Chapter 2

Nuclear Reactors

Introduction

This chapter provides an introduction to the RBMK reactor units at the Chernobyl nuclear power plant (NPP), which is necessary before chapter 3 which details the events which led up to the explosion and the subsequent radioactive releases into the atmosphere. Major components of a unit are illustrated: turbine hall, central reactor hall, control room and the dosimetry measurement (i.e. monitoring) recording laboratory after the accident which has had to replace the previous system, now destroyed, in the control room. For further reading on the nuclear fuel cycle, reactor operation and types of nuclear reactor, the book by Patterson[1] is recommended.

2.1 Chain reaction

The nuclear chain reaction in ^{235}U is the basis for electricity generation using nuclear reactors, as well as for nuclear weapons such as the atomic bomb at Hiroshima, although a ^{239}Pu chain reaction is also possible such as in the atomic bomb at Nagasaki.

In a mass of uranium there are always a few stray neutrons, produced either by spontaneous fission or by cosmic rays. If one of these stray neutrons produces fission of a ^{235}U nucleus, then, as well as the two fission products, two or three high energy neutrons will also be produced. *Prompt neutrons* are those that emerge at the instant of fission and the probability of this occurring is better than 99:1. However, there is a slight chance that a neutron will not emerge until some seconds later, this is a *delayed neutron*.

The three possibilities open to a high energy fission neutron are that it reaches the surface of the material and escapes; it strikes another nucleus and is absorbed without any breakdown of the nucleus or it strikes another nucleus and causes this nucleus to rupture. This third possibility, of induced fission, depends on the energy of the neutron and on the nucleus it strikes. Occasionally a *fast neutron*, fresh from an earlier fission, will rupture a nucleus, indeed only a fast neutron can rupture a nucleus of ^{238}U. However, if the neutron hits several nuclei, one after the other, giving up some of its energy at each collision, it soon slows down and becomes a *slow neutron*, often termed a *thermal neutron*.

A thermal neutron takes much longer to traverse a nucleus than a fast neutron and is thus much more likely to cause fission in a nucleus of ^{235}U. This radionuclide has three fewer neutrons than ^{238}U and in naturally occurring uranium this nuclide with a mass number of 235 forms only 0.7% of the ore.

If there are enough ^{235}U nuclei close together then the neutrons can induce more and more fissions, releasing more and more neutrons. This is termed a *chain reaction*, which, when out of control as in an atomic bomb, will cause a nuclear explosion, but when controlled can form the basis for nuclear reactor design.

Reactor fuel contains *enriched uranium*, by which it is meant that there is more than 0.7% of ^{235}U but even a small increase, of say 2–3%, can make a marked difference, provided that there are sufficient thermal neutrons. To ensure this, the core of the reactor contains not only the uranium fuel but also a *moderator*. This is a material with light nuclei, such as hydrogen or carbon, which are used in the form of water or graphite.

2.2 Reactor operation

Reactor fuel is sealed in casings termed *cladding*, which confines the fission products which are produced. Assemblies of sealed fuel are termed *fuel elements* and are interspersed with moderators, and also with neutron absorbers such as boron, to control the reaction. These are the *control rods* which in the Chernobyl accident were not inserted quickly enough to stop the explosion.

The region in which the chain reaction occurs is termed the *core* of the reactor. When the reactor becomes *critical* with the establishment of a self-sustaining chain reaction, each neutron lost by causing fission is replaced by exactly one neutron, prompt or thermal, which does likewise. The dependence of the chain reaction on thermal neutrons permits a gradual adjustment of the reaction rate.

Removing an absorber, that is, a control rod, out of a stable chain reaction, is called adding *reactivity*, the neutron density increases and the rate of the chain reaction increases. Inserting an absorber is termed adding *negative reactivity* and produces a reverse effect.

However, before removing the control rods sufficient for the reactor to become critical, precautions must be taken against gamma-radiation and neutrons pouring out of the core, since they can, for example, depending on their energy, travel through metres of concrete. The reactor must therefore be surrounded by enough concrete or other protective material to cut down the radiation level outside. In many types of reactor installations this is achieved by a specially designed *containment building*, such as at Three Mile Island, where the presence of a containment building limited the effects of that disaster. For the RBMK-1000 reactors at Chernobyl there was no such containment building and the *biological shield* of 2000 tonnes on the top of the reactor space was blown out of position and came to rest at an angle of 15° to the vertical.

