Gesellschaft für Anlagen-
und Reaktorsicherheit
(GRS) mbH

The Accident and the Safety of RBMK-Reactors

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GRS in Eastern Europe

The accident in the Chernobyl Nuclear Power Plant has shown the necessity of international cooperation in the field of reactor safety in a dramatical way. Under this impression GRS initiated first contacts to Eastern European expert organizations at the end of the 80ies. Within the framework of projects commissioned by the Federal Ministry for the Environment, Nature Conservation and Reactor Safety, the Federal Ministry for Education, Science and Technology, the European Union and other international organizations these have developed to an intensive cooperation in the course of the years. Together with its French partner organization, the Institut de Protection et de Sûreté Nucléaire, GRS established technical offices in Moscow and Kiev and equipped these with modern telecommunication to render the cooperation with these countries more efficient.

In Eastern Europe GRS concentrates on three main areas:

- **Cooperation in reactor safety research**
  At the beginning of the technological-scientific cooperation with Russia and other Eastern European countries which is getting closer and closer there was an exchange of information with the Kurchatov-Institute in Moscow. Possibilities for the use of German computer codes to simulate accidents in Soviet reactors were thus created, for example, and a joint further development of such tools was initiated. The knowledge acquired during these joint projects at the same time represent the basis for safety assessments of Eastern European nuclear power plants and for the establishment of a mutual understanding of essential safety issues.

- **Support of Eastern European safety authorities**
  Independent, competent and strong safety authorities are vitally important for reactor safety in Eastern European countries. GRS supports the establishment and strengthening of these authorities and their technical expert organizations in multiple ways, e.g. by the transfer of know-how, technical aid during the creation of an infrastructure and explaining Western procedures within the framework of joint safety analyses.

- **Design and implementation of technical improvements**
  GRS directly participates in the design and the implementation of concrete measures in nuclear power plants increasing safety. It coordinates support projects to provide equipment increasing safety, in pilot projects it works on the improvement of plant and operational documentation and it provides assistence during the preparation and quality control of safety reports.

Imprint

The report represents the opinion of GRS and it is based on findings acquired in connection with examinations carried out for the Federal Ministry for the Environment, Nature Conservation and Reactor Safety, the Federal Ministry for Education, Science and Technology, the European Union and the European Bank for Reconstruction and Development (London).

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List of Abbreviations

AR	Global automatic power control
ATHLET	"**A**nalyse der **T**hermo**h**ydraulik von **Le**cks und **T**ransienten" (Name of the thermohydraulic code developed by GRS)
BIPR 8	Name of the neutron kinetics programme in Russia
Bq	Becquerel
Ci	Curie
Gy	Gray
He	Helium (noble gas)
MCP	Main Coolant Pump
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IPHECA	International Programme of the Health Effects of the Chernobyl Accident
IPSN	Institut de Protection et de Sûréte Nucléaire
LAR	Local automatic power control
keff	effective multiplication factor
MPa	Megapascal
MW	Megawatt
MWd/t	Megawatt days per ton of fuel
MWd/kg	Megawatt days per kilogram of fuel
N_2	Nitrogen
Nb	Niobium
NW	Nominal width [mm]
ORM	Operational reactivity margin
RBMK	Graphite moderated boling water pressure tube reactor
Sv	Sievert
WHO	World Health Organization
WWER	Russian pressurized water reactor
Zirkaloy	zirconium alloy
Zr	zirconium

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Introduction

The accident in the Ukrainian nuclear power plant at Chernobyl on April 26, 1986 brought along great harm for many people. There were immediate damages and consequential burdens for human beings, the environment and the economy over long distances. The Soviet Union and later on its succession states Russia, the Ukraine and Belorussia have made great efforts to limit the worst consequences of the accident.

The Ukraine, Russia and Lithuania, the countries still operating RBMK nuclear power plants, have done a lot to improve the safety of these nuclear power plants in the meantime. Western countries provide assistance within the framework of bilateral and international support programmes.

But despite all efforts the consequences of the accident still have not been coped with and the reactor safety deficiencies have only partially been removed. The reasons herefor cannot only be seen in the scope of the problems, but above all in the precarius economic situation of the states particularly affected by the accident, i.e. the Ukraine, Russia and Belorussia.

Thus, even in the 10th year after the accident there remains a lot to be done. The long-term reconstruction of the Chernobyl site must be started on. The affected population of the Ukraine, Russia and Belorussia still urgently requires help. The radioecological and health consequences must be collected more systematically than before to help more effectively. The safety of all Soviet-type reactors must be improved further, especially as a short-term, premature closure even of older plants is hardly to be expected.

The programmes to solve these tasks must be developed further, the mechanisms of cooperation must be improved, and new financial sources have to be found. In this context it will be necessary to bring the knowledge about Chernobyl-related issues which has become increasingly fragmented after the decay of the Soviet Union together again and to develop it further. Chernobyl thus remains a challenge for cooperative thinking and acting in the fields of reactor safety, waste disposal as well as environmental and radiation protection.

A variety of examinations and research projects have been carried out in the decade after the accident which have considerably improved the understanding of the complex questions connected with Chernobyl. GRS participated in many of these examinations within the framework of projects of the Federal Minister for the Environment, Nature Conservation and Nuclear Safety (BMU), the Federal Minister for Education, Science, Research and Technology (BMBF) and the Commission of the European Union. Together with its foreign partner organizations GRS assessed essential safety issues and made practical suggestions for improvement.

With this report GRS makes the knowledge acquired in the course of these studies available to a broader public. It thus wants to make its contribution that measures to cope with the consequences of the accident and to improve reactor safety in the states affected are taken in a problem- and subject-matter-oriented way.

