sarcophagus construction in September 1986. About 3,000 reserves were engaged in this work. The exposure limit was set 25 Roentgen (about 250 mSv), but it is said there were a lot of cases of over exposure.

Up to the end of 1990, the total number of liquidators amounted to 800,000 people, among which 200,000 worked in 1986 and 1987 under the condition of strong radiation.

✧ 28 acute radiation deaths

In the evening of the day of the accident, a special medical team arrived from Moscow. Among the patients accommodated at the hospital in Pripyat, serious ones were selected to be sent to No. 6 hospital in Moscow. Dr. Gale, a US specialist of bone marrow transplantation came to Moscow to help the treatment. He and his colleague did operation of bone marrow transplantation for 13 patients, but all cases could not survive. In spite of insensitive care at No. 6 hospital, 28 people died of radiation syndrome. Tabl 3 lists these 28 people together with two persons who died on the day of the accident. It is noted that most of the

Table 3. List of deaths by radiation syndrome

Name	Working place	Age	Date of death	Remarks
Firefighters 6: persons				
Lieutenant Pravik V.P.	NPP fire station	23	May 11	
Lieutenant Kybenok V.M.	Pripyat fire station	23	May 11	
Sergeant Vashchuk M.V.	do.	27	May 14	
Staff sergeant Ihnatenko V.I.	do.	25	May 13	
Staff sergeant Tytenok M.I.	do.	26	May 16	
Sergeant Tyshchura V.I.	do.	26	May 10	
Plant staff and business traveler: 24 persons				
Akymov O.F.	Chief operator shift	33	May 11	15Gy
Toptunov L.F.	Reactor operator	25	May 14	
Kudryavtsev O.H.	Trainee operator	28	May 14	
Proskuryakov V.V/	do.	31	May 17	
Perevozchenko V.I.	Chief reactor engineer	39	June 13	
Kurhuz A.K.	Reactor engineer	28	May 12	
Khodemchuk V.I.	Machine engineer	35	April 26	Missing inside debris
Dehtyarenko V.M.	do.	31	May 19	
Perchuk K.H.	Turbine engineer	33	May 20	> 10 Gy
Vershynun Y.A.	do.	27	July 21	do.
Brazhnyk V.S.	do.	29	May 14	do.
Novyk O.V.	do.	24	July 26	do.
Lelechenko O.H.	Deputy of electric section	47	May 7	25 Gy, dead in Kyiv
Baranov A.I.	Electric engineer	32	May 20	
Lopachuk V.I.	do.	25	May 17	
Shapovalov A.I.	do.	45	May 19	
Konoval Y.I.	do.	44	May 28	
Sytnykov V.I.	1・2 block deputy engineer	46	May 30	
Orlov I.L.	Deputy chief of 1st block	41	May 13	
Popov H.I.	Engineer	46	June 13	Trip from Harkov
Savenkov V.I.	do.	28	May 21	
Shashenok V.M.	Engineer of industrial meter	45	April 26	Dead by burns on the day
Luzhhanova K.I.	Guard	59	July 31	Entrance gate
Iwanenko K.O.	do.	53	May 26	Spent fuel building

deaths occurred in the middle of May, 2 - 3 weeks after the accident, which indicates that the blood-forming functions of their bone marrow were destroyed by radiation.

According to Gorbachev's speech on May 14, about 300 firemen and plat staff were hospitalized because of radiation syndrome. In November 1986, this number was reduced to 237 people. Then, after "reexamination of syndrome", the current number is given to be 134 cases [8].

When the present author visited the Chernobyl museum in Kyiv, he found an exhibition of a medical certificate that a serviceman (31 yr) of Ukrainian ministry of Internal Affairs was admitted at No.25 hospital in Kyiv on May 22 – August 12, 1986 and received bone marrow transplantation. He was again at hospital December 1 – 31, 1986. His dose was estimated 3.2 – 3.7 Gy. Of course this case was not included in the official reports. We have to wonder how many such patients were who were not included in official reports.

✧ Acute radiation syndrome among residents

According to official reports beginning from the USSR report [2] in 1986 up to the Chernobyl Forum report [6] in 2005, acute radiation syndrome occurred only among station staff and firefighters who were at the scene of the accident, but no radiation syndrome was observed among residents living around the ChNPP. However, a number of descriptions about radiation syndrome among the residents were found in the secret protocols of the communist party that was disclosed after the collapse of USSR [9]. In the former USSR, The communist party was the core of its centralized power system, and its central committee in Moscow was the summit of the power. When the Chernobyl accident occurred, a special

Table 4. Excerpts of descriptions of the health state of inhabitants from the secret protocols of the Communist Party of the Soviet Union .

<Date of protocol>	<Description of the health state of people>
1986 May 4:	As of May 4, 1,882 people are hospitalized in total. Total number of examined people reached 38,000. Radiation disease of various degrees of seriousness appeared in 204 people, including 64 infants.
May 5:	Total number of hospitalized people reached 2,757, including 569 children. Among them, 914 people have symptoms of radiation disease. 18 people are in a very serious state and 32 people are in a serious state.
May 6:	As at 9:00 on May 6, the total number of hospitalized people reached 3,454. Among them, 2,609 people are in hospital for treatment, including 471 infants. According to confirmed data, the number of radiation disease cases is 367, including 19 children. Among them, 34 people are in a serious state. In the 6th Hospital in Moscow, 179 people are in hospital, including two infants.
May 7:	During the last day, an additional 1,821 people were hospitalized. At 10:00 May 7, the number of people in hospital for treatment is 4,301, including 1,351 infants. Among them, diagnosis of radiation disease was established in 520 people, including staff of the Ministry of Internal Affairs of the USSR. 34 people are in a serious state.
May 8:	During the last day, the number of hospitalized people increased by 2,245, including 730 children. 1,131 people left hospital. As at 10:00 May 8, a total of 5,415 people are in hospital for treatment, including 1,928 children. Diagnosis of radiation disease was confirmed for 315 people.
May 10:	During the last two days, 4,019 people were hospitalized, including 2,630 children. 739 people left hospital. In total 8,695 people are in hospital, including 238 cases with diagnosis of radiation disease, among which 26 are children.
May 11:	During the last day, 495 people were hospitalized and 1,017 people left hospital. In total, 8,137 people are in hospital for treatment and examination, among which 264 people with diagnosis of radiation disease. 37 people are in serious state. During the last day 2 people died. Total number of death by the accident amounted to 7 people.
May 12:	During the last day, 2,703 people were hospitalized, most of which were in Belarus. 678 people left hospital. 10,198 people are in hospital for treatment and examination, among which 345 people have symptom of radiation disease, including 35 children. Since the time of the accident, 2 people perished and 6 people died of diseases. 35 people in serious state.

