AFTrain'25

Yusuf Ziya Öner Science High School Model United Nations Conference

H-UNGASS

Agenda Item:

The Aftermath of Chernobyl Catastrophe

CO-Under Secretary General:

Gülşah Dirlik

CO-Under Secretary General:

Özge Koçalan

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Distinguished delegates,

It is with profound honor and an enduring sense of purpose that we extend our warmest welcome to you all for AFTRAIN’25. As the Secretaries General, we are genuinely honored to see this conference once again gather bright young minds who share a belief in dialogue, diplomacy, and cooperation.

First and foremost, gratitude must be extended to our dedicated academic and organization teams. Without their unwavering efforts, the vision we aim to share with our generation would have never come to life.

We live in a time when global knots grow more complex every day, yet it is also a time filled with opportunities. The work you will do here represents what diplomacy truly means, the ability to seek solutions, wind up those complications and connect them across tough conditions.

On behalf of the Secretariat, we wish you an inspiring and memorable experience. Let us bow our heads, the king is back!

Kind regards,

Kaan Muştu & Ömer T. Demirel

Co-Secretaries-General

AFTRAIN’25

II. Letter From Co-Under Secretary General

Honourable Delegates,

It is my great pleasure to welcome you all to AFTRAIN'25 and The Historical United Nations General Assembly Special Session (UNGSASS). My name is Gülşah, and I have the distinct honor of serving as your Co-Under-Secretary-General, alongside my beloved Co-Under-Secretary-General.

I am honored to welcome you to this Historical UNGASS session. It is truly exciting to lead such a rare committee format, as H-UNGASS is seldom seen in the MUN circuit. Combining this prestigious platform with an agenda item as fascinating as the Chernobyl catastrophe creates a unique challenge. I am thrilled to see how you will navigate this complex historical crisis and look forward to a high-level debate.

Additionally, due to my heavy academic workload, this comprehensive and extremely well-crafted guide would not have been possible without the extraordinary efforts of my Co-USG, Özge. I would like to express my deepest gratitude to her for her hard work and dedication in ensuring this guide is of the highest quality for all of you.

I kindly urge you to read this study guide thoroughly and attentively. While it will provide you with a strong foundation, it should not be your only source. Independent research will be critical in deepening your understanding and enriching the debates to come.

It is my heartfelt hope that you not only engage in meaningful, constructive discussions but also form lasting friendships and memories throughout this conference. May AFTRAIN'25 be an experience that is both intellectually rewarding and personally inspiring.

Sincerely,
Gülşah Dirlik

Co-Under-Secretary-General

III. Letter From Co-Under Secretary General

My most esteemed representatives,
It is my greatest honour to welcome you all to our committee, the Historical-United Nations General Assembly Special Session, and to this beloved conference, the Antalya Fen Model United Nations Train Conference.

As you all know, it is the year 1986, when this special session was called upon by the General Assembly. Historically, this catastrophe was discussed during the United Nations International Atomic Energy Agency sessions. Nevertheless, you, the most honoured representatives of your most honoured nations, have been chosen for this committee in this conference.

The world had witnessed the biggest nuclear disaster in the history of mankind. This disaster is not the outcome of merely the failure of men of power, a failing system nor a country, but of the greed of us all. This, as mentioned further in the study guide, is not the first nuclear disaster, and it will not be the last unless the way things are changes.

In this committee, we expect you all to manage your disagreements and search for the truth via your discussions. It is your duty as the representatives of your most honoured nations to shape our future. I would like to draw attention to the fact that this session takes place in the first half of 1986, which means that the information that has been internationally revealed and published is limited due to the censorship put on the disaster by the Soviet government.
Furthermore, I see the need to draw attention to the necessity of further researches upon your assigned representative, your country's politics and the approach to the matter of our agenda item alongside general researches upon the disaster.

I would like to wish the best for you all alongside my hopes for this prestigious conference to be up to your expectations.
With my best regards;
Özgenur KOÇALAN
Co-Under Secretary General

IV. Introduction of the Committee

The United Nations General Assembly Special Session (UNGSASS) is a special session assembled upon the request of the Security Council or of a majority of the Members of the United Nations, as mentioned under Chapter IV, article 20 of the United Nations Charter, *"Special sessions shall be convoked by the Secretary-General at the request of the Security Council or of a majority of the Members of the United Nations."* . However, since 1975, all special sessions have been called by the General Assembly (GA).
Each special session deals exclusively with one topic with a short agenda. They are typically high-level events with the participation of heads of state and government ministers.
A GA high-level meeting is a GA event on a specific issue or topic with the participation of the Heads of State, the Heads of Government, and the government ministers. As they are not part of the regular GA agenda, high-level meetings must be mandated by a GA resolution or decision. In these resolutions/decisions, high-level meetings are sometimes given other descriptive names. They are chaired by the President of the General Assembly (PGA). Sometimes, the outgoing and the incoming PGA are both invited to co-chair a high-level meeting that takes place at the beginning of a GA session. GA high-level meetings consist of formal plenary meetings and informal meetings and can last from one to several days.
GA high-level meetings consist of formal plenary meetings and informal meetings and can last from one to several days.

This session has been assigned by the General Assembly after the consideration of the recent nuclear disaster that had occurred in Chernobyl and the conclusion of the necessity of taking measures in order to decrease the harm of the radioactive fallout. It is your duty to participate in this session and draw a conclusion upon the matter as the heads of state.

V. Introduction to the Agenda Item

On 26 April 1986, Reactor Number 4 of the Vladimir Ilyich Lenin Nuclear Power Plant (known as the Chernobyl Nuclear Power Plant):
An unanticipated disaster occurred during a safety regulation test that had gone wrong after one too many errors. This safety regulation test, called the "turbine generator rundown test" or "loss-of-offsite-power turbine rundown test", was necessary due to the working principle of the RBMK-1000 (*Реактор большой мощности канальный, РБМК; Reaktor Bolshoy Moshchnosti Kanalnyy RBMK, high-power channel-type reactor*). The operators of the night shift carried out the test despite learning about the test as they began their shift, an accidental drop in reactor power, and due to design issues, attempting to shut down the reactor in those conditions resulted in a dramatic power surge. The reactor components ruptured and lost coolant, and the resulting steam explosions and meltdown destroyed the reactor building. This was followed by a reactor core fire that spread radioactive contaminants across the Soviet Union and Europe. Following the explosion, which resulted in the direct death of two engineers (*Valery Alekseyevich Khodemchuk*: stationed in the southern main circulating pumps engine room, his body was never found, likely buried under the wreckage of the steam separator drums; he has a memorial sign in the Reactor 4 building; and *Vladimir Nikolaevich Shashenok*: stationed in Room 604, found unconscious and pinned down under a fallen beam, with a broken spine, broken ribs, and deep thermal and radiation burns; he died in the hospital without reworkers whoworkers, who were hospitalised showed symptoms of acute radiation syndrome (ARS); 28 of them died within three months after the disaster. Over the next decade, 14 more workers (nine of whom had ARS) died due to various causes, mostly unrelated to the radiation exposure.

36 hours after the accident, a 10-kilometre exclusion zone was established and followed by the evacuation of approximately forty-nine thousand (49,000) people. Later, the exclusion zone was expanded to 30 kilometres and followed by the exclusion of approximately sixty-eight thousand (68,000) more people. The city of Pripyat *(Прип'ять, known as Prypiat),* built to house the families of the workers of the Chernobyl Nuclear Power Plant, was abandoned and replaced by the city of Slavutych (Славутич).

The Chernobyl Nuclear Power Plant sarcophagus, or Shelter Structure *(Ukrainian: Об'єкт "Укриття", romanised: Ob'yekt "Ukryttya", Russian: Объект «Укрытие», romanised: Ob'yekt «Ukrytiye»)* is the name of the massive steel and concrete structure covering Reactor 4 of the Chernobyl Nuclear Power Plant, built in 1986 in the aftermath of the disaster in order to reduce the spread of radioactive contamination and to provide radiological protection for the undamaged reactors.

VI. Explanation of Atomic/Nuclear Energy

Atomic/nuclear energy is the form of energy that is released through a nuclear reaction or radioactive decay process caused by the nucleus, the core of atoms, made up of protons and neutrons.
This source of energy can be produced in two ways: fission, when nuclei of atoms split into several parts, or fusion, when nuclei fuse together.

A. Nuclear Fission

Nuclear fission is a reaction where the nucleus of an atom splits as a result of a neutron slamming into a larger atom, forcing it to excite and split into two or more smaller nuclei and atoms (also known as fission products) while releasing a tremendous amount of energy. For instance, when hit by a neutron, the nucleus of an atom of uranium-235 splits into two smaller nuclei, for example, a barium nucleus and a krypton nucleus, and two or three neutrons. These extra neutrons will hit other surrounding uranium-235 atoms, which will also split and generate additional neutrons in a multiplying effect, thus generating a chain reaction in a fraction of a second. Each time the reaction occurs, there is a release of energy in the form of heat and radiation. This chain reaction is the fundamental principle behind nuclear warheads and nuclear power plants, as the only difference is the control of the reaction.

1. Uranium

Uranium ($_{92}U$) is a common element on Earth and has existed since the planet formed. While there are several varieties of uranium, uranium-235 (^{235}U or U-235) is the one most important to the production of both nuclear power and nuclear bombs. U-235 decays naturally by alpha radiation: it throws off an alpha particle, or two neutrons and two protons bound together. It is also one of the few elements that can undergo induced fission. Firing a free neutron into a U-235 nucleus causes that nucleus to absorb the neutron, become unstable and split immediately. The decay of a single U-235 atom releases approximately 200 MeV (million electron volts). That may not seem like much, but there are lots of uranium atoms per kilogram of uranium. So many, in fact, that a kilogram of highly enriched uranium, as used to power a nuclear submarine, is equal to about 8,344,312.61 litres of gasoline.

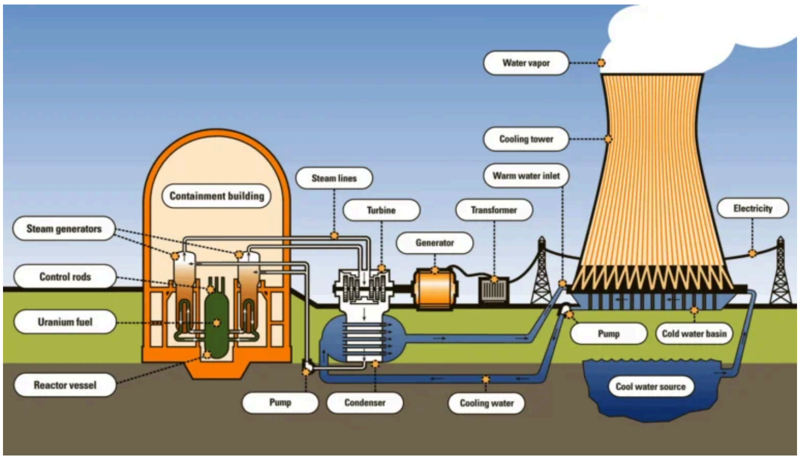
2. Plutonium

Plutonium ($_{94}PU$) is a rare element on Earth, as all the plutonium that had existed in the Earth's crust has decayed except for trace quantities, unlike uranium. All the usable $_{94}Pu$ is formed in nuclear power reactors from ^{238}U by neutron capture.

Plutonium-239 (^{239}Pu orPu-239) is the most significant isotope of $_{94}Pu$ for both nuclear energy and nuclear weapons, as it is radioactive by its nature, and it decays by alpha radiation, emitting an alpha particle consisting of two protons and neutrons. In addition, Pu-239 is one of the few materials capable of induced nuclear fission. The nucleus of Pu-239 absorbs the neutron and becomes excited, followed by splitting into two smaller atoms within a second and triggering a self-sustaining chain fission reaction, alongside releasing major amounts of energy after being hit by a neutron. The fission of a single Pu-239 atom releases approximately 210 MeV of energy, slightly more than the amount released by U-235. As this amount of energy is insignificant on the scale of a single atom, one kilogram of Pu-239 releases energy equivalent to millions of litres of gasoline.

B. The Working Principle of a Nuclear Power Plant

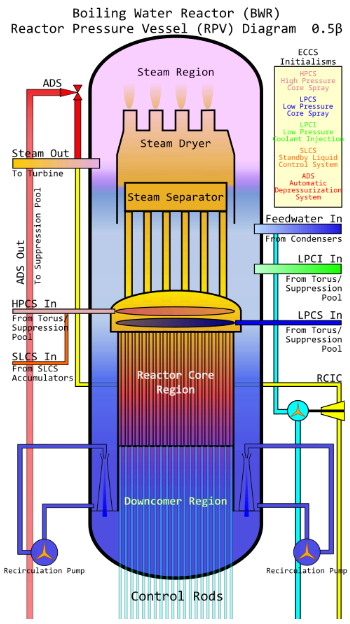
A nuclear power plant (NPP), also known as a nuclear power station (NPS), nuclear generating station (NGS) or atomic power station (APS), is a thermal power station in which the heat source is a nuclear reactor. As is typical of thermal power stations, heat is used to generate steam that drives a steam turbine connected to a generator that produces electricity. While older plants burn fossil fuels, nuclear plants depend on the heat that occurs during nuclear fission, when one atom splits into two and releases energy. Nuclear fission happens naturally every day. Uranium, for instance, constantly undergoes spontaneous fission at a very slow rate. This is why the element emits radiation and why it is a natural choice for the induced fission that nuclear power plants require.



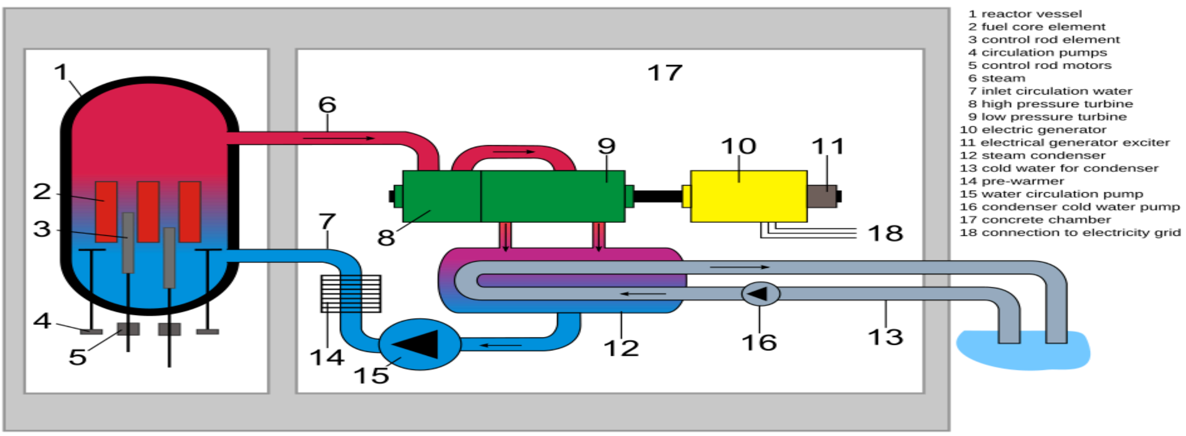
1. Nuclear Reactors

The nuclear reactor is the heart of the station. In its central part, the reactor's core produces heat due to nuclear fission. With this heat, a coolant is heated as it is pumped through the reactor and thereby removes the energy from the reactor. The heat from nuclear fission is used to raise steam, which runs through turbines, which in turn power the electrical generators. Nuclear reactors usually rely on uranium to fuel the chain reaction.

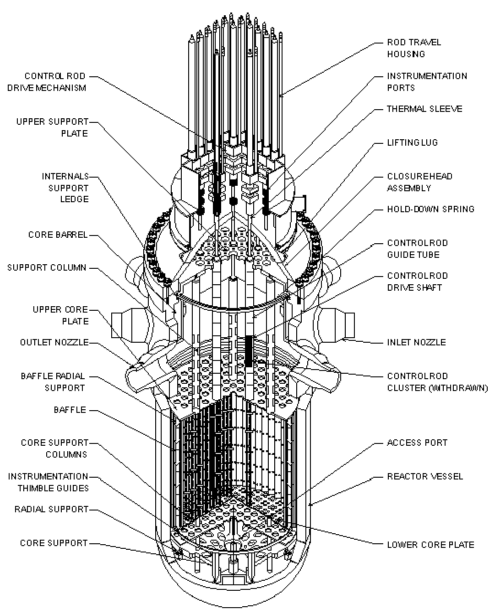
Boiling Water Reactors:



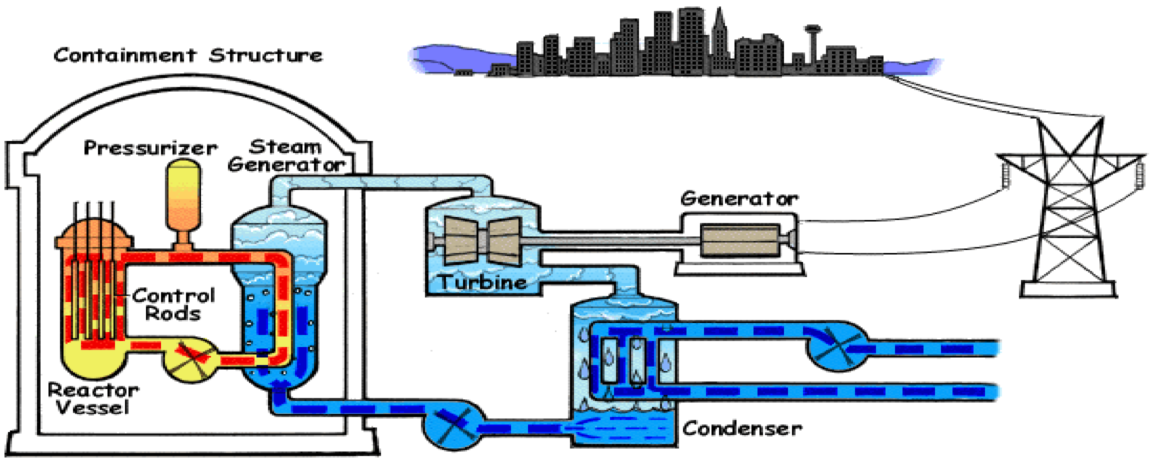
A boiling water reactor uses demineralised water as a coolant and neutron moderator. Heat is produced by nuclear fission in the reactor core, and this causes the cooling water to boil, producing steam. The steam is directly used to drive a turbine, after which it is cooled in a condenser and converted back to liquid water. This water is then returned to the reactor core, completing the loop. The cooling water is maintained at about 75 atm (7.6 MPa, 1000–1100 psi) so that it boils in the core at about 285°C (550°F). In comparison, there is no significant boiling allowed in a pressurised water reactor (PWR) because of the high pressure maintained in its primary loop—approximately 158 atm (16 MPa, 2300 psi). The core damage frequency of the reactor was estimated to be between 10^{-4} *and* 10^{-7} *(i.e., one core damage accident per every 10,000 to 10,000,000 reactor years).*



Pressurised Water Reactors:



In a PWR, water is used both as a neutron moderator and as coolant fluid for the reactor core. In the core, water is heated by the energy released by the fission of atoms contained in the fuel. Using very high pressure (around 155 bar: 2250 psi) ensures that the water stays in a liquid state. The heated water then flows to a steam generator, where it transfers its thermal energy to the water of a secondary cycle kept at a lower pressure, which allows it to vaporise. The resulting steam then drives steam turbines linked *to an electric generator. A boiling water reactor (BWR), by contrast, does not maintain such a high pressure in the primary cycle, and the water thus vaporises inside of the reactor pressure vessel before being sent to the turbine. Most PWR*



designs make use of two to six steam generators, each associated with a coolant loop.