Normal start-up and shutdown of a reactor are both lengthy processes and may take many hours. If, however, it is necessary to stop the chain reaction, for instance in the event of a malfunction, the emergency shutdown is termed a *scram*. At Chernobyl the emergency scram button was pressed on the orders of the shift foreman at 01:23:40 hours on 26 April 1986 but by then this had no effect and could not stop the explosion which occurred at 01:23:44 hours, due to the rapid increase in power which is estimated to have been 100 times full power.

If an operating reactor is left to itself its reaction rate will gradually fall, in part because of the build-up of fission products which absorb neutrons. One of the most effective fission produced neutron absorbers is ^{135}Xenon and the phenomenon is termed *xenon poisoning*. ^{135}Xe is produced by the decay of ^{135}Tellurium and ^{135}Iodine which are generated for several hours after start-up. ^{135}Xe nuclei which fail to capture a neutron undergo beta decay into ^{135}Caesium. If the chain reaction rate remains constant then the average concentration of ^{135}Xe in the core also remains constant. The half-life of ^{135}Xe is 6.7 hours.

Nuclear fuel eventually has to be replaced because the ^{235}U reduces as fission occurs. The replacement procedure is termed *refuelling* and the *spent fuel*, is then stored. Currently some of the highest radiation dose rates inside the Sarcophagus are in the room where the spent fuel still remains. There are many different fission products which occur, including those of plutonium radionuclides with mass numbers 239, 240 and 241: it was ^{239}Pu which was the fissile material for the atomic bomb dropped on Nagasaki. However, not all fission products are solids, some are gaseous such as xenon and krypton, all of which escaped into the atmosphere at Chernobyl.

Complete fission of all the nucleii in one kilogram of ^{235}U would release energy totalling one million kilowatt-days. The nuclear fuel in the core is so arranged that the heat is given off gradually enough to keep the temperatures manageable. The amount of heat given off per unit volume in a reactor core is termed the *power density*.

Heat is removed from the reactor by pumping a heat-absorbing fluid through the core past the hot fuel elements. This fluid is the *coolant* and may be a gas such as air or carbon dioxide, or a liquid such as water. The cooling system can be open-ended or designed as one or more closed circuits. A closed circuit can be pressurized. For electricity generation the heat released can generate steam to run turbines, as with the Chernobyl power station.

There are several different reactor types, see table 2.1, of which the Chernobyl RBMKs are of a pressure tube design in which the fuel elements lie in vertical pressure tubes filled with light water, as distinct from heavy water, and are surrounded by a graphite moderator.

Table 2.1. Reactor types.

Gas cooled power reactors	e.g. Magnox reactors and advanced gas cooled reactors
Light water reactors	e.g. Pressurized water reactors boiling water reactors
Heavy water reactors	e.g. CANDU (Canadian-deuterium-uranium) reactors
Fast breeder reactors	e.g. Liquid metal FBRs

2.3 RBMK-1000 nuclear power units at Chernobyl

2.3.1 History of RBMK reactors

The history of RBMK type reactors in the Soviet Union had been, until 1986, very successful. After the early development of the system, the USSR went directly to full scale 1000 MW(e) units. The first RBMK-1000 was put into service at Leningrad in 1974. The Leningrad, Kursk and Chernobyl power stations each have four units built in pairs, each unit supplying two 500 MW(e) turbogenerators. The first two (of four) units are operating at Smolensk and two more were being constructed at Chernobyl at the time of the accident.

The first of the two larger, 1500 MW(e), versions of these reactors was put into service at Ignalina, Lithuania, in 1984. Its physical size is similar to that of the RBMK-1000 but it has a fuel power density 50% higher.

In safety terms, there had, before 1986, been practical demonstration that the design can handle significant faults. For example, at Kursk nuclear power station in January 1980, a total loss of station internal load occurred that was sustained satisfactorily, and there have been a number of feedwater system transients. None of these presented severe plant safety problems. Electricity production for the period 1981–85 at the Chernobyl NPP was 106.6×10^9 kilowatt-hours.