remark: The total number of 40 protocols are contained in the secret document.

working group was formed at the central committee to decide basic policies to cope with the accident consequences. The disclosed documents were protocols of the WG meetings.

Excerpts from the protocols are shown in Table 4. The numbers of deaths and serious patients seem to correspond to those of station staff and firefighters, but it is certain that a lot of radiation patients were also among residents. For example, on May 12 when the evacuation of the 30-km zone almost finished, it was written, “10,198 people are in hospital for treatment and examination, among which 345 people have symptom of radiation disease, including 35 children”.

A noteworthy description is that two infants were at No. 6 hospital on May 6. In the protocol of the same day, it was written “taking into consideration the situation that American doctors are working at No. 6 hospital, the proposal from Health Ministry was agreed that the number of patients and their condition should be announced properly”. This means that the information would not have been released if Dr. Gale and his colleague were not at the hospital.

Meanwhile, Lupandin of Sociological Institute, Russia investigated in 1992 the remaining carte that was made at the time of the accident at the central district hospital, Khoyniki, Gomel region, Belarus. A part of Khoiniki district was included in the 30 km zone (Fig. 9). Lupandin found 8 cases of radiation diseases as well as 20 cases with some radiation symptoms. He described that more than 1,000 cases of acute radiation diseases could have been in total at that period [10].

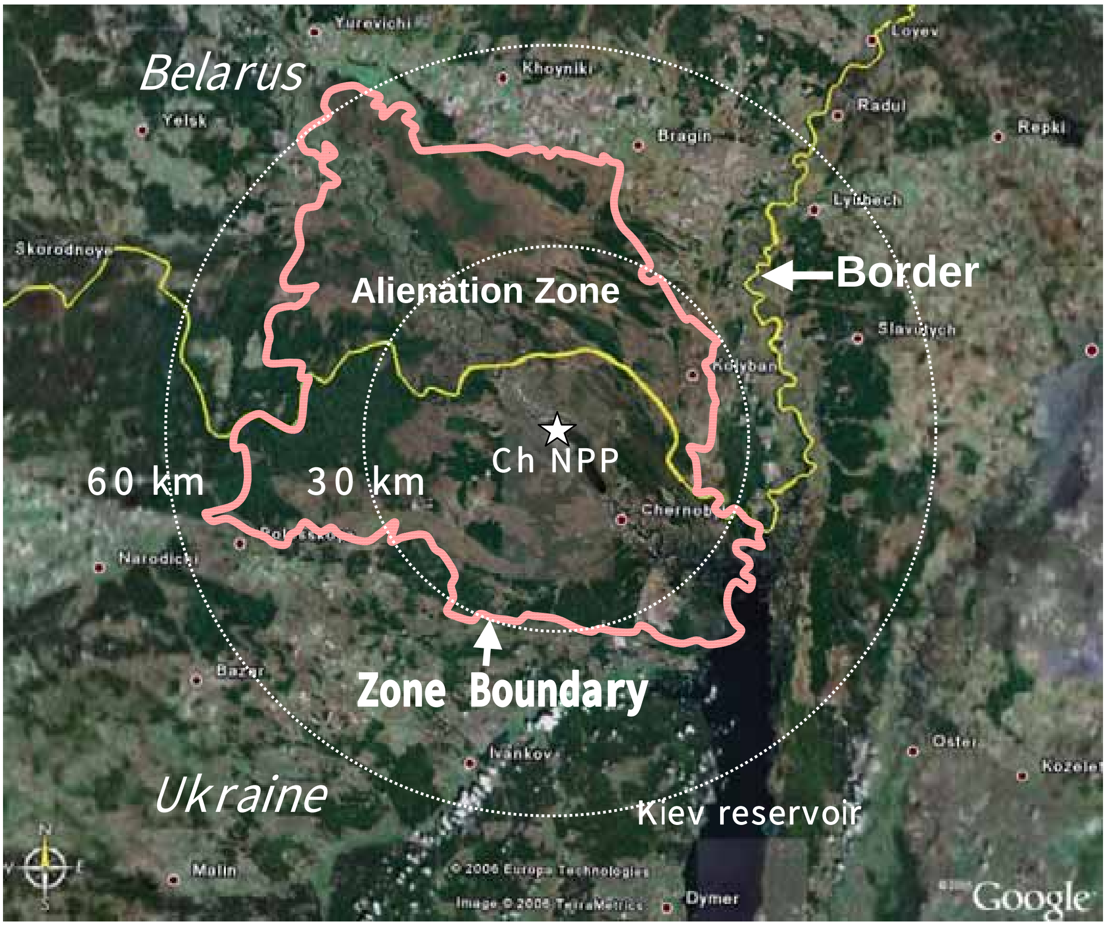

Fig. 9. Current alienation zone around Chernobyl. The areas on Ukrainian and Belarusian sides are 2,000 and 1,700 km^2, respectively. The map is made based on the figure in *National Geographic,* April 2006. Basic photo is made using Google Earth.

