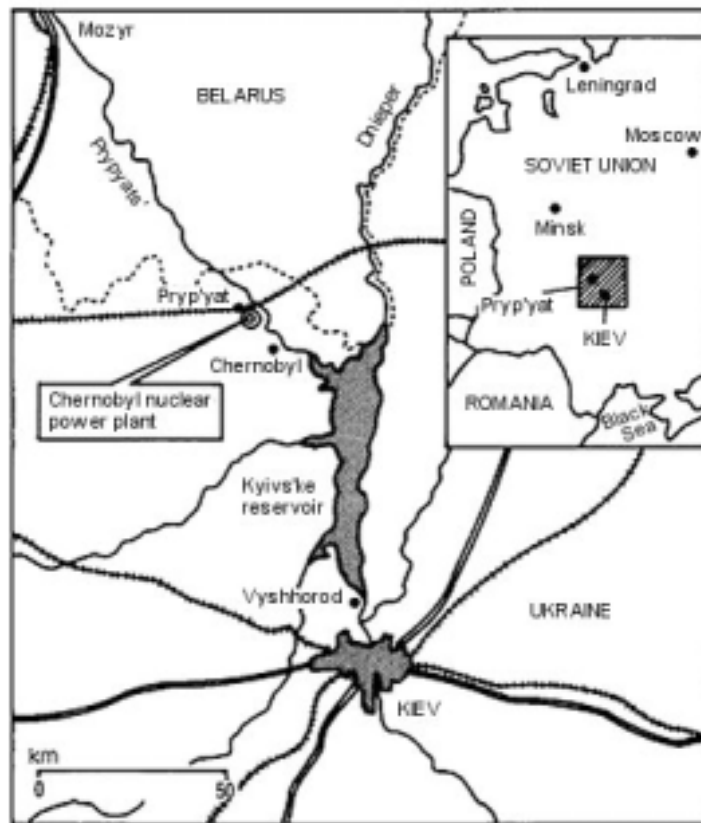


Chernobyl Accident

April 26, 1986 at the Chernobyl nuclear power plant, Prip'yat, Ukraine (then part of the Soviet Union)

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The Chernobyl station was testing the Unit 4 reactor's turbine generator to determine the turbine power generation in the rundown phase (Figure 1). Flaws in the reactor design that it could easily cause nuclear burst and inadequate operators' judgment caused the power of the reactor to increase rapidly during the test. The following explosion blew up the reactor building. The death toll reached 31 as of the end of July, 1987, and 135,000 people living within a 30 km radius of the plant were evacuated. The accident released a significant amount of radioactivity throughout the world contaminating agricultural produce including milk, meat and vegetables. Hundreds of thyroid cancer cases and deaths have been reported, however, the situation has not been very clear.



(New York Times, April 30, 1986)

Figure 1. Location of the Chernobyl Nuclear Power Plant [2]

1. Event

The Chernobyl station was testing the Unit 4 turbine generator to determine the turbine power generation

in the rundown phase. The power of the reactor increased rapidly during the test. A large steam explosion destroyed the reactor building. The death toll reached 31 as of the end of July in 1987, and 135,000 people living within a 30 km radius of the plant were evacuated. The accident released a significant amount of radioactivity worldwide, contaminating agricultural produce including milk, meat and vegetables. The accident released a significant amount of radioactivity throughout the world contaminating agricultural produce including milk, meat and vegetables. Hundreds of thyroid cancer cases and deaths have been reported, however, the situation has not been very clear.

2. Course

The reactor at Chernobyl is a RBMK (*reaktor bolshoy moshchnosti kanalnyy*, which means in English “reactor of large power of the channel type”) reactor that uses light water for cooling and graphite for moderation. As Figure 2 shows, an RBMK employs long (7 meter) vertical pressure tubes running through graphite moderator. The 1,693 pressure tubes (80 mm caliber, 88 mm outside diameter) are made of zirconium alloy and called channels. Fuel is low-enriched uranium oxide made up into fuel assemblies 3.5 meters long. The water pumps inject coolant water (270 degrees C, 70 millibars) into the tube from its bottom at a rate of 1.2 m/ sec. The coolant water, evaporating partially, removes heat from the fuel assemblies as it passes through the core. The steam-water mixture then continues to the large separator drums in which the water settles. The steam proceeds to the turbines, generating power. Temperature of graphite reaches 600 degrees C during normal operation.

