

## **Radioactive Contamination and Social Consequences Caused by the Chernobyl Nuclear Accident**

**Tetsuji IMANAKA**

**Research Reactor Institute, Kyoto University**

**Noriyuki KAWANO**

**Institute for Peace Science, Hiroshima University**

### **SUMMARY**

The power excursion that occurred on April 26, 1986 at the 4th unit of the Chernobyl Nuclear Power Plant in Ukraine of the former USSR led to the worst accident in the history of nuclear energy utilization. The basic sequence of the accident was described in this report as well as the process of radioactivity release in the environment. As a result of the radioactive contamination, the area where people had to relocate amounted to about 10,000 km<sup>2</sup>. About 400,000 people were forced to leave their homes. Because of radioiodine intake by children during the early stage after the accident, about 4,000 cases of thyroid cancer were observed up to 2002. The estimate of total cancer deaths due to the Chernobyl accident ranged from 4,000 to 90,000 cases, depending on the models used by the estimators. The size of economic loss was estimated to be 235 and 180 billion US dollars for Belarus and Ukraine, respectively, for the period of 1986 –

2015. Through the investigation of the consequences of the accident, we became confident that the real scale of the Chernobyl accident can not be measured by the amount of radioactivity or radiation.

## **1. Introduction**

A huge amount of radioactivity is inevitably accumulated in the reactor core with the operation of a nuclear power plant. So, the primary task of nuclear safety technology is to prevent this radioactivity from being released into the environment at all costs. Although a concept of ‘defense-in-depth’ is applied and various safety measures are taken in the design of nuclear power plants, the following two types of accident have been pointed out as possible events that can lead to catastrophic release of radioactivity into the environment. The first type is called ‘loss-of-coolant accident’. In the case of this type of accident, after losing coolant due to loop rupture etc, the temperature of the reactor core rises leading to a melt down. The other type is called ‘power excursion accident’. In this case, the fission chain reaction goes out of control, surging the reactor power up to explosion. The Three Mile Island NPP (Nuclear Power Plant) accident in USA in March 1979 was a typical loss-of-coolant accident. A half of the coolant water was lost from the core and the upper half of the reactor’s fuel melted, but the containment building remained intact and prevented catastrophic release of radioactivity. A power excursion accident occurred on April 26, 1986 at the 4th reactor of the Chernobyl NPP (1 GW electric, 3.2 GW thermal) <sup>1</sup> in Ukraine of the former USSR. The explosion due to the power excursion simultaneously destroyed the reactor and the whole building. Then, a graphite fire began in the reactor and continued for more than ten days, releasing a large amount of radioactivity directly into the environment. Thus, the Chernobyl accident became the worst accident in the history of nuclear energy utilization.

The Nuclear Safety Research Group at Research Reactor Institute of Kyoto University, including one of the present authors, has been engaged in safety issues of nuclear energy for more than thirty years, warning of the potential risks of catastrophic events at nuclear facilities. It has been one of our primary tasks to investigate the consequences of the Chernobyl accident as an example of the worst NPP accident that could also occur in Japan <sup>2-4</sup>.

## **2. RBMK Reactor**

The reactor type used at the Chernobyl NPP is called RBMK <sup>5</sup>. It was developed based

on reactors constructed to produce plutonium for Soviet atomic bombs. The basic scheme of RBMK is shown in Fig. 1. A large number of graphite blocks that work as neutron moderators are piled up cylindrically in the reactor core (12 m diameter and 7 m height). In the center of each graphite block, there is an 11 cm diameter vertical hole where a channel tube containing fuel rods is inserted. Coolant water goes up inside the channel and is partially heated to steam in the channel. Water and steam are separated at the water-steam separator drum and then the latter is led to the turbine to generate electricity<sup>6,7</sup>.

The merits of RBMK are as follows. Refueling can be carried out without stopping the reactor. This is characteristic of plutonium production reactors. Upgrading of the reactor power is easily achieved by adding additional channels. RBMK can be easily built at in-land sites without transport problems because it does not need such heavy structures as the thick reactor vessel used in light water reactors. On the other hand, it has the following demerits. Because of the large number of channels to be controlled (1661 fuel channels in Chernobyl-4), reactor operation is relatively complex and needs experience. In addition there were two serious defects in the reactor design that were directly connected with the accident. The first one is called ‘positive void coefficient of reactivity’ meaning that an increase of steam volume (void) in the core has the effect of promoting the fission chain reaction. The other is ‘positive scram’. Usually ‘scram’ means a rapid shutdown of the reactor. The expression ‘positive scram’