✧ The blame was put on the operators

In August 1986 USSR government presented the report on the Chernobyl accident to IAEA [2]. Then the first expert meeting on the Chernobyl accident was held in August 25 – 29, 1986 at the IAEA headquarters in Vienna. Specialists from the western countries were impressed with the frank presentation by Dr. Legasov of the chief of the Soviet delegation, and accepted his explanation about the accident.

According to the 1986 USSR report, the reason for the Chernobyl accident was “a very rare combination of a series of regulation violation by the operators”. Six violations pointed in the USSR report are listed in Table 5. As a result of the combination of these violations, the reactor began runaway during the test of emergency generator. The operator, having noticed sudden power increase, turned on the scram button, AZ-5, but it was too late to stop the reactor.

Table 5. Six violations by the operators pointed in the 1986 USSR report.

1. Reactor was operated in a condition that operational reactivity margin (ORM) was below the permissible limit.
2. The generator test was conducted below the planned power level in the test program.
3. Coolant flow rate exceeded the limit because two additional pumps were operated.
4. Reactor trip signal for steam valve closure was bypassed.
5. Reactor trip signal for parameters in steam separator tank was bypassed.
6. ECCS signal was dispatched.

Dyatlov, Deputy Chief Engineer was responsible at the control room at the time of the accident. He was sentenced to 10 years confinement in 1987. After being discharged from the prison earlier than the term in 1990, he wrote an article [11] appealing, “There was noting extraordinary in the control room until the operator switched on AZ-5. It was three seconds after pushing AZ-5 when the alarms of power increase appeared. Operators should not be blamed due to decrease of operational reactivity margin (ORM) because there was no instrument directly indicating ORM. Operating reactor at low power was not forbidden, but such regulation was made after the accident... The primary causes of the accident was design defects of the reactor as well as the people who did not take countermeasures knowing such design defects” and “The 1986 USSR report was full of lies. I can not understand why specialists of IAEA could accept such explanation”.

It was already pointed out in May 1986 that the main causes of the Chernobyl accident likely were

Fig. 10 Control room of 4th block. October 2002.

Fig. 11 Control rod position panel of 1st block

"positive void coefficient of reactivity" and "positive scram" [3]. It is a conventional trick by the authorities to put the responsibility on personnel at the scene. If the cause of the accident was found to be the design defects in RBMK, the responsibility should be asked of its designer of Academician Alexsandrov, the president of USSR Academy of Sciences. In addition, it would become difficult to continue operation of 14 RBMK reactors other than the ChNPP. At the beginning of July, the official conclusion on the cause of the accident was decided at the meeting of the central committee of the USSR communist party where Gorbachev also participated [12].

With the progress of "Perestoroika" and "Glasnost" at the final period of USSR, intensive efforts were made at the USSR parliament to reevaluate the consequences of the Chernobyl accident. In 1991 a special committee nominated by the parliament released a report. It concluded that the real cause of the accident was not the regulation violations by operators, but design defects and idleness of authorities neglecting them. According to the report, the accident such as Chernobyl was inevitable [3].

✧ Positive void reactivity coefficient and positive scram

Neutrons produced by nuclear fission are with high energy (average 2 MeV), the speed of which is about 1/10 of light. Because of a small probability of high speed neurons to be caught by other uranium nuclei, it is difficult to maintain fission chain reaction using high energy neutrons. So, in thermal reactors such as RBMK, neutrons are designed to collide with light nuclei of "moderator" to slow down the speed. If the distribution of neutron speed becomes equilibrium with the temperature inside the reactor, these neutrons are called as "thermal neutrons". The ability of thermal neutrons to cause fission reaction with uranium nucleus is about 500 times larger than "fast neutrons". Thermal neutrons are also captured easily by other nuclei than uranium. Therefore, thermal reactors are designed to slow down neutrons using moderator and, avoiding neutron capture by materials other than fuel, make thermal neutrons to be captured by uranium as much as possible. Good candidates of moderator are heavy water and graphite, while light water is worse than them because light water itself will capture neutrons.