2. **The Core**

Since nuclear fission creates radioactivity, the reactor core is surrounded by a protective shield. This containment absorbs radiation and prevents radioactive material from being released into the environment. In addition, many reactors are equipped with a dome of concrete to protect the reactor against both internal casualties and external impacts.

3. **The Control Rods**

To prevent overheating, control rods made of a material that absorbs neutrons are inserted into the uranium bundle using a mechanism that can raise or lower them. Raising and lowering the control rods allow operators to control the rate of the nuclear reaction. When an operator wants the uranium core to produce more heat, the control rods are lifted out of the uranium bundle (thus absorbing fewer neutrons). To reduce heat, they are lowered into the uranium bundle. The rods can also be lowered completely into the uranium bundle to shut the reactor down in the event of an accident or to change the fuel.

4. **The Turbine**

The purpose of the steam turbine is to convert the heat contained in steam into mechanical energy. The engine house with the steam turbine is usually structurally separated from the main reactor building. It is aligned so as to prevent debris from the destruction of a turbine in operation from flying towards the reactor and important safety systems.

In the case of a pressurised water reactor, the steam turbine is separated from the nuclear system. To detect a leak in the steam generator and thus the passage of radioactive water at an early stage, an activity meter is mounted to track the outlet steam of the steam generator. In contrast, boiling water reactors pass radioactive water through the steam turbine, so the turbine is kept as part of the radiologically controlled area of the nuclear power station.

5. The Outer Surroundings of the Reactor Core

A concrete liner typically houses the reactor's pressure vessel and acts as a radiation shield. That liner, in turn, is housed within a much larger steel containment vessel. This vessel contains the reactor core, as well as the equipment that plant workers use to refuel and maintain the reactor. The steel containment vessel serves as a barrier to prevent leakage of any radioactive gases or fluids from the plant.
An outer concrete building serves as the final layer, protecting the steel containment vessel. This concrete structure is designed to be strong enough to survive the kind of massive damage that might result from earthquakes or a crashing jet airliner. These secondary containment structures are necessary to prevent the escape of radiation/radioactive steam in the event of an accident. (The absence of secondary containment structures in Russian nuclear power plants allowed radioactive material to escape in Chernobyl.)

6. The Electric Generators

The electric generator converts mechanical power supplied by the turbine into electrical power. Low-pole AC synchronous generators of high rated power are used. A cooling system removes heat from the reactor core and transports it to another area of the station, where the thermal energy can be harnessed to produce electricity or to do other useful work. Typically the hot coolant is used as a heat source for a boiler, and the pressurised steam from that drives one or more steam turbine-driven electrical generators.

VII. Historical Background of the Agenda Item

A. The History of Nuclear Energy

Throughout human history, perhaps the most misunderstood phenomenon has been radiation. Despite its well-known effects, even today the word ‘radiation’ still evokes a terrifying, extreme reaction in most people. In the joyful years following its discovery at the beginning of the century, people adopted a more reckless attitude due to their illiteracy.

Marie Curie, the most famous pioneering researcher on radiation, died in 1934 from aplastic anaemia (severe anaemia) caused by years of unprotected exposure to the pale, shiny substances found in her pockets and desk drawers (radioactive elements). Together with her husband, Pierre Curie, she worked tirelessly in ‘an abandoned hovel used as the autopsy room of the Faculty of Medicine’ on the campus of the University of Paris, laying the foundations for Wilhelm Röntgen's discovery of X-rays in 1895. Curie herself wrote: "One of our sources of joy was going to our study at night... Those glowing test tubes looked like faint little decorative lights." The pair, researching the element uranium, discovered and named the new elements thorium, polonium and radium, and spent considerable time studying the effects of the unusual waves emitted by these four elements. Marie Curie named these waves ‘radiation’ and was awarded the Nobel Prize for her work. Until then, it was believed that the atom was the absolute smallest thing that existed. Atoms were considered whole, indivisible, and the building blocks of the universe on their own. Curie's discovery that atoms split when radiation was produced was a groundbreaking revelation. Curie's discovery that fluorescent radium destroyed diseased human cells faster than healthy ones led to the birth of a whole new industry in the first half of the 20th century, with people going door to door selling this miraculous new element (mostly imagined) to an uninformed and misguided public.

This craze was supported by experts, including Dr C. Davis, who wrote in the American Journal of Clinical Medicine that “Radioactivity prevents insanity, brings out noble sentiments, delays ageing, and creates an extraordinary, youthful and cheerful life.” *Wristwatches, nails, military instrument panels, sights, and even children's toys were manually painted with radium by young women working for the United States Radium Corporation* in factories. Unaware of the danger, these women licked the brushes they used for their delicate work, allowing radium particles to enter their digestive systems each time, but years later, their teeth and skulls would begin to disintegrate. ‘The modern weapon of curative science’ and Radithor, one of several medical radium products of the era, boasted of being able to cure people's rheumatism, arthritis and neuritis. *Radium condoms, chocolates, cigarettes, bread, wicks, wool, eye drops, the Scrotal Radiendocrinator (a product of the same genius who developed Radithor) to increase sexual potency in men, and even children's sandboxes, which were touted by the manufacturer as "more hygienic and... world-renowned healing mud baths*," as well as other radioactive products such as *children's sandboxes*, which were touted as being more beneficial than the mud from world-renowned healing baths. *Radium cosmetic products and toothpastes*, which were claimed to revitalise the skin and teeth, also maintained their popularity for several years.

The real dangers of radium, which is approximately 2.7 million times more radioactive than uranium, were not recognised or accepted by society until the 1930s and 1940s. While scientists across Europe made significant breakthroughs, the fervent efforts to unravel the mysteries of the atom continued throughout the early 20th century. In 1932, American physicist James Chadwick discovered the neutron and won the Nobel Prize; he had found the unknown up until that time. With Chadwick's discovery, the keys to the atom's structure had been unlocked: an atom consisted of a nucleus, a central section composed of protons and neutrons, surrounded by electrons. The atomic age had now truly begun.

A few years later, in 1939, physicists Lise Meitner, Otto Frisch, and Niels Bohr discovered that when an atomic nucleus splits into two new nuclei (a process known as nuclear fission), it releases an enormous amount of energy and that this fission (splitting) could cause a chain reaction. This discovery led to the theory that such a chain reaction could potentially be used to produce unlimited clean energy for ships, aeroplanes, factories and homes, or as a weapon of immeasurably destructive force. Just two days before the beginning of World War II, Bohr and John Wheeler published an article claiming that fission would work better in an environment containing a “moderator” to slow down the speed of neutrons moving within the atom, thereby increasing the likelihood of them colliding and splitting apart.

Once the hazards of radioactive materials were better understood and their popularity in society had waned, the hopelessness and inevitability of the Second World War led to other significant advances in this field. *Britain was the first* country to devote itself most fully to unravelling the mystery of the fission bomb. *Germany had a nuclear programme, but it focused on developing a power reactor.* After the Japanese attack on Pearl Harbour on 7 December 1941, *America, which had previously been focused on powering its navy with nuclear energy, began its first significant fission research*, allocating enormous resources for the development of the atomic bomb. Within a year, the world's first nuclear reactor, the Chicago Pile-1, was built at the University of Chicago as part of the American Manhattan Project, under the control of Enrico Fermi, winner of the Nobel Prize in Physics. Described by Fermi in his famous words as ‘a crudely assembled pile of black bricks and wooden poles’, this reactor first reached criticality (i.e., achieved a self-sustaining chain reaction) on 2 December 1942. This reactor, which used graphite as a moderator, had neither a radiation shield nor any cooling system. It was an enormous and reckless risk taken by Fermi, who had to convince his colleagues that his calculations were accurate enough to prevent any explosion.

A physicist named Georgi Flerov, upon returning from the front lines, noticed that all research on nuclear physics had vanished from recently published international scientific journals. Joseph Stalin then discovered that the United States, Britain, and Germany were conducting research on fission. This young man, who had discovered an artificial chemical element now named after him (Flerovium), realised that the articles had been classified and wrote a letter to Stalin saying, ‘Build the uranium bomb immediately,’ to emphasise the significance of their absence from the scene. The dictator took note of this letter and allocated more resources to the potential of fission energy. He ordered Igor Kurchatov, one of the leading Russian scientists, to focus on gathering intelligence on the Manhattan Project and to initiate any secret research that might be necessary for the Soviets to build the bomb. To do this in absolute secrecy, Kurchatov established a new laboratory in the wooded area of Moscow.

The Allied forces announced a victory over Germany on 8 May 1945, and America directed its focus to Japan. By this time, Kurchatov had made considerable progress; however, he still lagged behind the Americans, who had successfully tested the first atomic weapon on 16 June 1945 at 05:29:21 near Alamogordo, New Mexico, under the leadership of Robert Oppenheimer. Due to the uncertainty surrounding the results of the first test of such a destructive weapon, Fermi suggested that the physicists and military personnel present at the time place bets on whether the bomb would blow up in the atmosphere and whether this would destroy only the state or the entire planet. This explosion, codenamed ‘Trinity’, created a crater 365 metres in diameter and generated temperatures of ‘tens of millions of degrees Fahrenheit’. Physicist George Kistiakovski, terrified by what he witnessed, said, ‘When the end of the world comes, I believe that in the last millisecond of this planet’s existence, the last remaining human being will see what we just saw. Just three weeks later, on 6 August, a modified Boeing B-29 Superfortress dropped the first atomic bomb on the Japanese city of Hiroshima, with a population of 350,000. This bomb converted 0.6 grams of uranium into energy equivalent to 16,000 tonnes of TNT. A second bomb was dropped on Nagasaki three days later. Over 100,000 people, mostly civilians, lost their lives instantly. Japan surrendered three days later, and the Second World War came to an end. Despite these horrific sights, the initial fear in some parts of the world that such a small device could generate so much energy eventually turned into curiosity and optimism over time. Even so, weapons development continued.

Russia's first plutonium-producing reactor *(plutonium does not occur naturally, as previously mentioned)* began operating in Mayak in 1948, and in August 1949, the Russians conducted their first atomic bomb test in the deserts of Kazakhstan. Apart from the Soviet Union, the West was interested in the civilian use of fission's unprecedented energy potential. Five days before Christmas of 1951, America's small

Experimental Breeder Reactor 1 became the world's first electricity-producing reactor when it generated enough electricity to light four 200-watt bulbs. Two years later, in an address to the nation, US President Eisenhower announced the ‘Atoms for Peace’ programme with the following words: “We are determined to solve the atom's terrifying mystery—to do so, we must devote our whole hearts and minds to finding a way to use humanity's extraordinary creativity not to destroy life, but to bless it.”

The Atoms for Peace programme, which was partly a genuine initiative to support civilian infrastructure for nuclear power and encourage research, and partly a propaganda exercise to silence global critics of nuclear energy and provide a cover for developing nuclear weapons, led to the creation of America's nuclear power plants. One of Russia's existing military plutonium production reactors was redesigned for electricity generation, and, in June 1952, AM-1 *(AM-1: “Атом Мирный”, Atom Mirny, the Russian acronym for ‘Peaceful Atom 1’)* became the world's first civilian nuclear power plant, producing 6 megawatts of electricity (MWe). This plant was a graphite-moderated, water-cooled reactor that served as a prototype for the RBMK reactors at Chernobyl. Two years later, when Queen Elizabeth II opened Britain's first commercial 50 MWe nuclear reactor at Windscale, the government declared that Britain had “the world's first power station to generate electricity from atomic energy on a fully industrial scale.” Both of the world's leading superpowers recognised the clear potential advantages of a power source that would only require refuelling every few years for naval vessels and worked extensively to reduce the size of reactor designs. By 1954, miniaturisation had progressed so far that the United States launched the world's first nuclear submarine, the USS Nautilus, and within the next five years, both America and Russia possessed nuclear-powered surface vessels.

In the year 1973, the first high-power RBMK-1000 reactor *(the same type used at Chernobyl)*, which had been under construction for several years, was put into operation in Leningrad. At that time, the United States and most Western countries had reached a consensus that the Pressurised Water Reactor design, the safest option, slowed down and cooled by water, was the most secure choice.

For Further Consideration:

From the late 1970s to the early 2000s, the construction of new reactors was suspended as a reaction to the Chernobyl and Three Mile Island incidents and as a result of improvements in the power capacity and efficiency of existing reactors. Nuclear power reached its peak in terms of reactor numbers in 2002, with 444 reactors in use; however, the highest level of electricity generated from nuclear energy was achieved in 2006: 2,660 terawatt-hours in one year. As of 2011, more than 430 *commercial nuclear reactors operating in 31 countries met 11.7% of the world's electricity needs. When combined, these reactors produced 372,000 megawatts of electricity. Although Japan's Kashiwazaki-Kariwa Nuclear Power Plant, with its seven reactors producing 8,000 MW, is currently the largest nuclear facility, it is not in operation (is not in use) at present. France is the country most reliant on nuclear power, meeting 75% of its electricity needs from nuclear power plants, while the United States and Russia hover around 20%. Slovakia and Hungary are other countries that generated more than 50% of their electricity needs from nuclear power by the end of 2015, while Ukraine, where Chernobyl is located, still relies on nuclear power for 49% of its energy needs.*

Nuclear power has become a source of power for most large naval vessels. This situation reached its peak in the first half of the 1990s, when the number of nuclear reactors on ships (usually more than 400 submarines belonging to the military) exceeded the number of commercial power plants generating electricity. Although this number has declined since then, there are still approximately 150 ships and submarines equipped with nuclear reactors. Russia is building the world's first floating nuclear power plant barge for use in the Arctic region, which can be deployed wherever power is needed. The Akademik Lomonosov, which contains two naval reactors converted from icebreakers and has a capacity of 70 MW, is expected to be ready in September 2016. 27 Although the Russians claim to have the first barge that generates nuclear power, floating power stations are not a new idea. The United States built the first floating power plant by converting the Liberty ship, a vessel left over from the Second World War, in the late 1960s. However, none of these are currently in operation. China is also preparing to enter this market and anticipates that its first floating nuclear power plant will begin generating electricity in the 2020s.

1. A Comparison of the Damage Caused by Nuclear and Other Energy Production Methods

The total number of deaths resulting from accidents related to civil nuclear power is relatively low, considerably lower than the number of deaths occurring at conventional coal, oil and hydroelectric power stations.

To gain some perspective on this issue, let us consider the death tolls from the worst accidents involving conventional power sources. Coal mining, which is well known to be dangerous, causes serious fatalities. While just 32 major coal mining accidents caused nearly 10,000 deaths in total, coal mining accidents in the United States since 1893 have resulted in the deaths of more than 15,000 people. The worst of these incidents was the disaster at the Benxihu Coal Mine in China on 26 April 1942, exactly 44 years before the Chernobyl disaster, when a gas explosion killed 1,549 miners.

The Nigerian National Petroleum Company's Jesse Oil Pipeline explosion in 1998 resulted in the loss of over 700 lives – just one of numerous similar incidents occurring in the country. The cause of this explosion was never determined, as everyone in the vicinity had lost their lives; however, it was either due to inadequate maintenance or, more likely, deliberate vandalism by thieves attempting to steal oil. Another oil/gas accident occurred near the city of Ufa in Russia. When a leak occurred in a large gas pipeline in a remote area of the French-Siberian railway, rather than locating and repairing the leak, workers solved the problem by increasing the gas pressure in the pipe. This gradually flooded the valley with a mixture of eight kilometres of flammable petrol and propane-butane until people began reporting the smell of gas. On 4 June 1989, two trains carrying a total of 1,200 holidaymakers travelling in opposite directions passed each other alongside this leaking pipeline. Sparks from the trains' wheels ignited the gas suspended in the air, triggering an explosion with a destructive force equivalent to 10,000 tonnes of TNT. According to Soviet Chief of General Staff Mikhail Moiseyev, two locomotives and 38 carriages burst into flames and were thrown from the tracks. The explosion was so powerful that it ‘uprooted all the trees within four kilometres of the site of the incident’, Moiseyev stated. This accident claimed the lives of 675 people, 100 of whom were children.

The most devastating accident at a hydroelectric power plant had occurred during Super Typhoon Nina, which brought a year's worth of rain to China's Henan Province within 24 hours. The Central Meteorological Observatory in Beijing had forecast 100 mm of rainfall prior to the event, leaving people unprepared for what was to come. At its peak, 190 mm of rainfall was recorded in just one hour. According to official records, survivors described the event as follows: ‘As the rain continued, the raindrops fell like arrows, and the days seemed to turn into night.’ ‘After the rain, the mountains were covered with dead sparrows.’ Shortly after 1 a.m. on 8 August, the Bangio Dam collapsed with a noise ‘as if the sky was falling and the Earth was cracking.’ An unstoppable flood of water then triggered a chain reaction, affecting the dam and the water reservoir. The resulting 11-kilometre-wide wave, travelling at 50 km/h, ultimately led to the deaths of 171,000 people, the destruction of over a million homes, and the complete erasure of some villages from the map.

2. A Summary of Past Nuclear Disasters

It is impossible to say exactly how many people have lost their lives as a result of nuclear accidents, because it is generally impossible to determine whether cancers and other medical conditions caused by exposure to radiation were actually caused by radiation or by some other factor. As far as can be seen from public archives, approximately 70 nuclear and radiation accidents resulting in death have occurred. Although almost all of these resulted in fewer than 10 deaths, there is no doubt that many more have been concealed from the public. Interestingly, the vast majority of these incidents are attributed to incorrect calibration or the theft of medical radiotherapy equipment.