The aim of the test was to determine the ability of the reactor’s turbine generator to generate sufficient electricity to power the reactor’s Emergency Core Cooling System (in particular, the water pumps) in the event of a loss of external electric power.

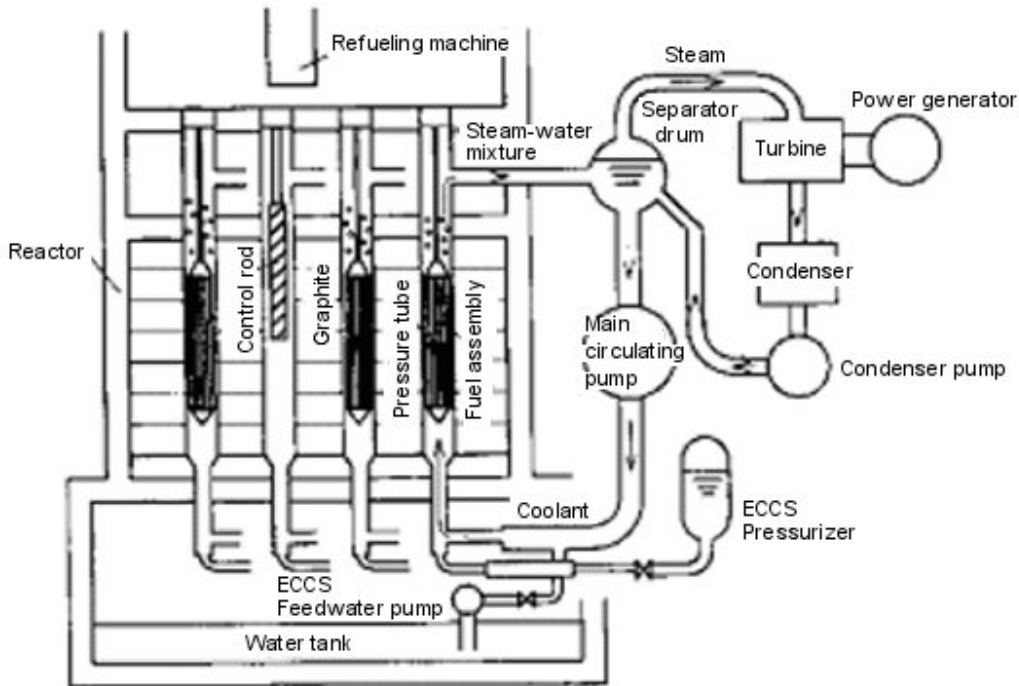
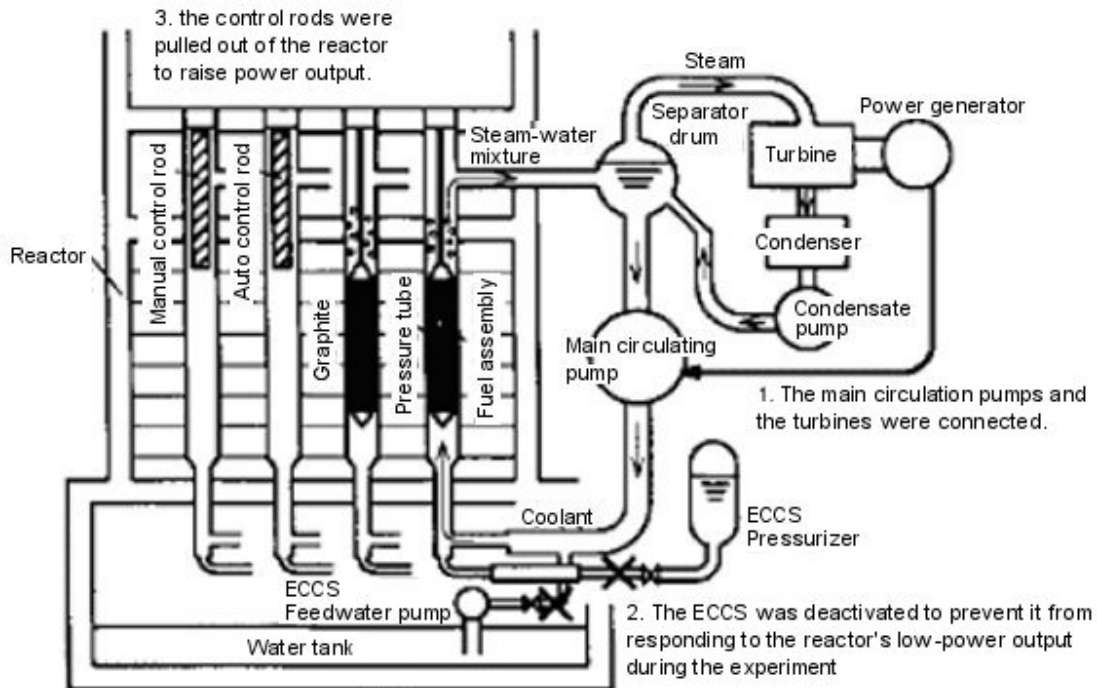