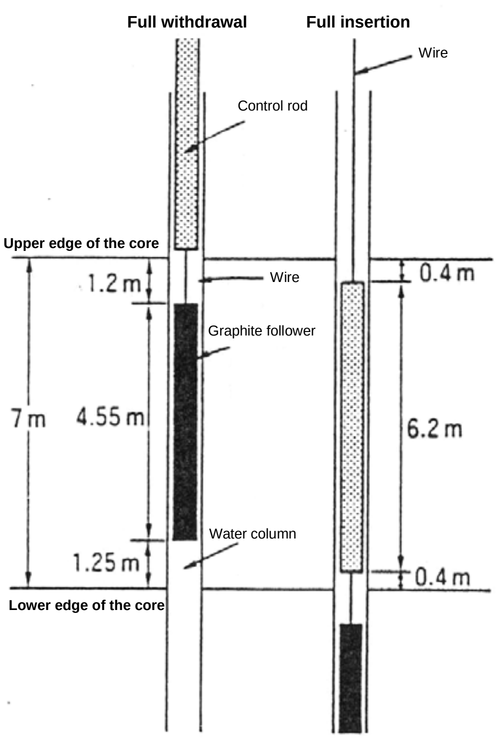

Fig. 12. Control rod and graphite follower

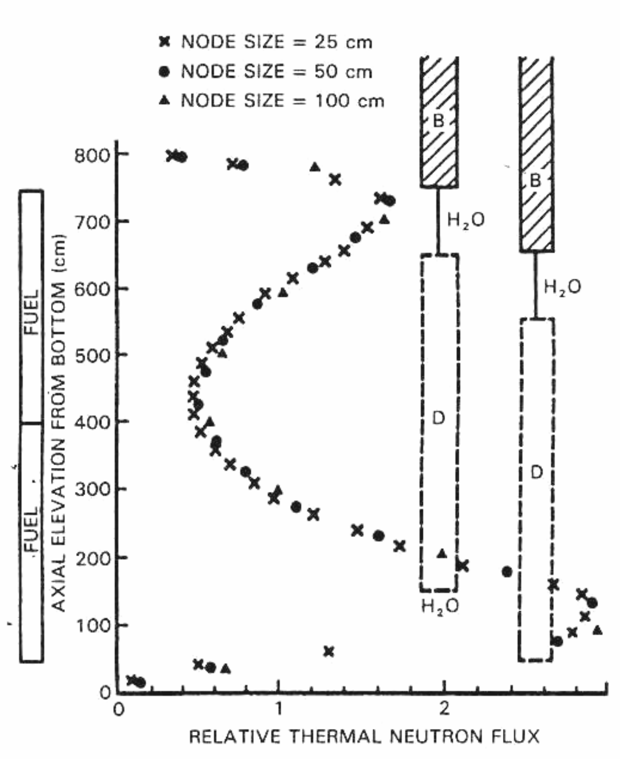

Fig. 13: Power distribution before the

¤Positive void coefficient of reactivity: “Reactivity” indicates a scale how fission rate is increasing or decreasing. If reactivity = 0, the number of fission per unit time is constant. If it >0, the reactor power will increase and if it<0, the reactor power will decrease. Reactivity depends on various factors such as position of control rods, fuel enrichment, fuel temperature etc. “Void coefficient of reactivity” indicates how reactivity will be effected by density change of coolant material. If it is positive, the reactor power will increase when steam fraction at the core increases.

In the case of the Chernobyl accident, a positive value of void reactivity coefficient was exaggerated by the facts operating the reactor at low power and pulling almost control rods out of the core. After several channel tubes were ruptured by “the first power excursion”, which made the steam fraction having increased. Subsequently a more large power excursion was caused by the positive void coefficient of reactivity”. It lifted up the upper structural plate tearing all channel tubes at a time, which led to another excursion [1,3].

¤Positive scram: “Scram” means emergency shutdown of nuclear reactor. “Positive scram” is a word made after the Chernobyl accident, reflecting an unbelievable event that the reactor power increased by pushing the scram button.

The structure of RBMK control rod is shown in Fig. 12. A graphite follower is pending under the control rod that absorbs neutrons. The left part of the figure illustrates the complete pullout, making a water column under the graphite follower at the bottom of the core. The right part shows the full insertion. Plotted data in Fig. 13 are power distribution it the core just before the accident [13]. An interesting feature is seen that a large peak of power distribution was at the lower part of the core. The operator of the 4th block pushed the scram button (AZ-5) when almost control rods were fully pulled out. Water columns in the left part of Fig. 12 were replaced with graphite followers, producing positive reactivity at the lower part of the core, which was considered to cause the first power excursion [1].

✧ The amount of released radioactivity

Amount of radioactivity accumulated in the reactor core of 1 GWe NPP is about 1.5×10^{20} Bq, excluding those of short half-lives. It is rather difficult task to estimate the amount of radioactivity released into the environment for such case as Chernobyl because radiation monitor was useless in the situation that the reactor core exploded and ruined together with the building. Several methods were elaborated to estimate the amount of released radioactivity, for example, using ground contamination data of all over the world from Chernobyl fallout. Table 6 is the radioactivity release estimated in the Chernobyl Forum report in 2005 [6]. Rare gas elements such as ^{133}Xe were released 100 % of the reactor core. Radioiodines to which attention should be paid at the early stage were released 55 %. ^{137}Cs, which is important at long-tem contamination, was 30 %. Smaller fractions were seen for less volatile isotopes of ^{90}Sr and ^{239}Pu. Compared with previous values given in the 1986 USSR report, these estimates were 2.8 and 2.3 times

Table 6. Estimates of radioactivity released by the Chernobyl accident (decay-corrected to 1986.4.26)

Nuclide	Half life	Released activity, Bq	Ratio to core inventory
Xenon-133	5.3 days	7×10^{18}	100 %
Iodine-131	8.0 days	2×10^{18}	55 %
Caesium-137	30 years	9×10^{16}	30 %
Strontium-90	29 years	1×10^{16}	4.9 %
Plutonium-239	24,000 years	2×10^{13}	1.5 %
＜Total release including others＞		1.4×10^{19}	About 10 %

large for ^{131}I and ^{137}Cs, respectively. In total, about 10 % of the radioactivity in the core was released into the environment beyond the territory of ChNPP.

¤Where is nuclear fuel?: The nuclear fuel mass loaded in the core of the 4th block was 190 ton. According to the 1986 USSR report, about 3 % of nuclear fuel was released, while the rest remained in the core where channel tubes, fuel tubes, graphite blocks etc were crowded together with materials of sands, lead etc thrown down from helicopters to distinguish the fire (about 5,000 ton). Two year after the accident, TV camera was inserted into the core through a hole bored in the side wall of the reactor cavity. Surprisingly almost vacant space was found at the position of the reactor core (Fig. 14) [14]. 5,000 ton of material did not reach the core, but only piled up on the floor of the central hall.