Figure 2.1. Map of the site of the power plant in relation to the city of Kiev and the Kiev reservoir[2]. (Courtesy: USSR KGAE.)

2.3.2 Location of the Chernobyl NPP site

The Chernobyl NPP is situated in the eastern part of a large region known as the Belarussian–Ukranian woodlands, beside the 200–300 m wide river Pripyat which flows into the Dnieper. Figure 2.1 is a map of the immediate area surrounding the NPP including the 30 km exclusion zone. The NPP's cooling pond is linked to the Kiev reservoir. Minsk, the capital of Belarus with a population of 1.3 million, is 320 km from the NPP, and Kiev, the capital of Ukraine with a population of 2.5 million, is 146 km from the NPP. The regional centre is the 12th century town of Chernobyl with a population of 12 500 in 1986, situated 15 km south-east of the NPP. Nearer to the NPP, only 3 km distant, is the town of Pripyat where 45 000 power plant workers and their families lived. The population of all Belarus is 10 million, including 2.3 million children, and of Ukraine is 60 million including 10.8 million children under the age of 15 years.

Figure 2.2 is a map of a wider area and shows the capital cities of Ukraine, Belarus, Poland, Austria, Hungary, Yugoslavia and Romania. One of the earliest concerns was the possibility of contamination of the river Dnieper, all its tributaries, and eventually the Black Sea.

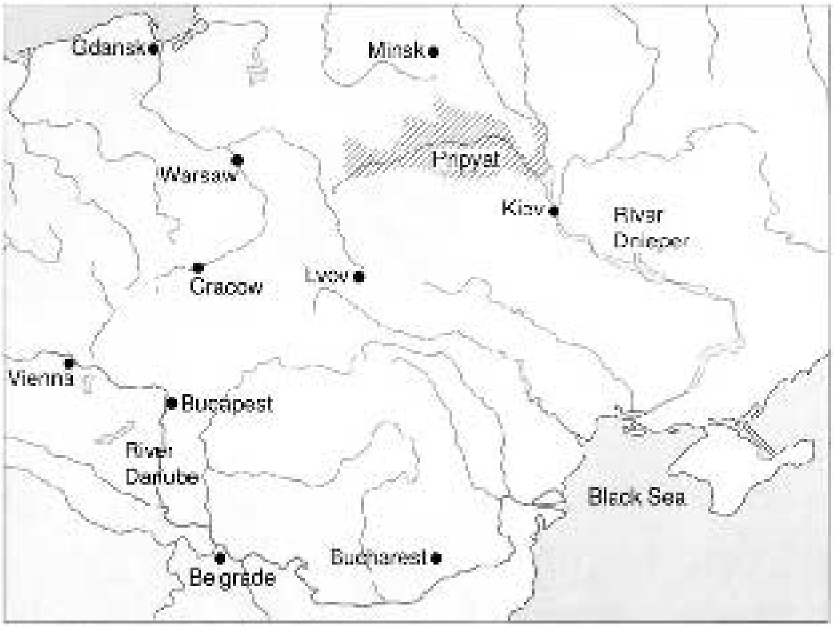

Figure 2.2. Map of Kiev and the Pripyat marshes in relation to Belarus, Poland, Austria, Hungary, Yugoslavia, Romania and the Black Sea.

2.3.3 Construction plans

Construction was planned for three stages with each stage comprising two RBMK-1000 units. The first stage of Units No. 1 and No. 2 was constructed between 1970 and 1977, and the second comprising Units No. 3 and No. 4 was completed in late 1983. It was Unit No. 4 which exploded. In 1981 work was begun on the construction of two more units also using RBMK-1000s, at a site 1.5 km to the south-east of the existing site. They were almost completed for commissioning when the accident occurred but were immediately abandoned and have been left to rust.

2.3.4 Overall view, central reactor hall and turbine hall

Plate I is an aerial view of the NPP taken five months after the accident. The cooling pond is in the background, the tall chimney in the centre is a ventilation stack and was contaminated from top to bottom, the shattered reactor Unit No. 4 is clearly seen and just in front of it, the long white building houses the turbine hall on which damage to the roof is shown. The yellow painted turbines can just be seen through the hole in the roof.