The report gives an overview on the situation at Chernobyl and explains the principles and safety features of the reactors which are still operated at that site as well as of other nuclear power plants of this type:

- Are the causes and the sequence of the reactor accident sufficiently known? Have sufficient measuress against a repetition of such an accident been taken?
- How are the risks and the safety properties of these reactors to be evaluated? Have the necessary measures against disturbances and accidents been derived?
- How is the further operation of the Chernobyl-type nuclear power plant to be assessed?

In addition, questions relating to radiation protection, health effects and disposal at the Chernobyl site are dealt with:

- Which dangers does the sarcophagus represent?
- Which dangers do the contaminations and the radioactive wastes existing at the nuclear power site represent?
- How are the radiation exposures and the effects on the health of individuals affected by the accident to be evaluated? Do additional preventive measures have to be taken or can these be taken, respectively?

Finally, the significance of this accident for safety and radiation protection in Germany is dealt with:

- Which consequences does the Chernobyl reactor accident imply for safety of German nuclear power plants?
- Which consequences for radiation protection prevention in Germany can be derived from the Chernobyl reactor accident?

The report is subdivided into three main areas:

- Section 1 provides an outline of the situation at the Chernobyl site as well as of the functioning and the safety properties of the reactors operated there.
- In Sections 2 to 6 the causes and the course of the reactor accident as well as the effects on the Chernobyl nuclear power plant, its environment and the health of the human beings affected are described.
- In Sections 7 to 9 safety problems of Chernobyl-type reactors, the safety-relevant improvements performed as well as the necessary rehabilitation measures on the site and future radiation protection tasks are described and assessed.
- The gist and the conclusions are summarized in Section 10. A glossary (Section 11) explains important technical terms. References and further literature are contained in Section 12.

In this report GRS relates to extensive studies and information of Eastern and Western European experts as well as to its own research results. GRS in particular wishes to thank the Russian experts for their open discussions and the information they provided.

This report is also published in French, Russian and German language.

Cologne, Garching and Berlin in March 1996

1 The RBMK Reactor Type and the Accident in the Chernobyl Nuclear Power Plant

1.1 The Chernobyl Nuclear Power Plant

The construction of the Chernobyl Nuclear Power Plant goes back to decisions taken by the USSR in 1966. Nuclear energy was supposed to increasingly contribute to power supply. Several nuclear power plants (NPP) with an overall electrical power of 12 000 MW should be built within a short period, 8 of these plants should be RBMK-1000-type reactors. This type was developed in the middle of the 60ies. One here could refer to the experience gathered with the first Soviet nuclear power plants Obninsk and Belojarsk.

It was the aim of this development of RBMK plants to build a significant number of big power reactors (1 000, 1 500, 2 400 MW) within a relatively short period using known and proven components and systems, i.e. without larger investments into the development of new technologies or into the establishment of new production industries. The

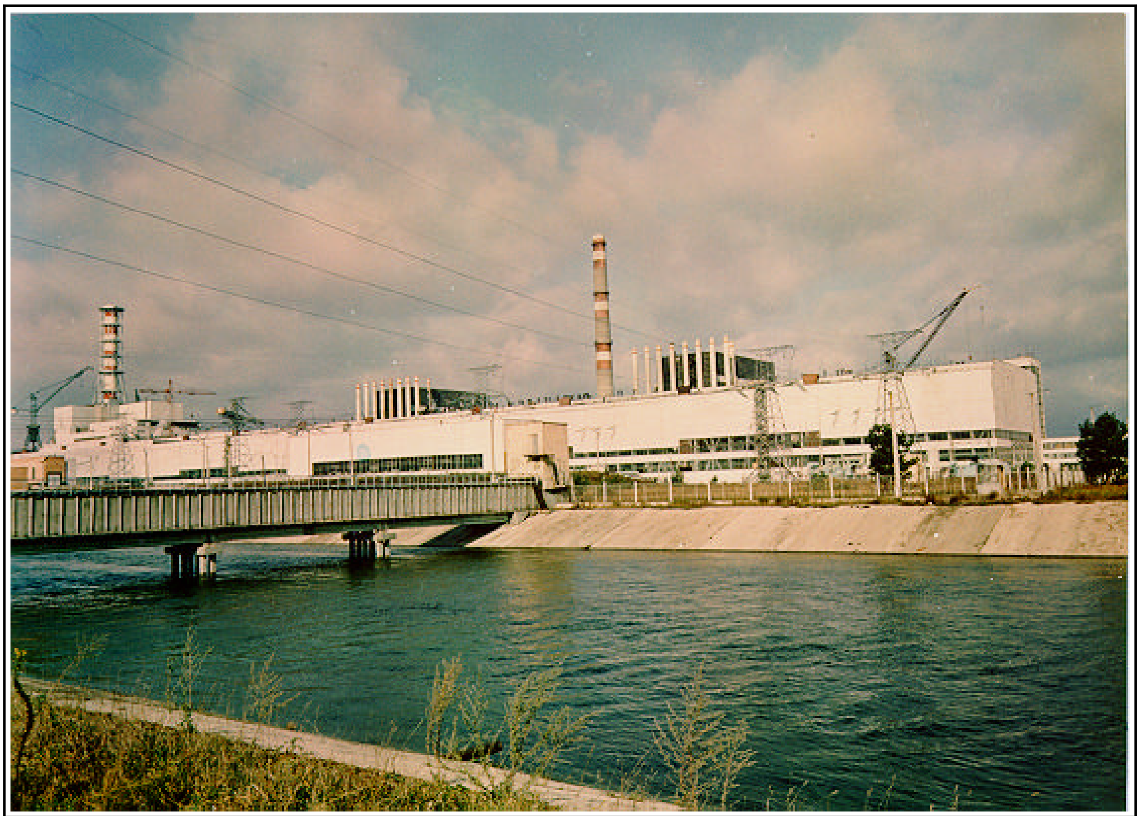


Fig. 1-1 The Chernobyl Nuclear Power Plant before the accident in 1986
(Unit 4, which was destroyed later, is located on the left, behind the stack)