Part of the reactor core was blown up and away by the explosion around the destroyed building. The remaining fuel and channel tubes melted due to high temperature and formed materials like lava, which moved along the floor and corridor to the lower compartments and dropped into pools (Fig.14). Most of 1,700 ton graphite in the core was considered to burn out during the fire that continued about 10 days. Interestingly, as can be seen in Fig. 14, a concrete panel of the building wall was on the bottom of the reactor cavity. Considering the size of the concrete panel, it was supposed that this panel fell down into the cavity while the upper core structure plate (2,000 ton) was blown up in the air by the explosion.

Strong radiation as well as additional layers of concrete pored during the construction of Sarcophagus is still preventing detailed investigation inside Sarcophagus. A current estimate for the amount of nuclear fuel remaining inside Sarcophagus is about 60 % (± 20 %) of uranium in the core at the time of the accident.

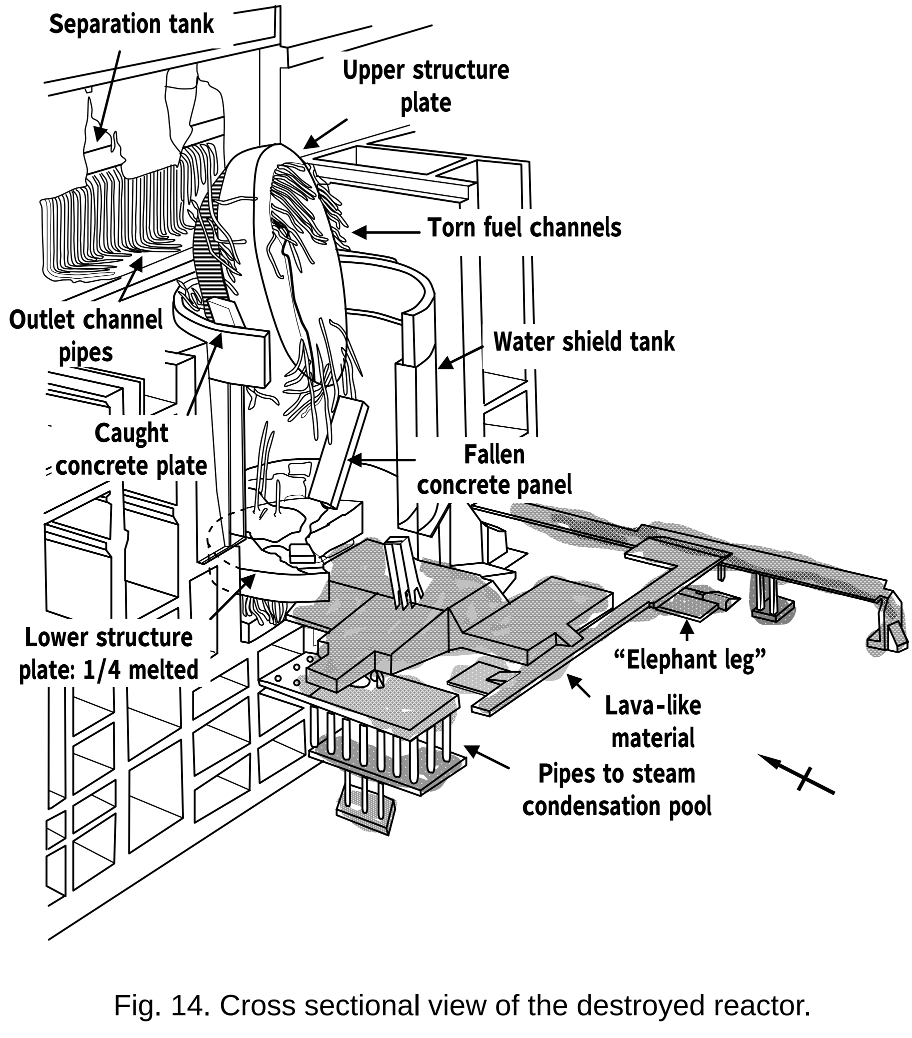

Fig. 14. Cross sectional view of the destroyed reactor.

✧ High level contamination at 200 km away was disclosed 3 years later

The Chernobyl accident happened in the midst of the cold war between USA and USSR. In USSR Mr. Gorbachev appeared in March of the previous year as the General Secretary of Communist Party, and began to propose two slogans of Perestoroika (reconstruction) and Glasnost (openness), but innate characteristics of the communist acquired for the past 70 years hardly changed. Citizens, even scientists, were forbidden to talk freely about the consequences the Chernobyl accident.

It was in spring of 1989, about three years after the accident that the situation seemed to changed with enlargement of the movement seeking for democracy in USSR. A ^{137}Cs contamination map around Chernobyl was published in a newspaper in Belarus for the first time. Although previous contamination maps reported by USSR specialists were limited to the area just near Chernobyl, the new map indicated a shockingly wide-scale of contamination. As can be seen in Fig. 15, there were spreading of strong contamination detachedly at distances 200 – 500 km from Chernobyl [15].

Various kinds of radionuclides will be released by reactor accidents. Iodine-131 (half life: 8 days) is important at the early stage after the accident, which irradiates specifically thyroid grand when incorporated into the body. From the point of long-term contamination, ^{137}Cs is the most important because of its long half life (30 yr), high volatility and transportability, and accessibility to foodstuff. A vast area was contaminated by ^{137}Cs in Ukraine, Belarus and Russia. (Table 7) [16].

In July 1989 the Belarus parliament, which began to criticize the Moscow government requesting countermeasures for the Chernobyl consequences, decided to relocate 110,000 residents from the contaminated territories. At the end of 1991, however, the central USSR government that should take primary responsibility of the Chernobyl accident disappeared. Then, the responsibility of countermeasures and compensation was transferred on the shoulder of newly independent governments. Each affected republic independently established laws for countermeasures and compensation from the damages by the Chernobyl accident.