It was on this roof that many of the firemen who died received their high radiation doses. All the forests in this photograph were contaminated and had to be cut down.

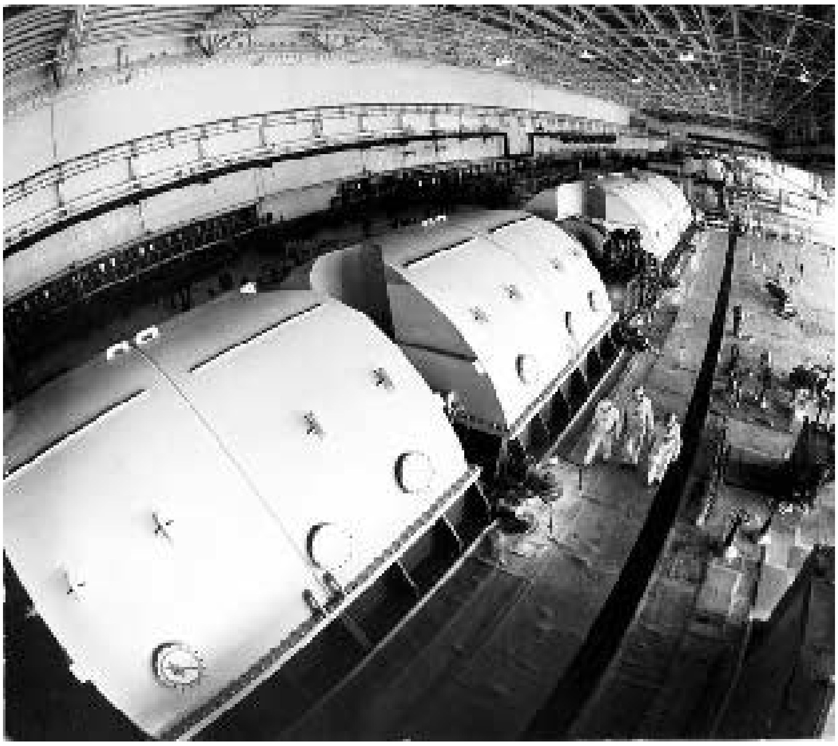

Figure 2.3. Turbine hall, November 1982. (Courtesy: TASS.)

Figure 2.3 is a photograph of the turbine hall in 1982 taken at a celebration of the 60th anniversary of the USSR, and figure 2.4 is the central reactor hall of Unit No. 1 in June 1986. The small squares in its centre are the covers to the heads of the fuel rods: these covers were reported to have been blown into the sky at least 1 km when the explosion took place.

2.3.5 Design features

The design features of RBMK nuclear reactors, of which there were four originally operational at the Chernobyl NPP, are well described by INSAG[3] and by UNSCEAR[4].

A cross-section view of a typical unit at Chernobyl NPP is seen in figure 2.5. Each reactor in a pair supplies steam to two 500 MW(e) turbines. The

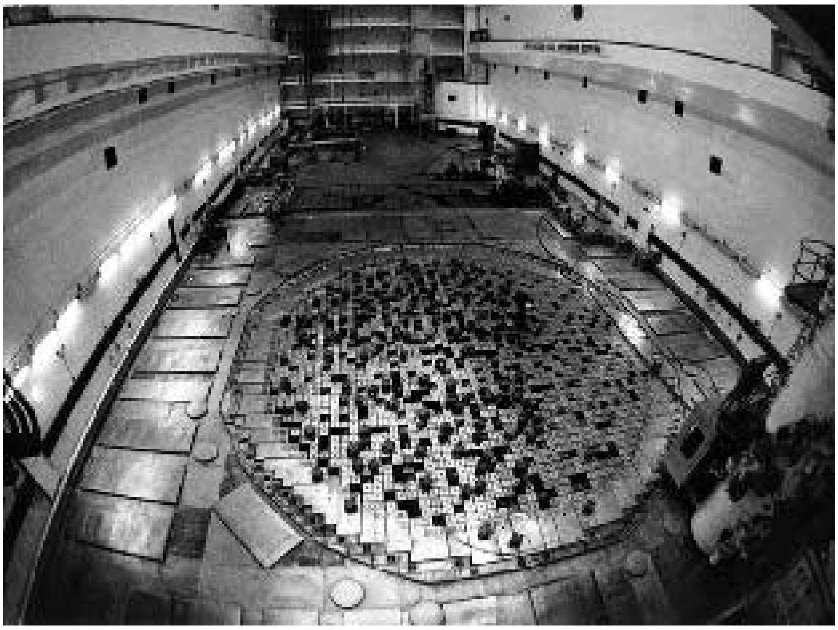

Figure 2.4. Central reactor hall of Unit No. 1, June 1986. (Courtesy: TASS.)