RBMK is a graphite-moderated boiling water pressure tube reactor. Instead of a pressure vessel, a large number of pressure tubes (so-called "technological channels") were used, where the nuclear fuel is located. The special advantages of this reactor type according to the Soviet side were:

- high reliability as every individual pressure tube could be controlled at any time
- increase of the overall power of the nuclear power unit is easy by addition of the same construction elements, i.e. further pressure tubes
- it is possible to exchange fuel elements during operation

Prototypes were Units 1 and 2 of the nuclear power plant at Leningrad[1)] (Leningrad-1 and -2). The following plants were Units 1 and 2 at Kursk as well as Units 1 and 2 at Chernobyl.

Fig. 1-2 The geographical location of the Chernobyl Nuclear Power Plant

1) The Leningrad Nuclear Power Plant is also called Sosnovyi Bor.

The Chernobyl Nuclear Power Plant is situated in the Ukraine in a forest area (Polesje) directly on the banks of the river Pripjat. In the surrounding area of about 400 km there was a considerable demand for electrical power. Transport and network connections were favourable. The density of the population and the agricultural production in the surrounding were low.

Kiev, the capital of the Ukraine with its 2.6 million inhabitants, is situated about 110 km south of the power plant. The town of Chernobyl which provided the name for the nuclear power plant has 12 000 inhabitants and is 12 km away in south-eastern direction. 3 km from the site, the town of Pripjat was built for the employees of the nuclear power plant. 45 000 inhabitants lived there at the time of the accident.

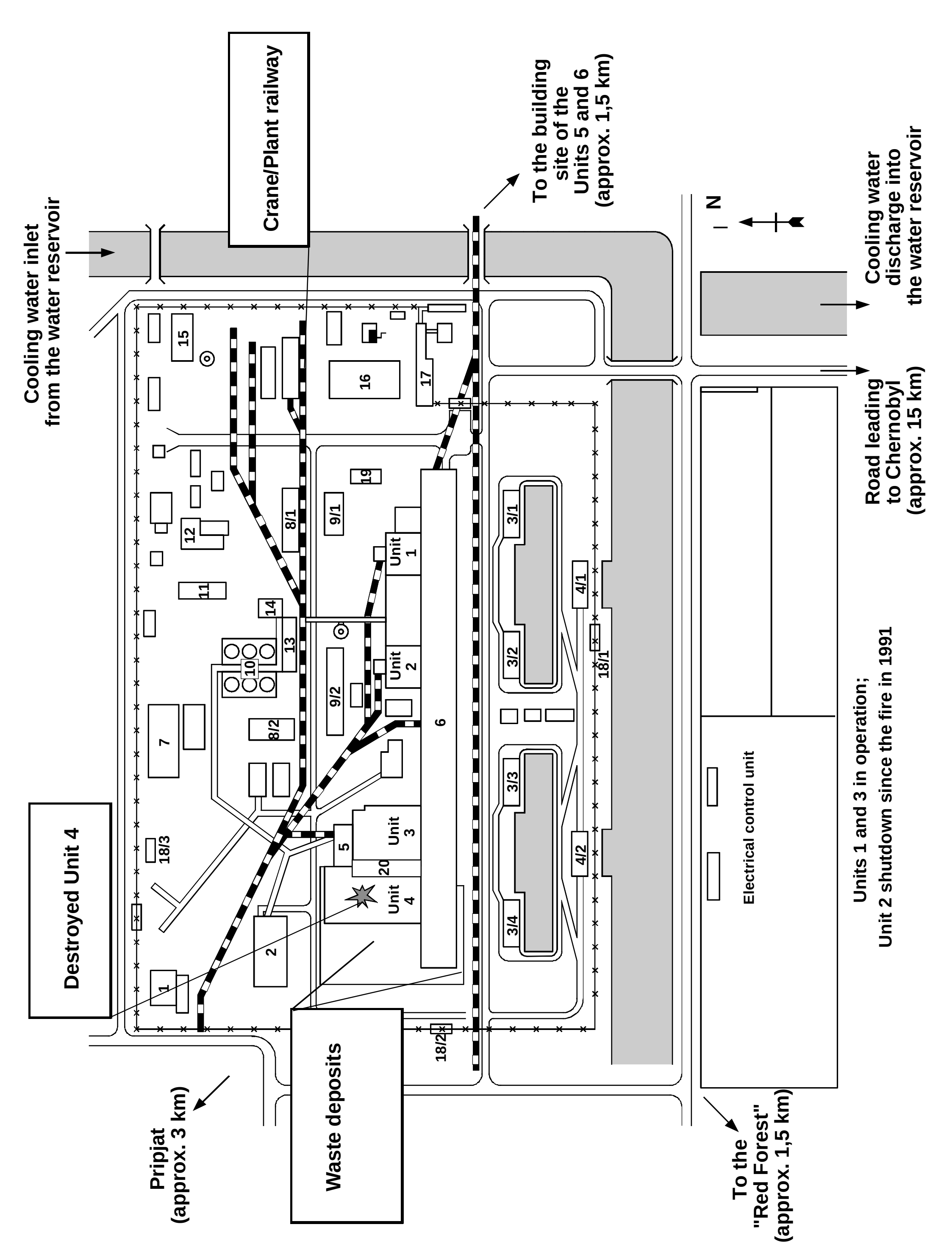
A total of six RBMK units with 1 000 MW each were planned for the Chernobyl site. The first unit started its operation in September 1977, the second unit in December 1978.