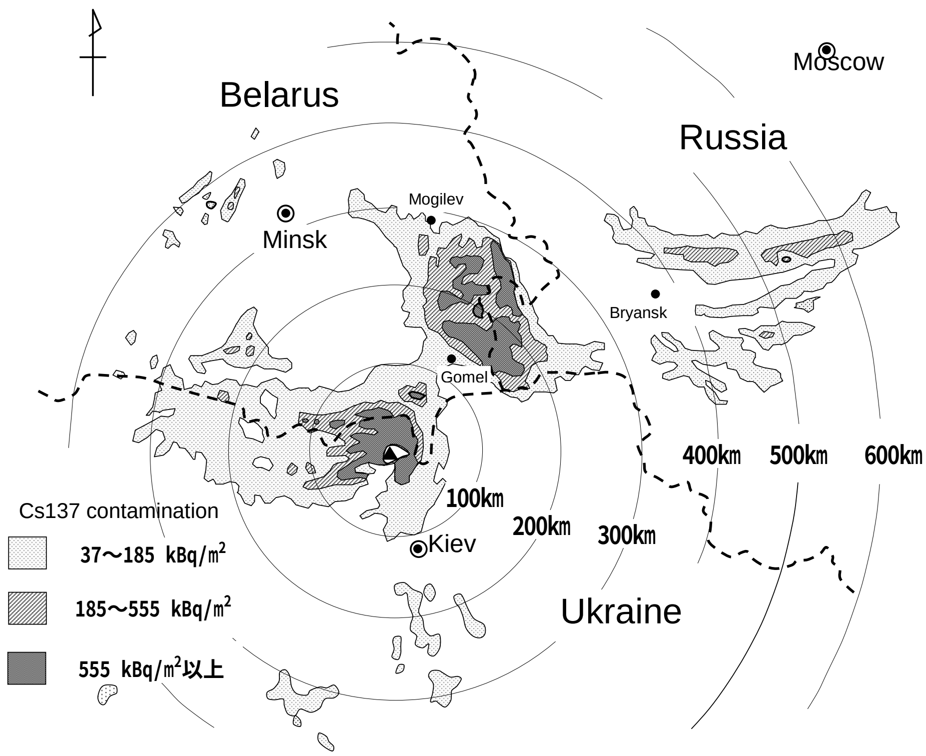

Fig. 15. Cesium-137 contamination map around Chernobyl.

Table 7. Areas contaminated with ^{137}Cs in three affected countries, km^2.

	Level of ^{137}Cs density (kBq/m^2)				
	37 ~ 175	175 ~ 555	555 ~ 1,440	> 1,440	>37 total
Russia	48,800	5,720	2,100	300	56,920
Belarus	29,900	10,200	4,200	2,200	46,500
Ukraine	37,200	3,200	900	600	41,900
Total	115,900	19,120	7,200	3,100	145,320

According to Chernobyl laws in these countries, contaminated territories are classified by the level of caesium-137 contamination on the ground as follows:

- > 1,440 kBq/m^2 :zone of alienation,
- 555～1,440 kBq/m^2 :zone of obligatory resettlement,
- 175～555 kBq/m^2 :zone of guaranteed voluntary resettlement,
- 37～175 kBq/m^2 :zone for radiation control.

✧ Almost all northern hemisphere was contaminated

In the morning of April 28, 1986, an alarm of radiation monitor sounded at the Forsmark NPP located in the southern part of Sweden, 1,200 km away from Chernobyl. Radioactivity leakage from the Forsmark plant was suspected, but no extraordinary was founded. In this morning radiation level also increased at other nuclear facilities in Sweden. Radioactivity likely came from the USSR territory passing over the Baltic Sea. It was 9:00 pm on April 28, responding the query from the Swedish government, that TASS News Agency in Moscow reported a short announcement about the accident at the Chernobyl NPP.

Table 8. Area of ^{137}Cs contamination in European countries (excluding Ukraine, Belarus and Russia): km^2

Country	Area (km^2)	Level of ^{137}Cs contamination, kBq/m^2		
		10～20	20～37	37～185
Sweden	450,000	31,000	33,000	23,000
Finland	337,000	32,000	59,000	19,000
Bulgaria	111,000	27,500	40,400	4,800
Austria	84,000	28,000	25,000	11,000
Norway	324,000	44,000	23,000	7,200
Rumania	238,000	54,000	13,000	1,200
Germany	366,000	29,000	14,000	320
Greece	132,000	21,000	8,300	1,200
Slovenia	20,000	8,100	8,700	610
Italy	301,000	15,000	7,000	1,400
Moldova	34,000	19,000	1,900	−
Switzerland	41,000	6,400	2,300	730
Poland	313,000	10,000	3,500	520
Hungary	93,000	5,200	230	−
U.K.	240,000	15,000	1,700	160
Estonia	45,000	1,700	280	−
Litania	65,000	50	−	−
Chex	79,000	13,000	3,500	210
Slovakia	20,000	6,800	800	20
Croatia	56,000	1,100	30	20
France	550,000	1,200	−	−

Remark: The level due to previous nuclear tests is 2 – 3 kBq/m^2.

The fire at the Chernobyl 4th block continued about 10 days, releasing a large amount of radioactivity. The first radioactive plume from ChNPP moved to the north-west direction, passing over the territories of Belarus, Latonia and the Baltic Sea, and then arrived at Scandinavia. The second plume went to the west direction over Belarus and Poland, which then reached Austria and Switzerland at the end of April. Table 8 shows ^{137}Cs contamination in European countries [17]. High level of the contamination was observed in the Scandinavian countries and the Alpine countries, where rain occurred with the passage of the radioactive plumes. Simply saying, the average level of ^{137}Cs contamination in European countries was equal to the sum of the past fallout contamination by all atmospheric nuclear tests in 50s and 60s.

