The Chernobyl Reactor: Design Features and Reasons for Accident

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Abstracts

The report describes the main features of the Chernobyl reactor and possible reasons of the accident that happened on 26 April 1986. Analysis of scientific results established after the accident demonstrates that shortcomings in the design, and freak infringements of safety regulations for the construction as well as inadequate documentation for reactor operation were the main reason of the Chernobyl accident. Various scenarios proposed for this accident are also analyzed in the report. It is concluded that a very high probability of the nuclear explosions at the reactor of the Unit 4 of the Chernobyl accident exists. The power of it could be equivalent to 200 tons of the trinitrotoluene (TNT).

Introduction

The accident at Unit 4 of the Chernobyl Nuclear Power Plant (NPP) on 26 April 1986 is the most severe accident in the history of the peaceful use of the nuclear energy. As a result of this accident the reactor of the fourth unit of the Chernobyl accident was fully destroyed. This caused a release of a very high amount of radioactive species into the environment. The total activity of all radionuclides that escaped from the active core of the reactor during 10 days after the explosions is assessed as approximately 10^{19} Bq [1]. The reasons for the Chernobyl accident and its consequences were the subject of the Post-Accident Review Meeting held on 25-29 August 1986 in Vienna, Austria [2]. It was organized under the auspices of the IAEA. The Soviet experts reported at the meeting their version of the reasons of the accident as well as its possible consequences [3]. The accident occurred during a turbogenerator test carried out at the chance of the shutdown of the unit for a planned maintenance. The destruction of the reactor happened 6-7 seconds after the operator pressed the scram button, AZ-5 to insert all control rods into the core.

According to the Soviet experts the prime cause of the accident at the Chernobyl NPP was "…an extremely improbable combination of violations of instructions and operating rules committed by the staff of the unit" [3]. This conclusion sets a full responsibility for the accident at the Chernobyl NPP on its stuff. Participants of the Post-Accident Review Meeting [2] also accepted the Soviet version. However, it was incorrect. This was demonstrated in 1990 by the commission of the State Committee for Atomic Safety Survey of the USSR which concluded that the main reasons of the Chernobyl accident were serious shortcomings in the design of the Chernobyl reactor as well as inadequate documents regulating a safe operation of the reactor [4]. Various errors, that were made during the turbogenerator testing by the personnel of the fours unit of the Chernobyl NPP, according to the commission, could only contribute to the development of the accident. This commission will be named in the present report as the Sternberg commission after the name of its chairman.

The conclusions of the Sternberg commission were accepted later by the International Consultative Group on the Nuclear Safety that issued in 1993 a Supplement to INSAG-1 [5]. In this report of the International Consultative Group on the Nuclear Safety, the main accent was laid also on various shortcomings of the RBMK design. At the same time the International Consultative Group on the Nuclear Safety indicated that the important reason of the Chernobyl accident was an inadequate "nuclear safety culture” in the nuclear industry of the former USSR.

Main design features of the RBMK reactor

History of the RBMK

The abbreviation RBMK means in Russian: a channel-туpe reactor of a large power. There were two modifications of the RBMKs in the USSR: RBMK-1000 and RBMK-1500. They differ only in their capacity. The RBMK-1000 has the nominal power equal 1000 MW electrical gross. The nominal capacity of the RBMK-1500 is 1500 MW electrical gross. Some principal characteristics of the RBMK-1000 are given in Table 1. It is a kind of a boiling water reactor with enriched uranium as fuel, graphite as moderator and water as coolant. Reactors of this type were constructed and operated only in the USSR. The construction of the first RBMK was begun in March 1970 (Leningrad NPP) [6]. It was put into the commercial operation in November 1974. Later other 14 RBMK reactors were constructed and put into operation in the USSR before the Chernobyl accident [6]. Thus, 15 RBMK reactors were in operation in the USSR at the time of the Chernobyl accident. They were 4 reactors at the Leningrad NPP, 4 at the Chernobyl NPP, 4 at the Kursk NPP, 2 at the Smolensk NPP and 1 at the Ignalina NPP [6]. The RBMK reactors were built in pairs, with two units occupying opposite sides of a single building complex. Turbogenerators of such pair of reactor units were constructed in one building. Reactors of the first two units of the Leningrad, Chernobyl and Kursk NPPs belong to the first generation of RBMKs. The other RBMKs belong to the second generation of the reactors of this type.

The difference between RBMKs of the first and second generations was not very significant. All these reactors were practically copies of the first RBMK. They were constructed by using the technical project of the first RBMK reactor that was developed in 1960s [4]. This means that all RBMKs had similar shortcomings and an accident similar to the Chernobyl accident could happen at each Soviet NPP with a channel-type reactor [4].

The first and second units of the Chernobyl NPP belonged to the first generation of RBMKs and the third and fours units to the second generation. The construction of the Unit 1 of the Chernobyl NPP started in June 1972 [6]. The commercial operation of it began in May 1978. The construction of the Unit 4 started in April 1979 and commercial operation began in March 1984 [6].

Core of the RBMK

The core of the RBMK reactor (element 1 in Fig.1) has a form of a vertical cylinder with an equivalent diameter of 11.8 m and height of 7 m [7]. The schematic presentation of it is given in Fig.1.

Table 1. Principal characteristics of the reactor RBMK-1000 [3].

Characteristics	
Thermal power	3,200 MW
Electrical power	1,000 MW
Fuel enrichment	2.0 %
Mass of uranium in an fuel assembly	114.7 kg
Number of sub-assemblies in an fuel assembly	2
Number of fuel elements in a fuel sub-assembly	18
Diameter of fuel elements	13.6 mm
Fuel burnup	20 MW·d/kg
Coefficient of nonuniformity in radial power density	1.48
Coefficient of nonuniformity in vertical power density	1.4
Maximum design channel power	3,250 kW

The core is constructed from closely packed graphite blocks. They are stacked into columns with vertical cylindrical openings into which channels for fuel (pressure tubes) as well as channels for absorbing rods are inserted. The core is surrounded at top, bottom and lateral by graphite reflectors. The thickness of the lateral reflector is 1 m. The thickness of the top and bottom reflectors is 0.5 m. The weight of the core graphite is 1,700 t. The weight of graphite reflectors is about 300 t.

The RBMKs of the first generation have 1,693 fuel channels (technological channels) and 179 channels for rods of the control and protection systems (CPS) [8]. The RBMKs of the second generation (for example, the Unit 4 of the Chernobyl NPP) have 1,661 fuel channels and 211 channels for the control and protection systems. The fuel assemblies of the RBMK reactor are made in a form of a cluster [7,8]. Each fuel assembly consists of two sub-assemblies, one over the other. The sub-assembly contains 18 fuel elements. The diameter of fuel elements is 13.6 mm. The weight of uranium containing in one fuel assembly is 147.5 kg The fractions of a pressure tube that are located in the active core are made of zirconium alloy. The lower and upper parts of it are made of steel.