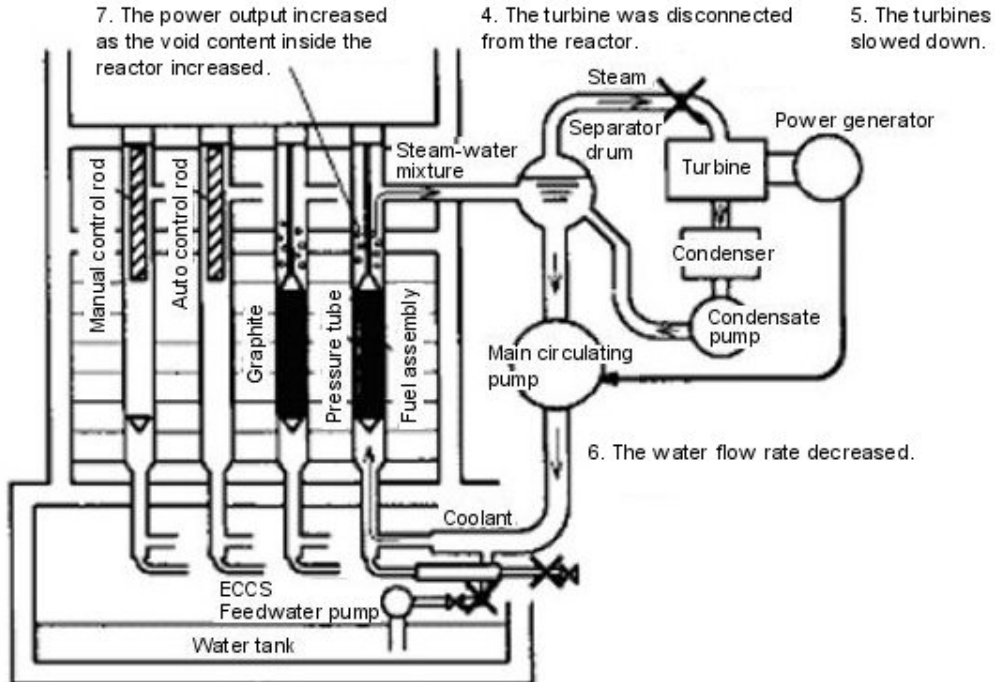
Figure 2. The RBMK Graphite-Moderated Reactor and Heat Cycle [1]