Reactor units 3 and 4 started operation in 1981 and 1983. As early as 1981 the construction of two further reactor units was begun 1.5 km south-east of units 1 to 4. The commissioning of Unit 5 was planned for autumn 1986. After the accident the construction of the two units was stopped.

Units 1 and 3 are operating at present. There was a fire in the turbine hall of Unit 2 in October 1991. As a consequence of the fire a part of the turbine hall roof collapsed. The unit had to be shutdown and has not been started up again until today. Preparations for a recommissioning have been carried out.

At the time of the accident four reactor units of the RBMK-1000 type were operating at the Chernobyl site. The accident took place in the fourth unit which is situated at the western end of the 4-unit plant. After the accident the so-called Sarcophagus was build around the destroyed reactor unit. The Sarcophagus is supposed to limit the release of radioactive substances into the environment and to safely enclose the radioactive substances in the destroyed unit for 30 years - this was stated as the design target.

On the site of the nuclear power plant extensive damage removal and decontamination measures were carried out to render a further operation of Units 1 to 3 possible. Unit 3 as well as Units 1 and 2 were shutdown on April 26 or April 27, 1986, respectively. On October 1, 1986 Unit 1 was put into operation again, Unit 2 on November 5, 1986 and Unit 3 on December 3, 1987.



Legend:

1 Spent fuel storage
2 Liquid waste store
3 Condenser coolant pumps
4 Main cooling water pumps
5 Emergency core cooling system of Unit 3
6 Turbine hall (8 x 500 MWe turbo-generators; total length approx. 750 m)
7 Tar-/aphalt processing and suppllies
8 Diesel -generator building
9 Processing plant and store for nitrogen and oxygen
10 Liquid and low level radioactive waste
11 Garage and purification plant
12 Store for components
13 Service water conditioning
14 Container for used gases
15 Construction hall for boiler and generator
16 Administration building
17 Visitors' centre and main entrance
18 Floodgate
19 Compressor station
20 Auxiliary building

Fig. 1-3 Layout of the Chernobyl Nuclear Power Plant (4x1 000 MW RBMK)

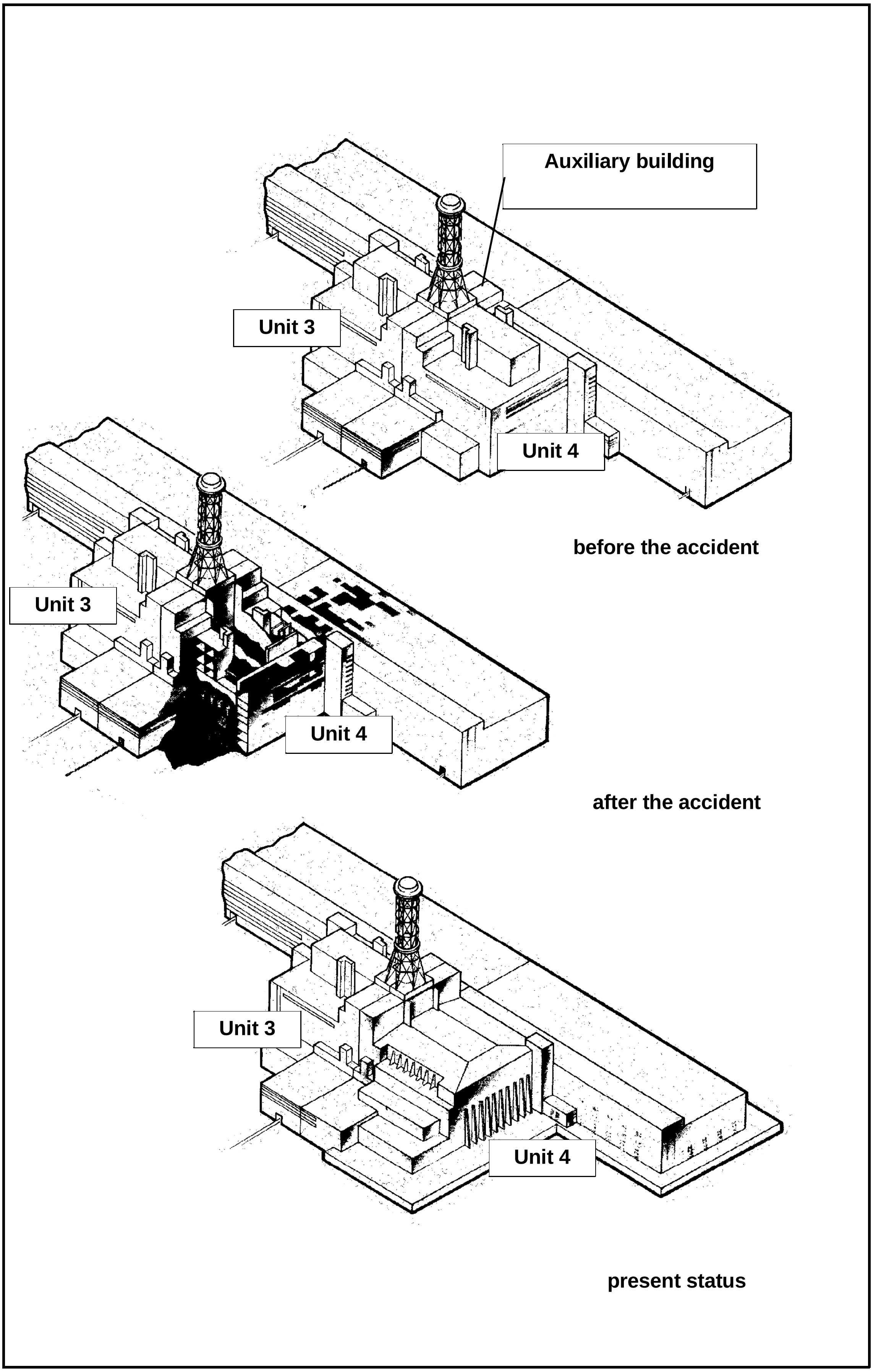


Fig. 1-4 Diagrammatic view of Unit 4 at Chernobyl before and after the accident

The further surrounding around the nuclear power plant was radioactively contaminated to such a high extent that, in particular, the towns of Pripjat and Chernobyl had to be evacuated.After the evacuation a ring-shaped 30 km control and 10 km prohibited zone was established around the nuclear power plant which is practically uninhabited today.