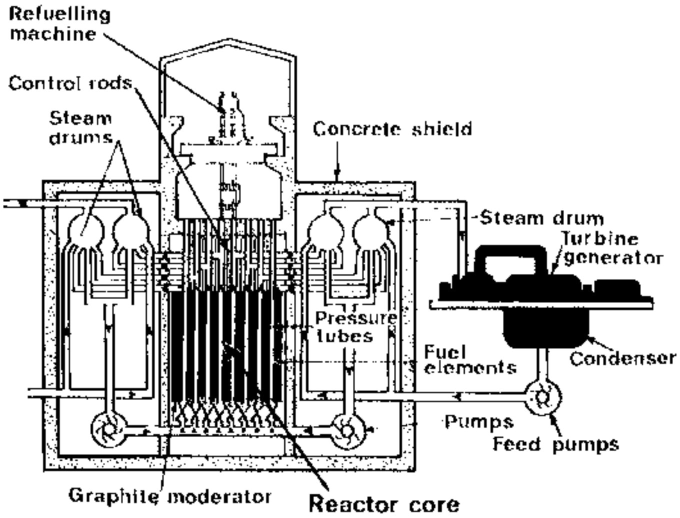

Figure 2.5. Cross-sectional view of the RBMK reactor nuclear power unit[2]. (Courtesy: USSR KGAE.)

two reactors, together with their multiple forced circulation circuits, are located in separate blocks, between which are installed auxiliary systems, and the turbine generator room, figure 2.3, is common to two reactor units. It houses four turbogenerators and associated systems.

An RBMK-1000 reactor is a graphite-moderated light-water cooled system with uranium dioxide (UO_2) fuel in 1661 individual vertical channels. The geometrical arrangement of the core consists of graphite blocks 250 mm × 250 mm, 600 mm in height, stacked together to form a cylindrical configuration 12 m in diameter and 7 m high. The mass of the graphite moderator is 1700 tonnes. It is located in a leaktight cavity formed by a cylindrical shroud, the bottom support cover and the upper steel cover. In the accident the bottom cover dropped 4 m leaving a gap through which molten fuel could travel. This was not initially realized and the search for the *missing fuel* took a considerable time. Working in the nearest room to the reactor it took 18 months to drill through the adjoining wall. Oil industry engineers were the drillers and the work was completed in October 1988. To their surprise the reactor room was empty. The next approach was to use, because of the high dose rates, a remote controlled device which consisted of a child's toy tank costing 15 roubles, to which a camera was strapped: this was also unsuccessful in locating the fuel. Eventually it was found that this 4 m gap was present and nuclear fuel masses, the lava, were finally located.

Each graphite block has a central hole which provides the space for the fuel channels, thus forming a lattice pitch of 250 mm. Fuel and control rods channels penetrate the lower and upper steel structures and connect to two cooling systems below and above the core. The drives of the control rods are located above the core below the operating floor shield structure.

The fuel, in the form of UO_2 pellets, is sheathed with a zirconium–niobium alloy. A total of 18 fuel pins, approximately 3.5 m in length are arranged in a cylindrical cluster of which two fit on top of each other into each fuel channel. Fuel replacement is done by a refuelling machine located above the core. One to two two fuel channels can be refuelled each day.

The coolant system consists of two loops and the coolant enters the fuel channels from the bottom at a temperature of 270°C, heats up along its upward passage and partially evaporates. The wet steam of each channel is fed to steam drums, see figure 2.5, of which there are two for each cooling loop.