The experiment started after connecting the main circulation pumps and the turbines (1) and deactivating ECCS so that it would not respond to the reactor's low-power output during the experiment (2). The reactor operators reduced the power level too rapidly, close to the maximum scale of the power drop allowed by safety regulations. Then, the control rods were pulled out of the reactor somewhat farther than normally allowed by safety regulations to raise the power output (3). Then there was hardly any margin left to safely control the reaction in the reactor. Nevertheless, the operators shutdown the steam supply to the turbine to continue the test(4), and the turbines slowed down to coast (5). The recirculation pumps that were receiving power from the generator then slowed down and the cooling water flow dropped (6). The reactor then gained reactivity and the power started to rise (7). Automatic control rods were inserted in an attempt to lower the power, however, their slow speed failed to suppress the reactivity rise (8). The operators further ordered full insertion of emergency control rods (9), however, inserting these rods chased out the cooling water and the first 6 seconds rather boosted the reactivity. Soon a nuclear burst started further raising the fuel temperature and they ruptured (10). It was only 40 seconds after the experiment had started. Sudden steam generation stopped the coolant water circulation and the fuel temperature reached 3,000 – 4,000 degrees C. By that time the entire core coolant was boiling and the steam pressure rapidly increased (11). The pressure tubes ruptured to let the coolant water to gush out (12) which then came in contact with the graphite moderators and a steam explosion occurred. The explosive force blew off the reactor lid and the upper part of the reactor and the reactor building was destroyed (13). A second explosion threw out fragments of burning fuel and graphite from the core and allowed air to rush in, causing the

graphite moderator to burst into flames (14).