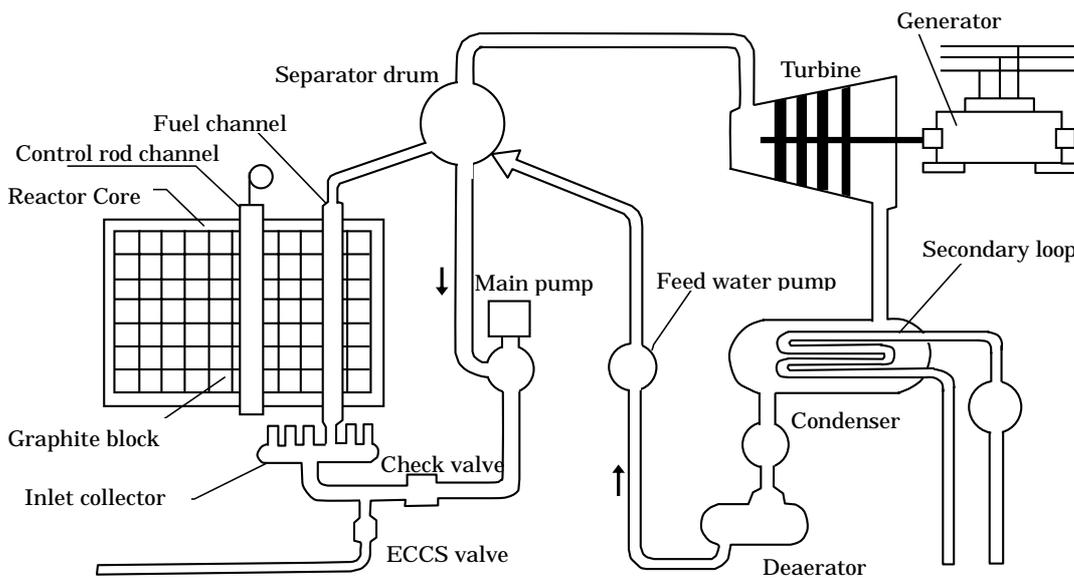


Fig. 1. Basic scheme of RBMK reactor

was coined after the Chernobyl accident. Under the extreme condition where almost all control rods are pulled out from the core of a RBMK reactor, the scram signal introduces a power increase during the initial several seconds after the signal. At the time of the Chernobyl accident, four RBMK reactors were in operation at the Chernobyl NPP and two others were under construction. In USSR, 17 RBMK reactors were in operation.

### **3. Explosion on April 26, 1986**

In the early morning of April 25, 1986, operators in the control room of the Chernobyl-4 reactor started the procedures to stop the reactor for the first time since the reactor began operating in December 1983. An experiment of an electric power generator using a free-wheeling turbine was scheduled at the time of the reactor shutdown. The aim of the experiment was to get emergency power for a short period before the diesel generator could provide emergency power in the case of a power failure accident.

At 13:00 April 25, when the reactor power was reduced to 1,600 MWt, a half of the nominal (3,200 MWt), the central grid controller in Kiev ordered Chernobyl NPP to keep the 4th unit at this power level. At 23:00, the power decrease was restarted again. At 24:00, there was a change of shift in the control room. At 00:30 April 26, the operator failed to control the power and it reduced to almost zero, although the experiment was planned at the power level of 700 MWt.

The Chernobyl accident would not have happened if they had given up doing the experiment at this moment. But, by the decision of the Deputy Chief Engineer, the person responsible for the experiment, the operators managed to restart the reactor. Usually restarting nuclear reactors soon after shutdown is difficult because of 'xenon poisoning effect': i.e. one of the fission products, xenon-135 (half life; 9.1 h) accumulated in the core has a big ability to absorb neutrons and interrupts the fission chain reaction. Therefore, the operator pulled out almost all control rods from the core and somehow managed to increase the power up to 200 MWt. At this moment, the reactor was in an extreme condition due to both the 'positive void coefficient', that was intensified at low power level, and due to the 'positive scram' accompanying the withdrawal of the control rods.

At 01:23:04, the experiment began by shutting down the steam valve to the turbine. During the experiment there was no sign of extraordinary events. When the turbine rotation was reduced to 2,500 per min, the chief operator called “reactor shutdown!”. Then, the scram button was turned on at 01:23:39 in order to insert all control rods into the core. Four seconds later (01:23:43), there were emergency signals in the control room for ‘power increase rate high’ and ‘power level high’. Due to the positive scram effect at first, a partial power excursion is thought to have occurred in the lower part of the core. Some fuel became very hot as a result of the excursion and melted and contacted with coolant water inside the channels. Small steam explosions are thought to have occurred and ruptured the channel tube of several channels, generating a large amount of steam as well as increasing pressure inside the reactor cavity. The upper shield structure of the core was lifted up and the tube rupture was propagated to all channels. At 01:23:49, a large-scale excursion occurred due to the effect of the positive coefficient of reactivity, which blew the materials in the reactor core up in the air and destroyed the reactor building (Fig. 2). According to witnesses of the accident, there were two subsequent explosions, which looked something like fireworks in the night sky.



Fig. 2. The 4-th reactor on the day of the accident. Photo by Igor Kostine.