For Further Consideration:

For the record, in September 1987, over 240 people in Goiânia, Brazil, were exposed to radiation when thieves opened a steel and lead capsule stolen from a nearby dilapidated hospital. This capsule, containing radioactive caesium from a radiotherapy machine, had been hidden in the back garden of one of the thieves. Within a few days, both thieves fell ill, and the pair cut through the protective steel casing until they reached the core. Attributing their symptoms to something they had eaten, they did not suspect the stolen material and soon sold the dangerous capsule to a scrap dealer named Devair Ferreira. That night, Devair noticed that the substance inside the capsule radiated a blue light, leading him to believe it was valuable and even supernatural. He hid the capsule in the house he shared with his wife, Gabriela. and distributed some of the powder and small particles among his friends and family. These included Devair's brother-in-law, who gave caesium dust to his six-year-old daughter. Fascinated by the magical blue light, the little girl played with it, rubbing it on herself like glitter and swallowing some of the radioactive particles. Two of Devair's employees spent several days trying to open the capsule and remove the lead inside. Gabriela was the first to notice that she and everyone around her began to fall seriously ill. Although her doctor told her she was having an allergic reaction to something she had eaten, she was certain that the cause was that strange substance that had bewitched her family. Gabriela retrieved the capsule from another scrap dealer who sold it and boarded a bus to a hospital, exclaiming, 'This is killing my family.' Gabriela's foresight had prevented the situation from becoming much more serious.

The next day, a visiting medical physicist, who was asked by a doctor at the hospital to investigate the substance, arrived 'just in time to prevent the firemen from taking the source and throwing it into a river.' Until then, the substance had been lying unidentified in the hospital garden. Gabriela lost her life, along with the little girl and *two of Devair's employees. Despite receiving a much higher dose than the four people who lost their lives, Devair himself survived. Because the capsule had been opened and moved over a period of two weeks, some areas of the city had also been contaminated, and several buildings had to be demolished.*

The total number of deaths resulting from accidents related to civil nuclear power is relatively low, considerably lower than the number of deaths occurring at conventional coal, oil and hydroelectric power stations.

Commercial Purpose Nuclear Reactor Related Disasters:

Several nuclear accidents are also worth emphasising. One of the earliest examples of a nuclear accident involved 6.2 kilograms of plutonium that became critical in two separate incidents at the Los Alamos nuclear research laboratory in the US state of New Mexico. This was later dubbed 'The Demon Core'. The first accident occurred on 21 August 1945 when Harry Daglian, working alone, accidentally dropped a neutron-reflecting brick onto the core, causing a sudden and uncontrolled chain reaction. Harry realised what had happened; however, he had to partially disassemble his experiment to remove the brick and had already been exposed to a lethal dose. He died twenty-five days later. Despite a review of safety protocols after the accident, another accident occurred with the same piece of plutonium less than a year later when physicist Louis Slotin accidentally caused two neutron-reflecting hemispheres to wrap around the core, bringing it to criticality. Slotin, leaning towards the core, was exposed to a lethal dose in less than a second and died nine days later due to 'complete breakdown of bodily functions'. After this second accident, manual experiments were halted, and special remote-control machines began to be used. After the war, scientists placed the Devil's Core inside a nuclear bomb and detonated it underwater at Bikini Atoll as part of America's Crossroads Operation – this operation was a study aimed at testing the effects of nuclear weapons on naval vessels.

Great Britain's worst nuclear accident occurred as a direct result of the improper reconversion of two existing plutonium-producing reactors at Windscale (now Sellafield) in Cumbria, which were converted without proper planning to produce tritium for its use in thermonuclear bombs. These graphite-moderated, air-cooled reactors were not well suited to this task, which required a higher temperature and more intense fission reaction than their design allowed. Engineers made changes to the core to enable tritium production, at the expense of reduced safety. When the initial tests were successfully completed without any apparent problems, full-scale tritium production began. No one knew that the modifications to the reactor had dangerously altered the temperature distribution within the core; the reactor was now overheating in areas that had previously been cool, and there were no suitable sensors to measure the temperature. When the Windscale reactors were designed and built, British scientists had no experience of how graphite reacted when exposed to excessive neutrons and were unaware that it could lead to ‘potential energy accumulation causing crystalline structure deterioration’ which could then spontaneously escape in a dangerous temperature surge. On 7 October 1957, Windscale workers carried out the routine annealing process by first applying heat treatment and then shutting down the reactor to allow it to cool; however, they soon realised that the energy release was not occurring as expected. The workers reheated the core a second time, but on the morning of 10 October, it became apparent that something had gone wrong: the core temperature should have dropped when the graphite energy release slowed down, but it had not. The uranium fuel inside the reactor had caught on fire. *(Incidentally, although it was initially reported to be a graphite fire, further analysis later showed it to be a uranium fire.)* Unaware of this critical piece of information, the workers attempted to help cool the core by increasing the air flow blown into it; however, this caused the flames to flare up. At this point, they noticed that the radiation monitors on top of the chimney were beyond standard levels. A quick manual inspection of the reactor revealed that it was on fire and had been burning for two days. After strenuous efforts to extinguish the flames, first using carbon dioxide and then water, Windscale manager Tom Tuohy evacuated everyone except essential personnel and shut down the cooling fans and ventilators. He then climbed to the top of the tall chimney several times to get a clear view of the rear of the reactor from above to ensure that the fire had been extinguished. He later recounted his experience, saying, “I really leaned to one side, hoping that would be enough, but looking directly into the core of a shut-down reactor undoubtedly exposes you to a considerable amount of radiation.” This incident (horrifically) could have turned into a disaster had it not been for "Cockroft's Folly". Sir John Cockroft was the director of the British Atomic Energy Research Establishment and, along with Ernest Thomas Sinton Walton, won the Nobel Prize in Physics in 1951 for their groundbreaking work on the transmutation of atomic nuclei using artificially accelerated atomic particles. During the construction of Windscale in 1947, Cockroft had intervened and insisted that expensive radiation filters be reinstalled, despite all objections. When Cockroft's filters were added, those symbolic chimneys appeared. Until these filters prevented radioactive particles from spreading into the surrounding area and causing a catastrophe, the chimneys were called ‘Cockroft's Folly’. Almost all information about the accident was withheld from the public for 30 years; however, a report published by the National Radiological Protection Board in 1983 stated that 260 people had probably contracted thyroid cancer as a result of the accident and that more than 30 people had either died from it or suffered genetic damage that could cause illness or death in their children. The Windscale incident was considered the worst reactor accident until Three Mile Island and is a very compelling event in its own right.

A malfunction occurred in the SL-1 reactor used by the US Army for testing. Engineers were carrying out maintenance work that required the removal of the large main control rod from its drive motors. Reconnecting it required John Byrnes, a specialist serving in the army, to lift the rod a few centimetres manually. Pulling the rod too far caused the reactor to suddenly become critical. The water inside the core vaporised explosively, causing a pressure wave to hit the lid from inside the reactor and propel the reactor tank upwards, ejecting the control rods and protective plugs from their housings. One of the protective plugs entered construction electrician Richard C. Legg's body through his groin, emerged through his shoulder, pierced his body, and pinned him to the ceiling. Legg was standing on top of the reactor. Barnes himself died from the water and steam, and an intern standing nearby later died from his injuries.

Submarine Nuclear Reactor Disasters:

On 4 July 1961, a serious leak occurred in the cooling system of the reactor on the Soviet ballistic missile submarine K-19, causing the coolant pumps to fail. Despite inserting control rods into the core to neutralise the reaction, decay heat (the process by which radioactive isotopes lose energy and decay, the same process that contributes significantly to the Earth's core heat) raised the internal temperature to 800°C. During construction, a welder had accidentally dropped a piece of solder onto one of the cooling pipes, causing a microscopic crack. During a training exercise, this crack burst open under high pressure. Captain Nikolai Zateyev realised he had no choice but to create a temporary cooling system for the reactor by cutting one of the ventilation valves and welding a water pipe over it. Crew member Alexander Fateyev would later recount, "We could have had a Chernobyl, only 30 years earlier." This emergency solution worked; however, the entire crew was exposed to high doses of radiation, and the six brave men who had entered the reactor compartment to work on the pipes lost their lives within weeks due to radiation poisoning. Sixteen more crew members eventually died. Captain Zateyev described the incident after the collapse of the Soviet Union: ‘Right at that point, their appearance began to change,’ he recounted. "Their unprotected skin turned red, while their faces and hands swelled. Blood spots appeared on their foreheads and scalps. Within two hours, we could no longer recognise them. These people died in terrible agony. They were conscious. They couldn't speak. They could barely whisper. They begged us to kill them."

On 10 August 1985, the Echo-II class submarine K-431 ran aground in the choppy waters of the Kajma Bay naval facility, located southeast of Vladivostok at the junction of the Russian, Chinese and North Korean borders. The twenty-year-old submarine was in the final stage of a ten-step refuelling process. This required the 10-tonne reactor cover to be detached from the control rods and lifted by a crane arm reaching over the water from a nearby refuelling ship to install the new fuel assembly. The reactor cover had been replaced, the control rods had been reinstalled, and the cooling system had been refilled with water; however, the submarine's crew noticed that the cover did not form a perfect seal as it should have. Without waiting for proper authorisation, they attempted to solve this problem by lifting the cover a few centimetres to gain time, without removing the rods. At the worst possible moment, a navy attack boat passed rapidly alongside, creating a wave violent enough to rock the refuelling vessel and the crane arm. At that moment, the attached cover and control rods were torn from the core by the shock, causing the reactor to reach criticality and creating a steam explosion powerful enough to expel the contents of the core from the compartment and shatter the submarine's pressure hull. Eight officials and two employees lost their lives in the explosion, while 290 employees were exposed to significant levels of radiation during the four-hour struggle to bring the fire under control. This accident remained confidential until 1993, when a book revealing previously classified documents published after the collapse of the Soviet Union brought it to light.

B. Union of Soviet Socialist Republics' Nuclear Programmes

1. Organisation of the Soviet Atomic Energy Programme

The Soviet atomic energy programme was directed by two organisations placed under the supervision of the Supreme Council of the National Economy: the State Production Committee for Medium Machine Building and the State Committee for the Utilisation of Atomic Energy. The State Production Committee for Medium Machine Building was, prior to 15 March 1963, the Ministry of Medium Machine Building. The Chairman of the Committee, Ye. P. Slavskiy, had retained his rank of Minister. The Committee was responsible for the overall direction of the atomic energy programme, including the production of fissionable materials and nuclear weapons. The State Committee for the Utilisation of Atomic Energy was responsible for non-military applications of the programme and official contacts with the atomic energy programme of foreign countries.

According to some resources, the Ministry of Defence participates with the State Production Committee, Medium Machine Building, in the development, testing, and stockpiling of nuclear weapons. The weapon research and development centres were probably under the administrative control of the State Production Committee, but there was undoubtedly direct military participation at these centres, according to some resources. The nuclear weapon proving grounds were probably under military operational control with technical direction provided by the State Production Committee. The Ministry of Defence was believed to control operational nuclear weapon storage facilities located at military bases.

The State Production Committee remained organised along the customary ministerial lines, with its overall activities subject to technical review by a collegium composed of outstanding production and scientific leaders both from within and without the committee. In addition to its mining and production enterprises, the Committee had several factories which made specialised equipment. The Committee has its own supply elements and its own design and construction directorate. A design bureau of the State Committee was located in Leningrad. Construction directorates of the Chief Directorate for Capital Construction and elements of the Chief Installation Directorate responsible for the construction of all installations. Finally, the State Production Committee also had laboratories under its direct control, probably including the nuclear weapon development centres at Sarova and Kasli.

The State Production Committee and its installations were operated under a system of rigid security. Installations as well as classified shipments were guarded by uniformed troops or members of the Counter-Intelligence Directorate of the Committee of State Security *(Russian: Комитет государственной безопасности, romanised: Komitet gosudarstvennoy bezopasnosti, IPA: [kəmʲɪˈtʲed gəsʊˈdarstvʲɪn(ː)əj bʲɪzɐˈpasnəsʲtʲɪ]), abbreviated as KGB (Russian: КГБ, IPA: [ˌkɛgɛˈbɛ];)*. Extensive physical security around atomic energy installations was prevalent and included the compartmentalisation of installations into a number of fenced and guarded internal areas. Almost all information concerning the atomic energy programme was considered a state secret and was subject to various security classifications and access on a need-to-know basis.

The State Committee for the Utilisation of Atomic Energy was concerned with non-military applications of atomic energy within the USSR and also cooperation between the USSR and other countries in the non-military uses of atomic energy. It was involved with the introduction of atomic energy into industry and the coordination of research in nuclear technology for peaceful uses. In the non-military field it had concerned itself with the production and supply of radioactive isotopes, the transportation of radioactive materials, and with problems of radioactive waste disposal. There was very close coordination between the State Production Committee and the State Committee for the Utilisation of Atomic Energy. The State Production

Committee appeared to exercise a certain amount of control over the installations and activities of the State Utilisation Committee.

The USSR maintained a substantial degree of control over the atomic energy activities of the Soviet Bloc Nations through interlocking associations of top Soviet personnel and by means of bilateral agreements. Uranium mining in these countries was probably directed by the State Production Committee. The other atomic energy activities were coordinated through the Standing Committee for Peaceful Uses of Atomic Energy of the Council for Mutual Economic Aid (CEMA) under the Chairmanship of V. S. Emelyanov. Emelyanov was also a Deputy Chairman of the State Committee for the Utilisation of Atomic Energy and a member of the Board of Governors of the International Atomic Energy Agency. The long-range plan of the CEMA Committee was to provide a single integrated atomic energy programme by dividing tasks in atomic energy among the satellite nations. This type of inter-country collaboration was probably intended by the Soviets to preclude the development of an independent nuclear military capability by the other participating nations.

2. Nuclear Reactor Programme

Research and Testing Reactors:
The Soviets had constructed and were operating 23 known research reactors (due to the lack of information at the time the resource was written (1960s)) of 13 different types within the USSR. (See Table III.)
The US had in operation nearly 100 research, testing and teaching reactors of about a dozen different types. The Soviets had supplied 12 foreign countries with research reactors of the tank of swimming pool type (VVR-S, IRT and TVR-S). The TVR-S reactors were 7-10 MW heavy-water-moderated reactors designed specifically for China and Yugoslavia. The knowledge of the construction of reactors of this design in the USSR was not publicised during the glory days of the fallen union. Most Soviet research reactor facilities were used for a variety of purposes. For instance, they were used for nuclear training of personnel as well as for extensive studies of neutron physics, materials testing and development, radiochemistry, isotope production, and new reactor concepts. The variety of research reactors constructed indicates an excellent capability in this field. The Soviets had adopted the IRT swimming pool type as their general-purpose research reactor; they had also designed and built a few research reactors of exceptional originality as of the 1960s-70s. For instance, the IBR, a merry-go-round type of pulsed reactor at Dubna, provides a burst of 1018 to 1019 neutrons over a period of 40 microseconds. However, this pulse degenerates in the one-kilometre time-of-flight spectrometer to 10 neutrons/cm^2-sec so that the actual usable beam strength is quite small.

At Obninsk, the BR series of fast reactors was used not only for the development of breeder-type reactors but also for the development of compact reactor systems for future propulsion systems. For irradiating materials under high fluxes, a 50-megawatt, intermediate flux trap-type reactor (SM) with unperturbed thermal flux in the central trap of 2.2 x 1015 neutrons/cm^2-sec was built at Melekess. Its major aim was the production of small quantities of californium-252 (^{252}Cf), probably for research purposes. A 5 MW organic moderated and cooled transportable reactor was also located at Melekess. The VVR-M reactor located at Kiev was also being used to produce materials for transuranium research. The Soviets had had a need for high-flux reactors suitable for testing large engineering systems under irradiation. Construction had begun at Melekess on a 75-thermal-megawatt materials test reactor with beryllium and water moderation. It was similar to the RPT reactor rebuilt at the Institute of Atomic Energy in Moscow. The Melekess reactor was expected to be completed in 1965.