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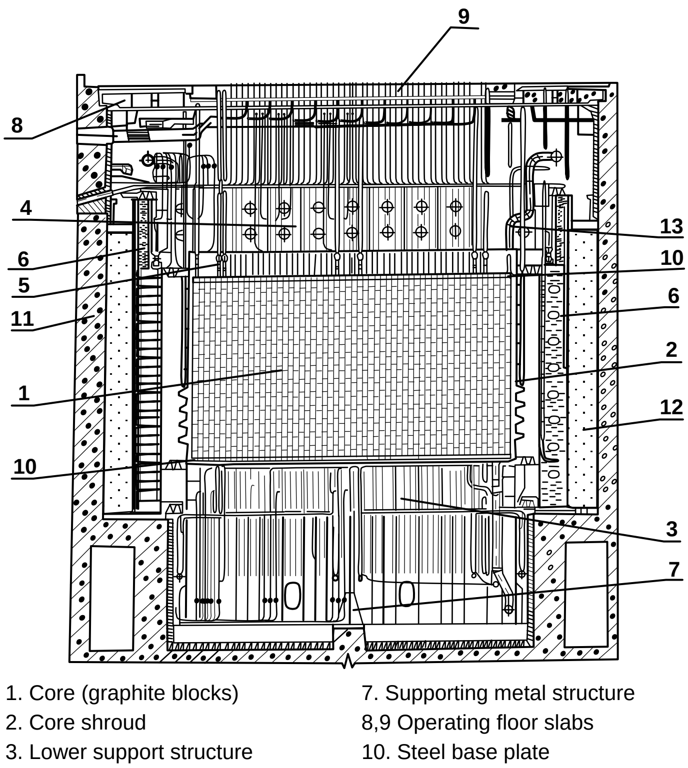
At the time of loading the core with fresh fuel, one part of fuel channels (230-240) is loaded with special *additional absorbing rods* (AAR) because the control rods can not compensate the large reactivity surplus of the core [7]. The geometrical parameters of the AAR rods do not differ from those of fuel assemblies. Therefore, the additional absorbing rods can be inserted at any channel of the core. With increase of the fuel burnup the AAR rods are withdrawn gradually one after the other. The fuel assemblies are inserted then in the channels that were occupied previously by additional absorbing rods. Thus, the weight of uranium in the core increases with increase of fuel burnup. At the beginning of operation it is about 165 t and reaches 192 t by achieving the stationary operation [7].

The graphite stack lays on a base steel plate (element 10 in Fig.1) that is placed on a bottom metal structure (element 3 in Fig.1). The bottom metal structure is a cylinder of 14.5 m in diameter and 2 m high.



1. Core (graphite blocks)
2. Core shroud
3. Lower support structure
4. Upper core cover and shield
5. Fuel channel duct
6. Annular water tank
7. Supporting metal structure
8,9 Operating floor slabs
10. Steel base plate
11. Reactor vault
12. Sand filling
13. Core ventilation pipe

Fig. 1. The arrangement of the core of Chernobyl Unit 4 [8].

The upper and lower plates of the cylinder are made from steel (10CrNi1Mo) of 40 mm thick [8]. They are welded to the lateral shell by means of leak-tight welds, and welded to each other by means of vertical strengthening fins. The bottom metal structure is mounted on the supporting metal structure (element 7 in Fig.1) that composed of plates with reinforced fins of 5.3 m high. They intersect each other perpendicularly at the center of the reactor [8].

The construction of the top metal structure (element 4 in Fig.1) is similar to the construction of the bottom metal structure. It is a cylinder of 17 m in diameter and 3 m high [8]. The upper and the bottom plates of it are made from steel (10CrNi1Mo) of 40 mm thick. They are also welded to the lateral shell and to each other by means of vertical strengthening fins. The holes in the top and bottom plates are for the tube ducts (element 5 in Fig.1) holding the fuel and absorber channels. The similar ducts for the fuel and absorbers channels are made in the bottom supporting structure.

The space between different tubes and communications in the top and bottom metal structures are field with serpentinite (a mineral containing bound water of crystallization) [8]. The metal top covering of the core (element 8 in Fig.1) is covered with the removable floor constructed from steel slabs (element 9 in Fig.1).

The lateral side of the graphite stack is surrounded by a cylindrical shroud (element 2 in Fig.1) made of steel sheeting (10CrNi1Mo) of 16 mm thick. It has an outer diameter of 14.52 m and height of 9.75 m [8]. The shroud together with the top and bottom metal structures creates a closed reactor space that is placed into the concrete vault (element 11 in Fig.1). The shroud of the reactor is surrounded laterally by water tanks and sand filling (elements 6 and 12 in Fig.1).

About 5% of the heat generated in the core are released to the graphite stack [3]. This heat is removed to fuel and partially to CPS channel. To reduce a thermal resistance and prevent oxidation of the graphite the cavity in the graphite stack is filled with a slowly circulating mixture of helium and nitrogen. The piping bends of the circulating system of this mixture are shown in Fig.1 (element 13).

System of the RBMK reactor cooling

Cooling of the RBMK reactor is assured with help of two parallel loops [7,8]. Thy are schematically showed in Fig. 2. Each loop is designed for cooling of one half of the reactor core (the *left and right halves*) and consists of 2 steam separators and 4 main circulating pumps (MCPs). Three main circulating

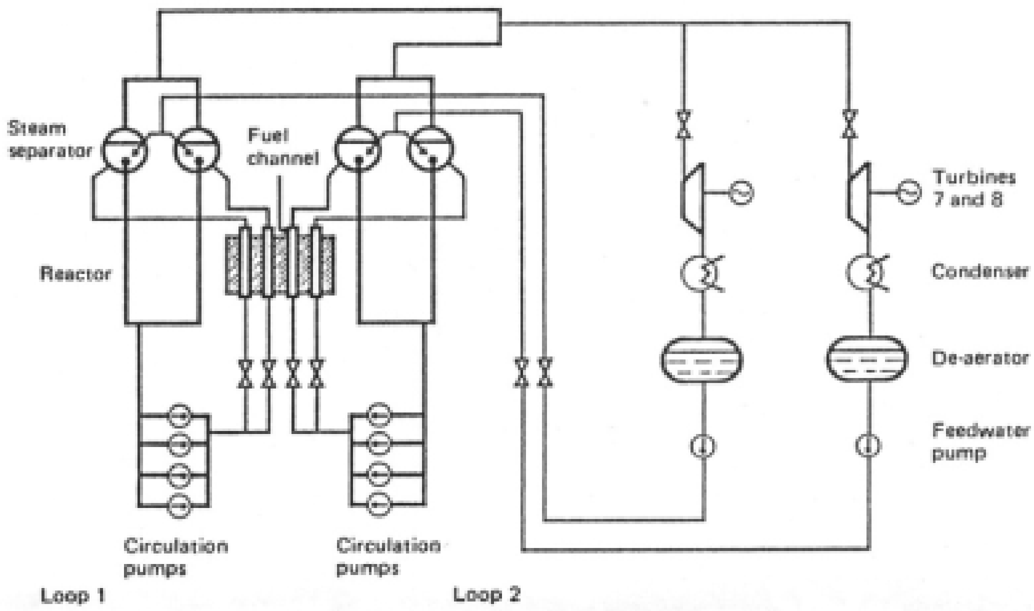


FIG. 2. Schematic diagram of the main water and steam circuits of Chernobyl Unit 4 [2].

pumps are used for normal operation of the reactor. One pump is in a reserve for a breakdown of one of the operating pumps [7,8]. The main circulation pumps of one cooling loop are switched to busbars of the first turbogenerator of the unit. The main circulation pumps of other loop are switched to busbars of the second turbogenerator of the unit.