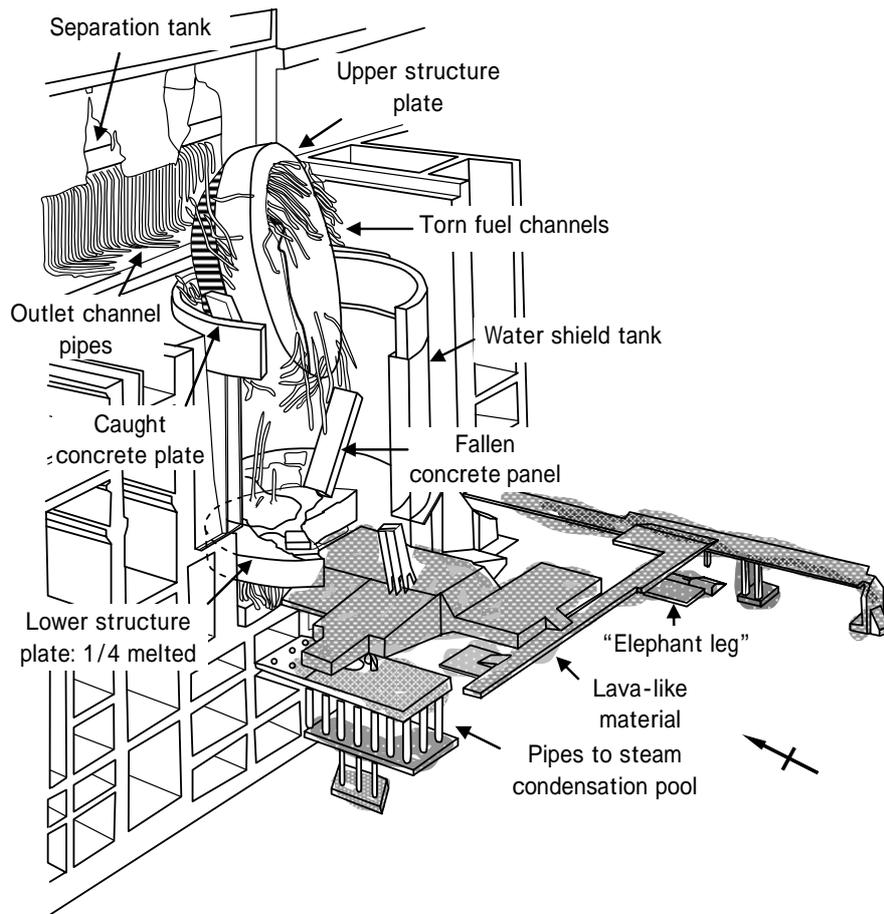


Fig. 3. Cross sectional view of the destroyed reactor.

Fires began on the roof of the turbine building and other places. The first firefighters arrived five minutes after the explosion. They extinguished fires before the morning, but graphite blocks in the reactor core began to burn. This fire continued for more than ten days releasing a large amount of radioactivity.

According to the USSR report<sup>6</sup> that was presented at the IAEA (International Atomic Energy Agency) conference held in August 1986 in Vienna, the main cause of the Chernobyl accident was described as an incredible combination of serious violations of regulation by the reactor operators. This conclusion was accepted at the conference including specialists from western countries. But it was apparently the tradition of Soviet authorities not to take responsibility themselves, but rather to blame the people on the site. Five years later, a special committee of the USSR parliament reinvestigated the Chernobyl accident and found that the principal reasons of the accident were the design defects of RBMK reactor<sup>7</sup>. It also concluded that responsibility for the accident lay with the authorities who knew the defects of the reactor and did not take effective

countermeasures.

It was not until two years after the accident that the situation of the exploded reactor became known when a remote TV camera was inserted into the core<sup>8</sup>. A cross sectional view of the destroyed reactor is shown in Fig.3. Scientists are still continuing their efforts to analyze the physical process of the accident and the discussion about the characteristics of the explosions<sup>9,10</sup>.

#### 4. Radioactive Contamination

On the morning of April 28, 1986, a radiation monitor sounded the alarm at the Forsmark NPP in Sweden located 1,200 km from Chernobyl. Increased radiation levels were also observed at other nuclear facilities in Sweden<sup>11</sup>. A nuclear accident was presumed to have occurred in the territory of the USSR. It was in the evening of April 28 that Moscow radio broadcasted that a nuclear accident had happened at the Chernobyl NPP in Ukraine. By the beginning of May, radioactivity from Chernobyl had reached almost all European countries. In Japan, our group first observed the arrival of Chernobyl radioactivity in rainwater on May 3<sup>12</sup>. More than twenty radionuclides were

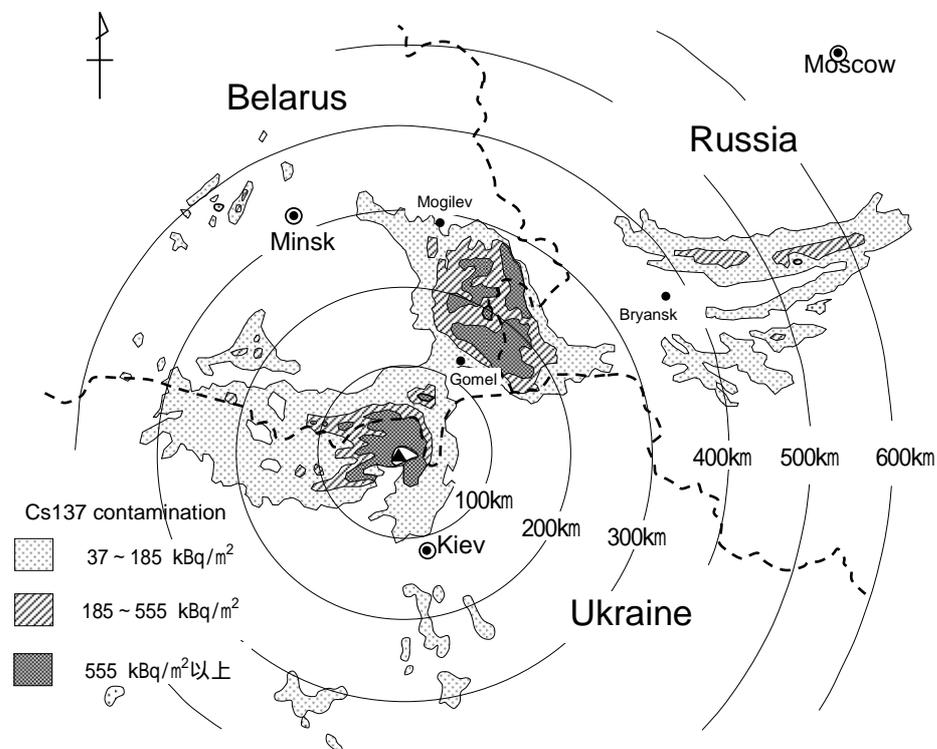


Fig. 4. Caesium-137 contamination map around Chernobyl.