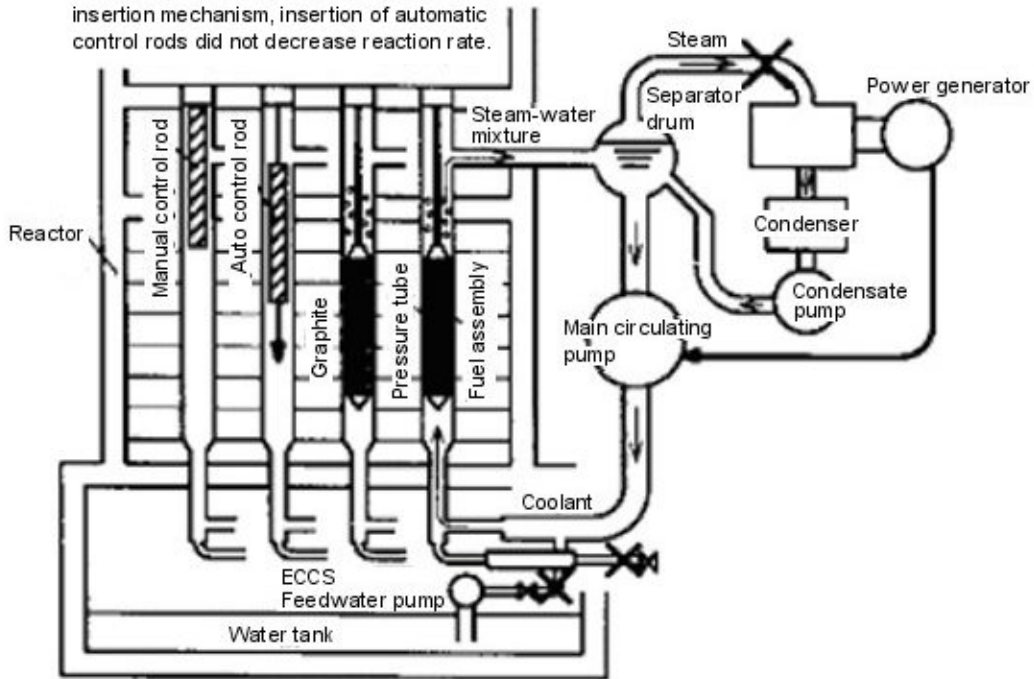
1. Preparation of the experiment



2. Experiment started

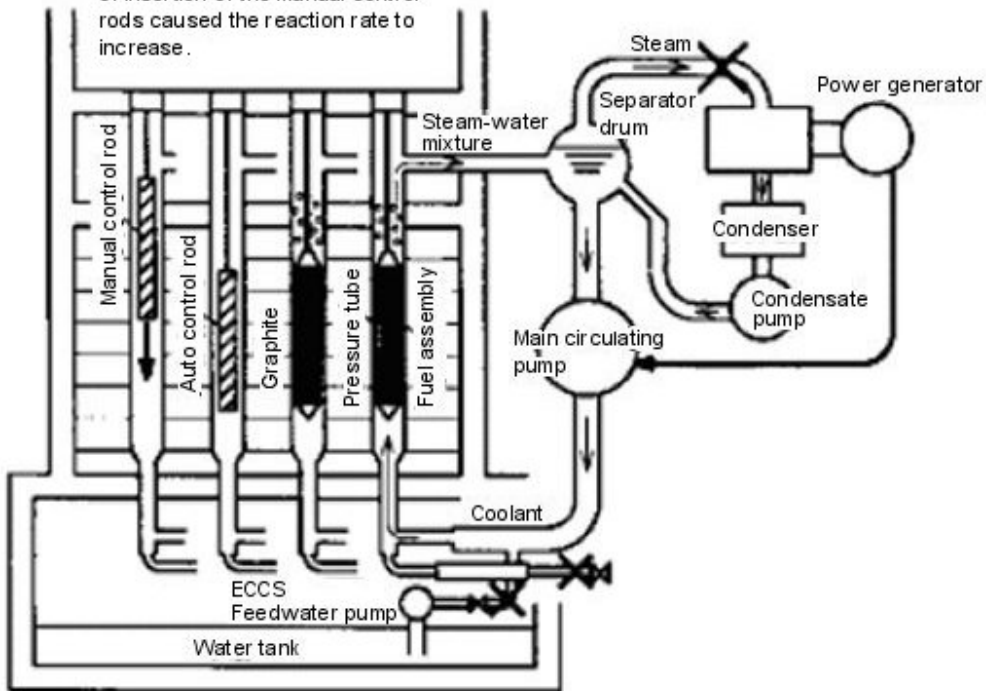
Figure 3. Chernobyl Accident: Sequence of Events 1 [1]

8. Due to the slow speed of the control rod insertion mechanism, insertion of automatic control rods did not decrease reaction rate.