The separated dry steam, with a moisture content of less than 0.1%, is supplied via two steam pipes to two turbines, while the water, after mixing with the turbine condensate, is fed through 12 downcomers to the headers of the main circulation pumps. The condensate from the turbines enters the separators as feedwater, thereby sub-cooling the water at the main circulation pump inlet. The circulation pumps supply the coolant to headers which distribute it to the individual fuel channels of the core.

The coolant flow of each fuel channel can be independently regulated by an individual valve in order to compensate for variations in the power distribution. The flow rate through the core is controlled by circulation pumps. In each loop four pumps are provided, of which one is normally on standby during full power operation.

From the fission reaction approximately 95% of the energy is transferred directly to the coolant. 5% is absorbed within the graphite moderator and mostly transferred to the coolant. The latter part of the fission energy is transferred to the coolant channels by conduction leading to a maximum temperature within the graphite of approximately 700°C. A gas mixture of helium and nitrogen enhances the gap conductance between the graphite blocks and provides chemical control of the graphite and pressure tubes. The control and protection system in the RBMK reactors has the basic functions listed in table 2.2.

Table 2.2. Basic functions of the RBMK control and protection system[3].

- Regulation of the reactor power and reactor period in the range 8×10^{-12} to 1.2 times full power
- Manual regulation of the power distribution to compensate for changes in reactivity due to burnup and other effects
- Automatic stabilization of the radial-azimuthal power distribution
- Controlled power reduction to safe levels when certain plant parameters exceed preset limits
- Emergency shutdown under accident conditions

The system includes 48 measuring devices. These are 24 ionization chambers placed in the reflector region which are used to drive three banks of automatic regulation rods and 24 fission chambers which are in-core detectors located in the central openings of the fuel assemblies which are used to drive the local automatic controllers. There are 211 absorbing rods in the core which are functionally grouped, table 2.3.

When the reactor is started up, the 24 emergency protection rods are the first to be raised to the upper cut-off switches. The speed of the control rods is 0.4 m per second. When a control rod is disconnected from its drive, which is necessary in the case of a power loss, the speed is about 0.4 m per second driven by free fall. Flow resistance precludes a higher velocity. The highest level of emergency is Level 5, which results in the insertion of all the rods (except the 24 shortened absorber rods) into the core up to the lower cut-off switches. The over-power trip set point is set at present power plus 10% of nominal power. The system includes the measurements and subsystems listed in table 2.4. For a full description of the safety systems including the emergency core cooling system, see INSAG[3], and for

Table 2.3. Functional grouping of the 211 absorbing rods[3].

• 24 shortened absorbing rods	
• 24 auto-control rods	12 local auto-control (LAC): regulation rods in 12 zones. 12 average power control: 3 banks of 4 rods per bank.
• 139 manual rods and 24 emergency rods	24 emergency control: uniformly selected. 24 local emergency protection (LEP): 2 rods per zone. 115 manual control.

a summary of the IAEA's co-operative programme for consolidating the technical basis for further upgrading the safety of RBMKs see the 1996 paper by Lederman[5].

Table 2.4. Measurements and subsystems for the RBMK reactor[3].

- Flow rates in all the fuel channels and the control channels: 1661 plus 223 points.
- The temperatures of the graphite core and metal structures: 46 plus 381 points.
- A system of monitoring the main components of the forced circulation system, such as the drum separators, the main circulation pumps and the suction and pressure headers.
- A system for monitoring the power distribution: 130 radial plus 84 axial.

2.3.6 Control room

Major areas of a nuclear power unit, besides the reactor, include the reactor central hall, the turbine hall, and the control room of the unit, which were similar for all four units. The control room is shown before and after the accident in figures 2.6 and 2.7.

2.3.7 Principal specifications

The principal specifications[4] are given in table 2.5.