detected from Chernobyl, including mainly iodine-131 and caesium-137. Thus, most of the northern hemisphere was contaminated by the Chernobyl fallout <sup>13</sup>.

Our group began to analyze the scale of radioactive contamination using the data obtained from all over the world. The Chernobyl accident happened, however, in the period of the cold war between USSR and USA. The most important data about the contamination on the territories inside USSR could not be obtained. This situation finally changed three years after the accident. Along with the democratic movement in the USSR, the caesium-137 contamination map around Chernobyl was published for the first time in spring of 1989 (Fig. 4) <sup>14</sup>. It was a real surprise to us that the heavily contaminated areas extended something like isolated islands even out to 300 - 600 km from Chernobyl.

The basic feature of nuclear accidents is determined by the amount of radioactivity released into the environment. Table 1 <sup>15</sup> summarizes estimates of the main radionuclides released beyond the territory of the Chernobyl NPP. Iodine-131 was the most important contaminant at the early stage after the accident. Thyroid tissue is selectively irradiated by iodine-131 when it is incorporated into human body because iodine is a material of thyroid hormone. Iodine-131 decayed out in several months after the accident because of its relatively short half-life of 8.0 days. But, the effect of thyroid irradiation began to appear in the form of thyroid cancer among the children around 1990 <sup>16</sup>

From the point of long-term contamination, attention should be paid to contamination by caesium-137 (half life 30 yr). When caesium-137 exists on the ground, people receive external irradiation from its gamma-rays. When caesium-137 is

Table 1. Estimates of radioactivity released by the accident (decay-corrected to 1986.4.26)

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

transferred to foodstuffs such as milk or crops and then into the body, it gives internal irradiation to the people both from beta-rays and gamma-rays.

The USSR government, which should be held responsible for the consequences of the Chernobyl accident, disappeared at the end of 1991. Instead, the responsibility to take countermeasures for radioactive contamination and to care for sufferers was moved onto the governments of three newly independent countries: Ukraine, Belarus and Russia. According to Chernobyl laws in these countries, contaminated territories are classified by the level of caesium-137 contamination on the ground as follows <sup>14</sup>:

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

The contaminated area in the three countries is summarized in Table 2. The total area of contaminated territories amounts to 145,000 km<sup>2</sup>, which corresponds to about 40 % of Japanese territory. The sum of alienation and obligatory resettlement areas is 10,300 km<sup>2</sup>, nearly equal to the sum of Fukui (4,200 km<sup>2</sup>), Kyoto (4,600 km<sup>2</sup>) and Osaka (1,800 km<sup>2</sup>) prefectures in Japan, where 12 million people are living.

Table 2. Areas contaminated with caesium-137 in three affected countries, km<sup>2</sup>.

	Level of caesium-137 density ( kBq/m <sup>2</sup> )				>37 total
	37 ~ 175	175 ~ 555	555 ~ 1,440	> 1,440	
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

## 5. Chernobyl Sufferers

Sufferers from the Chernobyl accident can be classified into the following five categories (Table 3) <sup>14</sup>.

**A. NPP staff and firefighters:** At the time of the accident, 176 shift personnel were

Table 3 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 <sup>2</sup> )	6 million	Average 10 mSv

\*; The present authors consider that this value is underestimated.

working at the 1st – 4th reactors and 268 construction workers were at the construction place of the 5th and 6th reactors. About 200 firemen participated in the efforts to extinguish the fire. During extinguishing work the firemen became sick one by one with symptoms of nausea and vomiting. Such acute radiation symptoms appear when people receive large doses of radiation exceeding 1 Sv<sup>17</sup> at a time. They were transported to the hospital in Pripyat city. In the evening of the first day, a special medical team arrived from Moscow. Patients in a serious condition were transferred to a special treatment hospital in Moscow.

Soviet authorities announced that about 300 people were hospitalized because of acute radiation syndrome, among which 28 died during the next three months. In addition, two personnel died on the day of the accident: one due to serious burns and one missing under the debris. Adding one death from unknown cause, it was officially reported that 31 people died in the accident

**B. Liquidators:** In order to manage the serious situation caused by the accident, the chemical unit of the Soviet army, having been trained to prepare for nuclear war, was immediately mobilized to Chernobyl. They arrived at Chernobyl on April 27. Meanwhile, the helicopter unit of the Soviet air force dropped 5,000 tons of various materials such as sand, dolomite, lead etc on the destroyed reactor to extinguish the graphite fire. The first step to clean up the site was carried out by the chemical unit, but the details of their work and their radiation doses are not yet clear.