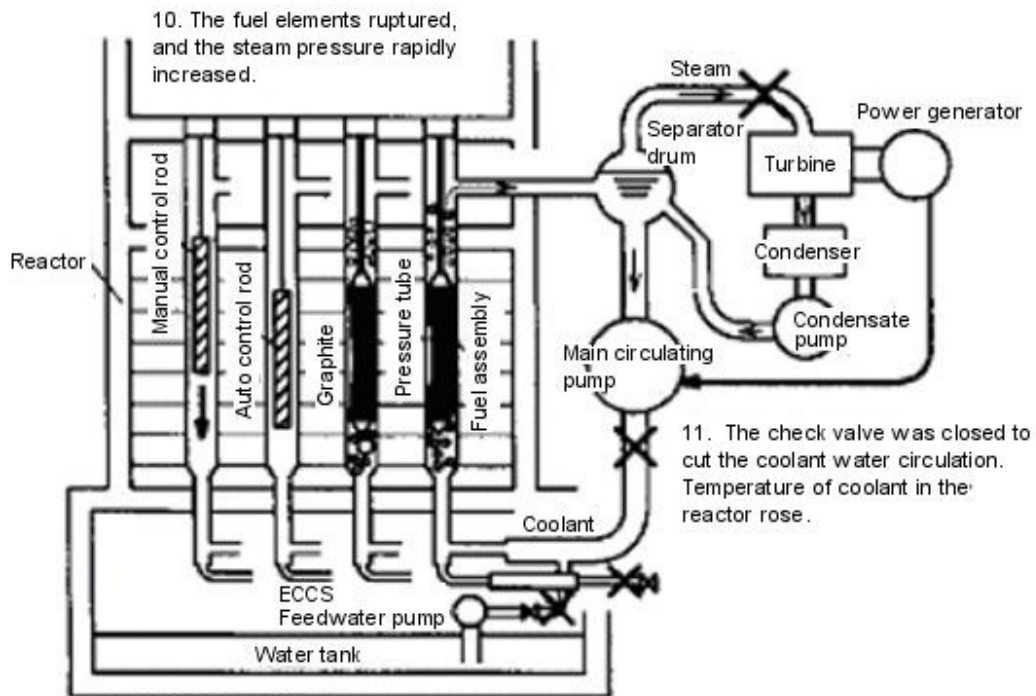
3. Experiment: 20 seconds

9. Insertion of the manual control rods caused the reaction rate to increase.

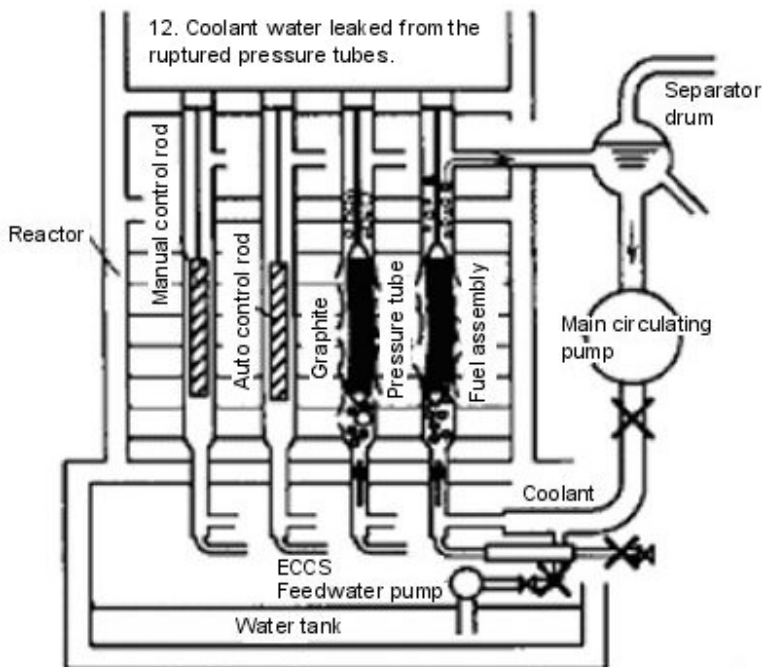


4. Experiment: 36 seconds

Figure 4. Chernobyl Accident: Sequence of Events 2 [1]