The coolant (light water) enters the fuel channels from the bottom of the core. The inlet pressure and temperature are 8.2 MPa and 270 ^{0}C, respectively [8]. By passing of the channel the pressure of water decreases to approximately 7 MPa and temperature increases up to 284.5 ^{0}C at the core outlet. The increase of the temperature and the decrease of pressure cause boiling of water. This process begins at the distance approximately 2.5 m from the inlet to the core [7]. At the outlet of the core, steam content reaches the value of to 14.5 wt%. This steam-water mixture flows into steam separators, where it is separated into saturated steam and water. The separated steam flows then to the turbines and after passing of them goes to condensers where it is condensed to water. This water (feed water) is then pumped by electrical feed water pumps to steam separators. Here the feed and separated out water is mixed together. On this way the temperature of the separated out water decreases to 270 ^{0}C. This provides the necessary cavitation margin required for operation of the main circulating pumps and boiling of water at the inlet to the core (the saturation temperature of water at the pressure at the inlet to the core is about 284 ^{0}C).

At normal operating circumstances, each of the 6 main circulating pumps can work with flow-rate about 7,000 t/h [8]. Their operating with higher flow-rates at the stable power output of the reactor is not desirable. Such operation causes a change of the relation between the mass of feed water and the mass of water separated out in steam separators. The average temperature of the mixture of feed and the water separated out water increases in this case and this causes a decrease of the cavitation margin. This can cause cavitation of the main circulating pumps and boiling of the coolant even at the inlet to the core. The same situation arises in case of operations of the main circulating pumps at their nominal flow-rates when reactor is operated at decreased power.

In case of the RBMK the coolant flows separately to each fuel channels. This requires an individual regulation of flow-rate to each fuel channel. Therefore, the thermohydraulic scheme of the reactor is much more complicated than PWRs and BWRs.

Control and protection system

The control and protection system (CPS) of the RBMK reactor has absorbing rods and different measuring devices for a control of a number of parameters. There are 211 absorbing rods in case of the RBMK reactors of the second generation [3,4]. According to their functions they are divided in 4 groups [7]:

- shortened absorbing rods (SAR) for regulation of the axial neutron distribution;
- absorbing rods for a manual regulating of the radial neutron distribution (MR);
- absorbing rods for an auto control of the reactor power (AC);
- emergency rods (ER).

The total numbers of the SAR, AC, MR and ER absorbers are 24, 24, 139 and 24, respectively [4]. The absorbing rods used for control and protection systems of the RBMK reactor are assembled from the identical absorbing elements made of carbide boron [7]. These elements have the same length equal to 967.5 mm. The absorbers of the type SAR have only three absorbing elements. Their length is 3,050 mm [7]. Other absorbing rods are assembled from 5 absorbing elements. Their length is 5,120 mm [7]. There are another feature in absorbing rods of the RBMK reactor. The absorbing rods of the type SAR, MR and ER have special graphite displacers that are assembled from 5 graphite elements. These displacers remain in the core by full withdrawal of absorbing fractions of rods. The use of graphite displacers improves significantly the neutron economy of the RBMK reactor because graphite absorbs neutrons much less than the light water. Fig.3 demonstrates schematically different absorbers of the control and protection systems

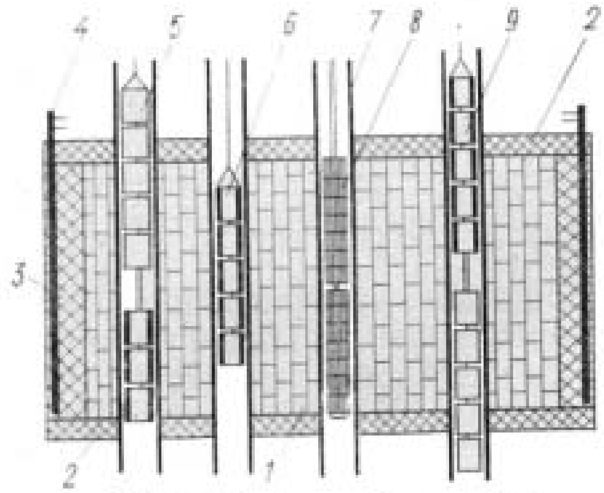


FIG. 3. Structure of the core [7].
1 - graphite stack; 2 - bottom reflector; 3 - lateral reflector; 4 - channel of lateral reflector cooling; 5 - shortened absorber rod (SAR); 6 - auto control rod (AC); 7 - fuel channel (technological channel); 8 - fuel assembly; 9 - manual regulation absorber (MR) and emergency absorber (ER).

of the RBMK reactor.

Negative features of the RBMK reactor.

The RBMK reactors have a number of negative features that strongly influence the safety of their operation. Some of them were eliminated after the Chernobyl accident. However, we shall discuss here the negative features of the RBMK reactor that existed before the accident.

One of them is an enhanced sensitivity of neutron fields to the moving of control rods [7]. This effect is caused through a big number of absorbers in the core for compensation of a large reactivity surplus. By withdrawal of some absorbers, especially absorbers in peripheral zones, a local criticality is also possible. According to [7], it can appear in the zone consisting of 15 - 20 channels loaded with fuel when there are no one absorber among them. These features of the core cause significant problems in controlling of the RBMK reactors in comparison to PWRs and BWRs.

Another significant problem creates the large positive steam-void coefficient of the RBMK reactor. Experimental studies carried out at the end of 1970s have shown that the steam-void coefficient increases up to 5 β_{eff} by decreasing of the number of additional absorbing rods (AAR) in the core and by increasing of the fuel burnup [4]. Appearance of such large positive reactivity decreased the period of the power stabilization of the core to 3 minutes [4]. This made the safe operation of the RBMK reactor quite problematic. A special local auto-control system was developed in order to prevent uncontrolled power excursions. It was clear already in 1970s how to decrease the high steam-void coefficient [4]. It disappears by introducing of a certain number of additional absorbing rods in the core. The permanent presence of them in the core required fuel with a higher enrichment. Therefore, from 1970s the enrichment of fuel used for RBMKs was 2 % instead of 1.8 % used at the beginning of the operation of the first RBMK (reactor of the Unit 1 of the Leningrad NPP). It was found later that the enrichment of fuel up to 2 % was not enough for decreasing of the steam-void coefficient [4]. Experimental studies carried out at the end of 1970s has shown that only by enrichment 2.4 % and by the permanent presence of about 80 additional absorbers in the core the value of the steam-void coefficient could be made less than β_{eff}. These data were also confirmed in a experimental study carried out after the Chernobyl accident [9]. However, the use of additional absorbers and fuel with higher enrichment was implemented for RBMKs only some years after the Chernobyl accident.