In June 1986, the construction of the ‘Sarcophagus’ (a large concrete shelter to confine the ruined reactor) began and volunteer workers gathered from all over the USSR. At the same time a large number of 30-40 year-old reserves were called up to

clean up the NPP site and the contaminated territory in the 30 km zone. They were called ‘liquidators’ and numbered about 600 – 800 thousand. Among them, 200 thousand who worked in 1986-1987 under bad radiation conditions were considered to have received relatively high doses.

In order to investigate the health status of Chernobyl sufferers, a system of national registration was founded in 1987. About 360 thousand liquidators were registered in three countries. However, drastic social changes and economical difficulties after the collapse of the USSR have made it difficult to properly follow up the situation of the liquidators. In such circumstances an interesting piece of data was published from the Russian national registry <sup>18</sup>. Among 65,905 liquidators (average dose; 120 mSv) who were followed up in Russia from 1991 to 1998, 4,995 deaths (7.6 %) were observed. Considering that their average age was 35 at the time they were working at Chernobyl, the death rate of 7.6 % during a period of just 8 years seems to be very large.

The current Shelter, which is now planned to be covered by a second Shelter, and the waste deposit for clean-up equipment in the 30 km zone are shown in Figs. 5 and 6, respectively.



Fig. 5. Chernobyl Sarcophagus. Photo in November 2002 by Imanaka T.



Fig. 6. Deposits of equipment used for liquidation. Photo taken March 2000 by Ohshima H.

### *C. Evacuees from the 30-km zone:*

Pripyat city (population ~50,000) was constructed for NPP workers and located 3 km from the power station. It was lucky for Pripyat citizens that the first ‘hot’ plume released by the explosion passed over several km south of the city. Due to extremely strong radiation, pine trees there died in several days and were later called ‘red forest’. In the morning of the second day, April 27, dose rates in Pripyat began to increase. Around noon the evacuation was announced by radio saying, “In relation to the accident at the power station, evacuation has been ordered from the city. Please bring passport and food for three days. Evacuation will start at 2 pm”. Using 1,200 buses mobilized from Kiev, the evacuation finished for three hours without panic<sup>19</sup>. People thought that they could come back home in three days, but they could never return.

In contrast with Pripyat city, which was evacuated rather quickly, people in the 30 km zone other than Pripyat were given no information. Their evacuation was decided on May 2, one week after the accident. Compared with the case of Pripyat city, the evacuation of the 30-km zone was difficult. It was a rural area and tens of thousands of cattle were evacuated at the same time. The evacuation reminded many people of World War II when German troops invaded. They were able to return that time, but this time

they could not. In total, 116,000 people within the 30 km zone, including 45,000 from Pripyat city, were evacuated during the first two weeks after the accident <sup>20</sup>.

According to the official reports by the USSR, there was no radiation syndrome among the people evacuated from the 30 km zone. But soon after the disappearance of the USSR, the secret protocols of the USSR Communist Party from the period of the Chernobyl accident were disclosed <sup>21</sup>. Immediately after the accident, to cope with the emergency situation, a special working group was organized in the Politbureau of the Central Committee of the Communist Party. A lot of descriptions of radiation patients among the inhabitants were found in the disclosed protocols, some of which are

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>
<b>1986 May 4:</b>	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.
<b>May 5:</b>	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.
<b>May 6:</b>	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.
<b>May 7:</b>	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.
<b>May 8:</b>	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.
<b>May 10:</b>	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.
<b>May 11:</b>	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.
<b>May 12:</b>	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.

excerpted in Table 4.

***D. Inhabitants in highly contaminated areas and resettlers:***

The detailed information about the Chernobyl accident had been kept secret for three years. People in the contaminated areas did not know the level of contamination where they were living. After it was disclosed that a wide area outside the 30 km zone was also contaminated, people began to request the USSR government to take countermeasures. Although the Moscow central government wanted to minimize the countermeasures, the Belarus government decided in 1989 to resettle all 110,000 people living in the territory with caesium-137 contamination of more than 555 kBq/m<sup>2</sup>. Then, after the collapse of the USSR, resettlement was promoted by the independent governments.

In Ukraine 72,000 people were obligatorily resettled and in Russia 52,000 were resettled. In total 350,000 people were compulsorily or obligatorily resettled, including 116,000 from the 30 km zone just after the accident<sup>22</sup>. Taking into account the people who voluntarily left home, it can be stated that 400,000 – 500,000 people had to leave their home behind as a result of the Chernobyl accident.

***E. People in the contaminated areas:***

The average level of caesium-137 contamination in Japan from Chernobyl was 0.2 kBq/m<sup>2</sup>, which gave us a dose of 0.004 mSv during the first year after the accident. In the three most affected countries the ‘contaminated area’ is defined for the place where caesium-137 is more than 37 kBq/m<sup>2</sup>. About 6 million people were living in the contaminated areas. In 1990, the Soviet government, which was in difficulties due to the strong request from the inhabitants for countermeasures, asked the IAEA to investigate the radiological situation in the contaminated areas and propose countermeasures that should be taken. After one year of investigation, the IAEA team concluded saying there were “no health disorders that could be attributed directly to radiation exposure. The accident had substantial negative psychological consequences in terms of anxiety and stress...”<sup>23</sup>.