✧ Radioactive fallout in Japan

The present author clearly remembers that it was in the morning of April 29,1986, the holiday for the previous Emperor's birthday that for the first time he heard the unfamiliar name of "Chernobyl". TV news told that something serious NPP accident occurred at "Chernobyl", while the details were unclear. The Chernobyl news became bigger and bigger with time, reporting radioactive contamination in various European countries. Japanese meteorologists told in TV rather negative opinions about whether or not radioactivity would come to Japan, traveling 8,000 km of the distance from Chernobyl.

Hearing the news of radioactive contamination in European countries, Imanaka and his colleague, which were used to radioactivity monitoring around nuclear facilities in Japan, half in doubt prepared to observe radioactive fallout from Chernobyl at their institute in Osaka. The first radioactivity was observed in rainwater that was sampled in the evening of May 3. A clear gamma-ray peak of 361-keV specific to ^{131}I was seen by gamma-ray spectrometry using Ge detector. Figure 16 indicates gamma-ray spectrum of air filter sampled on May 5. A series of fission products can be seen: ^{131}I, ^{132}I, ^{132}Te, ^{134}Cs, ^{136}Cs, ^{137}Cs, ^{103}Ru… Seeing this spectrum, Imanaka was surprised, asking himself, "Can we breathe this air?" He quickly calculated concentrations and, comparing them with permissible levels, said to himself, "It's irritating, but we can not live without breathing air". Iodine-131 concentration at that time was 0.8 Bq/m^3 [18]. If an infant breathed this air for one day, thyroid dose from inhaled ^{131}I would be 0.01 mSv using a

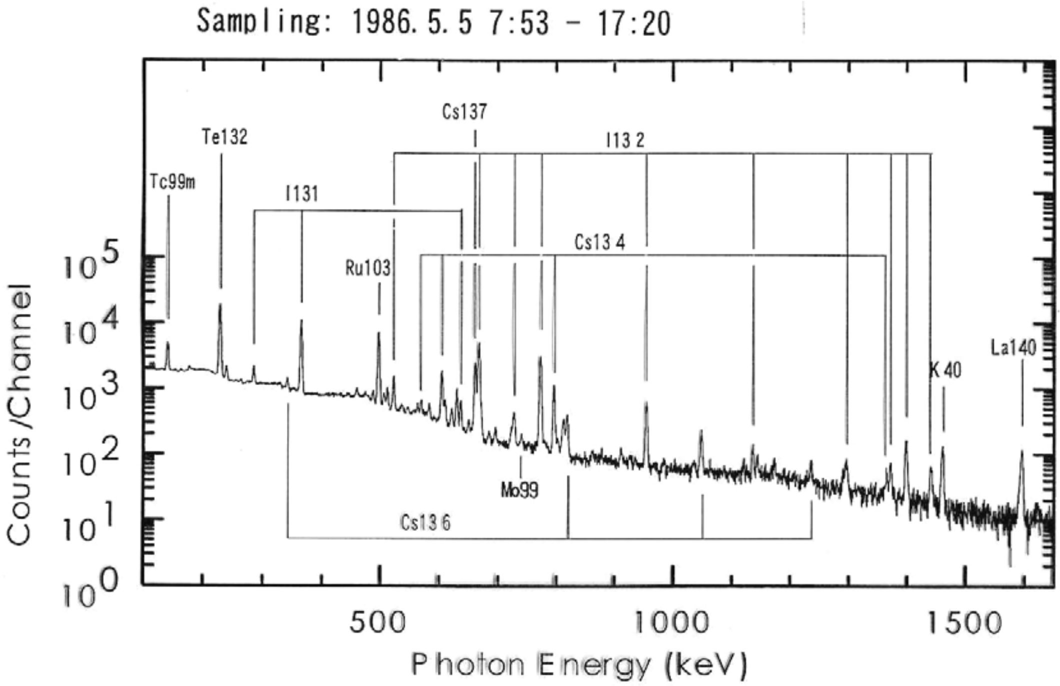

Fig. 16. Gamma-ray spectrum of air filter sampled May 5, 1986 at Research Reactor Institute, Kyoto University in Kumatori, Osaka.

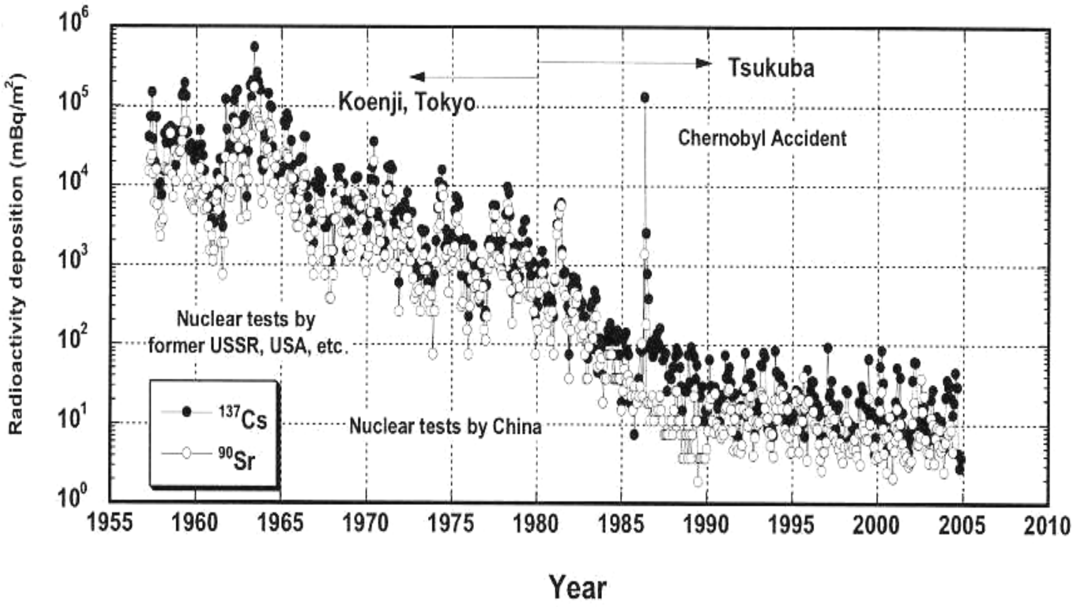

Fig. 17. Monthly deposition of ^{137}Cs and ^{90}Sr observed at Meteorological Research Institute, 1955 - 2005.

breathing rate of 3 m^3/day and a dose conversion coefficient of 3.7×10^{-3} mSv/Bq. This value seemed not so high to be nervous and not so low to be negligible.