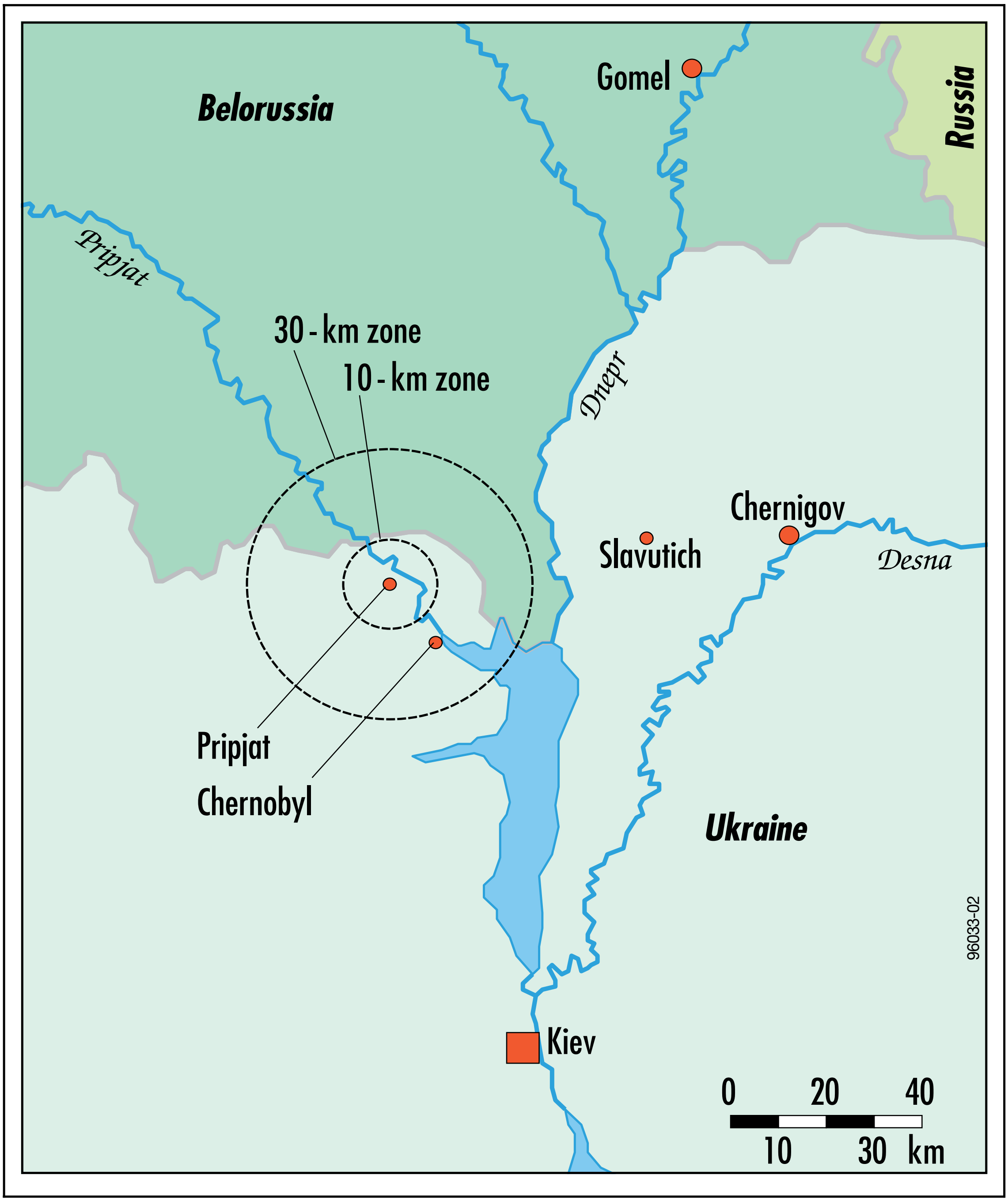


Fig. 1-5 Control (30 km) and prohibited zone (10 km) around the Chernobyl Nuclear Power Plant; approx. 50 km to the east is the new town of Slavutich, where the employees of the Chernobyl Nuclear Power Plant live today

It comprises an area of approx. 2 700 km^2 and, together with Pripjat and Chernobyl, 76 settlements.

The zone is subject to special administration. Economic or scientific activities in the zone are restricted to the operation of the Chernobyl Nuclear Power Plant including the Sarcophagus and to measures for coping with the consequences of the accident. A total of about 15 000 people work in the zone, among these 5 500 for the operation of the nuclear power plant. About 120 different scientific and technical organizations work in the zone, mainly in the town of Chernobyl. After the evacuation, the new town called Slavutich was built outside the zone for the employees of the nuclear power plant.