Around the same period the number of thyroid cancers began to increase among the children whose thyroid was affected by irradiation at the time of the accident. The increasing trend of thyroid cancer in Ukraine is shown in Fig. 7<sup>24</sup>. Child thyroid

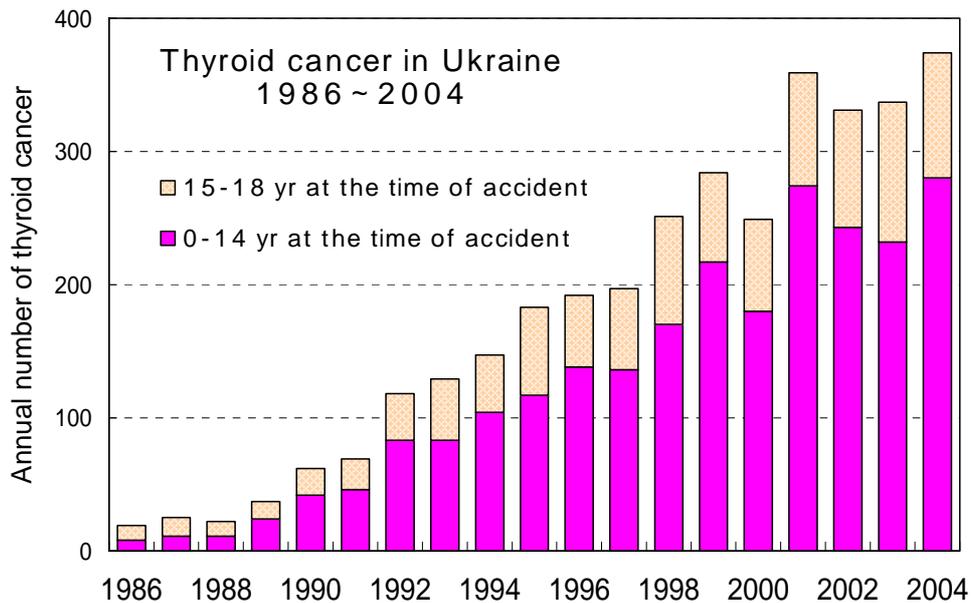


Fig. 7. Thyroid cancer in Ukraine after Chernobyl.

cancer is usually very rare. In Belarus, before Chernobyl child thyroid cancer was about one case a year, but it increased to 95 cases in 1995. Up to 2002, about 4,000 thyroid cancers were observed in the three most affected countries among the children who were 0-14 years old at the time of the Chernobyl accident. Considering that thyroid cancer will continue even in the future, 20,000 – 70,000 thyroid cancers can be estimated <sup>25</sup>. Fortunately the mortality of thyroid cancer is not high at about 1 %. However, patients who received operations have to take thyroid hormone medicine for the rest of their life.

## 6. Cancer Deaths and Indirect Effects

An international conference called “Chernobyl Forum” was held in September 2005 at the headquarters of IAEA in Vienna <sup>15</sup>. The Chernobyl Forum consisted of representatives of seven UN related organizations, including IAEA, WHO, UNDP etc., as well as the three most affected countries, Ukraine, Belarus and Russia. As a result of 20-years of investigations on the consequences of the Chernobyl accident, it was concluded at the conference that the total number of deaths due to the accident was 4,000 people, including the future cancer deaths. Citing 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 600,000 liquidators and inhabitants in heavily contaminated areas.

The conclusion of the Chernobyl Forum was criticized by specialists from Ukraine and Belarus as well as by the Belarusian government. In addition, WHO <sup>26</sup> and IARC (International Agency for Research on Cancer)<sup>27</sup> published their own estimates that were several times larger than that of the Chernobyl Forum.

Table 5 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 <sup>28</sup> is more than 20 times larger than that of the Chernobyl Forum. This difference reflects the fact that the number of cancer deaths largely depends on the risk model and the size of population postulated by the evaluator. The present authors consider that a total of 20,000 – 60,000 cancer deaths seem to be a reasonable estimate.

One comment should be added about the health effects of the Chernobyl accident. Through the experience of the present authors, having been involved with Chernobyl for more than twenty years, it became clear that radiation effect is only one aspect of the huge catastrophe that the Chernobyl accident brought upon the society. More attention should be paid to the effects that were not directly related to radiation exposure. For example, it can easily be imagined what an adverse change of life would arise when old people quietly living in rural areas are suddenly obliged to evacuate to a big city such as Kiev. Some evacuees might lose their jobs and become alcoholics in despair of their future. These cases should be recognized as indirect effects of the Chernobyl accident. In Ukraine the death of the householder due to the Chernobyl

Table 5. Various estimates of cancer deaths due to the Chernobyl accident

Evaluator	Cancer deaths	Population	Cancer death risk per 1 Sv
Chernobyl Forum (2005) <sup>15</sup>	3,940	600,000	0.11
WHO (2006) <sup>26</sup>	9,000	7.4 million in three countries	0.11
IARC (2006) <sup>27</sup>	16,000	570 million in Europe	0.1
NGO Kiev conference(2006) <sup>25</sup>	30,000 ~ 60,000	Whole world	0.05 ~ 0.1
Greenpeace (2006) <sup>28</sup>	93,000	Whole world	-

accident has been recognized and special privileges granted to 19,000 families <sup>29</sup>. This number suggests that indirect deaths could be more than direct deaths from radiation exposure as a result of the Chernobyl accident.