Table III

SOVIET RESEARCH REACTORS AND REACTOR EXPERIMENTS

Reactor Designation	Location	Power Thermal (KW)	Max. Thermal Neutron Flux (neutrons/ cm^2 sec)	Fuel	Moderator	Coolant	Date Critical	Remarks
Operating Research Reactors								
1. Fursov Pile	Moscow Inst. of A.E.	500 (max)	..	45 tons of natural U	Graphite	Air	1946	Similar to US CP–1, served as prototype for 1st Soviet production reactor.
2. TR (rebuilt)	Moscow, Inst. of Theoretical & Exp. Physics	2,500	$2.5x10^{13}$	270 kg of 2% enriched U	Heavy Water 4.5 tons	Heavy Water	June 1957	Originally a 500 kw prototype for Soviet heavy water production reactors. Critical in April 1949. Rebuilt version has 9 vertical & 52 horizontal experimental channels.
3. RPT–III	Moscow Inst. of A.E.	20,000	$2x10^{14}$ $6x10^{14}$ (flux trap)	90% enriched U	Beryllium & Water	Water (20 atms.)	Under const.	Old RPT loop facilities to be retained; 200 atm. coolant loop; 60 atm. helium loop; 2.5 MW power loop.
4. BR–1 Fast Reactor	Obninsk	0.10	..	12 Kg Pu	none	none	Early 1955	Uranium & copper reflectors.
5. BR–3 combined fast thermal reactor	Obninsk	0.05	..	Pu	none	none	Mid-1957	Uranium & water reflector.
6. VVR–2 (rebuilt)	Moscow Inst. of A.E.	3,000	$4x10^{13}$	45 kg of 10% enriched U	Water	Water	1955	Original version critical in 1952. Tank-type reactor designed for testing of shielding materials & configuration. Now has 5 horizontal channels with choppers, 3 vertical channels, & a "neutron multiplier" (spent fuel elements in a tank adjacent to reactor).
7. VVR–S	Moscow, Moscow State Univ.	2,000	$2.5x10^{13}$	60 kg of 10% enriched U	Water	Water	1955	Tank-type; 10 vertical channels, 9 horizontal channels. Supplied to Rumania, Hungary, Czechoslovakia, E. Ger., Poland & Egypt.
8. VVR–S	Tashkent, Inst. of Nuclear Physics	2,000	$2.5x10^{13}$	60 kg of 10% enriched U	Water	Water	Late 1959	Tank-type; 10 vertical channels; 9 horizontal channels.
9. IRT	Moscow Inst. of A.E.	2,000	$3.2x10^{13}$	40 kg of 10% enriched U	Water	Water	Nov. 1957	Swimming-pool type for use in universities & institutes. Reactor to be modified to 4000 KW using 36% U–235.
10. IRT	Tbilisi	2,000	$3.2x10^{13}$	40 kg of 10% enriched U	Water	Water	Nov. 1959	Swimming-pool type for use in universities & institutes.
11. IRT	Moscow Inst. of Physical Engineering	2,000	$3.2x10^{13}$	40 kg of 10% enriched U	Water	Water	1962	Same as above.
12. IRT	Riga	2,000	$3.2x10^{13}$	40 kg of 10% enriched U	Water	Water	1962	Same as above.
13. IRT	Minsk	1,000	$1.6x10^{13}$	40 kg of 10% enriched U	Water	Water	1962	Same as above.
14. IRT	Tomsk	1,000	$1.6x10^{13}$	40 kg of 10% enriched U	Water	Water	1962	Same as above.
15. IRT	Sverdlovsk	1,000	$1.6x10^{13}$	40 kg of 10% enriched U	Water	Water	1962	Same as above.
16. VVR–M	Leningrad Physical-Technical Institute	10,000	$1x10^{14}$	20 kg of 20% enriched U	Water	Water	Dec. 1959	Beryllium reflected, used for neutron diffraction studies, probably in connection with solid-state work in Leningrad.
17. VVR–M	Kiev Physical Technical Inst.	10,000	$1x10^{14}$	20 kg of 20% enriched U	Water	Water	Feb. 1960	Beryllium reflected, used for isotope production, prod. of trans U elements.
18. Intermediate Flus Trap (SM–2)	Melekess, Ul'yanovsk Oblast	50,000	$2.2x10^{15}$	13 kg of 90% enriched UO_2 in a Ni matrix	Water	Water	Oct. 1961; Full Power Nov. 1962	BeO reflected, central water cavity where max. thermal neutron flux is obtained.
19. IBR (Merry-go-round)	Dubna Joint Inst. of Nuclear Research	1 Ave. 100,000 Max.	10^{17} during burst	UO_2 impregnated in graphite Pu O_2 in stator	Graphite	Water	June 1960	Used with a 1 km time of flight spectrometer.
Table III (*Continued*)								
Operating Research Reactors								
20. Isotope Reactor (IR)	Unknown–Possibly Kyshtym	50,000	$3–4.5x10^{13}$	3 tons of 2% enriched U	Graphite	Water	1952	Experimental facility for production of isotopes.
21. BR–5 Fast Reactor	Obninsk	5,000	10^{15} (fast)	50 kg Pu Oxide	None	Sodium	June 1958; full power July 1959	Uranium & nickel reflector.
22. VVR–Ts	Alma Ata	10,000	$1x10^{14}$	25 kg of 20% enriched U	Water	Water	1963	Specialized radio-chemical research reactor.
23. OR	Moscow Inst. of A.E.	20,000	..	U-unknown concentration	Organic Fluid-possibly isopropyl-diphenyl	Same as moderator	Prob. 1962	The first organic cooled & moderated reactor in the Soviet Union.
Low Power Reactor Experiments Now in Operation								
1. Fast Zero Power Critical Assembly (BFS)	Obninsk	..	..	U discs	..	..	1962	Used to study large diluted reactors.
No Longer in Operation								
1. Beryllium Physical Reactor (BFR)	Obninsk	0.05	..	U_3O_8 with 20% enriched U	Beryllium metal	none	Aug. 1954	Zero-power critical assembly, bare & reflected.
2. BR–2 Fast Reactor	Obninsk	100	.. 10^{14} (fast)	Pu-U	none	Mercury	Early 1956	Uranium reflector. (Dismantled to make BR–5).
3. UF_6 Gas-fueled reactor	Moscow Inst. of A.E.	1.5	$2.7x10^{10}$	UF_6 with 90% enriched U	Beryllium metal	none	Aug. 1957	Probably dismantled.

Nuclear Electric Power Program:
Following the successful operation of a 5 electrical megawatt (MWe) nuclear electric power station at Obninsk in June 1954, the USSR announced plans in February 1956 for the installation of 2000-2500 MWe of nuclear generating capacity by the end of 1960. This ambitious programme was cut back considerably in 1958 and had consistently been slipping behind subsequently revised schedules. Soviet officials had stated that their nuclear power programme was reduced for economic reasons, since their nuclear reactors were not yet competitive with conventional power sources except in special locations. However, it was also certain that the Soviets underestimated the engineering difficulties in a major nuclear power programme.

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Table IV

SOVIET NUCLEAR POWER STATIONS AND EXPERIMENTAL CENTERS

Station Location	No. of Reactors and Type	Elec. Power Per Reactor (MW)	Thermal Power Per Reactor (MW)	Fuel Loading Per Reactor	Conversion Ratio	Annual Consumption ETP U–235 Per Reactor (Kg)	Annual Production Pu Per Reactor (Kg)	Fuel Lifetime	Estimated date of Full Power Operation	Remarks
Tomsk	3 reactors in various stages of construction	200 (est.)	1400 (est. peak power)	200 metric tons of natural U	0.8	..	400	..	1st reactor critical 1958; in mid-1960 at 100 MWe.	Construction to be completed by end of 1968.
Beloyarsk	1 Graphite-moderated water cooled, pressure tube configuration	100	286	90 metric tons of 1.3% U metal	0.65 at beginning of cycle, 0.55 at end	74	66	2 yrs	1963	Employs nuclear superheat. Est. schedule: 1st. reactor, 1963. 4 originally planned.
	Unit 2	200	..	..	..	..	..	..	1966	..
Novo Voronezh	1 water-moderated water-cooled pressure vessel configuration	210	760	23 metric tons of 1.5% UO_2 % 17 metric tons of natural UO_2 (820 kg U–235 metal equivalent)	0.75 to 0.80	108	117	1.5	1963	Zr-Nb alloy clad fuel elements. 2 originally planned.
	Unit 2	360	..	..	..	..	..	..	1966	..
Obninsk	1 Graphite-moderated, water cooled, pressure tube configuration	5	30	550 kg of 5% U metal	0.32	..	3	100 days	1954	First Soviet nuclear power station. Prototype of Beloyarsk reactors. Used extensively for experiment as well as power production.
Obninsk	1 package power water-moderat-	2	10	..	0.5 assumed	..	1	..	1959	Assembled for testing at Obninsk.
Melekess, Ul'yanovsk Oblast	1 boiling water reactor	50	250	..	0.60 assumed	..	43	..	1965	Same type fuel element as large P.WR's. Plant factor assumed 0.6.
	1 organic reactor (ARBUS)	0.75	5	22.5 Kg 10–15% U–235	..	..	..	..	1963	Package power reactor.
Bohunice (Czechoslovakia)	1 gas-cooled heavy water reactor	150	590	25,400 kg natural U	...	..	..	..	1965	Possible trouble with pressure vessel in 1962.
Rheinsberg (East Germany)	1 pressurized water reactor similar to Novo-Voronezh	70	265	19,600 kg UO_2 1.5%	0.75–0.80	36	40	1.5 yr.	1965	Progress very slow.

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The US Atomic Energy Commission delegation to the USSR in 1963 noted that the programme at the experimental reactor site near Melekess in the Ul'yanovsk Oblast was proceeding at the reduced rate suggested by Soviet unofficial statements. The 50

The MWe experimental boiling water reactor station at this site was under construction and was expected to be completed in 1964. The 2 MWe portable nuclear power station which was nearing completion at Obninsk in 1958 probably began operation in 1959. It was mounted on four heavy trailers.
Two large nuclear electrical power stations were under construction in the USSR in the late 1950s to early 1960s, one at Novo-Voronezh, which would develop 210 MWe from a 760 thermal megawatt (MWT) pressurised water reactor, and another at Belo-yarsk, where 100 MWe would be produced from a 285 MWT graphite-moderated pressure-tube reactor. Both were expected to be completed late in 1963. Expansion of the Novo-Voronezh station with a second unit of 360 MWe and the Beloyarsk station with a second unit of 200 MWe was underway with a planned completion date of about 1965-1967.
The USSR was assisting the governments of Czechoslovakia and East Germany in the design and construction of nuclear power plants. The station at Bohunice in Czechoslovakia, designed to develop 150 MWe from a gas-cooled, heavy-water-moderated reactor, was scheduled for completion in 1965. The station at Neu-Globsow in East Germany was essentially a one-third capacity copy of the Novo-Voronezh station and was reported to produce 70 MWe from a pressurised water reactor system.
Longer-range plans favoured construction of pressurised water and fast neutron reactors. The Soviets seemed to be concentrating on very large units where overall efficiency was more favourable than with smaller ones. Calculations had been made on the design of a pressurised water reactor which generates supercritical steam and is theoretically capable of developing 1000 MWe. In the fast neutron reactor field, a power station with a capacity of 800-1000 MWe was being studied but would not be constructed until 1970. Nevertheless, smaller mobile stations were not being completely neglected. An organically moderated and cooled reactor was under construction at Melekess. In December 1962 it was announced in "Pravda" that a 750 kW plant was to be built for use in the permafrost region.

In summary, the USSR would have about 500 MWe of nuclear generating capacity installed by the end of 1963 and not more than 1500 MWe by the end of 1968.

3. FISSIONABLE MATERIALS PRODUCTION

Uranium Ore Procurement

The State Production Committee for Medium Machine Building procured uranium ores from mining combines directly subordinate to it within the USSR and from contract operations probably under its supervision in the Bloc (except China, Albania, and Poland). A variety of deposits were exploited, including veins, sandstones, oil shales, limestones, subbituminous coals and iron ore slags. The US Geological Survey

estimated that the Soviet Bloc had reserves of several hundred thousand tonnes of uranium in medium-grade ore deposits and an even greater quantity in low-grade deposits. No large-reserve deposit similar in grade to the Ambrosia Lake deposit in New Mexico or the Blind River deposit in Canada had yet been discovered in the Soviet Bloc. The significantly lower grade sandstone deposits in Thuringia were the closest analogue. Thus, mining and ore concentration costs are high because of the relatively low grade of the ore bodies which the USSR had found to date.
There were three main uranium mining and ore concentrating areas in the USSR: the Central Asian area, the Krivoy Rog iron ore district in the Ukraine, and the Caucasus area. Most of the other producing areas were small operations, with the ore being shipped to concentration plants located in the main producing areas or being shipped directly to feed materials plants for upgrading. Ore concentration plants were well designed and have substantial capacities, usually of 500 to 1000 metric tonnes of ore per day, although several plants had larger capacities. For example, the concentration plant at Seelingstadt, Thuringia, in East Germany had had a peak design capacity of 12,000 metric tonnes of ore per day. Concentration plants had previously been identified at Dneprodzerzhinsk and Zhelty Vody in the Ukraine; Leninabad, Maily Say, Kadzhi-Say, Min Kush, and Karabalty in Central Asia; and Pyatigorsk in the Caucasus.
It was estimated that the USSR was procuring uranium ore at the rate of about 20,000 metric tonnes per year in terms of recoverable metal and that this rate would gradually increase over the next years to 25,000 metric tonnes per year. About half of these amounts were estimated to come from within the USSR itself. The estimated 190,000 metric tonnes of recoverable uranium procured through mid-1963 and the 300,000 metric tonnes estimated through mid-1968 were believed to be sufficient for the fissionable materials production estimated herein and for a very substantial stockpile throughout the period of the estimate. Values estimated could be higher or lower by 50%.

4. Atomic Cities

As the Soviet nuclear programme grew in the late 1940s, so did a sprawling nuclear complex across the Soviet Union. Entire cities were built and kept a closely guarded intelligence, with all mentions removed from documents and maps. They were collectively known as closed administrative territorial entities, *(Russian, zakrytye administrativno-territorial'nye obrazovaniia (ZATO))*.
During the two decades following World War II (WWII), numerous cities were built around the union. Some were named naukogradi *(science cities)* or akademgorodoki *(academic cities)*, while others developed military technologies, nuclear reactors and spacecraft. The cities were largely built by slave labour from the Gulag prison camps,

which at the time accounted for 23% of the non-agricultural labour force in the USSR. They were surrounded by barbed wire and guards, and no one was allowed to come near or go without authorisation. Many residents lived their entire lives without ever leaving. Nonetheless, the residents were privileged *(as they were the families and workers of the science facilities and more)*, enjoying a lifestyle with access to better housing, food, goods, and healthcare than Soviet citizens elsewhere. Some of the bigger ZATOs in the USSR included Arzamas-16 *(established in 1946, later on called Sarov),* Sverdlovsk-44 *(established in 1946, later on called Uralsk),* Chelyabinsk-65 *(established in 1947, later on called Ozersk)*, and Sverdlovsk-47 *(established in 1947, later on called Lesnoy).* The names were taken from those of the nearby cities, with the number signifying a post office box number. Some ZATOs remain closed, while some others have real names currently *(as mentioned).*

Arzamas-16:

Arzamas-16, currently known as Sarov *(its historic name),* was one of the most important sites during the early development of the Soviet atomic bomb. Located approximately 400 kilometres from Moscow, it was the centre of research and production of the first Soviet atomic bomb and the hydrogen bomb *(known as the Tsar Bomb).* In November 1942, physicist Igor Kurchatov (*the director of the Soviet atomic bomb project, referred to as "The Father of the Soviet Atomic Bomb")* was given a small Moscow laboratory, four grammes of radium, and 30,000 rubles to start the Soviet atomic bomb project. He could bring abroad as many scientists as he saw fit, but due to the enormous wartime housing shortage in Moscow, doing so proved difficult. As Klaus Fuchs (a German *theoretical physicist and spy who worked at Los Alamos during the Manhattan Project and passed atomic secrets to the Soviet Union)* passed more intelligence about the Manhattan Project to the Soviets, Kurchatov also had to check all the material to make sure it was correct, a process which required a functional laboratory. The Soviet atomic bomb project ultimately did not progress very far in its early years due to the distraction of WWII. Following the end of the war, Kurchatov, along with his fellow physicist Yuli Khariton *(a leading scientist on the Soviet atomic bomb programme, also referred to as "The Father of the Soviet Atomic Bomb")* and General Pavel Zernov *(Lieutenant-General of Technical-Engineering Service)*, began scouting for a suitable site to build a proper laboratory. They eventually settled on a provincial town in the Nizhny Novgorod Oblast, the site of a former monastery which was closed down after the 1917 Revolution. The new laboratory, Design Bureau No. 11 (KB-11), was established on April 13, 1946. Located 60 kilometres from the city of Arzamas, it was originally named Arzamas-60 but was soon changed to Arzamas-16 as authorities feared that the inclusion of "60" could give away its location. Khariton was appointed Chief Designer of KB-11, while General Zernov was the official director. The research began in 1947, and by 1948 Arzamas-16 was completely cut off from the outside world as strict security was instituted. As the authorities did not trust typists, scientists were ordered to write all reports by hand and to use code words for sensitive information. *("Zero points", for instance, was the code word for "neutron".)* Khariton and other top scientists had round-the-clock bodyguards, while government informers lurked everywhere. The identities of residents were even erased from the official census. The identities of residents were even erased from the official census. As physicist Yakov Zeldovich *(a Soviet physicist)* told Andrei Sakharov *(a Soviet nuclear physicist, often referred to as the "father of the Soviet hydrogen bomb")* when he visited Arzamas-16 in 1949, "There are secrets everywhere, and the less you know that doesn't concern you, the better off you'll be. Khariton has taken on the burden of knowing it all." Scientists, workers, and their families enjoyed privileged living conditions in Arzamas-16, sheltered from difficulties like military service and economic crisis. Soviet physicist Lev Altshuler *(a Soviet physicist)* called Arzamas-16 the centre of the "white archipelago" of the atomic research sites and nuclear plants across the Soviet Union, asserting that they "lived very well. Leading researchers were paid a very large salary for those times. Our families experienced no needs. And the supply of food and goods was quite different. So that all material questions were removed."

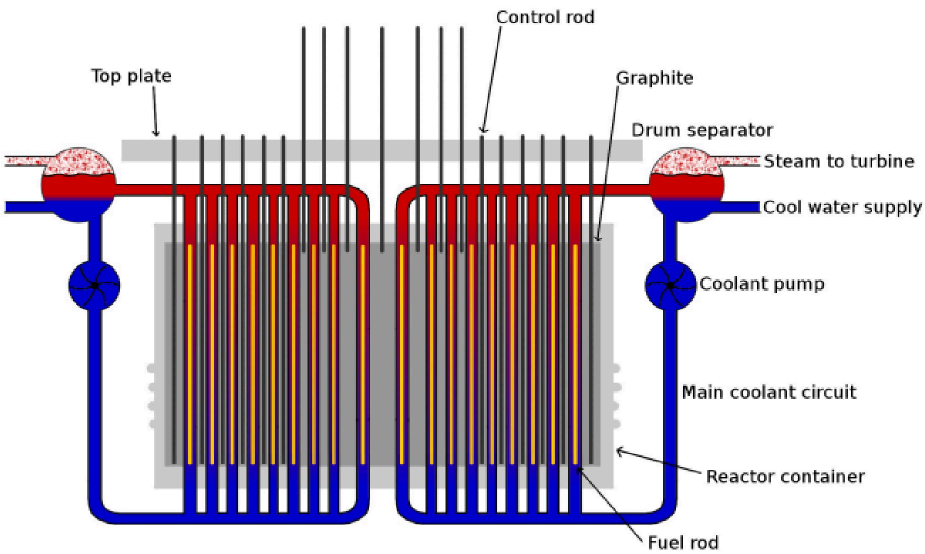
Chelyabinsk-65:

Another important ZATO was Chelyabinsk-65 *(currently known as Ozersk, as mentioned)*, home to a plutonium production plant *(similar to the American facilities built at Hanford, Washington).* Located near a collective farm in the southern Ural Mountains, Chelyabinsk-65 was *(unlike Arzamas-16) more* or less built from nothing. NKVD *(secret police)* General Yakov Rapoport *(the manager of some of the largest construction projects of the Stalin era)* gave the order to build Chelyabinsk-65 "at junction T, a remote crossing of two footpaths in the woods". Building the secret city was a tremendously difficult task. Gulag prisoners had to start by building a construction site, then a road, and then living quarters. After the basics of the city were completed, the early years were very difficult for the residents. The city lacked basic infrastructure and suffered from high rates of alcoholism and poor living conditions. The Mayak Plutonium Plant dumped nuclear waste in the nearby Techa River, causing a health crisis not only for the residents of Chelyabinsk-65 but also for all the villages which ran along it. As in Arzamas-16, security for the city was paramount. While most cities and towns in the Soviet Union were run by local communist party committees, military officials oversaw the secret city that would eventually be home to 100,000 people. Even during construction, officials were ordered to use trusted prisoners only *(meaning no Germans, POWs, hard criminals,* *political prisoners, Ukrainians, or Balts)*, although this was not strictly followed. Nevertheless, even living alongside Gulag prisoners, residents believed they were making a valuable contribution to their country. Nikolai Rabotnov, a resident of Chelyabinsk-65, remembered, “I was sure that within our barbed labyrinth, I inhaled the air of freedom!” Conditions at Chelyabinsk-65 would not improve until after the death of Joseph Stalin in 1953. Under the leadership of Nikita Khrushchev *(First Secretary of the Communist Party of the Soviet Union from 1953 to 1964 and the Chairman of the Council of Ministers from 1958 to 1964)*, there was a rising concern in the Soviet Union over the “standard of living”, an issue exemplified in the famous “Kitchen Debate” between Khrushchev and Richard Nixon *(37^{th} U.S. president)* in 1959. Architects came into Chelyabinsk-65 and designed new apartments, stores, and movie theatres. Residents enjoyed five-day workweeks, vacations, and “resorts” reserved for nuclear workers. At one point, residents owned two to twenty times as many cars and appliances as the average citizen in the rest of the Soviet Union. Despite the danger of radiation from the plutonium plant, residents of Chelyabinsk-65 actually had a higher life expectancy than the national average. When the government polled residents in 1989 and in 1999 over whether to open the city, they voted to keep it closed, while half of the nuclear scientists said they would refuse to stay if it was opened. As one resident explained, “We take pride in the fact that the state trusts us enough to live and work in Ozersk.”