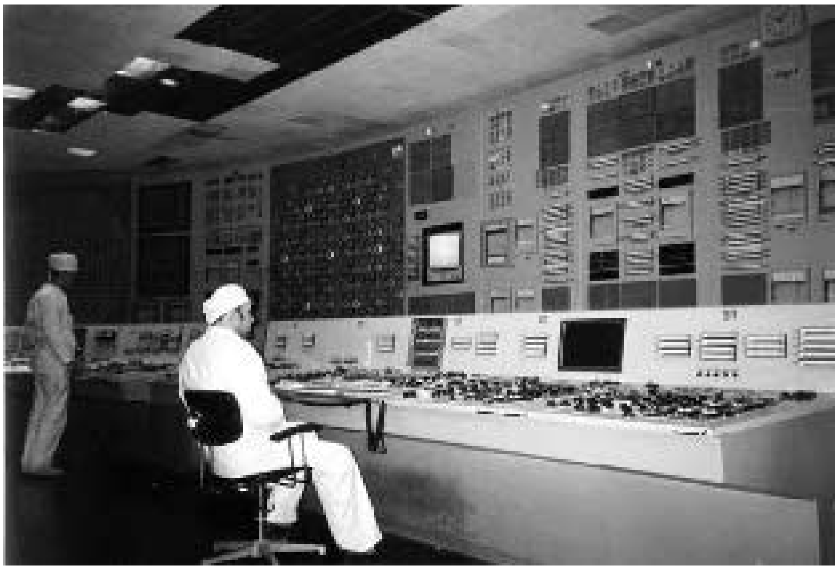

Figure 2.6. Control room of Unit No. 1, December 1987. (Photograph: R F Mould.)

Figure 2.7. Damaged control room of Unit No. 4, June 1998. (Photograph: R F Mould.)

Table 2.5. Principal specifications of the Chernobyl Unit No. 4 reactor.

Thermal power	3200 MW
Fuel enrichment	2.0%
Mass of uranium in fuel assembly	114.7 kg
Fuel burn-up	20 MW d/kg
Maximum design channel power	3250 kW
Isotopic composition of unloaded fuel	
^{235}U	4.5 kg/t
^{236}U	2.4 kg/t
^{239}Pu	2.6 kg/t
^{240}Pu	1.8 kg/t
^{241}Pu	0.5 kg/t

Figure 2.8. Radiation monitoring inside the Sarcophagus, October 1986. (Courtesy: V Zufarov.)

Figure 2.9. Measurement recording laboratory, June 1998. (Photograph: R F Mould.)

2.3.8 Measurement recording laboratory

Before the accident all the dosimetric and temperature monitoring information required by the power plant operators of Unit No. 4 would have been available in the control room. However, after the accident all the measuring systems were destroyed and had to be replaced.

The initial monitoring was performed manually, as there was no alternative, figure 2.8, but eventually bore holes were made for three types of sensors: those for the measurement of neutron dose rates, gamma dose rates and temperature. The laboratory in which these measurements are recorded is shown in figure 2.9 and seen to be rather basic. In June 1998 the maximum gamma dose rate was 4000 roentgen/hour: recorded in the spent fuel storage pond. The maximum temperature in June 1998 was recorded as 40°C. In 1986 the temperatures were some 300–400°C.

2.4 Measures to improve the safety of RBMK plants

Since the accident, several organizational and technical measures have been developed and implemented to improve the safety of operating RBMK plants. These have been reported to INSAG and table 2.6 summarizes the aims of these measures[6].

Table 2.6. Aims of improvement measures for RBMK plants[6].

• Reducing the positive steam (void) coefficient of reactivity and the effect on reactivity of complete voiding of the core. This has been provided by the installation of additional fixed absorbers, up to 90, into the core, and through the introduction of the use of fuel with 2.4% ^{235}U enrichment.
• Improving the speed of the scram system. The speed of insertion of control and safety rods has been increased with the time for full insertion into the core reduced from 18 s to 12 s.
• Introducing new computational codes for the operational reactivity margin (ORM) with numeric indication of the ORM in the control room. This has been increased to between 43 and 48 control rods, depending on the reactor.
• Precluding the possibility of bypassing the emergency protection system while the reactor is at power, through an operating limit requirement and the introduction of a two key system for the bypass action.
• Avoiding modes of operation leading to reduction of the departure from nuclear boiling margin for the coolant at reactor inlet. This addresses the question of adequate subcooling at the core inlet. Operating instructions have been updated to take into account lessons learned from the accident and among the new provisions is one which now sets a lower limit of 700 MW (th) for steady operation of an RBMK reactor.

Figure 2.10. The Chernobyl NPP was named after V I Lenin and his bust remains in front of the administration building in 1998. One of Lenin's quotes is 'Russia is communism and electrification'. (Photograph: R F Mould.)