## 7. Economic Losses from the Chernobyl Accident

In 1990, a price of 230 – 300 billion USD was estimated for the losses during 1986 – 2000 from the Chernobyl accident <sup>30</sup>. Three major items were direct expenses for the accident liquidation, indirect loss of useful land, and loss of electricity generation. The social expenses such as medical care, subsidies and privileges were not included in this figure.

In the national report of Belarus published for the 15th anniversary of the Chernobyl accident <sup>31</sup>, a total loss of 235 billion USD was estimated for the period from 1986 to 2015, which corresponded to 21 times the national budget of Belarus in 1991. Main components were social compensation and privileges (86 billion USD) and loss of agricultural sector (72 billion USD). In the 20th anniversary report of Ukraine, about 180 billion USD was estimated for the period 1986 – 2015 (Table 6) <sup>32</sup>. It is noted that the fraction of indirect loss is dominant in the economic loss in Ukraine. Between 40 and 60 % of the indirect losses are due to loss of land use and loss of electricity, respectively. The last factor includes the loss from delayed construction of new nuclear power plants and related loss of industrial production. Considering that GNP of Ukraine was 48 billion USD in 1997, the total loss by the Chernobyl accident amounts to 4 times the Ukrainian GNP.

Of course, it is very difficult to evaluate the accuracy of the above estimates. It seems safe to say, however, that the scale of the economic losses caused by the

Table 6. Economic loss in Ukraine: 1986 – 2015.

Category	Billion USD
1. Direct material losses: power plant, enterprises, houses etc.	2.2
2. Direct cost: countermeasures, compensation, privileges etc.	13.1
3. Indirect loss: losses of land use, electricity, industrial production etc.	163.7
Total	179.1

Chernobyl accident was such that the losses should be considered in terms of multiples of the national budget or GDP.

## 8. Closing Remarks

The biggest lesson from investigating the Chernobyl accident is that towns/villages around NPP disappear together with their local communities when a catastrophic accident occurs (Fig. 8).

After the Chernobyl accident, western specialists including Japanese said, “The most important point that led to the Chernobyl accident was the lack of ‘Nuclear Safety Culture’ in USSR”. In fact, the design defects of RBMK were pointed out before Chernobyl, but the Soviet authorities did not take necessary measures to prevent the



Fig. 8. Current alienation zone around Chernobyl. The areas on Ukrainian and Belarusian sides are 2,000 and 1,700 km<sup>2</sup>, respectively. The map is made based on the figure in *National Geographic*, April 2006. Basic photo is made using Google Earth.

accident. It can be said that the centralized power system of USSR was at the same time a centralized irresponsible system. Important things were always transferred to the upper level and decided in Moscow based on the principle that “Unlike capitalist countries, mistakes cannot happen in socialist countries”.

Meanwhile, how is the situation of ‘Nuclear Safety Culture’ in Japan? In September 1999, an incredible criticality accident, which was impossible from the common sense of nuclear engineers, occurred at JCO uranium processing company in Tokai-mura and two workers died from high doses of radiation. In March 2007, it was disclosed that a criticality accident at Hokuriku Electric Power Company’s Shiga-I (BWR, 540MWe) had been concealed for eight years. The accident occurred in March 1999, half a year before the JCO criticality accident. If this accident had been immediately announced, the JCO accident might have been avoided.

On July 16, 2007, a 6.8 magnitude earthquake hit the Kashiwazaki-Kariwa NPP in Niigata prefecture, the largest NPP in the world (7 BWRs, 8.2 GWe), the epicenter of which was 16 km north-west from the NPP and 17 km under the ground. Although a maximum acceleration more than 2 – 3 times larger than the resistant-earthquake design was recorded, fortunately the four reactors that were operating at the time could be stopped without serious discharge of radioactivity. Some nuclear energy proponents are saying this earthquake indicated the integrity of the safety system of NPP in Japan. On the other side, serious people are considering that this earthquake was a warning against building nuclear power reactors on islands where earthquakes will inevitably occur again in future.

Currently (December 2009), 435 nuclear power reactors (total 373 GWe) are in operation in the world, producing about 16 % of electricity. In Japan about 30 % of electricity is produced by 54 nuclear power reactors (49 GWe). It should be pointed out that the most dangerous thing is that the people working at nuclear facilities believe that there is no danger in nuclear energy. Considering the huge scale of a nuclear catastrophe, the decision whether or not our society will rely on nuclear energy should not be made by nuclear engineering specialists. It should be made based on the opinion of ordinary citizens.