The significant shortage was also in the design the SAR, MR and ER absorbers of the RBMK reactor. These absorbers had special graphite displacers in the length of 4.5 m [10]. By a withdrawal of the SAR, MR and ER absorbers up to their extreme top position above the core, the midpoint of each displacer is at the midpoint of the core. Because their length (4.5 m) is less than the height of the core (7 m), the water columns in the height of 1.25 m are formed below and above the displacers. On moving down of absorbers into the core, their displacers displace water columns from the lower part of the core. Thus, inserting of absorbers from their extreme top position introduces a positive reactivity into the core because graphite absorbs neutrons much less than water. This effect of absorber displacers is shown in Fig. 4. It was known by operators of RBMKs. They named it the “end-rods effect”. Specialists named the “end-rods effect” as the positive reactivity surge. It was not fully understood by them because it appeared occasionally and only by some neutrons distributions in the core. For example, in one document of the Chief Designer organization it was told that the positive reactivity surge could appear only in case of neutron field disturbed downwards [10]. This statement was wrong. It is known that before pressing the button AZ-5 the neutron field was distorted upwards and not downwards. This fact says about misunderstanding by the Chief Designer organization of the real nature of the positive reactivity surge caused by inserting of absorbers from their extreme top position.

The situation with the control and protection systems of RBMKs became complicated because of a very low speed at which the control and emergency rods could be inserted into the core from their extreme top position. The speed was only 0.4 m per second. Thus, they could be fully inserted into the core for 18-20 seconds [4,9]. Such protection system was not able to shut down the reactor in cases, when the excursion started. In such situation, the reactor period can be in order of some seconds.

The additional problems of RBMKs arise from a very complicated system of the core cooling and the use of the coolant that can change its physical state in the core.

Accident at the Unit 4 of the Chernobyl NPP

Chronology of the accident

The accident at the Unit 4 of the Chernobyl NPP occurred on 26 April 1986. This unit had to be shutdown on 25 April 1986 for the planned maintenance. Before the shutdown, it was planned to study the possibility of utilization of the mechanical energy of a turbogenerator after cut-off of steam supply, in

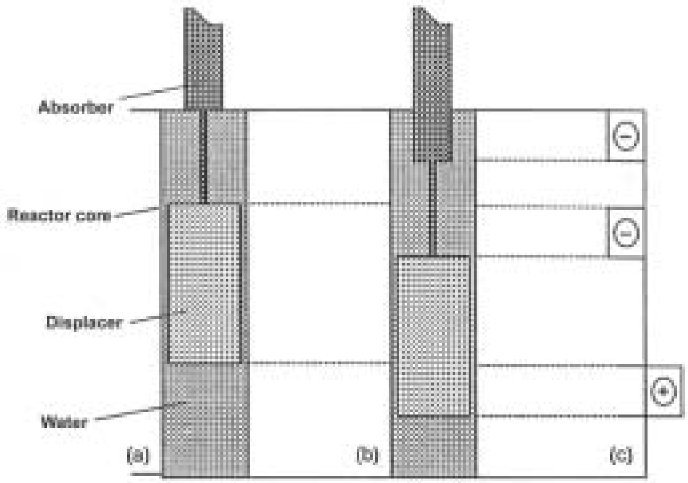


FIG. 4. Schematic presentation of the reactivity inserted by moving of CPS absorbers from their extreme top position.
(a) manual regulation rod is withdrawn;
(b) manual regulation rod is at the initial insertion stage;
(c) schematic presentation of the change in the reactivity by insertion of the rod [5].

order to ensure the power requirements in a case of a power failure [3]. This test had to be carried out at the power level 1,000 –700 MW thermal. The decrease of power began on 25 April 1986 at 01 hr 06 min. The reactor had at this time the nominal power 3,200 MW thermal (the time and other data are given here and below after records of the operator in the operative log-journal) [4]. At 03 hr 47 min the reactor power reached the level of 1,600 MW thermal. It fell to the value 1,500 MW thermal by the time 04 hr 13 min. The reactor was operated at this power until 12 hr 36 min. The operation reactivity surplus (ORS) beginning from 07 hr 10 min decreased to 13.2 manual absorbing rods (MR). At 13 hr 05 min, the turbogenerator TG7 was switched off. Four main circulating pumps, two electrical feed water pumps and other equipment that was connected with this turbogenerator were switched to the busbars of the turbogenerator TG8.

The following pump configuration arose as a result of these actions: four pumps running from the turbogenerator TG8 (MCP-13, 14. 23, 24), two pumps running from grid (MCP-12, MCP-22) and two pumps (MCP-11, MCP-21) connected to grid on standby. At the foreseen experiment the pumps MCP-13, MCP-14., MCP-23 and MCP-24 had to run together with the turbogenerator TG8. The main circulating pumps: MCP-11, MCP-12, MCP-13, MCP-14 belonged to the loop for cooling of the left half of the core. The main circulating pumps: MCP-21, MCP-22, MCP-23, MCP-24 belonged to the loop for cooling of the right half of the core.

At 14 hr, the emergency core cooling system (ECCS) was switched off according to the experiment program. At this time, the Kiev dispatcher of the electrical grid ordered to continue the operation of the Unit 4 because of a shortage of power [4]. From this time the reactor was operated at the power 1,500 MW thermal with the switched-off ECCS system. The order of the Kiev distributor caused an important disturbance for the test because the later continuation of the experiment had to be done by another shift of the Unit 4 that was not planned for this important work.

At 23 hr 10 min, the operator of the reactor was allowed to decrease the power of the unit. At 00 hr 10 min on 26 April, it reached the level 720 MW thermal that was the lower limit of the power according to the experiment program [4]. However, the operator could not stabilize the power of the reactor at this level. It continues to fall and at 00 hr 28 min, it fell down to 30 MW thermal. The operator of the reactor, the senior engineer, Leonid Toptunov and the shift foreman, Alexander Akimov decided to insert absorbing rods in the core in order to shutdown the reactor. They were forced by the deputy chief engineer for operation of Unit 3 and Unit 4, Aleksander Dyatlov to withdraw the absorbers out the core in order to increase the power of the reactor [11]. The latter wished to carry out the planned test at any price. The necessity of the withdrawal of practically all absorbers out the core was dictated by a very strong xenon poisoning as a result of very quick decrease of the reactor power.