A fuel storage belongs to the power plant. All fuel elements which came together during the operation of all units are stored here. In this store there is a total of about 14 000 burnt-up fuel elements now. The capacity of this store is thus almost exhausted. A reprocessing of RBMK fuel elements is generally not intended. For this reason new stores will be required, if the units continue operation. In addition, about 35 000 m^3 solid and 21 000 m^3 fluid radioactive operational wastes are stored on the power plant site. The interim deposits (waste graves) close to the surface with radioactive substances and wastes originating from the accident in Unit 4 represent a great problem.

The Ukrainian Chernobyl-Ministry and the National Academy of Science of the Ukraine developed a concept on the future of the 30 km zone and began with its implementation. The objective is to minimize the ecological, social and economic consequences of the accident as well as to lower the risk of further radiation exposures.

1.2 RBMK Nuclear Power Plants in the Ukraine, Russia and Lithuania

Type RBMK nuclear power plants were only built on the territory of the former Soviet Union. Today they are located in Lithuania, Russia and the Ukraine. There is a total of 15 reactors (units) of this type in operation at five power plant locations. Unit 5 under construction in Kursk shall be completed according to Russian plans. Further units under construction were given up.

Nuclear energy globally or regionally is still very important for power supply in Lithuania, Russia and the Ukraine. A significant proportion of the power generated by nuclear

Fig. 1-6 Location of RBMK-type nuclear power plants in the Ukraine, Russia and Lithuania

power plants originates from RBMK plants: In the Ukraine about 17 %, in Russia about 50 % and in Lithuania 100 %.

Table 1-1 Percentage of Nuclear Energy of the Power Supply in the Ukraine, Russia and Lithuania

Country	Percentage of Nuclear Energy of Power Supply			
	1991	1992	1993	1994
Ukraine	27.1	29.1	32.9	34.2
Russia	11.4	11.8	12.7	11.4
Lithuania	60	80	87.2	76.4

When trying to assign the RBMK plants to individual steps of development, one can speak of three plant generations with different safety designs and considerable differences existing within each individual generation. The first generation which started operation in the 70ies, among other things, is characterized by the complete lack of a confinement. In comparison thereto, reactors of the second and third generation - they started operation in the early 80ies - have an "accident-localization system" which comprises parts of the reactor system and which in case of leakages or breaks of tubes shall retain steam and radioactive substances from the environment like a confinement.

Table 1-2 List of RBMK Type Nuclear Power Plants

Country	Location	Unit	Electrical Power [MW]	Generation	Status	Start of Operation
Lithuania	Ignalina	1	1 500	2	in operation	1983
Lithuania	Ignalina	2	1 500	2	in operation	1986
Russia	Leningrad	1	1 000	1	in operation	1973
Russia	Leningrad	2	1 000	1	in operation	1975
Russia	Leningrad	3	1 000	2	in operation	1980
Russia	Leningrad	4	1 000	2	in operation	1981
Russia	Kursk	1	1 000	1	in operation	1976
Russia	Kursk	2	1 000	1	in operation	1978
Russia	Kursk	3	1 000	2	in operation	1983
Russia	Kursk	4	1 000	2	in operation	1985
Russia	Kursk	5	1 000	3	under construction	-
Russia	Smolensk	1	1 000	2	in operation	1982
Russia	Smolensk	2	1 000	2	in operation	1985
Russia	Smolensk	3	1 000	3	in operation	1990
Ukaine	Chernobyl	1	1 000	1	in operation	1977
Ukaine	Chernobyl	2	1 000	1	fire 1991	1978
Ukaine	Chernobyl	3	1 000	2	in operation	1981
Ukaine	Chernobyl	4	1 000	2	accident 1986	1983

The RBMK plants were designed for an operational period of 30 years. According to the ideas of the operator organizations they shall be operated even beyond full life-time in most cases.

1.3 Plant Description

Units 3 and 4 of the Chernobyl Nuclear Power Plant were executed as double unit plant. The two reactor buildings form one complex with the common auxiliary building located in between. A connecting section links this complex with the turbine hall. In the turbine hall there are two turbo-generators having 500 MW each for every unit. The turbine hall is directly adjacent to Units 1 and 2 where there are four further turbo-generators. Table 1-3 contains the technical data of Chernobyl RBMK-1000.