5. RBMK Reactors

RBMK is a nuclear reactor designed in the Soviet Union in the 1970s. The full name is “reaktor bolshoy moshchnosty kanalniy”, meaning high-power channel reactor *(as mentioned before)*. The reactor's main design principles were the usage of natural uranium as fuel, light water as coolant, graphite for neutron moderation and getting as big an output power as possible with low construction cost. The reactor core consists of 2052 large graphite stacks that have a square cross-section and a round hole at the centre. Their purpose is to act as neutron moderators, which in practice means slowing neutrons produced by fission so that they are able to hit atomic nuclei and continue the chain reaction. In the round holes are fuel rods, control rods of varying types or measuring instruments. Coolant water also passes through the holes, and between graphite blocks flows thermally conductive gas. The gas is 70–90% helium and 10–30% nitrogen. The core also has side, top and bottom reflectors made of graphite to keep the neutrons inside. The core is enclosed in a steel container. The heat produced by fission is used to partially boil the water passing through the reactor. Steam is then separated from the water in drum separators. After them, steam goes to turbines that spin the generators, producing electricity. Cooled steam condenses back to water and is pumped back to the reactor. Water that was not evaporated to steam is again directly pumped from the drum separators to the reactor. Temperatures and pressures in the main coolant circuits must be carefully monitored. RBMK-1000 has a designed nominal thermal power output of 3.2 GW, while RBMK-1500 is designed to have a nominal thermal power of 4.8 GW. The plants have an electrical power output corresponding to their names, 1000 MW and 1500 MW, respectively. Thus, a third of the thermal power is converted to electrical power in both reactor types. Fuel rods are inserted into the reactor from the top using a refuelling machine. This is possible even while operating the reactor. The same machine can also be used to inspect fuel channels. A total of 147 control rods are inserted from the top, and there are 40 lower control rods. For purposes of emergency shutdown, there are 24 fast-acting control rods that are inserted through the top plate. These rods are allowed to free-fall to the core for 5 seconds before being braked by an electrical system to prevent damage.

For a simplified presentation of the RBMK reactor's core with its main coolant circuits and manual control rods:

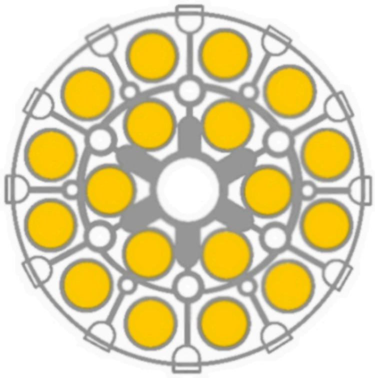


Nuclear fuel in detail:
RBMK is able to use natural uranium *(as mentioned before),* which consists of 0.7% uranium-235 *(^{235}U), 235U*, 99.3% uranium-238 *(^{238}U, 238U)* and traces of uranium-234 *(^{234}U, 234U)*. However, using natural uranium is inefficient, so in practice the uranium used is enriched to contain 2% of ^{235}U. *(After the Chernobyl accident enrichment was increased to 42.4% of 235U.)* This is still much less enrichment than what other reactor types use (3–4%) and thus cheaper. Lowly enriched uranium is mixed together with oxygen to create uranium dioxide. This is then powdered and pressed into pellets. Pellets are 15 mm long and 11.5 mm in diameter with a 2 mm diameter hole axially. The purpose of this hole is to dissipate heat from middle parts of the pellet. Pellets are stacked into tubes that are made of 99% zirconium *($_{40}Zr$)* and 1% niobium *($_{41}Nb$)*. This alloy is very resistant to corrosion

and able to withstand high temperatures. Also, it does not absorb many neutrons but lets them pass to react with heavier nuclei. However, the alloy has one major disadvantage: at high enough temperatures the zirconium reacts with water according to Formula 1, producing hydrogen. This, however, requires excess temperature in the core. Hydrogen also leaks from the coolant to the reactor hall at an estimated rate of 2 Mg/h.

FormuZr + 2 $\boldsymbol{H_2O \rightarrow ZrO_2 + 2\,H_2}$

Fuel rods made of zirconium alloy are 13 mm in diameter and 3.64 m in length. In addition to fuel pellets, the rods are filled with helium at a pressure of 500 kPa before sealing. Pellets are kept in place inside the rod by a radial retaining ring and an axial spring. These rods are then combined into fuel assemblies that consist of 36 fuel rods placed around a central support rod, 18 in the lower half and another 18 in the upper half. The support rod is a 15 mm tube made of zirconium running the whole length of the assembly and is connected to a connecting rod at the top and an end cap at the bottom of the fuel assembly. The assembly also contains 20 spacing grids, the lowest of them made of zirconium, the others made of stainless steel. These are welded to the support rod at intervals of 360 mm. The top half of the assembly also has 30 turbulence-enhancing spacers at intervals of 120 mm. *A cross-sectional drawing of a fuel assembly is presented in:*



The length of the fuel rods in the assembly is roughly 7.2 metres. In addition, there is a suspension system on top of it. This suspension system consists of the aforementioned connecting rod, an adapter around it, a top cap on it and a suspension bracket fixed to the top cap. This makes the total length 10.015 m. The fuel assembly is suspended to the reactor through the top plate via special caps on the plate. These should only be operated with the refuelling machine specifically designed for this purpose. Some fuel assemblies also contain neutron flux indicators inside their support rods. Then the rod has a different wall thickness than ordinary support rods. An RBMK-1000 reactor contains a total of 1693 fuel channels, while the RBMK-1500 has 1661 fuel channels. The difference is mainly due to heat exchange intensifiers in the fuel assemblies used on RBMK-1500 to give it higher effective thermal power. As one fuel rod contains 3.5 kg of uranium dioxide, and one assembly has 36 rods, the total mass of uranium dioxide is 126 kg. It is important to note that one fuel assembly contains only 111.2 kg of uranium itself. The difference is the oxygen in uranium dioxide. *See Formula 2 for calculations of mass without oxygen, using an enrichment rate of 2%.*

Formula 2: mU = 3,5 kg * 36 * (maU[2 %] / (2 * maO + maU[2 %]))
3,5 kg * 36 * (237,94 / (2 * 15,999 / 237,94)) = 111,064 kg

The fuel pellets are rated for a maximum temperature of 2373°K *(2099.85°C).* Their zirconium cladding is rated for a maximum of 973°K. Even lower temperatures can cause rapid hydrogen formation according to Formula 1, and increasing temperature naturally causes chemical reactions to speed up. The hydrogen can cause hydrogen embrittlement in fuel rods, leading to frailty in zirconium cladding. As one fuel assembly has a maximum energy output of 2.5 gigawatt days, the total output of the nuclear fuel in the reactor can be calculated using Formula 3.

Formula 3: Ethmax = 2.5 GWd * 1661 = 4.15 TWd

This result can then be divided by the total mass of fuel in the reactor, as shown in Formula 4, to get the maximum burn-up.

Formula 4: burn-upmax = 4.15 TWd / (111.2 kg * 1661) = 22.4 MWd/kg

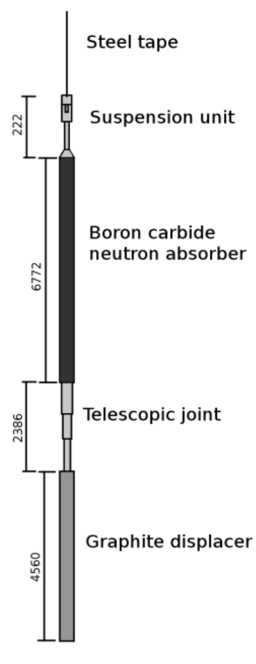
This value tells how much energy is produced when a kilogram of fuel has undergone fission. Values used are for RBMK-1500 with 2.4% enrichment and match closely with the values claimed by the fuel assembly manufacturer. Formula 5 shows the time a full load of nuclear fuel lasts if the reactor is constantly run on full power.

Formula 5: tmax = 4.15 TWd / (4.8 GW * 1 d) = 864.58 d ≈ 2 a 4 m

Boron carbide is used to absorb neutrons in the reactor and thus reduce further fissions and lower the total thermal power of the reactor. There are three different kinds of control rods: standard control rods, fast-acting scram rods and power distribution balancing control rods. The reactor has 147 standard control rods, 24 scram rods and 40 balancing rods. The latter are inserted from the bottom to the reactor, while the standard rods and fast-acting scram rods are inserted from the top. The standard rods are mainly used to lower and raise the reactor's activity by lowering and raising the rods.

For details on a post-Chernobyl control rod:

They can also be used for power distribution radially among the reactor area, while the 40 lower control rods are used to control power distribution axially.



Fast-acting scram rods are used for emergency power reduction and reactor shutdown. The shutdown process can be augmented by lowering normal control rods to the reactor. All control rods move in their own channels, which are cooled by separate circuits. Scram rods are cooled by gas; others by water. A standard control rod consists of a graphite tip used to displace water and to slow neutrons. Above the graphite there is a telescopic joint made of aluminium alloy, which shortens when the graphite touches the bottom damping support of the channel so that the boron carbide itself sets exactly to the active area of the reactor. On top of the telescopic joint there is the boron carbide, which acts as a neutron absorber, slowing the reaction. This is affixed to a suspension unit, where a steel cable is connected. (*After the Chernobyl accident these steel wires were replaced with steel tapes.)* The suspension unit absorbs mechanical shocks from movement and prevents rods from twisting in their channels.

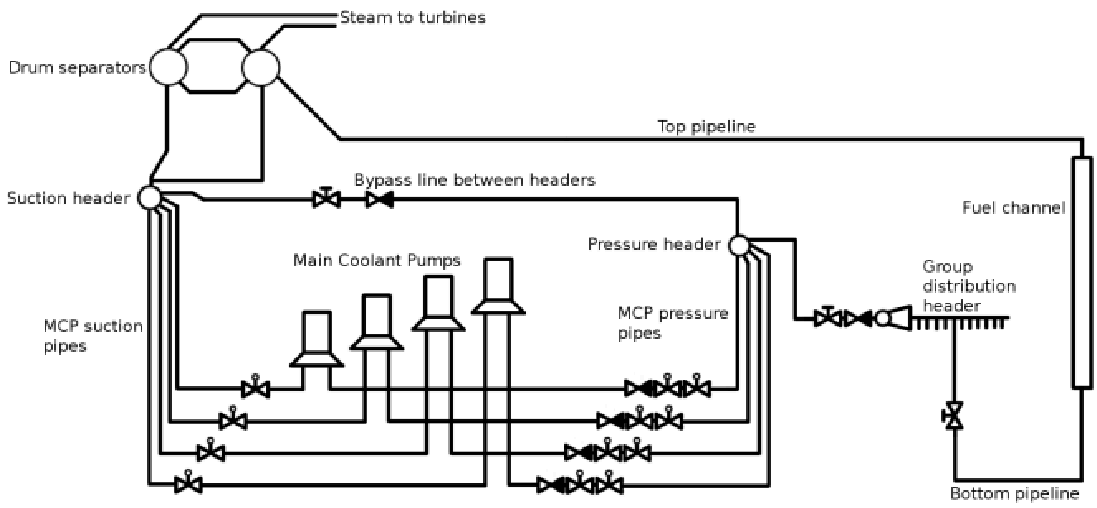
The other end of the steel tape or wire is fixed on a rotating drum where it wounds when the rod is raised. The drum is driven by a DC motor through a set of gears and an electromagnetic clutch. The clutch can be used to brake the movement of the control rod. There is also a self-synchronised indicator, which has a dial that rotates to show the position of the control rod. This can be seen when manually inspecting a control rod drive. In case the electronic system fails, rods can be controlled manually by a mechanism on top of the DC motor. If electricity is lost when moving the rods, the clutch locks and stops the rods. This is to prevent them from falling freely.

The control rod drive is similar to those rods that are moved to the reactor from the bottom. The clutch is replaced by a version acting inversely, the dial on the selsyn indicator is replaced, and the suspension wire or tape is replaced with an 8.035 m long version. Lower control rods have the boron carbide neutron absorber at the bottom, then a telescopic joint, a graphite displacer on top of it, and that connected to the fastening unit. The neutron-absorbing part is 4.088 m long, while the telescopic joint is 500 mm long when at full length. The graphite part is 6.7 m long. Fast-acting scram rods are driven by a similar drive as the standard rods, but they are given a valve to let the gas into the channel. If the channel becomes flooded with coolant water, the valve closes until the water is pumped away. As an 8 m free fall would generate a strong change of acceleration when the fall finally stops, causing structural damage to rods and their suspension, the scram rods are braked dynamically after about 5 seconds of falling. This is measured using a tachometer. Also the gear train is modified to have less inertial resistance. Scramrods consist of a 7.2 m long boron carbide absorber fixed to the fastening unit. There is no graphite displacer or telescopic joints. These types of rods are a post-Chernobyl modification. Apparently before the accident these 24 channels were used for standard control rods. Both the standard control rod channels and lower control rod channels are cooled by water pumped from the top. The gas-cooled fast-acting scram-rod channels pump nitrogen from the top together with a small amount of water that is sprayed lightly in the channel to achieve film flow on the rods. The channels have their own coolant circuit, separate from the main coolant circuit. This coolant is kept at about 313 – 363°K. Due to the fluid dampening effect of water, standard control rods and lower control rods move slowly in their channels. As they move with a velocity of 0.4 ± 0.1 m/s, the distance of 6.55 m for standard rods and 3.68 m for lower rods takes 16.375 ± 4.36 s and 9.2 ± 2.45 s to travel, respectively. Almenas et al states that the time to fully insert the rods is 12–14 s in both cases, which does not match even though the initial values of distance and velocity are taken from their writings. According to the IAEA, the time to fully lower 10 pre-Chernobyl standard control rods was about 18–21 s. As the fast-acting scramrods introduced post-Chernobyl are dropped freely to gas-filled channels, they only take 5–7 s when initiated by a manual scram signal and 2–2.5 s when dropped by an automatic system. Some control rods are left fully to reactor operators, while others are assigned to the Reactor Control and Protection System. This system monitors reactor activity and keeps it within desired limits using its two subsystems: Local Automatic Control and Local Emergency Protection. These use signals and instrumentation data provided by the Physical Power Density Distribution Control System. This system is in some sources called the Power Density Distribution Monitoring System. The aforementioned subsystems, LAC and LEP, drive some control rods to keep the reactor stable. In total, 40 standard control rods, 4 lower control rods and all 24 scram rods are controlled by these automated systems. Rods controlled automatically have some modifications on their drive to allow faster insertion. It is possible to convert manual control rods to automatic and automatic control rods to manual by the operators.

The Main Coolant Circuit:

The RBMK reactor has two main coolant circuits that are essential in keeping the reactor cooled and providing steam for the turbines to function. The circuits are symmetrical, and each provides coolant to half of the reactor, one to the left half and the other to the right half when looking from the main control room. Ordinary but purified water is used instead of the more expensive heavy water that contains deuterium and some tritium. Starting from the separation drums, two for each circuit, water flows to the suction header through 24 pipes in total. Each separation drum has a total volume of 335.6 m^3, and the suction header has a volume of 13.4 m^3. From there it is drained through 4 pipes to the main coolant pumps, which are centrifugal pumps and are powered by electric motors. Normally, three pumps are used while the fourth is on standby for backup purposes if one of the others fails. Before the pumps there are gate valves, used to disconnect the line for maintenance. After the pumps there are a set of valves, beginning with a check valve, then a throttling valve and finally a gate valve. Together with the valves are flow rate meters. These pipes then lead to a pressure header. The pressure header has a volume of 11.8 m^3. The pressure header combines all pump lines of one circuit into one. After the pressure header, the coolant water flows through 20 pipes. In each there is a set of valves, first a gate valve and then a check valve. The gate valve is used to disconnect lines for maintenance, while the check valve prevents backflow to the pressure header. After those valves there is a mixer that mixes water from the Emergency Core Cooling System to the Main Coolant Circuit. After the mixer the pipeline goes to a group distribution header

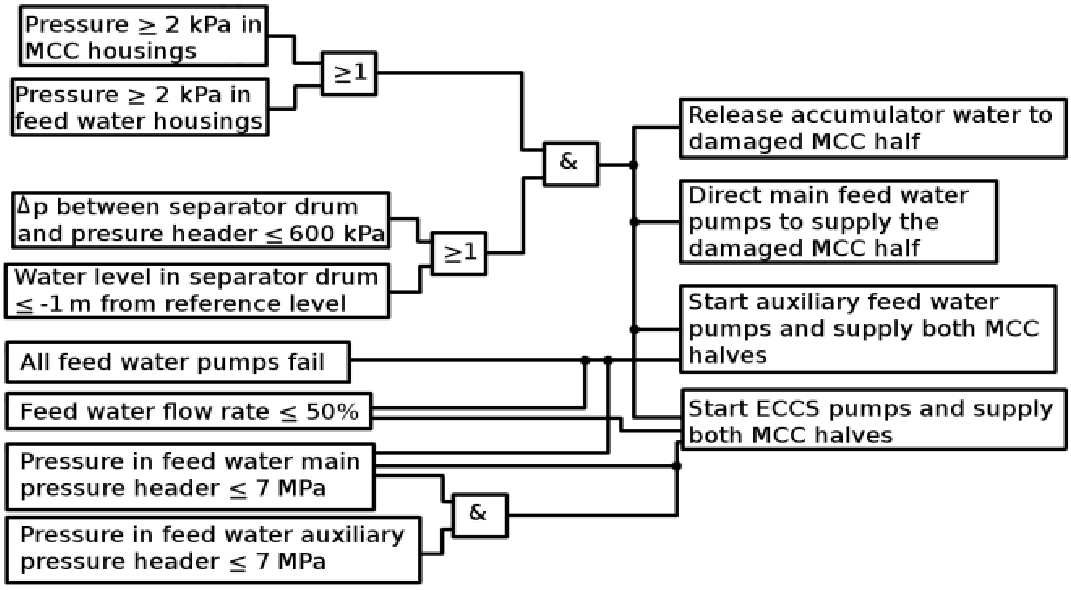
that has a volume of 32.6 m³. Each of the 20 group distribution headers in one half circuit divides the lines to 40–43 bottom pipes. Thus the Main Coolant Circuit has in total 40 group distribution headers and a maximum of 1720 bottom pipes. As the reactor only has 1693 channels for RBMK-1000 and 1661 for RBMK-1500, this is enough to cool each fuel channel, and thus many distribution group headers are not fully occupied. Each bottom pipeline has a control valve that is also capable of isolating the pipe from the rest of the circuit. The bottom pipes lead to the fuel channels and cool the reactor, where 23–29.1% of water mass boils to steam. These then return through top pipelines back to the drum separators, where the steam goes to turbines and water continues to the suction header. One fuel channel is 78.6 dm³ in volume. Steam coming from turbines is condensed back to water and then preheated, filtered and deaerated before being pumped by seven main feedwater pumps through mixers to the drum separators. One of the pumps serves as backup. There are also 6 auxiliary pumps that are used to pump the main coolant circuit full when starting the reactor, as well as to keep the pressures if the main feedwater pumps are tripped. They can also be used during start-up, shutdown and low-power operations. A bypass line goes between the suction header and pressure header in each half of the circuit. This pipeline is used to ensure natural flow due to gravity if the main coolant pumps are not in operation. The pipeline consists of 6 separate pipes, each with their own set of valves to control the flow. These valves are a gate valve to disconnect a pipe and a check valve to prevent backflow.
The figure below represents one half of the Main Coolant Circuit. This does not include any of the water feedback circuits or emergency cooling systems.