After the withdrawal of a number of absorbers, the power of the reactor began to increase. At 01 hr 03 min, it reached 200 MW thermal [4]. At this time 2 reserve circulating pumps were put additionally into operation. The total number of operating main circulating pumps reached 8 pumps. Therefore, the summary flow-rate of water through the core became higher than at the nominal power of the operation. Such increase in the summary flow-rate of the coolant was reached at very low reactor power and very low steam generation. This caused the decrease in a cavitation and boiling surplus. According to [4], it was only about 3 ^{o}C. Thus, the withdrawal of the majority of absorbers from the core after the fall of the power to 30 MW thermal put the reactor into an unstable thermo-hydraulic state.

The use of two additional main circulation pumps after reaching of the thermal power 200 MW was undertaken in order to guarantee a safe cooling of the reactor after finishing of rundown of the turbogenerator TG8 and 4 main circulating pumps connected to busbars of it (MCP-13, -14, -23, -24). Four circulating pumps (MCP-11, -12, -21, -22) had to remain after finishing of the rundown. Performing some actions the operating stuff could bring the reactor in a stable state before the experiment beginning [3,4]. An analysis carried later shown that no signals appeared indicating that something happened with the reactor that could hinder conducting of the experiment [4]. It seemed for the operating stuff that the reactor was in the normal state. This was a very serious mistaken. In reality, the reactor was in a very dangerous state. At 01 hr 22 min 30 sec, the operative reactivity surplus was only 8 rods [4]. It means that the water in the core, especially in its lower part, became the most important absorbers of neutrons. A decrease of a pressure or an increase of a temperature of water at the inlet to the core could cause a local boiling of water in the lower part of the core. Such process inserts the positive reactivity and as a result of a large positive power coefficient causes a high increase of the reactor power. .Unfortunately, the operator did not understand this dangerous feature of the Chernobyl reactor and continued to operate the reactor in this dangerous state.

At 01 hr 23 min 04 sec, the experiment was started. At this time, the emergency regulating valves of the second turbogenerator, TBG8, were closed [3,4]. The power of reactor was 200 MW thermal. The operative reactivity surplus was only about 6-8 absorbers. This was shown by the analysis carried out after the accident. Shortly after the beginning of the experiment, the reactor power began to rise [3,4]. At 1 hr 23 min 40 sec, the unit shift foreman gave the order to press the button AZ-5, which would send all control and scram rods into the core [3,4]. The rods began to move into the core. However, after several seconds a number of shocks were felt and the operator saw that the absorber rods had halted without plunging fully to the lower stops. Seeing this stop of absorbers the shift foreman cut off the current to sleeves of the servo drivers of absorbers in order to ensure the falling of rods [11]. -- This action did not help to insert the rods into the core. Some seconds later the reactor was fully destroyed.

According to observers that were outside of the Unit 4, at least 2 explosions, one after the other occurred in the reactor at 01 hr 24 min on 26 April 1986 [3]. Here is a story of one fireman that heard several explosions at the time of the experiment [11]: “At the time of the explosion I was near to the dispatcher bureau. I was in service. Suddenly we heard a loud clap of steam. We did not take into consideration this event because throws of steam into atmosphere were quite often. I wanted to leave the room for my rest and heard at this moment an explosion. I ran to the window and heard in a very shot time the other explosions.” This story was recorded in the clinic in Moscow where the affected fireman and personnel members were treated because of the acute radiation sickness.

Another observer (a concrete worker of the Chernobyl NPP) told the following story [10]: “I was near the Unit 4, about 500 meters away, when I suddenly heard a loud clap. Then came something like the sound of an explosion. I thought it was the steam valve, which we used to hear from time to time. Then in a couple of seconds a bright, blue flash was followed by en enormous explosion. When looking at the Block 4, I saw that there were only two walls of it left. The structure was in ruins, water was pouring out, bitumen was burning on the roof of the Unit 4”

Destruction of the reactor

The explosions at 01 hr 24 min completely destroyed the core of the reactor of the Unit 4 [12]. Walls and the ceiling of the central hall were demolished. Ceilings of the premises of the steam separators were displaced and walls were destroyed. Premises housing the main circulating pumps as well as two stories of the de-aeration stack were demolished. The reactor emergency cooling system was completely destroyed from the north side of the reactor building and buried with frame details. The upper metal structure together with top covering (the summary weight 2,000) and rests of the steam–water system were thrown into vertical direction and fell on the rib with the inclination angle 15^o [12]. The artist picture in Fig. 4 shows its position after the explosions as well as the scale of the reactor destruction. The lower metal structure after the explosion went down by 4 m lower than their initial position, crushing the supporting constructions and pulling the water pipeline system. The southeast quadrant of the lower metal structure does not exist. It was destroyed during the accident. The reactor space is empty. It does not contain any more or less large fragments of the reactor laying [12].

In addition to destructions listed here, many other premises and constructions were demolished too. By destruction of the reactor a large amount of core materials were thrown out the core [13]. Large pieces of graphite and whole graphite blocks, fragments of fuel channels and fuel assemblies could be found even in big distances from the reactor [13]. Practically the whole site of the Chernobyl NPP as well as all rooms of the reactor was covered with the graphite dust.

Physical nature of explosions

Soviet experts who participated at the Post-Accident Review Meeting in Vienna suggested the following hypothesis of the physical nature of explosions that demolished the Unit 4 of the Chernobyl NPP. According to them, the first explosion was a steam explosion [3]. It had to occur on the following scenario. A very fast and high increase of a heat generation occurred in the core. It caused an intensive steam formation and then a nucleate boiling. Soon, the melting of cladding and fuel as well as destruction of fuel tablets into small particles followed. Then the destruction of fuel channels occurred. The next step was a very massive steam generation because of contacting of the destroyed fuel with water. This caused a first explosion in the core because of a very high steam pressure. It can be named as a *steam explosion*. Later a number of explosions followed as a result of exothermic reactions in a mixture containing hydrogen formed in the water-zirconium process and carbon monoxide formed by a fire of graphite.

The hypothesis about the steam explosion was accepted by specialists [4,14]. However, the assumption about the role of exothermic chemical reactions in the mixture of hydrogen, carbon monoxide etc was not discussed more. It was shown in special model experiments carried out after the Chernobyl accident that the role of them was negligible [13].