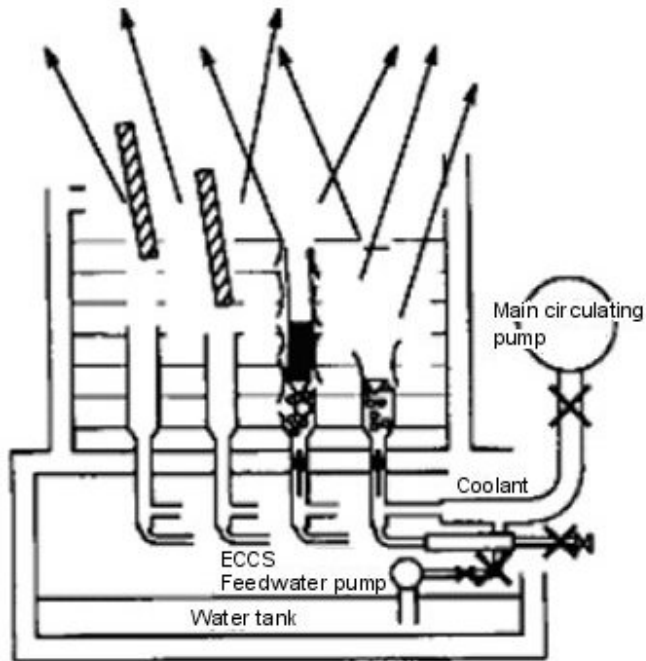
5. Experiment: 40 seconds



6. Experiment: 43 seconds

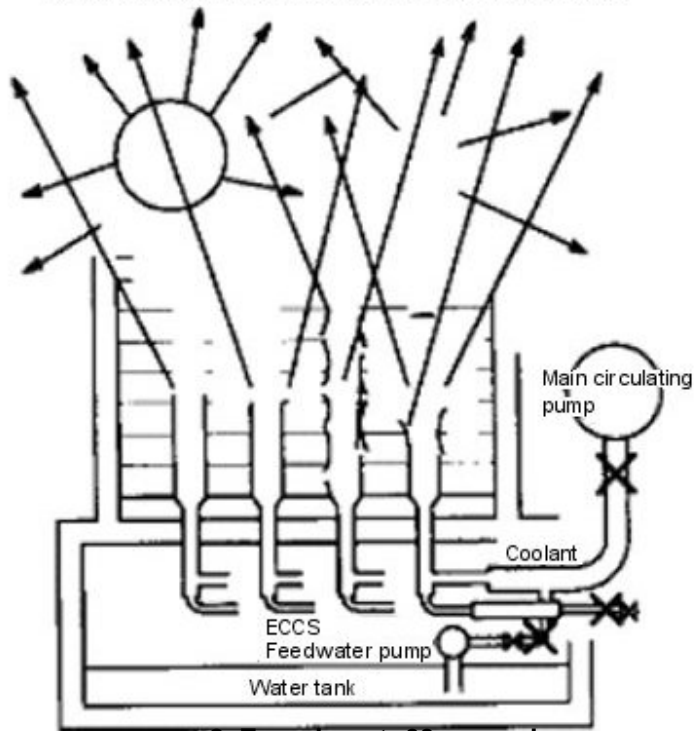
Figure 5. Chernobyl Accident: Sequence of Events 3 [1]

13. The explosive force of steam lifted off the cover plate of the reactor.



7. Experiment: 44 seconds

14. The second explosion threw out fragments of burning fuel and graphite from the core and sparked a graphite fire.



8. Experiment: 60 seconds

Figure 6. Chernobyl Accident: Sequence of Events 4 [1]

3. Cause

(1) Reactor without self controlability

This nuclear reactor was designed to have a positive output coefficient (ratio of the output to feedback when the output is added by a unit) during lower power operation. A positive output coefficient works to generate voids from the cooling water when it touches the fuel to raise the reactivity which then further increases the void generation to add reactivity. This was a basic design that can easily cause a reactivity accident (a runaway reaction). They avoided reactivity accidents with an operation rule to disallow operations at low power.

(2) Control rod design flaw

In a nuclear reactor, control rods are inserted into the reactor to slow down the reaction. However, in the RBMK reactor design, inserting the emergency control rods increased the reactor's power output because the partially hollow control rod extenders displaced coolant water.

(3) Reactor operators uninformed of design flaws

The Ministry of Machine Building, responsible for designing and building the reactors, did not inform details on the reactor to the Ministry of Atomic Energy that was responsible for operating reactors. The management and the operators were not informed about the reactor's unstableness and danger during low-power operation.

(4) Un reliable instrumentation

The pressure tubes were made of 4mm thin pipes. They were not strong enough to hold against pressure increase in abnormal circumstances. The reactor scheme had potential danger of a steam explosion caused by the extremely high temperature of graphite moderator and coolant water leaked from ruptured pressure tubes. The reactor core had neither a steel pressure vessel nor containment for pressure-proof. The reactor core had many pressure tubes running through vertically. The containment structure was relatively difficult to design because it must allow fuelling. Also, in order to allow fuelling, the reactor building was tall. The reactor building did not have a robust structure – the walls had only concrete slabs on trussed structure.

4. Immediate Action

To manage the immediate crisis, from April 28 to May 2, helicopters dumped boron, lead, clay, sand, and dolomite (5,000 tons in total) to smother the fire and cover the reactor. The government sent in 300,000 workers to close up the reactor. Despite their efforts, a large amount of radioactivity spread over the world. The worst contamination was reported in the area 300km north of Chernobyl station. The area within a 30km radius from the reactor was evacuated where it is still closed. There is evidence of leukemia due to radiation exposure from Chernobyl among people evacuated from the contaminated area and the workers involved in the recovery and cleanup after the accident. Some illness-related suicides are also reported. A

risk of genetic disorder due to radiation exposure from Chernobyl may become evident in future.