The drum separators are large cylinders with an outer diameter of 2.83 m and a length of 33.76 m. The length mentioned here is a modification done on the Ignalina Nuclear Power Plant; other plants use about 30 m long drum separators. The separators are also used to store coolant due to their high volume *(335.6 m³ for each)* and mixing of feed water with water already in circulation. Inside the drums there are special plates that the water-steam mixture impacts. After them, steam goes through perforated submerged plates to the upper part of the drum. Water stays in lower parts, as it loses a lot of kinetic energy when impacting with the special plates and is denser than steam. Feedwater flows to the drum from the top to a special header, where it is injected into the rest of the liquid. Feedwater mixes with coolant water already in circulation and proceeds down to downcomer pipes. Temperatures inside the drums are measured using thermocouples, while water levels are measured by floats. The drums are designed to withstand pressures of 7.5 MPa. Suction headers are 21.074 m long cylinders with an outer diameter of 1.02 m. They serve to connect the downcomers to one and then distribute the line to four pipes for the main coolant pumps. The pressure headers are also cylinders, with a length of 18.204 m and an outer diameter of 1.04 m. Their function is to connect all pump lines to one, then divide it to the group distribution headers and to supply water to the purification and cooling system. Main coolant pumps have a capacity of about 8000 m^3 of water per hour for each pump. Their rated shaft power is about 4.3 MW for each pump. This power is provided by electric motors on top of the pumps. These have an input power of 5.6 MW each. The motors are three-phase AC motors run on 6 kV lines. Their rotation speed is quite low, only 1000 rotations per minute, while most of the power is used on torque to handle high pressures. Motor shafts are equipped with flywheels to provide rotational inertia for a while even when electricity is lost. Due to the combination's massive inertia, accelerating the pump to full rotations will take 16 s, while deceleration takes 2–5 minutes. The pumps are used to create a pressure of about 1.962 MPa in an outlet pipe with an inner diameter of 206 mm. Pump seals are rated to withstand pressures of up to 9.81 MPa. Excess pressure causes leaks. A single pump measures 9.85 m in height, 3.07 m in length and 2.75 m in width. Each group distribution header is a horizontally mounted cylinder with an outer diameter of 325 mm. Each of them branches to 40–43 pipelines that have built-in isolation valves and flow rate meters. The readings of these meters can be seen in the main control room. The bottom pipelines leading to fuel channels have an inner diameter of 50 mm. The fuel channels themselves have an inner diameter of 80 mm. The pressure in each fuel channel can be as high as 8.6 MPa, and it drops to about 7.4 MPa on top of a channel. In practice the pressures as well as other parameters in channels are kept a little lower. After the channel, the steam-water mixture flows through 68 mm inner diameter top pipes to the drum separators. The total volume of the Main Coolant Circuit is 1992.7 m^3. Even though this is a sizeable amount of water, the loss of coolant accidents *(LOCA)* can be potentially catastrophic and thus are classified as design basis accidents *(DBA)* and in two cases even beyond design basis accidents *(BDBA)*. A guillotine break of a pressure header or a critical break of a group distribution header is BDBA and can

cause core damage. Every second, 111 kg of coolant water is directed to the purification and cooling system from the main coolant circuit. The purpose of this system is to filter corrosive minerals, salts and radioactive particles from the coolant while at the same time cooling it and supplying it to auxiliary pumps and a demineralised water storage tank. When the water first enters the system from the pressure headers, it is pre-cooled in a regenerator to about 341°K, utilising returning purified coolant flow to absorb heat. After that the incoming water is cooled again with an additional cooler, this time to about 323°K before it flows through filters. The first filter is a metal cylinder with a filtration bed of perlite used to filter mechanical particles and possible leaked-in lubricants. There are four perlite bed cylinders available, but only one of them is used at a time. The second filtering stage is made of ion exchangers utilising cations and anions. This binds potentially corrosive ions to the exchanger material instead of letting them bind to materials in the coolant circuit to cause corrosion. The ion exchanger is followed by a further mechanical filter.
The mechanical filters are rated for pressures up to 12 MPa. Other parts of the system also have similar pressure ratings; while in operation, the pressures in the system range on both sides of 9 MPa. After filtering, the coolant should not have more than 3 ppm of chloride ions, 100 ppm of mineral oils, 10 ppm of iron, less than 2 µg/kg of copper and practically no silicic acids. After filtration, the water is passed through the regenerator to absorb heat, afterwards being up to 513°K. Then the purified and heated coolant is pumped to the drum separators, passing through flow rate meters and thermocouples. Excess water can be pumped to a demineralised water storage tank.
The contents of the aforementioned demineralised water tank are used to fill four deaerator tanks that are used by the Emergency Core Cooling System. This tank has a volume of 1500 m^3, and it is forbidden to start the reactor without there being at least 1000 m^3 of water in the tank. The total volume of the deaerators is 480 m^3. There are also 16 accumulator tanks which are used for emergency cooling. They have a total of 212 m^3 of water, blanketed with pressurised nitrogen. Hot condensate chambers in the feed water system contain 1000 m^3 of water that can be used to cool the reactor core.
All this water is pumped by several pumps of various capacities. In case of emergency, the short-term cooling is provided by connecting water from the accumulators to the damaged half of the main coolant circuit using special fast-acting valves. This system is not capable of replacing the whole MCC. The accumulators are only able to provide cooling for roughly 100 seconds. Long-term cooling can be provided by pumping water from the deaerator tanks, condensate chambers and demineralised water storage tank. All these pumps can be used on diesel generators; thus, they work even if all electricity in the plant is lost. The short-term cooling from accumulators is supposed to be used only for the time it takes to start diesel generators and begin pumping from larger reservoirs. The long-term system can replace both halves of the MCC.

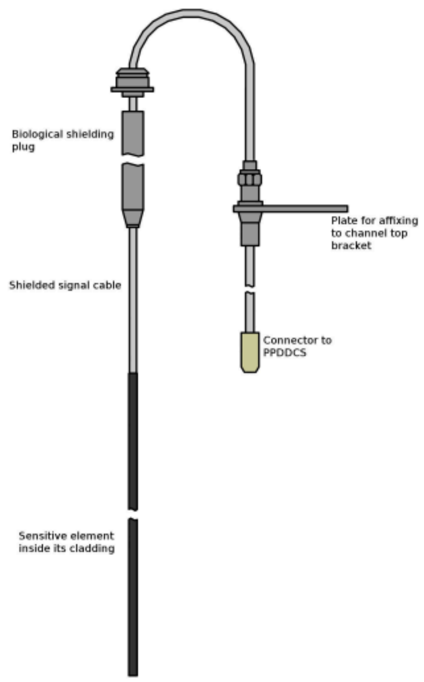
The Emergency Core Cooling System is actuated automatically in various situations (the system can also be triggered manually by operators) :



Physical Power Density Distribution Control System :

This system is used to measure and control both radial and axial power distribution of the reactor. The PPDDCS has several detectors inside the core to monitor activity levels and react to lack of power and excess power. The limits for power are 5% and 120% in total reactor power, while having 10% and 120% limits in local power. These limits are calculated using the nominal reactor power of the reactor, either 3.2 GW for RBMK-1000 or 4.2 GW for RBMK-1500. As the reactor core is big, it is very susceptible to local differences in power. For example, power in some cubic metre of the core can be much greater than in some other cubic metre on the other side of the reactor. This can cause problematic situations if the operators are either not aware of this or do not react to it, as excessive reactor power in some areas can cause damage to graphite blocks and fuel rod cladding. The PPDDCS counters such problems by balancing power differences in the reactor through usage of control rods assigned to it The Local Automatic Control system also keeps certain areas of the reactor balanced. Reactor activity is measured by 24 radial ionisation chambers and 252 power density measurement instruments in special channels. They have varying scales and provide data to the Reactor Control and Protection System, which shares the data with the PPDDCS. Measured values are transmitted to a central computer that makes calculations of the reactor power and power distribution. Possible actions are then triggered to keep the power distribution balanced and total reactor power stable. Neutron flux in the reactor is measured using four high-precision fission chambers, 16 ionisation chambers in the core and eight separate ionisation chambers that are active during the reactor start-up procedure. These instruments are placed inside thermal insulator tubes that are then placed in an inner tube, which is hermetically sealed. This inner tube is then placed inside an outer tube and again hermetically sealed. The cable from the instrument inside passes through these sealing caps in a protective tube. All this is secured to a suspension bracket that rests on top of the channel edges on a support plate. The ionisation chambers are structurally little different, lacking double tubes inside the bracket and being inside a nitrogen atmosphere. Ionisation chambers used during normal operation use linear scales, while those used during the reactor start-up use logarithmic scales, as do the fission chambers. These scales vary depending on the ionisation chamber's position in the reactor. Of the 252 power density measurement chambers, 127 are non-inertial and use hafnium oxide, while 125 are inertial with silver used inside. The latter are divided equally to the reactor, while the former are divided among local automatic control and local emergency protection zones. These measurement devices consist of a sensitive element with a length of 8.5 m placed inside the reactor core, suspended by a steel cable that goes through a 1.095 m long biological shielding plug that prevents radiation from leaking to the reactor hall. After the plug, the cable bends downwards to a sealed connector that connects the device to the PPDDCS computer. The sensitive element itself is a 3 mm diameter cylinder made of either hafnium oxide or silver, which is enclosed in a stainless steel container coated with magnesium oxide and filled with argon.

A drawing of a radial measurement chamber unit:



Apparently all these sensors work by producing a small electric pulse when the sensitive material is hit by ionising radiation. The amounts and amplitudes of these pulses can then be measured and used as a basis for calculations about the neutron flux and power in the reactor. If the system detects too high neutron flux in some areas, it lowers some control rods in the area to maintain values set by reactor operators. In case of too low values, control rods in the respective area are raised to allow greater power. Radial and axial power distributions calculated by the PPDDCS are presented to the operators in the control room on a display screen. Some other data measured is also shown using various dials and alarm lights. The PPDDCS is very important in maintaining a balanced reaction in the reactor, so it should not be disabled or automatic control of some control rods circumvented.

C. The City of Chernobyl

Construction of the Chernobyl Nuclear Power Plant, known during the Soviet era as the V. I. Lenin Nuclear Power Plant, began in 1970, located 15 kilometres northwest of the small town of Chernobyl, situated on Ukraine's marshy northern border. This remote area was chosen for construction because, in addition to being a safe distance from Ukraine's capital, it was connected to the Pripyat River, a relatively easily accessible water source, and to the existing railway line extending west to Ovruc and east to Chernigov. This plant was the first nuclear power station built in the country and was considered the Soviet Union's best and most reliable nuclear facility. Simultaneously with the construction of the power station, Pripyat, which would become the Soviet Union's ninth Atomograd (meaning ‘atomic city’ in Russian, as mentioned before), was being built 3 kilometres away to house the power station's 50,000 operators, construction personnel, support staff and their families. With an average age of 26, Pripyat was one of the Soviet Union's ‘youngest cities’. To manage this massive operation, Viktor Bryukhanov, a 35-year-old turbine specialist and staunch communist, was removed from his position as chief engineer at the Slavyanskaya thermal power plant in eastern Ukraine and appointed director at Chernobyl. He was probably well-liked and respected as a director, as one of the plant's chief engineers commented about him, ‘He really is a wonderful engineer. I mean that sincerely.’ In his new role, Bryukhanov was responsible for managing both the plant and the city's construction, as well as organising everything from the hiring process for workers to the supply of machinery and construction materials. Bryukhanov worked tirelessly; however, despite all his sincere efforts, the construction faced numerous problems typical of the Communist system. Thousands of tonnes of reinforced concrete were missing from orders, and specialised equipment was either impossible to procure or, when finally delivered, was of very poor quality. Consequently, Bryukhanov had to have temporary replacement materials manufactured in workshops on site. Although all these problems caused the plant to open two years later than planned, the first reactor, Unit D, was commissioned on 26 November 1977 after months of testing. Three more reactors followed: Unit 2 in 1978, Unit 3 in 1981, and Unit 4 in 1983. All four of these reactors were relatively new Soviet-designed ‘Reaktor Bolshoy Moshchnosti Kanalnyy’ (RBMK), or, in Turkish, ‘Yüksek Güçlü, Kanal Tipi Reaktörler’ (High-Power, Channel-Type Reactors), each producing 1000 megawatts of electrical power with 500 MW steam turbine generators. The RBMK-1000 was a graphite-moderated, boiling water-cooled reactor. In other words, it was an unusual and relatively old-fashioned combination designed in the 1960s to be powerful, fast, cheap, easy to build, relatively easy to maintain, and long-lasting. Each reactor was 7 metres long and 11.8 metres wide. In 1980, fourteen reactors of this type were in operation, while eight were still under construction. Two of these were being built in Chernobyl on the night of the 1986 accident, and Unit 5 was scheduled for completion that year. The four existing reactors met 10% of Ukraine's electricity needs at the time, and upon completion of Units 5 and 6, Chernobyl would have become the world's highest-capacity non-hydroelectric power plant. For reference, the world's largest hydroelectric power plant is the Three Gorges Dam in China, which has an incredible capacity of 22,500 MW. Nuclear reactors use the process of nuclear fission, sometimes referred to as 'splitting the atom', to generate electricity.

For Further Consideration: (All matter is composed of atoms. Atoms, in turn, consist mostly of empty space, with a small centre where protons and neutrons come together to form the nucleus, accounting for the majority of the atom's mass. The vast majority of the space remaining in the atom after the nucleus is occupied by electrons orbiting the nucleus at the centre. The differences between atoms arise from the number of protons and neutrons in a nucleus. For example, the element gold contains 79 protons and is renowned for its heaviness. Copper, on the other hand, has 29 protons and is much less dense than gold. Oxygen has only 8 protons. The number of electrons orbiting each atom is equal to the number of protons; however, atoms of the same element can have different numbers of neutrons. Different versions of the same element are known as isotopes. Stable isotopes—those that do not undergo spontaneous radioactive decay—are called stable nuclides, while unstable isotopes are known as radionuclides. Together, these two groups resulting from fission are called fission products, almost all of which are of the unstable radionuclide type. These radionuclides are hot and highly radioactive waste products of the reaction.

Like almost all other commercial nuclear reactors, the RBMK used uranium as its fuel source, the heaviest naturally occurring element with 92 protons. Uranium contains only the uranium-235 isotope, which is 0.7% fissile *(92 protons and 143 neutrons)*, can be used in fission, and a second-generation RBMK reactor such as Unit 4 at Chernobyl contained only 2% uranium-235 in 1,661 vertical pressure tubes, using cheap, only slightly enriched 98% uranium-238. *(As a reminder: During the nuclear reaction inside the reactor core, neutrons collided with the nuclei of other uranium atoms, splitting them and generating heat energy. This atomic fission produced two or three additional neutrons. These new neutrons then collided with more U235 fuel, splitting another uranium atom to produce more neutrons, and the process continued in this manner. This process is called a fission chain reaction, and it is precisely this reaction that generates heat in a nuclear reactor.)* At the same time, additional new elements are also created as hot fission products. Nuclear power generates the same atomic reactions that occur in a nuclear bomb; however, nuclear power plants are designed in such a way that they do not cause a nuclear explosion, controlling the spread of neutrons to generate the necessary heat. A nuclear power plant reactor contains a small amount of highly enriched uranium or plutonium fuel spread over a large area and surrounded by control rods to limit the reaction. A nuclear bomb is designed to cause the same reaction to occur instantly and at a much higher intensity by using explosives to apply force to two hemispheres of uranium or plutonium enriched to over 90%. Preventing radioactive release is the primary priority for all nuclear facilities. Therefore, nuclear power plants are constructed and operated according to a safety philosophy known as ‘defence in depth’. Defence in depth aims to prevent accidents through the adoption of a safety culture, while also accepting that mechanical *(and human-induced)* failures are inevitable. However, any potential problems that could unfortunately occur are anticipated and taken into account during the design phase with multiple redundancies. From this perspective, the goal is to add depth to the safety systems, much like Russian nesting dolls, each containing another until one reaches the baby at the core. If one element fails, another element is available to continue functioning. The first barrier is the ceramic pellets of the fuel, followed by the zirconium alloy cladding of each fuel rod. In a standard modern commercial nuclear power plant, the nuclear core where the fission reaction takes place is contained within a third barrier: a metal shield surrounding the reactor, called a ‘pressure vessel’, which is virtually impervious to cracking. In the RBMK, instead of a conventional pressure vessel, there is a plate made of heavy metal called a biological shield in the upper and lower sections and reinforced concrete around the edges of the reactor. It has been calculated that adding a pressure vessel in accordance with the standards and complexity required by the RBMK design would double the cost of each reactor. The fourth and final barrier is an airtight containment building. It is known that nuclear containment buildings are usually reinforced as much as possible with concrete and/or steel walls several metres thick. These buildings are constructed to withstand the external impact that could be caused by a passenger aircraft travelling at several hundred kilometres per hour; however, another purpose of these buildings is to prevent nuclear leakage in the event of an unexpected failure of the pressure vessel. Incredibly, the reactor building accompanying the RBMK was inadequate to be defined as a real containment building. The astonishing absence of two of the most critical protective barriers in the RBMK was likely a major oversight, probably part of cost-cutting procedures. As such, they should never have been permitted to be designed, approved, or constructed. It was believed that the RBMK would never cause a major accident, as industrial safety regulations would always be adhered to. It was decided that extra safety measures were unnecessary.