Some specialists are sure that after the steam explosion a nuclear explosion similar to an atomic bomb explosion occurred in the core of the 4th Unit [13,15,16]. Its power had to be much higher than

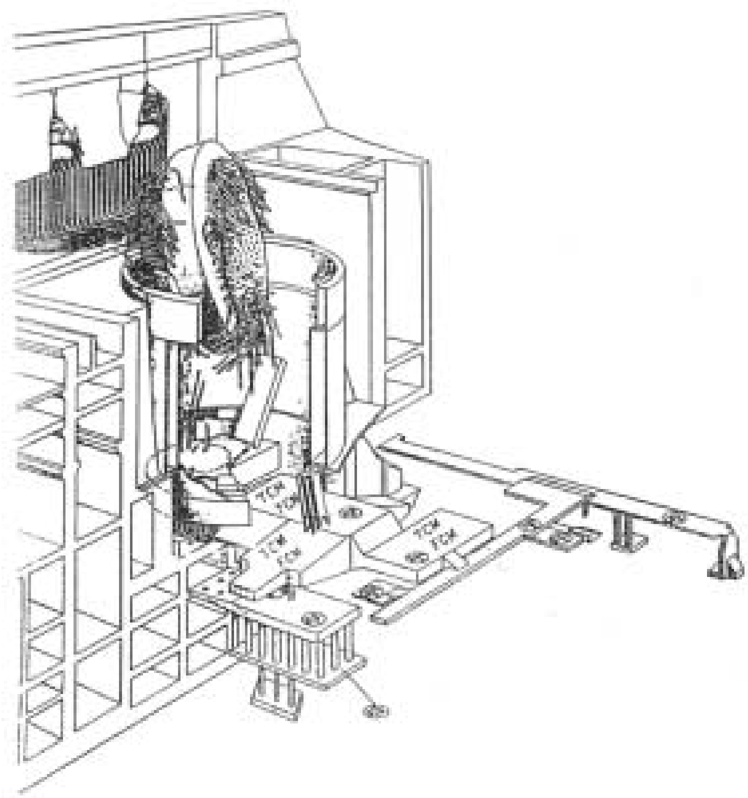


FIG. 5. The state of the reactor section of Unit 4 after the accident (the cut-away view): FCM - fuel containing masses [12].

power of the steam explosion.

The conclusion of the authors [15] is based on experimental findings established by studying of activities of isotopes ^{133}Xe and $^{133}Xe_m$ in the air that existed in the first days after the Chernobyl accident. Their study was carried out in the city Cherepovets that is about 1,000 km in north direction from the Chernobyl NPP. The authors [15] could find that the ratio of activities of these isotopes is the same as in the case of nuclear explosion.

Two different models of the nuclear explosions are known. According to [13], the core of the Chernobyl reactor transformed to a turbo-jet solid-phase engine after a very short initial overheating of fuel. It flied like a missile from the reactor vault to the central reactor hall by the hydrodynamic forces of gas-phase streams flushing down from the fuel channels. Then it exploded as an atomic bomb in the space of the central hall. Practically, the whole fuel and graphite had to be thrown away from the reactor by this explosion. This hypothesis explains a number of questions. For example, it explains why there is no fuel in the vault. It gives an answer on the question why the metal shroud of the core could be in the central reactor hall. It is situated now in the central reactor hall 35 meters from the entry to the reactor vault. This finding was established in 1995 [13]. The hypothesis [13] makes also clear how could remain without any visible demolishing the paint on the lower surface of the upper metal structure that stays now on its rib in the vault. This paint is able to sustain only up to 300 ^{o}C. In a case of graphite burning during a long time, it had to be destroyed. This is a reason for authors [13] to reject the possibility of graphite burning in the core after explosions. Their hypothesis seems quite reliable because it explains a number of other findings established some years after the accident. At the same time, it can not explain some very important facts. For example, it is well known that radioactive substances escaped from the destroyed reactor with a quite constant release during 10 days after the accident. This had to be only in a case when significant amounts of fuel and graphite remained after the explosions and a long term fire of graphite was in the core.

Data on composition of radionuclides deposited in the areas contaminated by the accident indicate also the presence of large amounts of fuel in the core after the explosions that destroyed the Chernobyl reactor. In case of a scenario proposed by [13], no fuel and graphite could remain in the core. This means that the radioactive contamination of territories affected by the Chernobyl accident had to be caused by radioactive substances discharged to the environment only during the explosions. However in this case, radionuclides, deposited at any place of the world, had to have the same composition as the composition in the core before the accident. Let's consider here only one example. According to [1] 280 PBq of the isotope ^{137}Cs and 200 PBq of the isotope ^{90}Sr were in the core of the Unit 4 before the accident. Their half-lives for the radioactive decay are quite similar. Thus, at any place of the world the ratio of the ^{137}Cs concentration to ^{90}Sr concentration has to be equal to 1.4. However, reliable experimental data [17] show that such values of this ratio exist only in areas close to the Chernobyl NPP. They increase up to 100 in areas that are more than 100 km from the Chernobyl NPP. These high ratios of ^{137}Cs concentration to ^{90}Sr concentration indicate that the discharge of radioactive substances into the environment had to be caused not only by explosions but also mainly as a result of fuel melting in the reactor core. This means that a significant part of fuel had to remain in the reactor after explosions. This could happen when only a part of fuel was thrown from the core by the nuclear explosion, for example, in case when the nuclear explosions occurred only in one part of the core. The last assumption explains why only one segment of the lower metal structure was destroyed.

Another model of the nuclear explosion was proposed by authors [16]. According to them, soon after the beginning of the experiment a sudden boiling of water occurred in the core. It was caused as a result of depressurization and flow rate reduction of the coolant. The introduced positive reactivity was higher than the anti-reactivity Doppler margin. Therefore, the fuel reached the enthalpy of disaggregation just being able to quench the first reactivity trip. Some tenth seconds after this first power burst, the energy deposited initially in the fuel was transferred to the water. This process was very fast and the heat transmission to the water was so high that convective streams could not develop within the water. The steam film and bubbles formed on the cladding. The internal pressure of the bubbles increased so rapidly that the water was expelled from the reactor. This was the first explosion (steam explosion). It caused a demolishing of coolant communications. The reactor became dried and more reactive than the wet one, and a new power burst occur. The authors estimated the energy of the last power burst to be 1.0 TJ. This energy is equivalent to the energy of explosion of approximately 200 tons of the trinitrotoluene [18]. Similar estimations were established also in the reports [13,15]. Western specialists claimed after the Chernobyl accident that the catastrophic consequences of this accident were caused because an absence of the containment of the Chernobyl reactor. However, it is clear that there is no such containment in the world that can sustain to such explosion.

The assumption about the nuclear nature seems reliable. It allows to explain some facts, for example, the observation of the witness that saw “a bright, blue flash” over the reactor of the Unit 4 and heard “an enormous explosion” at 1 hr and 24 min [10]. It is known that the blue light corresponds to the temperature about 6,000 ^{o}K. Such temperature can not appear at the steam explosion. It is also clear that in case of the steam explosion a gray ball of steam and graphite dust had to appear over the building but not a blue flash.

It is evident the hypothetical character about the possibility of the nuclear explosion in the core of the Chernobyl reactor despite of its seeming reality. It is necessary to carry out more detailed studies in order to establish a conclusion about its possibility.

Main reasons of the accident

According to the Soviet participants of the Post-Accident Review Meeting in Vienna severe violations made by the personnel of the Unit 4 of the Chernobyl NPP on 25-26 April 1986 were the main reasons of the Chernobyl accident [3]. As especially serious violations were named the following:

- operation of the reactor at a very low operative reactivity surplus (ORS),
- conducting of the experiment by the power below the level provided for test,
- blocking of the protection system relaying on water level and steam pressure in steam-separators,
- blocking of the protection system relaying on shutdown signal from two turbogenerators,
- connection of all the main circulating pumps to the reactor,
- switching off the emergency core cooling system (ECCS).