5. Countermeasure

The accident investigation committee of the Soviet Union reported that the accident was attributed to flaws in the RBMK reactor design and negligence of the power plant operators. However, anticipating public confusion and distrust, Politburo placed the blame solely on the power plant operators and the Ministry of Atomic Energy, which was responsible for operating reactors. Being afraid of stirring up international opinion against nuclear power generation in the Western countries at that time, the Soviet Union concealed the reactor flaws from The International Atomic Energy Agency (IAEA) at its General Conference.

In 1991, 5 years after the accident, the accident evaluation committee published its report and attributed the accident to flaws in the RBMK reactor design. The IAEA also acknowledged in 1992 that the RBMK reactor had design flaws. There is an ongoing investigation and study at the site about the actual sequence of events and circumstances.

6. Summary

A flawed reactor design operated by inadequately trained personnel and without proper regard for safety resulted in catastrophic steam explosions. Governmental organizations concealed crucial information about the reactor to evade their responsibility and placed the blame solely on the power plant operators. It delayed determination of the true cause including the reactor's design flaws. Since the Chernobyl accident, remaining RBMKs have been operated with some improvements, considerably enhancing their safety.

7. Knowledge

- (1) Unstable mechanism increases a risk of a devastating incident in which a small incident often leads to a deadly one. In particular, flaws in a large-scale system may result in a serious accident.
- (2) Designers must inform operators the reason for the given operational restrictions and the possible consequences of disobeying the rules so that the operators fully understand them.
- (3) Mechanical flaws and facts may be concealed to the for political reasons. For the technologies that have great impact on the society, the manufacturer should disclose its known issues and make improvement that the public approves.

8. Background

In the eastern part of Belorussia and the marsh-rich area, the Chernobyl station sits at the waterfront where the Prypyats' meets the Dnieper.

At the time of the accident, the Chernobyl station had 4 reactors in operation and 2 under construction. They were the RBMK, the boiling-liquidwater-cooled power reactors based on the Soviet Union's graphite-moderated plutonium production reactors designed to be able to produce plutonium for weapons as well as energy. The RBMK was built only in the Soviet Union, and it has benefits of refuel capability

while generating power, large gross capacity, and easier inland construction without need of heavy machinery. Its drawback was complicated control due to a great number of control rod channels.

The Unit 4 reactor at Chernobyl was an RBMK-1000, capable of producing 1,000KW of electric power.

The pressurized water reactor (PWR) and the boiling water reactor (BWR), typically used in nuclear power stations in Japan, use ordinary light water for both coolant and for neutron moderator. In the reactor core, the primary cooling circuit water is also the moderator, and if any of it turned to steam bubbles (void) the fission reaction would slow down (negative void coefficient). If the moderator and coolant are in separate circuits, or are of different materials, excess boiling of the coolant simply reduces the cooling and neutron absorption without inhibiting the fission reaction. Although the Unit 4 reactor had a large positive void coefficient, it was compensated by the negative feedback characteristic of the fuel under higher power conditions. However, at power conditions 20% lower than its normal capacity of 3.2 GW, the fuel's negative feedback fails to counter the positive feedback as the void form in the coolant water, making the reactor unstable and dangerous.

There was also a flaw in the safety system. The control rod insertion mechanism was too slow and it took more than 18 seconds to complete insertion of the control rods from their withdrawn position after the operators pressed the emergency button that ordered a full insertion of all control rods. The control rod insertion in the light-water reactor usually takes 2 – 4 seconds to complete.

References

- [1] Yotaro Hatamura (Editor), Jissai-no Sekkei (Practical Design) Research Foundation (1996) *Zoku-Zoku Jissai-no Sekkei (Practical Design III)*, The Nikkan Kogyo Shimbun, LTD.
- [2] Genshiryoku Hyakka Jiten (Nuclear Energy Encyclopedia), http://sta-atm.jst.go.jp/atomica/02070411_1.html
- [3] Koichi Hirokawa (1994) *Chernobyl Report*, Iwanami Shoten.