## Notes

- <sup>1</sup> GW electric (GWe); electric output of the turbine generator. GW thermal (GWt); thermal energy produced in the reactor. That is, GWe/GWt is the efficiency of energy conversion.
- <sup>2</sup> Imanaka T. ed., *Research Activities about the Radiological Consequences of the Chernobyl NPS Accident and Social Activities to Assist the Sufferers by the Accident*, KURRI-KR-21, (1998).  
<http://www.rri.kyoto-u.ac.jp/NSRG/reports/kr79/KURRI-KR-21.htm>
- <sup>3</sup> Imanaka T. ed., *Recent Research Activities about the Chernobyl NPP Accident in Belarus, Ukraine and Russia*, KURRI-KR-79, (2002).  
<http://www.rri.kyoto-u.ac.jp/NSRG/reports/kr79/KURRI-KR-79.htm>
- <sup>4</sup> Imanaka T. ed., *Many-sided Approach to the Realities of the Chernobyl NPP Accident: Summing-up of the Consequences of the Accident Twenty Years After*, KURRI-KR-133 (2008) <http://www.rri.kyoto-u.ac.jp/NSRG/reports/kr139/KURRI-KR-139.htm>
- <sup>5</sup> RBMK is initials of Russian name “Реактор Большой Мощности Канальный”, meaning “Reactor of Big Power and Channel-type”.
- <sup>6</sup> USSR State Committee on the Utilization of Atomic Energy, *The Accident at the Chernobyl Nuclear Power Plant and Its Consequences*, August 1986
- <sup>7</sup> Комиссия Госпроматомнадзора СССР, *О причинах и обстоятельствах аварии на 4 блоке черновыльской АЭС 26 апреля 1986г.*, 17.01.1991.
- <sup>8</sup> Абалин С.С. и др. Диагностические исследование аварийного реактора Чернобыльской АЭС// *АТОМНАЯ ЭНЕРГИЯ*. 68: 2 (1990) С.355-359.
- <sup>9</sup> Карпан Н.В. *ЧЕРНОБЫЛЬ: МЕСТЬ МИРНОГО АТОМА*, (Кантри Лайф, Киев, 2005).
- <sup>10</sup> Новосельский О.Ю. и др. *ТЕХНИЧЕСКИЕ АСПЕКТЫ АВАРИИ НА 4-М ЭНЕРГОБЛОКЕ ЧЕРНОБЫЛЬСКОЙ АЭС*, (Изд-Во «ГУП НИКИЭТ», Москва, 2005).
- <sup>11</sup> Devell L.H. et.al, “Initial observations of fallout from the reactor accident at Chernobyl” *NATURE* 321 (1986) pp.192-193.
- <sup>12</sup> Imanaka T. and Koide H. “Fallout in Japan from Chernobyl” *J Environ Radioact* 4 (1986) pp.149-153
- <sup>13</sup> United Nations Scientific Committee on the Effects of Atomic Radiation, *UNSCEAR1988 Report. Annex D* (United Nations: New York, 1988)
- <sup>14</sup> Imanaka T. “Reminding Chernobyl: Messages 20 Years After” (Citizens’ Nuclear Information Center: Tokyo, 2006). Bq (Becquerel) is unit of radioactivity. 1 Bq indicates radioactivity of one disintegration per second.
- <sup>15</sup> Chernobyl Forum, *Chernobyl’s Legacy: Health, Environmental and Socio-economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine*. IAEA, 2005
- <sup>16</sup> Kazakov V.S. et.al “Thyroid Cancer after Chernobyl”, *NATURE* 359(1992) p.21.
- <sup>17</sup> Sv (Sievert) is a unit of irradiation to the human body.
- <sup>18</sup> Maksoutov M. “Radiation Epidemiological Studies in Russian National Medical and Dosimetric Registry: Estimation of Cancer and Non-cancer Consequences Observed among Chernobyl Liquidators” in KURRI-KR-79, 2002. pp.168-187.
- <sup>19</sup> International Advisory Committee, *The International Chernobyl Project: Technical Report*, (IAEA: Vienna 1991) pp.80-82.

- <sup>20</sup> United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR2000 Report. Annex J (United Nations: New York, 2000)
- <sup>21</sup> А. Ярошинская. *ЧЕРНОБЫЛЬ: Совершенно Секретно*. Другие-Берега, Москва, 1992.
- <sup>22</sup> UNDP, UNICEF, UN-OCHA, WHO “The Human Consequences of the Chernobyl Nuclear Accident: A Strategy for Recovery” 2002.
- <sup>23</sup> International Advisory Committee, *The International Chernobyl Project: An Overview*, (IAEA: Vienna 1991) p.32.
- <sup>24</sup> Ministry of Ukraine of Emergencies and Affairs of population protection from the consequences of the Chornobyl catastrophe. *20 Years after Chornobyl Catastrophe: Future Outlook, National Report of Ukraine*, 2006. p.70.
- <sup>25</sup> Fairlie I. and Sumer D. A Scientific Report Prepared for the “Chornobyl+20: Remembrance for the Future” Conference, Kyiv, April 23-26, 2006.
- <sup>26</sup> WHO, *Health Effects of the Chernobyl Accident and Special Health Care Programmes*, Report of the UN Chernobyl Forum Expert Group "Health", 2006.
- <sup>27</sup> IARC, Press Release No. 168, 20 April 2006.
- <sup>28</sup> Greenpeace, *The Chernobyl Catastrophe: Consequences on Human Health*, 2006.
- <sup>29</sup> Ministry of Ukraine of Emergencies and Affairs of population protection from the consequences of Chernobyl Catastrophe. *20 Years after Chornobyl Accident: Future Outlook, National Report of Ukraine*. 2006. p.54.
- <sup>30</sup> И. Корякин Ю.И, Сколько стоит Чернобыль. // *Природа*, 1990 № 10 с.65-74
- <sup>31</sup> Е.Ф.Конопля и И.В.Ролевич, *Экологические, медико-биологические и социалино-экономические последствия катастрофы на ЧАЭС в Беларуси*. МЧС Беларуси и ИРБ АН Беларуси, Минск, 1996.
- <sup>32</sup> Ministry of Ukraine of Emergencies and Affairs of population protection from the consequences of Chernobyl Catastrophe. *20 Years after Chornobyl Accident: Future Outlook, National Report of Ukraine*. 2006. p.108.