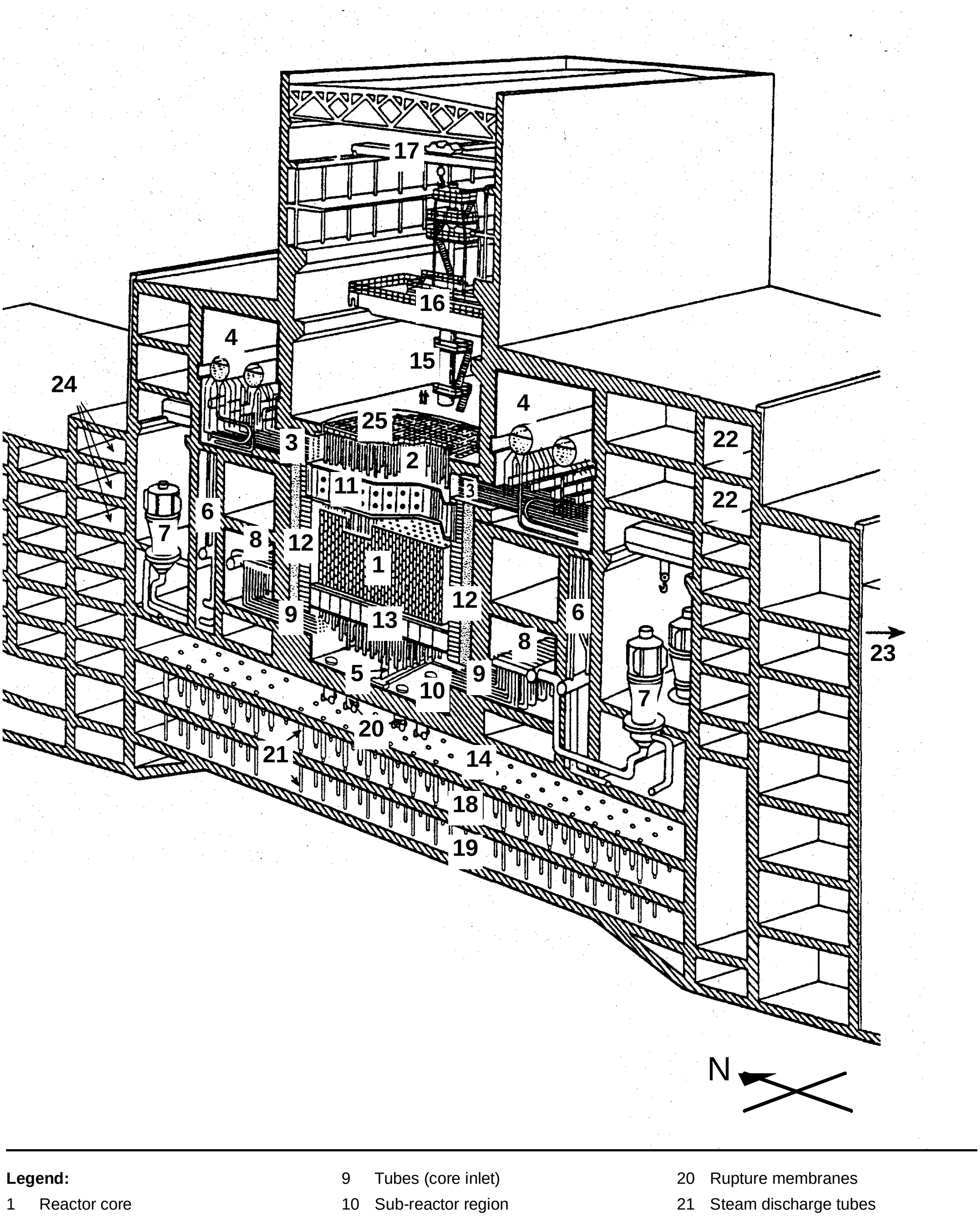
1.3.1 Reactor Building

The reactor and the components of the reactor cooling system as well as the respective control and supply facilities are located in the reactor building (Fig. 1-7 and 1-8).

In the two older units 1 and 2 there are no pressure-proof compartments for enclosing the components of the reactor cooling system. The two more recent units 3 and 4 have dry wells enclosing the lower areas of the reactor cooling system. Together with the accident localization system these sections form a confinement retaining coolant and radioactive substances upon breaks of tubes or leakages. The remaining components of the reactor cooling system, however, in particular the main steam line above the reactor core and the drum separators, are not located in the confinement.

Table 1-3 Technical Data of the RBMK-1000 in Chernobyl (mid 1980ies)

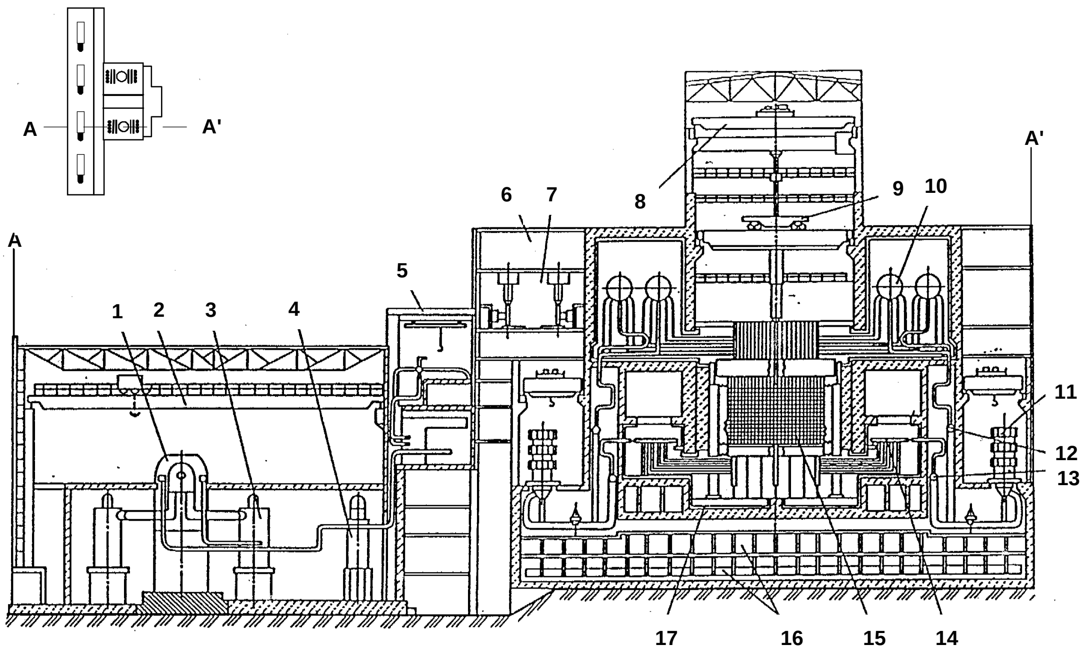
Reactor plant	**Chernobyl-1**	**Chernobyl-3**
Reactor power (thermal/electrical)	3 200 / 1 000 MW	
Turbo-generator	2 x 500 MW	
Cooling system		
Coolant	H_2O	
Cooling flow rate	37 500 t/h	
Coolant temerpature at core inlet/-outlet	265°C / 284° C	
Average steam mass content at core outlet	14.5 %	
Main steam pressure in separator	6.8 MPa	
Main steam flow rate	5 400 t/h	
Reactor core		
Height/diameter	7 m / 11.8 m	
Moderator	graphite (He-N_2-inerting)	
Moderator weight	approx. 1 700 t	
dimensions of one graphite unit (h x w x d)	600 x 250 x 250 mm	
Moderator temperature	between 500° C und 750° C	
Number of pressure tubes	1693	
Number of reflector cooling channels	156	
Number of stationary absorber rods [1)]	0	0
Number of control and shutdown rods	179	211
hereof half-long control rods from below	21	24
Rod insertion time upon reactor shutdown	18 - 20 s	
Rod insertion speed upon control	20 cm/s	
Total mass zirkaloy	ca. 177 t	
Pressure tube with fuel element		
Length of a pressure tube: total/zirconium content	ca. 22 m / 7.93 m (Zr 2.5 Nb)	
External diameter x wall thickness	88 x 4 mm	
Fuel rod bundles per fuel element	2 on top of each other	
Fuel rods per bundle	18	
Maximum power per pressure tube: design/operation	3.0 MW / 2.8 MW	
Average rod power	150 W/cm	
Fuel	UO_2	
Total mass uranium	approx. 190 t	
Enrichment	2.0% U-235	
Average burnup/maximum burnup	10 000 / 20 000 MWd/t	
[1)] only first load comprised stationary absorbers		