The same level of fallout contamination was observed through the whole territory of Japan. The maximum ^{131}I concentration was 500 Bq/l in rainwater and 25 Bq/l in cow milk. The average deposited amount of ^{137}Cs was 200 Bq/m^2. Figure 17 is the deposition trend of ^{137}Cs and ^{90}Sr observed at the meteorological research institute for the past 50 years in Japan [19]. The ^{137}Cs deposition from Chernobyl was about 3 % of the total deposition from nuclear tests. Estimates of the average dose for the first year after the accident in Japan is shown in Table 9 [20]. Compared with annual natural background dose of 1 mSv, the whole body dose from Chernobyl could be negligible, but some attention should be put on thyroid doses.

Table 9. Average radiation dose in Japan by Chernobyl fallout during the first year after the accident. mSv

	Adults	Children
External exposure: whole body	0.003	0.003
Internal exposure: whole body	0.001	0.006
Internal exposure: thyroid	0.15	0.5

✧ Chernobyl sufferers

Almost all people who were on the northern hemisphere at the time of the accident received some radiation from Chernobyl. Of course the contamination around Chernobyl was predominant. Chernobyl sufferers can be classified as listed in Table 10. Other than the total body dose, evacuees and inhabitants received 10 – 100 times lager dose to thyroid from incorporation of ^{131}I.

Table 10 Category of Chernobyl sufferers

Category	Population	Total body dose
A. Staff of NPP and firefighters who were at the scene.	1,000~2,000	1~20 Sv
B. Liquidators (military, construction workers etc)	600,000~800,000	0.1~1 Sv
C. Evacuees from the 30km zone	120,000	Average 30 mSv*
D. Inhabitants of highly contaminated areas and resettlers	250,000~300,000	Average 50 mSv
E. Inhabitants of contaminated areas (>37 kBq/m^2)	6 million	Average 10 mSv

*; The present author considers that this value is underestimated.

✧ Cancer deaths and indirect effects

As a result of 20-years of investigations on the consequences of the Chernobyl accident, Chernobyl Forum concluded that the total number of deaths due to the accident was 4,000 people, including the future cancer deaths [6]. Following this conclusion, mass media in the world announced "The true effects of the Chernobyl accident was found to be far smaller than those previously considered." The breakdown of 4,000 deaths is as follows: 60 deaths so far confirmed and 3,940 cancer deaths estimated by a model calculation among 200,000 people of liquidators in 1986 and 1987, 120,000 evacuees from the 30-km zone and 270,000 inhabitants in heavily contaminated areas.

This conclusion of the Chernobyl Forum was criticized by specialists from Ukraine and Belarus as well as by the Belarusian government. In addition, WHO [21] and IARC (International Agency for Research on Cancer) [22] published their own estimates that were several times larger than that of the Chernobyl Forum.

Table 11 summarizes various estimates of total cancer deaths due to the Chernobyl accident. The Chernobyl Forum gives the lowest estimate, while the highest estimate by Greenpeace [24] is more than 20 times larger than that by Chernobyl Forum. This difference reflects the fact that the number of cancer deaths largely depends on the risk model and the size of population used by the evaluator. Considering uncertainty of estimates, the present author considers that a total of 20,000 – 60,000 cancer deaths seem to be a reasonable one.

Table 11. Various estimates of cancer deaths due to the Chernobyl accident

Evaluator	Cancer deaths	Population	Cancer death risk per 1 Sv
Chernobyl Forum (2005) [6]	3,940	600,000	0.11
WHO (2006) [21]	9,000	7.4 million in three countries	0.11
IARC (2006) [22]	16,000	570 million in Europe	0.1
NGO Kiev conference(2006) [23]	30,000～60,000	Whole world	0.05～0.1
Greenpeace (2006) [24]	93,000	Whole world	—

One comment should be added about the health effects of the Chernobyl accident. Through the experience of the present author who has been involved in the study of the Chernobyl consequences for more than twenty years, it became clear that radiation effect is merely one aspect of the huge catastrophe that the Chernobyl accident brought upon. He thinks that more attention should be paid to the effects not directly related to radiation exposure. For example, it can be easily imagined what an adverse change of life would arise when the old people who had been quietly living in rural areas were suddenly obliged to evacuate to a big city such as Kyiv. Some evacuees who lost their jobs might become alcoholics in despair of their future. These cases should be recognized as indirect effects of the Chernobyl accident.

According to Scherbak Yu who gave a lecture about Chernobyl at the institute of the present author in April 2006, there were 17,000 families in Ukraine, the death of whose householder were admitted to be caused by the Chernobyl accident and receiving special privileges for it. This number suggests that indirect deaths could be far more than the direct deaths from radiation exposure.

The present author is sure that scientific approach is effective to reveal what happened. However, considering the areas is limited where the scientific approach is effective, he is also sure that our imagination should be trained in order to understand the whole picture of the Chernobyl accident.

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