The Sternberg commission [4] recognized only the first violation from given above. It stated that in accordance with existing technological regulations the operator had to shut down the reactor already at 07 hr 10 min on 25 April 1986. The power of the reactor was then 1,500 MW thermal and the OSR was 13.2 rods. The existed technological requirements for operation of the Unit 3 and Unit 4 required the shutdown of the reactor when the operative reactivity surplus decreased to such value at such power level. The operator did not fulfill this requirement. However, the Sternberg commission stated that this violation could not initiate the accident or influence it [4]. Records made by the operator in the operative logbook show that at 23 hr 10 min on 25 April 1986 the ORS value was 23 full rods. This means that in the period from 07 hr 10 min to 23 hr 10 min the reactor of the fourth unit was brought in accordance with technological requirements.

The Sternberg commission noticed at the same time that this violation was possible because of very unclear operation’s requirements existing in the USSR before the Chernobyl accident. For example, there were no documents before the accident indicated the ORS as an important technological parameter. Additionally, such equipment that could establish operative value of the ORS in a short time did not exist as a whole. The operator had to establish at first fractions of absorbers inserted into the core. Then he had to calculate the effective number of rods fully inserted in the core. The operator could also receive this information by using the computer of the reactor unit. In this case, he needed to wait 7-10 minutes for estimation of the operative reactivity surplus. These procedures for an operative estimation of the OSR value indicate clearly that the ORS was never considered as a factor determining the safe operation of the RBMK.

The Sternberg commission concluded that all other violations of the personnel named by Soviet experts did no influence on the initiation and development of the Chernobyl accident. Let us consider, for example, the switching off the emergency core cooling system. Data recorded by the reactor control systems show that no emergency signals came to the ECCS system during the development of the accident. They could not came because the sensors of the emergency core cooling system reacts on the events in the premise compartments, but not on the events in the core. This means that there was no difference, was this system switched off or in.

The analysis of the Commission demonstrated also that some violations of the Chernobyl NPP stuff were done because of a very poor regulations and instructions developed for operators of RBMKs by designers of this reactor. The Sternberg commission could demonstrate that the Chief Designer of the RBMK reactor was not able to understand clearly some negative features of the reactor, especially by operation at low power

There is no doubt that severe shortage in the design of the RBMK and freak infringements of safety regulations by construction of the Unit 4 are real reasons of the Chernobyl accident [4].

It is also evident today which physical factor caused the accident at the Unit 4 of the Chernobyl NPP. This factor was the large positive reactivity inserted into the core. However, it is unclear up to present what kind of initiating factors could cause this event.

Same specialists believe that the Chernobyl accident was triggered by pressing of the emergency button AZ-5 [4,17]. According to them, the accident developed after the following scenario. After pressing of the button AZ-5 all absorbers for the manual regulation and all emergency absorbers began to move into the core. Before the pressing of the button AZ-5 the summary lengths of all absorbing elements that were in the core was approximately worth 6-8 rods of full insertion into it [3,4]. By moving of all these absorbers down the water columns under the graphite displacers were displaced out the core. This caused the entry of the positive reactivity into lower part of the core.

In this case, the question about the responsibility for the Chernobyl accident is very easy to answer. It is clear that the Chief Designer organization is responsible when the pressing of the button AZ-5 triggered the accident. It designed such protection system that can introduce the positive reactivity into the core followed by fast increase of power instead of the negative reactivity required for the shutdown of the reactor. This means that a freak infringement of safety regulations was made by this organization for construction of the Unit 4 of the Chernobyl accident. According to these regulations, the control and protection systems have to be able to shut down the chain reaction at any circumstances.

On the contrary, the authors [16] believe that the pressing of the button AZ-5 did not play any role in initiating of the Chernobyl accident. According to them, the boiling of water in the lower part of the core caused because of the unstable thermo-hydraulic regime of the coolant flow was the initiating factor. There was an unstable thermo-hydraulic regime of the reactor before the accident. The temperature surplus for water boiling was very small at least in case of some fuel channels. This could cause the water boiling in the lower part of the core and introducing the positive reactivity into it. This caused an excursion of the power in the lower part of the core and a very high release of heat in fuel channels. The pressing of the button AZ-5 in this case had only a secondary meaning. It only added an additional positive reactivity to the lower part of the core.

The hypothesis of [16] explains the reason for pressing of the button AZ-5 by the operator of the Chernobyl NPP. We believe that he pressed this button because he could see a very rapid increase of power. Other reasons for pressing of the button AZ-5 are less probable.

Computer simulations made on the basis of more sophisticated codes [19,20] shown that acceptance only one hypothesis that were described above can not explain the development of the Chernobyl accident. They both have to be concerned in order to carry out the correct evaluation of the accident

An interesting assumption was proposed by Checherov [21]. He worked during some years as a head of the laboratory for fuel studying of the accidental unit of the Chernobyl NPP. Later he was a head a department for reconstruction of the accident reasons. Checherov could find that electric motors of the main circulating pumps of the Chernobyl NPP had the internal protection for a decline of frequency and voltage. This protection disconnects electrical motors of the MCPs in 30 seconds after the decrease of the frequency to 45 Hz and in 0.5-1-5 seconds after the decline of voltage to the level of 75% of its nominal value. Checherov [21] believes that as a result of the decrease of the frequency and voltage of the current of the turbogenerator TG8 approximately at 1 hr 10 min 40 sec electrical motors connected to busbars of the turbogenerator TG8 were disconnected by the signals of the internal protection of the electrical motors of the MCPs that participated at the run down experiment. This caused a significant drop in the pressure at the inlet to the core and boiling of water in its lower part. This caused an inserting of the positive reactivity and a large power excursion in the lower part of the core and the first explosion.

In the light of above discussed discrepancies, it is clear the necessity to carry out the further study of the initiating factors of the accident.

Discussion

The analysis of information on the main features of the design of the RBMK reactor indicated that a number of shortages and a low safety culture in the USSR caused the accident at the Chernobyl NPP on 26 April 1986. The infringements of operation regulations made by the personal of the Unit 4 could only contribute to the scale of the accident. It was very possible that the most severe destructions of the reactor were caused by the nuclear explosion that happened after the steam explosion.

The Chernobyl accident was practically "planned". Its roots lay in the history of the RBMK development. The RBMK design was developed by the same organizations and specialists that were involved in the development of the Soviet nuclear weapon. Therefore, the same level of secrecy was brought in the development of nuclear power reactors for electricity generation. It was forbidden in the USSR to make public any information about incidences even at foreign NPPs. The former deputy head of the department for the NPP construction supervision in the USSR Ministry of Power, Grigorii Medvedev remembered that the technical information about the accident at the Three Mile Iceland NPP was classified in the USSR [11]. No information was published in the USSR as a whole about various incidences and accidents at the Soviet NPPs. On the contrary, it was said every time that the Soviet NPPs were the safest in the world. Such statements were totally incorrect. A number of severe accidents occurred in the USSR before the Chernobyl accident [11]. They are listed below.