A fission reaction is carried out in an RBMK reactor via neutron moderators consisting of vertical graphite blocks surrounding the fuel channels. Each RBMK contains 1,850 tonnes of graphite. This graphite slows down the neutrons moving within the fuel, as slowed-down neutrons are more likely to collide with uranium-235 nuclei and cause fission. Graphite creates the most suitable environment for a chain reaction. The role of this moderator can be compared to that of oxygen in a fire: even with all the fuel in the world, a flame cannot form without oxygen. Using graphite as a moderator can be quite dangerous because, in this case, even if there is no cooling water or if there are vapour pockets called 'voids', the nuclear reaction will continue and even accelerate. This is known as the positive void coefficient, and its presence in a reactor is an indication of very poor design. Graphite-moderated reactors were used in the United States in the 1950s for research and plutonium production; however, the Americans soon realised their shortcomings in terms of safety. Almost all nuclear power plants in the West use either Pressurised Water Reactors (*PWR)* or Boiling Water Reactors (BWR). Both types use water as a moderator and coolant. In these designs, the water pumped into the reactor as a coolant is the same water that acts as a moderator, enabling the chain reaction. Therefore, if the water supply is interrupted, the chain reaction cannot be sustained, and fission stops – a much safer design. Only a few commercial reactor designs use graphite as a moderator. Apart from the RBMK and its derivatives, the only reactor currently using graphite as a moderator is the EGP-6 Advanced Gas-Cooled Reactor *(AGR)* design in Britain. The AGR is soon to be joined by a new type of experimental reactor at China's Shidao Bay Nuclear Power Plant, which is currently under construction.

Due to the extremely high heat generated by fission, the reactor core must be cooled at all costs. According to British nuclear expert Dr Eric Voice, this is particularly important for the RBMK, which operates at a 'surprisingly high temperature' compared to other reactor types, with hot spots reaching up to 700°C and a normal temperature of 500°C. The operating temperature of a standard PWR is approximately 275°C. Different reactors use different coolants, ranging from gas to air to liquid to metal and salt; however, as in most other reactors, normal water was used at Chernobyl. The plant was initially to be equipped with gas-cooled reactors; however, this was ultimately changed due to a lack of the necessary equipment. In this reactor, water is pumped into the bottom of the reactor at high pressure (1000 psi or 65 atmospheres), where it boils and rises, exiting the reactor through a condenser that separates the steam and pressure. All the remaining water is pushed back into the reactor by another pump. Meanwhile, the steam enters a steam turbine that generates electricity. Each RBMK reactor produces 5,800 tonnes of steam per hour. After passing through the steam turbine generator, the steam is condensed back into water and fed to the pumps to restart the cycle.

There is a significant drawback to this cooling method. Compared to a standard PWR, the water entering the reactor is the same water that passes through the cooling pumps and then through the turbines as steam. This means that highly radioactive water is present throughout the entire system. In a PWR, however, a heat exchanger is used to ensure that the water entering the reactor is clean and low-pressure, preventing contamination of the turbines. This process is more beneficial for safety, maintenance, and disposal. A second issue is that allowing steam to form inside the core increases the likelihood of dangerous steam pockets forming and also increases the possibility of a positive void coefficient. Unlike in PWRs, where water is used both as a coolant and a moderator, this problem does not exist in conventional boiling water reactors. However, the same problem exists in BWR models, where graphite is used as a moderator. Control rods are used to control the energy release by nuclear reactors. RBMK control rods are long, thin cylinders made of boron carbide, which absorbs neutrons to inhibit the reaction. The tip of each rod is made of graphite to prevent the cooling water, which also absorbs neutrons, from entering the area where the boron part of the rod is drawn out of the core. This is intended to ensure that when that part is replaced, it has a greater effect on reactivity. The 211 control rods at Chernobyl are lowered into the core when necessary, and 24 specially shortened 'absorber rods' are used to assist in this. These absorber rods are inserted from the bottom upwards, ensuring an even distribution of power throughout the entire width of the core. The more control rods inserted into the reactor core and the deeper they penetrate, the lower the power level will be. Conversely, fewer rods mean more power. Each control rod can be inserted together, allowing the operator to insert as many as required, or they can be removed or inserted in groups depending on conditions. RBMK control rods are incredibly slow by Western standards, taking 18 to 21 seconds to fully withdraw from their uppermost positions. There is little information available on whether any other serious accidents occurred at Chernobyl prior to the 1986 disaster, which resulted in a partial core meltdown in Unit 1. An incident occurred on 9 September 1982; however, it was kept secret for several years. It is quite difficult to find detailed and reliable reports written in English; however, it appears that the cooling water control valve was closed, causing the water channel to overheat and resulting in partial damage to the fuel equipment along with the graphite inside the reactor. A confidential KGB report from the following day stated: "In connection with scheduled maintenance at the first fuel unit of the Chernobyl Nuclear Power Plant, which was planned for completion on 13 September 1982, a trial run of the reactor was carried out on 9 September 1982. When the power was increased by 20%, a malfunction occurred in one of the 1640 pressure channels/loaded fuel assemblies. At the same time, the column containing the fuel assembly cracked, and the graphite pile was partially wetted." This situation resulted in the graphite becoming saturated through the pipes, preventing the coolant from reaching the reactor without issue and leading to partial meltdown, with fission products escaping through the chimney.

The operators were unsure of what was happening for a long time and ignored the warning alarms for approximately half an hour. The KGB team that later investigated the accident also appears to have overlooked the negligent actions of the plant workers *(The flow of coolant was deliberately stopped)*. There are also discrepancies between the findings of two institutions measuring radioactive contamination near the plant: While the nuclear industry committee appointed by the government concluded that there was no contamination, a team of biophysicists from the Nuclear Research Institute of the Ukrainian Academy of Sciences found that radiation levels were ‘a hundred times higher than permitted levels’. 80 Two important figures who would later analyse the 1986 disaster also rejected the official explanations of events. According to them, the reactor operators on duty that day claimed they had done nothing wrong. Nikolai V. Karpan, a senior engineer who worked at Chernobyl from 1979 to 1989, wrote the following about the incident: As an eyewitness who was involved in eliminating this accident and its consequences, I have nothing further to add to the Institute of Power and Technology Scientific Research and Design *(NIKIET)* version, which accuses the Chernobyl ATS engineer of completely shutting off the water supply, other than to say that this has become one version of events. The foreman and the entire team who were adjusting the flow that day repeatedly denied that this error was their fault. That day, they were carrying out their routine work in strict compliance with the regulations. According to the regulations, a guide plate had to be placed on the regulator to mechanically prevent the flow of water into the channel from stopping completely. It is likely that a flaw in the reactor's design or, more likely, poor manufacturing quality has been identified as the primary cause of this accident; however, politicians have chosen the easy way out by preferring to blame the engineer who carried out the operation. It must have seemed more reasonable to attribute the accident to a single human error than to admit that there was a flaw in the design of the new nuclear reactor, which had been developed and built at enormous expense and was already in operation at two existing power stations. Contrary to official records, this version of events is also supported by the plant's research supervisor, who conducted his own investigation and used the following statements in his report: "It was found that the zirconium channel pipes fractured due to stress build-up in their walls. The manufacturing plant had changed the production process for the channel pipes on its own initiative, and this innovation led to the accident at the reactor." Even before the incident at Chernobyl in 1982, another serious accident involving the RBMK design had occurred at the Leningrad Nuclear Power Plant in November 1975. This time, a partial meltdown occurred in Unit 1. This occurred even before the incident at Chernobyl in 1982; another serious accident related to the RBMK design had occurred at the Leningrad Nuclear Power Plant in November 1975. This time, a partial meltdown occurred in Unit 1. It is more difficult to obtain detailed information on this incident than on the accident that occurred in

1982; however, Viktor M. Dmitriev, a Russian nuclear engineer working at the Institute of Nuclear Power Operations in Moscow, has created a web page explaining what happened here. There are significant similarities between this accident and the disaster that occurred at Chernobyl in 1986.

Unit 1 at Leningrad was restarted after routine maintenance and reached 800 MW when operators removed one of the two turbines due to a malfunction. Power was reduced to 500 MW to keep the reactor stable, and the afternoon shift handed over control to the night shift. At 2 a.m., someone in the control room accidentally disconnected the remaining turbine, triggering the emergency computer system and causing the reactor to shut down automatically. This left the operators with no choice but to either struggle to restart the reactor at full power or allow it to shut down, leading to reactor poisoning; however, allowing either to happen would already have negative consequences. About ten years later, they chose to increase the power, just as they had done at Chernobyl, but things did not go well. Someone who was an intern at Chernobyl during that shift recounts: "After the shutdown, without removing any rods or taking any action to change the reactivity, the reactor suddenly reduced its acceleration time. In other words, it accidentally started to accelerate. In other words, it tried to explode. The reactor acceleration was stopped twice by the emergency protection system [in fact, the emergency protection system was triggered more than twice due to both excessive power and growth rate – Viktor M. Dmitriev]. The operator's attempts to reduce the rate of capacity growth using standard methods failed, as the lowering of a manually controlled group of rods and four automatically controlled rods proved unsuccessful, and the power increase continued. However, it was halted by the triggering of the emergency protection system. By the time the reactor was finally brought under control, it had reached a power level of 1720 MW, nearly double its nominal capacity. A government committee tasked with investigating this accident found serious design flaws and recommended in 1976 that the void coefficient be reduced, the control rod design be changed, and a ‘fast-acting emergency protection system’ be installed. Drawings for new rod designs were made but were never added to the reactors. On 16 October 1981, a report highlighting a series of concerns about the quality of the structure and equipment at Chernobyl was submitted to the KGB. It stated that during the first four years of the plant's operation, there had been 29 emergency shutdowns, eight of which were due to personnel errors and the rest due to technical malfunctions, and that ‘the control equipment did not meet reliability requirements.’ According to the KGB, these malfunctions had been brought to the attention of the Ministry of Power and Electricity and the institute responsible for the reactor's design ‘many times’ up to the date the report was prepared; however, no measures were taken. Towards the end of 1983, shortly after commissioning tests began on the first RBMK reactor at Lithuania's new Ignalina Power Plant, a problem quickly emerged: control rods entering the reactor simultaneously were causing fluctuating power. This was also the cause of the disaster that would occur at Chernobyl a few years later. The fuel at Ignalina was new, the reactor was stable, and the rods reached all the way down the core, allowing the reaction to be controlled using boron. Despite this critical discovery being communicated to the relevant nuclear ministries and institutes, nothing changed. Another KGB report prepared in October 1984 drew attention to the cooling system failures observed in Unit I. The necessary information was sent to the relevant ministries at the time; 'however, even in Units 5 and 6, which were under construction at the time *(in 1984)*, these recommendations were not taken into account.'

D. The Disaster

Shortly after 1 a.m. on 26 April 1986, a test was due to begin at Chernobyl's Unit 4 reactor. What followed led to the worst nuclear disaster in history. That night, in addition to the 176 men and women on duty at the plant, there were 286 construction workers at Unit 5, located a few hundred metres to the southeast. The operators in the control room of Unit 4, together with a representative from Donenergo, the state electricity supplier and designer of the plant's turbines, were testing a safety feature intended to allow the unit to power itself for about a minute in the event of a major failure. One of the most important issues in a nuclear reactor, especially an RBMK reactor that uses graphite as a moderator, is the uninterrupted flow of cooling water towards the core. Without cooling water, an explosion and meltdown can occur. Even if the reactor is shut down, the fuel in the reactor will continue to produce decay heat that could damage the core. The pumps that direct the water flow use electricity generated by the plant's own turbines; however, in the event of an outage, the power source can be connected to the national grid. If this also fails, the diesel generators on site automatically start to power the water pumps; however, it takes approximately 50 seconds for them to gather enough energy to start operating those enormous pumps. There are six emergency tanks that can deliver a total of 250 tonnes of pressurised water to the core within 3.5 seconds, but an RBMK reactor requires 37,000 tonnes of water per hour – 10 tonnes per second – so 250 tonnes cannot compensate for this 50-second gap. Hence: the 'Stalled Unit' test. When an electrical failure occurs, the fission reaction will continue to generate heat, and the water remaining in the pipes will continue to move for a short time. In other words, steam production will continue. In response, the turbines will continue to turn and generate electricity, albeit at a rapidly decreasing capacity. This surplus electricity could be used to run the pumps for a few critical seconds and could provide enough time for the diesel generators to ramp up and take over; what was being tested here was the equipment behind this task. Despite the Soviets' initial claims that this experiment was intended to test a new safety system, this stationary unit was actually a standard feature of the RBMK design and should have been operational three years earlier when Unit 4 was commissioned. In order to open the power plant earlier than planned, Viktor Bryukhanov, the Chernobyl Power Plant Manager, together with members of various ministries responsible for the construction and testing of the new facility, made verbal commitments that the tests would be completed, presenting the unfinished safety tests as if they had been completed. This seemingly careless procedure was routine practice, as completing work ahead of schedule in the USSR brought significant bonus payments and rewards to everyone involved. Meticulous calibration and revisions of the equipment were required, and the test had been carried out three times before in Unit 3 in 1982, 1984, and 1985; none of these tests had provided sufficient voltage, but the engineers had made additional adjustments to the voltage regulators by that time, and the same thing would be attempted again. The shutdown test was initially scheduled for the afternoon of 25 April, but the Kiev national grid control requested Chief Engineer Nikolai Fomin to postpone it until after the evening peak in electricity consumption had passed. The workers on the afternoon shift had been briefed about the test and knew exactly what they had to do, but they went home when their shift ended. The evening shift took over, but then they also left, leaving the responsibility of initiating a test they were unprepared for and had not planned to perform to the night shift, which had not previously conducted a test and was relatively inexperienced. The situation was made worse by the fact that Unit 4 had reached the end of its fuel cycle. One of the features of the RBMK design is that it can take in fuel while operating. This allows spent fuel to be replaced without having to shut down the reactor. Since the fuel is not burnt evenly throughout the core, it is not unusual for the reactor to contain both old and new fuel, which is normally replaced every two years. On 26 April, approximately 75% of the fuel was nearing the end of its cycle. This old fuel had been given time to accumulate hot and highly radioactive fission products. This could have caused a malfunction in the cooling water to rapidly damage the old fuel channels, causing the reactor to generate heat faster than its design could handle. Unit 4 was scheduled to be shut down for an extended period after the test was completed, and the annual maintenance period was to begin. During this time, the old fuel would be replaced. It would have made more sense to conduct the test with new fuel, but management decided to postpone this as well. During the test, 211 control rods would be partially inserted to create a low power level resembling a power outage, and the reactor would continue to cool to compensate for the fission products. The remaining steam would be used to start the turbine, which would then be isolated and allowed to stop, attempting to generate electricity through its own inertia. The electrical output would be measured to enable engineers to determine whether sufficient power could be supplied to the water pumps in an emergency. The deliberately reduced power levels would appear as a power failure in the control computer, automatically activating the safety system. These systems, which included backup diesel generators and the Emergency Core Cooling System *(ECCS)*, had been dismantled to be retested in case the test failed. Otherwise, the ECCS would automatically shut down the reactor, preventing the test from being repeated. following year. Surprisingly, despite previous reports claiming otherwise, these measures were not considered a violation of safety procedures when approved by the Chief Engineer. The extent to which these systems would have affected the outcome is debatable; however, it was undoubtedly a foolish decision. Along with Nikolai Fomin, Viktor Bryukhanov, who approved the test, paid the price for this accident with ten years' imprisonment in a labour camp and expulsion from the Communist Party. Countless others paid for it with their health and their lives.

There were problems from the very beginning. The test programme, left to the night shift, was full of footnotes and handwritten changes. The transcript of a telephone conversation between an unidentified operator and someone else working elsewhere in the building contains some rather frightening statements: "One operator called another operator and said, 'What should I do? There are instructions in the programme on what to do, but a lot of things are crossed out, so he's calling to ask. His colleague thinks for a moment and replies, 'Follow the crossed-out instructions.' Then, at 00:28, while lowering the power level enough to start the process, which would take about an hour, Senior Reactor Control Engineer Leonid Toptunov made a mistake while switching from manual to automatic control, causing the control rods to drop further than intended." Toptunov had only been in this role for a few months, and the reactor's electrical power had never decreased before. Perhaps he lost his nerve. The power levels, which were supposed to be maintained at 1500 megawatts thermal (MWt) for testing, dropped to 30 MWt. *(The reactor's output is measured as thermal power, while the turbogenerator's power is measured as electrical power. Energy loss occurs during the transfer from steam to electricity; therefore, thermal figures are higher.)* It is stated that the power output dropped to zero in the Chernobyl experiment and that the 30 MWt figure in particular is incorrect; however, I must also state that everywhere I have read, the figure given is 30. Either way, there is almost no difference between 30 MWt and complete shutdown, and this is not enough energy to run the water pumps. At such a low power level, a process that "poisons" the reactor begins – the xenon-135 isotope, which absorbs and seriously inhibits the fission reaction, is released, and the test had to end before it even began. Had such a massive power drop not occurred, the test would have continued without incident, and the dangerous shortcomings of the RBMK might never have come to light. However, the fifty-five-year-old Chief Engineer Anatoly Dyatlov, who was critically responsible for conducting the test, did not stop. Dyatlov was born into a poor family in central Russia. Thanks to his tireless diligence and lifelong determination to achieve a better life than his family, he grew up to be a self-educated, intelligent young man and graduated with honours from the Moscow National Nuclear Research University in 1959. Throughout his working life prior to moving to Chernobyl in 1973, he had installed small VVER reactors on submarines off Russia's southern coast. 102 However, his irritability, intolerance of mistakes, and tendency to take offence easily meant that those working under him did not secretly like him. Dyatlov was present that day when the test was postponed, and his patience was wearing thin. Rather than accepting that continuing would be futile, he reportedly flew into a rage and began shouting in the control room. Not wanting another test to go to waste and his reputation to be tarnished, he ordered the operators to fix the reactor and restart it. After dropping to such a low power level, continuing the experiment caused the reactor to become unstable enough to explode, and Dyatlov took full responsibility for this critical decision. His behaviour can be partly explained by the fact that, despite numerous accidents occurring at other nuclear power plants in the Soviet Union, nuclear facility operators were unaware of them. While telling the public that this technology was the best and most reliable in the world, the authorities covered up the deaths that occurred. Worst of all, it was believed that the RBMK could only crack in one or two water lines; everyone laughed at the possibility of an explosion. Toptunov decided that Dyatlov's decision to continue after such a massive power drop violated safety procedures and, like Unit Shift Supervisor Alexander Akimov, refused to comply with this order. Like most of the plant's senior staff, Akimov was Russian. Born on 6 May 1953 in Novosibirsk, the country's third largest city, Akimov graduated from the Moscow Power Engineering Institute in 1976 with a degree in thermal power automation processes and began working at the Chernobyl plant as a turbine engineer in 1979. Dyatlov, angered by this situation, told Toptunov and Akimov that if they would not do the job, he would find someone else to do it. Akimov and the relatively inexperienced Toptunov (only twenty-six years old) backed down, and the test continued. It should also be remembered that being a nuclear power plant operator carried with it a prestigious career and that the possibility of losing this career was a serious threat. Not only that, but Dyatlov was perhaps the most experienced nuclear engineer at the plant. Chief Engineer Fomin was also an electrical engineer – a turbine specialist like Bryukhanov. Consequently, they respected Dyatlov's expertise.