- ✧ On 7 May 1966, an accident occurred at an experimental boiling water reactor in Melekess (near to the city Gorjkii, now Nizhni Novgorod). In case of this accident, a power excursion appeared because of chain reaction by prompt neutrons. The operator and shift foreman received high doses of irradiation.
- ✧ During 1964 – 1979, a series of destruction of fuel channels occurred in the reactor of the Unit 1 of the Beloyarsky NPP. The reactor of this NPP was of a channel-type reactor quite similar to the RBMK. These accidents caused every time a significant irradiation of the personnel.
- ✧ On 7 January 1974, an accident happened at the Unit 1 of the Leningrad NPP. In case of this accident, a ferroconcrete gasholder of the system to retain radioactive gases was destroyed. There were no victims by this accident.
- ✧ On 6 February 1974, a rupture of the intermediate circuit of the Unit 1 of the Leningrad NPP occurred

because of water boiling in it. Three persons were killed by this accident. High radioactive water together with radioactive sludge of the filter powder was discharged into the environment.

✧ In October 1975, a partial destruction of the core of the Unit 1 of the Leningrad NPP occurred. The reactor was shut down and the core was cleaned on the next day after the shutdown by pumping of an emergency reserve of nitrogen through the core to the ventilation chimney. Consequently, approximately 1.5 million Curie of radioactive substances was discharged into the environment.

✧ In 1977, 50% of fuel channels were melted in the core of the Unit 2 of the Beloyarsky NPP. The reactor of this NPP was of a channel-type also quite similar to the RBMK. Repairing of the reactor was about 1 year long. The high irradiation of the personnel occurred.

✧ On 31 December 1978, a large fire at the Unit 2 of the Beloyarsky NPP. The fire was initiated through a downfall of a covering plate of the powerhouse hall on the turbine oil tank. 8 persons received high doses during an organization of the core emergency cooling.

✧ In September 1982, a fuel channel in the center of the core of the Unit 1 of the Chernobyl NPP was destroyed as a result of mistakes made by the personnel. A large amount of radioactive substances was released to the industrial site of the NPP and the city Pripyat. The personnel involved in the liquidation of the consequences of this accident received high irradiation doses.

✧ In October 1982, the generator of the Unit 1 of the Armenian NPP exploded. The hall for the turbogenerator burnt down. The main part of the personnel of the NPP simply fled from the plant leaving it in the emergency state. The special operative group of specialists from the Kolsk NPP flew by an airplane and helped to save the Armenian NPP.

✧ On 27 June 1985, an accident occurred at the Unit 1 of the Balakovo NPP. One secure valve of the cooling circuit was pulled out. Therefore, the water steam at the temperature 300 ^{o}C came to a room where people worked. 14 people were killed by this accident. The accident happened because of an unusual tempo of the work and because of low experience of people.

✧ In August 1985, a severe accident happened in the bay near Vladivostok when reloading submarine reactors [22]. This time, a water-water type reactor exploded. 10 people were killed by the accident. The spontaneous chain reaction with a high release of energy arose. It caused a prompt evaporation of the coolant. As a result of the explosion, the core with the fresh fuel was thrown to the pier. This accident demonstrated clearly that water-water nuclear reactors can explode too.

Unfortunately, the information about these and other accidents was accessible only for high authorities. The Soviet government forced the construction of nuclear power plants because this energy source was considered in the USSR as a sign of the technological development. This practice did not allow the Soviet specialists to improve the safety of nuclear powers. Such situation inspired them with an idea that nuclear power plants do not differ significantly from the conventional power plants.

Detailed study of the accidents at nuclear power reactors in the USSR could have significantly increased the safety culture and prevent the Chernobyl accident. Already at the end of 1975 specialists could understand that the partial destruction of the core at the Unit 1 of the Leningrad NPP in October 1975 was caused by the positive reactivity surge [23]. The Chief Scientific Supervisor suggested a solution of this problem: operation of RBMKs with permanent presence of a quite high number of additional neutron absorbers in the lower part of the core and use of fuel with higher enrichment. This recommendation was implemented only after the Chernobyl accident.

The reasons of the accident that happened in October 1975 at the Leningrad NPP or at other Soviet NPPs was never discussed at scientific workshops and meetings. The similar power excursion because of positive steam-void coefficient occurred also at the Unit 1 of the Chernobyl NPP in September 1982 [23]. There were still similar situations at other RBMKs when the central fuel channel was destroyed [23]. However, practically nothing was made in order to eliminate even known shortages of the RBMK reactor.

Two reasons were responsible for this strange practice. The first was the hyper-secrecy even in the field of the peaceful use of the nuclear energy. At second, such policy arose from the poor economics of RBMKs. According to [23], the constant use of a large number of additional absorbers in the core and the increase in the fuel enrichment were considered to decrease the competitiveness of this type of the nuclear reactor as much as it could not compete with any other sources of the energy. At the same time, the Soviet industry was not able to produce enough vessels for PWRs that could find a very bright use in other countries of the world. The USSR was practically forced to construct and operate such unsafe reactors as RBMKs.

The next complication arose from the fact that the Soviet specialists had not enough possibilities for detailed study of nuclear reactors in various situations. This was the reason why the designer of the RBMK was not able to receive a clear imagination about all features of it. All these circumstances resulted at the end in the Chernobyl accident, which caused immense losses for the USSR. This accident made also very negative influence on the development of the nuclear industry in the whole world.

The authorities of the former USSR tried to save the image of the Soviet nuclear industry and the political system of the country. In order to achieve this goal the Soviet specialists at the Post-Accident Review Meeting held on 25-29 August 1986 in Vienna, Austria [2] tried to put the responsibility for the accident on the operation stuff of the 4th Unit of the Chernobyl NPP[3]. This attempt was totally inadequate because the operating stuff as it was established later by the Sternberg commission [4] operated in frames of the existed regulations and instructions.

Conclusions

The main reasons of the accident at the Chernobyl NPP were sever shortages of the design, severe infringements of the safety regulations for construction of the reactor as well as low safety culture in the USSR preceding the accident. These factors were responsible for various errors of the operators that tried to carry out the electromechanical experiment at the time of shutdown of the Unit 4 of Chernobyl NPP. The reactor was brought by operators into unstable regime of operation in which a positive reactivity surge was introduced to the core. Possibly, the accident began from the boiling of water in some fuel channels in the lower part of the core because of a small temperature surplus. The pressing of the button AZ-5 by which all control and protection absorbing rods began to insert into the core increased the positive reactivity surge instead to decrease it. This caused fission chain reactions by prompt neutrons and uncontrolled excursion of the power. There is a high possibility that a number of explosions occurred in the core. One of these explosions was a nuclear explosion that destroyed the reactor of the Unit 4 of the Chernobyl NPP. The further studies are required in order to establish the real initiating factors of the Chernobyl accident and the real scenario of it.

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