About half an hour later, at 01:00, they managed to increase the power level to 200 MW by removing half of the control rods, but that was the maximum they could achieve – it was impossible to even approach the planned 700 MW. Xenon poisoning had already begun and had significantly reduced the reactivity of the fuel. Russian safety regulations had been amended to require that a normal RBMK reactor be maintained at a minimum of 700 MWt during operation due to thermal-hydraulic instability at reduced power. Knowing that 200 MWt was still too low to conduct the test, they disabled additional automatic systems and manually increased the control rods slightly to compensate for the poisoning effect. At the same time, they also connected the eight main circulation pumps, increasing the flow rate of water to the core to around 60,000 tonnes per hour. This volume of water again violated safety regulations, as the high flow rate would cause cavitation in the pipes. The increased coolant level meant less steam, which would cause the turbine speed to slow down within a short time. As a precaution against negative reactivity due to all this extra coolant water, the operators removed most of the control rods inside the reactor until there were 8 fully inserted rods left. At that time, the normal absolute minimum was 15, and after the accident, this number was increased to 30.

Under normal conditions, the automatic safety systems would have shut down the reactor by then. A few minutes before the disaster, at 01:22:30, Toptunov noticed that the numbers displayed on the computer indicated that the reactor should be shut down. Toptunov and the operators next to him were calm but had begun to worry about the reactor's condition. Razim Davletbaev, Chief of the turbine corridor in the 1987 accident investigation, recounted, "There was a bit of tension at the control panel before the programme was started. Dyatlov kept saying to Akimov, 'Don't dawdle. ' I find it difficult to understand why Dyatlov wanted to continue at this point. The reactor was clearly unstable and miles away from the power levels required for the experiment. Therefore, it would have been impossible to collect any measurement results that would have been useful for their work. If Dyatlov had accepted that continuing was futile, his men could have shut down the reactor. He did not accept this, and the test began. The experiment had failed many times up to that point, and Bryukhanov and the members of the Soviet Academy of Sciences wanted to bring the matter to a close as soon as possible. Therefore, it is conceivable that Dyatlov did not care whether the results were useful or not. He may have simply wanted to report that the test had been carried out. This is, of course, just my theory; however, this illogical behaviour, carried out by a man who was otherwise perfectly logical, can only be explained in this way.

At 01:23:04, turbine number 8 was disconnected and began to slow down. The operators still could not predict what might happen and were calmly discussing among themselves that the reactor's task had been completed and they could begin to shut it down. From this point on, there is no definitive information about exactly what happened. Dyatlov later claimed that the test had started normally without any problems and that when the test was completed as planned, Akimov pressed the AZ-5 *(EPS-5)* emergency safety button. According to others' statements, however, Akimov pressed the button after Toptunov saw numbers on the control panel indicating a serious problem. Although reactivity increased relatively as the turbine speed decreased, some reports and simulations concluded that the numbers on the control panel were normal under normal conditions and that no unusual event occurred before the button was pressed. A subsequently published IAEA report stated: "In addition to the unintended reactivity changes caused by the [control] rods, there must have been other factors contributing to the accident. The factors put forward include MCP cavitation, unbalanced steam injection at the core inlet, shutdown of the [main circulation pumps] before the EPS signal, boiling of cooling water at the reactor inlet, partial leaks in the lower water channels, and brief opening of the steam safety valves." Regardless, at 01:23:40 on 26 April 1986, 32-year-old Alexander Akimov decided to press the AZ-5 emergency safety button to initiate the SC-RAM, causing all remaining control rods to slowly descend into the core, and announced this to those around him. It was a decision that would change the course of history. What Akimov clearly preferred was an emergency shutdown. The reason the core had become so unstable was largely because nearly all 211 rods had been removed; consequently, Akimov and the other workers had little left to control the reactor with. If what is said about Toptunov shouting at Akimov is true, then considering how many safety systems had been disabled, he may have thought this was his only option. Alas, this was the worst thing Akimov could have done. Within seconds, the control rods stopped moving. The main circulation pumps began to cavitate, filling with steam and reducing the valuable cooling water flow, causing vapour pockets *(pockets of steam where water should be)* to form in the core. A positive void coefficient was occurring: the lack of cooling water led to an exponentially increasing power surge. Simply put, more steam = less water = more power = more heat = more steam. As power increased, the amount of water supplied to the reactor gradually decreased because four of the eight water pumps were operating with a turbine whose momentum was decreasing. "Clicking" noises could be heard throughout the building, coming from the direction of the main reactor room. Akimov's control panel showed that the rods had only descended 2.5 metres from their position. Thinking quickly, he released the clutch on the auxiliary motor to allow the heavy rods to fall onto the core under their own weight, but the rods did not moabsorber, and were stuck. Six years later, recalling this moment, Dyatlov said, "I felt as if my eyes were popping out of their sockets. There was no way to explain it. There was no doubt that this was no ordinary accident. It was something much worse. It was a catastrophe." Akimov didn't understand what was happening either. Like the other helpless operators in the control room, he was unaware that there was such a fatal flaw in the reactor's design. While all the control rods were made of boron, a neutron absorber, and were about 5 metres long, their tips were made of graphite, which was used as a moderator in the RBMK core to increase the reaction. There was a long, empty section between the graphite and the boron. The purpose of the graphite tips was to replace the cooling water, which was a weak moderator compared to the graphite in the rod's path, and to increase the boron's moderating effect on the fuel. The moment all these graphite tips began moving towards the reactor, a massive increase in both heat and steam production resulted in a sharp rise in positive reactivity in the lower part of the core. The heat cracked part of the fuel assembly and damaged the control rod channels, preventing them from advancing smoothly through the core. When a control rod was fully inserted, its tip would extend to the bottom of the core; however, on this occasion, more than 200 control rods had settled right at the centre of the core. Those who designed the RBMK admitted that, although they were unaware of this flaw when the RBMK was first created, they forgot to mention it when they realised it due to "carelessness". Anyone with knowledge of fission can foresee that the control rods should not be designed in this way. The situation is either this, or it must be a matter of pride or money so as not to damage the prestige of Soviet science, because making changes would have resulted in a critical power source being shut down for a long period of time, along with significant expenditure.

Within four seconds, the reactor's energy output exceeded the planned capacity several times over. Within four seconds, the reactor's energy output exceeded its planned capacity several times over. The excessive heat and pressure deep within the core caused cracks in the fuel channels and then in the water pipes, triggering the automatic safety valves on the pumps to close. This halted the flow of cooling water, increasing the rate of steam formation from the core's dwindling water supply. Although the reactor's own safety valves attempted to release the steam, the pressure was so high that these valves also ruptured. At that very moment, there was someone in the large reactor hall of Unit 4 who witnessed all of this. Valeriy Perevozchenko, night shift supervisor of the reactor workshop, began to run when he saw the 15-metre-wide disc at the top of the reactor, consisting of 2,000 independent metal caps covering the safety valves, begin to bounce. The reactor's uranium fuel was rapidly increasing in power; the temperature reached 3000°C while the pressure rose to 15 atmospheres per second. Exactly at 01:23:58, just 18 seconds after Akimov pressed the AZ-5 button, steam pressure overwhelmed Chernobyl's fourth reactor, rendering it inoperable. A steam explosion blew apart the reactor's 450-tonne, 3-metre-thick biological shield and dropped it to the ground at a right angle to the scorched earth it left behind. The core was exposed. Valeriy Khodemchuk was tragically killed by the blast while in the main circulation pump room. His corpse was never removed; it remained buried inside Unit 4.

Measuring radiation is a complex process. Units such as curie, becquerel, rad, rem, roentgen, grey, sievert and coulomb are used. In 1986, the basic unit used to measure exposure to ionising radiation at Chernobyl was the roentgen. This unit is no longer in use today; however, all measurements in accident reports are given in roentgens. Everyone is constantly exposed to radiation from various sources such as aeroplanes, rocks, food, and the sun, and the average person is exposed to a harmless background radiation dose of 23 microroentgens per hour *(μR/h)* or 0.000023 roentgens per hour

(R/h). A chest X-ray exposes the patient to 0.8 roentgens; the United States Nuclear Regulatory Commission has set the annual radiation dose limit for radiation workers at 0.0028 R/s. The Nuclear Regulatory Commission has determined that the public can be exposed to 0.1 roentgens of radiation per year. Aircraft crews, who are exposed to higher doses than radiation workers because they work in the upper atmosphere, where protection from solar radiation is reduced, and they are exposed to 0.3 roentgens of radiation per year. The radiation in the reactor room of Chernobyl's Unit 4 is currently around 30,000 roentgens per hour, which is instantly lethal. Exposure to 500 roentgens of radiation over a period of 5 hours is a lethal dose. 400 roentgens is a lethal amount for 50% of those exposed. Exposure to amounts close to this dose will, if you are lucky, result in months in hospital; if you are unlucky, it will leave you bedridden. The volume and density of radioactive particles released into the atmosphere on the night of the accident, excluding the hundreds of tonnes of reactor fuel and graphite that fell on the plant, were equivalent to ten times the bomb dropped on Hiroshima.

When we returned to the control room, Akimov tried to call the fire brigade, who were already on their way and responding immediately to the accident, but the telephone line was down. The explosion had severed the water pipes supplying cooling water to the lower part of the core, preventing water from being pumped into the reactor through the crushed pumps. Unfortunately, the operators did not realise this – or did not want to accept the terrible consequences that a reactor explosion could cause – and their ignorance led them to take wrong actions that only made the situation worse and cost many lives. Instead, Chief Engineer Dyatlov believed that the explosions were caused by hydrogen in the Safety Control System and that the reactor was still intact. Although he had no solid basis for this explanation—and could have realised his mistake by looking out the window—he acted on this belief throughout. It is impossible to believe that there would be another reason for an otherwise intelligent and rational person to ignore something that was quite obvious. The version of events as Dyatlov believed them to be was recounted to everyone who asked, including Bryukhaov's report to the government in Moscow, and it was believed throughout the day that this was how things had happened. Interestingly, although he initially accepted that the explosion was caused by hydrogen in the water tank, Dyatlov would later use the following words: "I don't know how he came to the conclusion (that Bryukhanov's reactor did not break apart). He didn't ask me whether the reactor had been damaged – besides, I was in such a bad state that I couldn't say anything; I felt sick. By that time, I was beside myself."

Everyone in the control room was in shock and confused; when they reviewed the situation, they believed they had done everything right. After Dyatlov convinced him that the reactor could be saved, Akimov tried to start the diesel generators before witnessing his superior send two interns, Viktor Proskuryakov and Aleksandr Kudyavtsev, into the reactor room with orders to manually lower the control rods. Dyatlov had sent these trainees to their deaths. He would suffer the pangs of conscience for the rest of his life. "When they ran into the corridor, I realised it was a stupid thing to do. If the rods couldn't be lowered by electricity or gravity, it was impossible to lower them manually. I ran after them, but they disappeared," he recounted a few years before his death. The trainees reached the enormous reactor chamber by passing by the damaged rooms and lifts, but they only stayed there for a minute – what they saw blew their minds, but even that was enough. A few weeks later, they lost their lives. When they arrived at the control room of Unit 4, turned dark brown from the enormous amount of radiation they had been exposed to, the pair said the reactor was no longer there. Dyatlov did not believe them and insisted they were mistaken: the reactor was intact; the explosion had been caused by the oxygen/hydrogen mixture in the emergency tank. Water had to be fed into the core. Dyatlov and the operators in particular displayed strong signs of a psychological phenomenon known as groupthink, which has been linked to man-made disasters. Psychology Professor Dr James T. Reason believes that this groupthink, described as "a desire for harmony and conformity within the group that leads to irrational and dysfunctional decisions," was one of the key factors influencing the behaviour of the Unit 4 operators. He states that the actions taken by these operators in the hour before the explosion were "undoubtedly a manifestation of an illusion that their behaviour was sound." "It is highly probable that they attempted to rationalise any problems that might have caused them to be concerned (or alerted) about the dangers of their actions." The 38-year-old Valeriy Perevozchenko, who witnessed the reactor valve covers bouncing up and down, was the first official to realise and acknowledge exactly what was happening. He picked up a radiometer showing a reading of 1,000 micro-roentgens, which was significantly higher than normal. The radiometer's needle had gone off the scale. Incredibly, while the explosion had burnt out the powerful sensors in the building, there were no other measuring devices in the plant except for two radiometers buried under the rubble and locked in a safe. Even the standard safety equipment was locked away and inaccessible. Perevozchenko estimated that it could be 5 roentgens per hour. It wasn't even close. Taking charge, Perevozchenko assigned two people to search for the missing few. Together, they managed to find and rescue Vladimic Shashenok, who was unconscious under a collapsed beam. Shashenok, a young automatic system adjuster who monitored pressure gauges, had suffered deep thermal and radiation burns over his entire body when the room he was in was destroyed by the explosion. The two brave men who rescued him also suffered serious radiation injuries; Shashenok had placed his hand on the back of one of them while being carried, causing radiation burns. Although one of them was exposed to far more than a normally lethal dose, both miraculously survived. Vladimir Shashenok, a father of two who celebrated his 35th birthday four days ago, succumbed to his horrific injuries without regaining consciousness during the four and a half hours he spent in hospital. He was the first and last person to die on the first day. His wife was shocked when she saw Shashenok: "That wasn't my husband; it was just a swollen corpse." Meanwhile, Perevozchenko had already gone out to search for Khodemchuk, who had lost his life. As he made his way through the rubble, he carried fuel and graphite fragments with his bare hands and tried to find his friend in the darkness. After an exhausting search, finding nothing but rubble and twisted metal, he accepted that his friend was lost and decided to return to Unit 4. Meanwhile, Perevozchenko, exposed to strong radiation, was staggering towards the control room, vomiting incessantly and losing consciousness. When he finally reached the room, he told Dyatlov that the reactor had been destroyed, but Dyatlov again refused to accept it. The operators had already begun feeding water into the core. Radioactive reactor fuel and graphite were scattered everywhere. Part of the roof had collapsed onto the turbine room of Unit 4, causing a fire in turbine number 7 and rupturing an oil pipe. The rupture of the pipe caused the fire to spread to the roof of the room. Falling debris had broken the pressure valve above the feed pump, which was spewing radioactive boiling water. While people struggled to contain the flames, isolate the electrical systems, and manually open the oil drain and cooling water valves, they were rushing past pieces of uranium fuel. The vast majority of these brave souls lost their lives because they ran past the reactor fuel without realising it. Akimov and Toptunov, however, chose to remain at the plant to join the desperate efforts to resolve the problem when the morning shift ended at 6 a.m. The pair decided that the flow of water to the reactor was being blocked by a valve somewhere and went together to the half-destroyed water supply room, where they opened the valves on two water supply lines. They then went to another room and spent hours wading through an excessively radioactive mixture of fuel and water, absorbing the radiation until they were exhausted and taken to the Pripyat hospital, continuing to open valves that were half submerged in water. However, these noble efforts were in vain. The water pipes throughout the reactor were destroyed – they were opening the valves in vain – yet the operators in the control room continued to feed water into the reactor even six hours after the explosion.

The workers at the Chernobyl plant behaved like true heroes that night. Even though they could have escaped, they chose not to. Instead, they remained at their posts and prevented another explosion by replacing the hydrogen coolant in the generators with nitrogen; they added oil from the external emergency tanks to the damaged turbine tanks and sprayed water over the oil tanks to prevent the fire from spreading. Had these actions not been taken, the fire could have spread to the 600-metre turbine hall, and a larger section of the roof could have collapsed. The flames could then have spread to Units 1, 2 and 3, potentially resulting in the explosion of all four reactors.

Aleksandr Lelechenko went to the electrolysis area three times to prevent young electricians from entering the high radiation zone and to stop the flow of hydrogen to the emergency generators. Considering that the electrolysis area was next to a pile of debris, that there were fuel fragments and graphite used in the reactor everywhere, and that the radioactivity was between 5,000 and 15,000 roentgens per hour, we can understand how moral and heroic it was for this 47-year-old man to risk his own life to deliberately protect the lives of young people. He also later checked the condition of the switch box to try to supply voltage to the feedwater pumps while standing in radioactive water up to his knees. The total radiation he was exposed to was 2,500 rads *(2,851 roentgens),* a dose high enough to kill him five times over; however, after receiving first aid at the medical facility in Pripyat, Lelechenko ran to the unit and worked there for several more hours. The frustrating thing here is that most of what these people did to save the reactor only made the situation worse. They wasted their lives for nothing. Even after returning to work at the power station, Lelechenko insisted he was fine, refused to go to hospital, and went home to have dinner with his wife. Despite barely sleeping, he had gathered enough energy to wake up the next morning and go to work. He told his wife, "You can't even imagine what's going on there. We have to save the power station." Two weeks later, on 7 May, he died in a hospital in Kiev: he was Chernobyl's third victim. He was so ill that he died on the flight to Moscow's hospital specialising in radiation, where other power station workers were later to be taken. For his courage, Lelechenko was posthumously awarded the Order of Lenin. The highest national medal of the Soviet Union.

IX. For Further Consideration

Çernobil Felaketi Sovyetler Birliği'nin Sonunu Nasıl Getirdi?: The video is short and more like a summary. Everything is simplified, which is crucial to understanding the disaster at the beginning.
https://youtu.be/HFmZSnPzTPg?si=W9U2Th6nKLQJrKt5
HBO CHERNOBYL MINISERIES: Some real parts were taken out and some were added, as it is a TV series. Should not be taken as a source but may help with grasping the situation.
Secrets of the Chernobyl Control Room, Zero Hour: A documentary that should be watched with care for understanding what had happened in the control room.
https://youtu.be/C97AWUfkCO8?si=JaAwQ_bF0aww4qac

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Chernobyl 01.23.40 by Andrew LEATHERBARROW