Legend:

1 Reactor core
2 Upper end of the pressure tubes
3 Water/steam lines (reactor outlet)
4 Drum separator
5 Bearing structure of the reactor (component S)
6 Downcomers
7 Main coolant pumps
8 Group distribution headers
9 Tubes (core inlet)
10 Sub-reactor region
11 Upper biological shield
12 Lateral biological shield
13 Lower biological shield
14 Steam distribution corridor
15 Refuelling machine
16 Crane for refuelling machine
17 Bridge crane
18 Pressure supression pool - 2nd floor
19 Pressure surpression pool - 1st floor
20 Rupture membranes
21 Steam discharge tubes
22 Ventilation rooms
23 To turbine hall
24 Room for emergency core cooling systems
25 Upper covering stones

Fig. 1-7 Perspective cross-section through the reactor building (Chernobyl-4)



Legend:

1 Turbine
2,8 Bridge crane
3 Separator reheater unit
4 Low pressure heater
5 Connecting part of the building
6,7 Rooms of the ventilation system
9 Refuelling machine
10 Drum separator
11 Main coolant pump (MCP)
12 Suction header of the MCP
13 Pressure header
14 Group distribution header
15 Reactor core
16 Pressure supression pool
17 Insulation

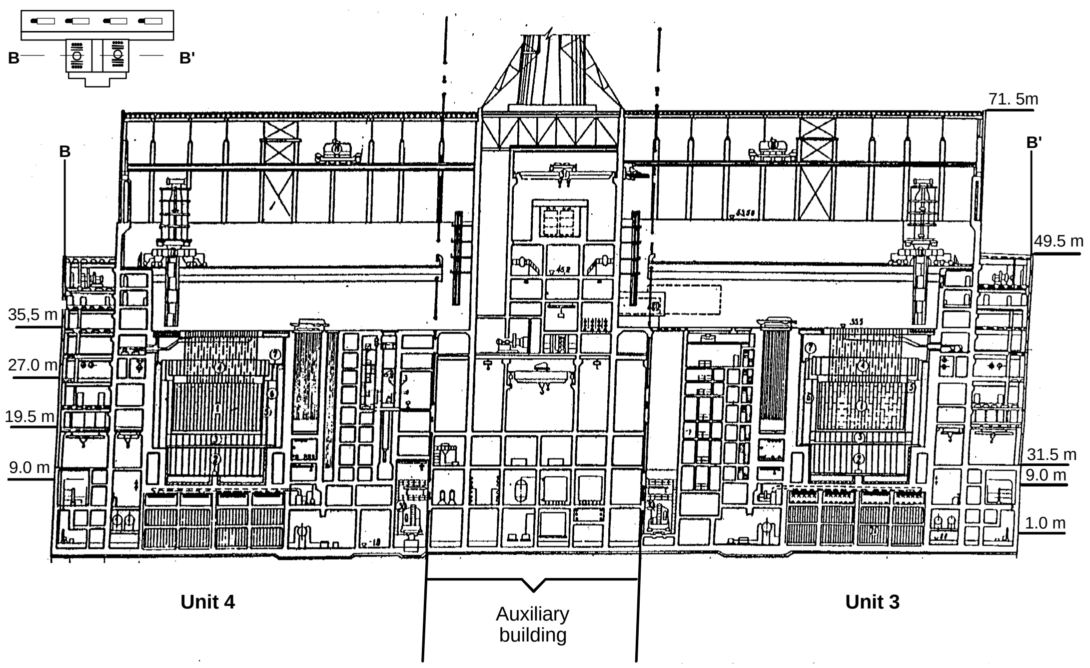


Fig. 1-8 Different sectional views of the Chernobyl Nuclear Power Plant, at the top: Unit 4 with the turbine hall, at the bottom of the page: Units 3 and 4 with the auxiliary building

1.3.2 Reactor Core

The reactor has the form of an upright cylinder-shaped unit. It consists of 2 488 rectangular graphite columns composed of individual graphite units of different heights. In the graphite units there are vertical bores which contain the pressure tubes and the tubes of the special channels of the coolant system for the control and protection system, the reflector cooling and the in-core instrumentation.

The four external lines of graphite columns serve as side reflectors. In their bores there are graphite rods or further special channels for reflector cooling.

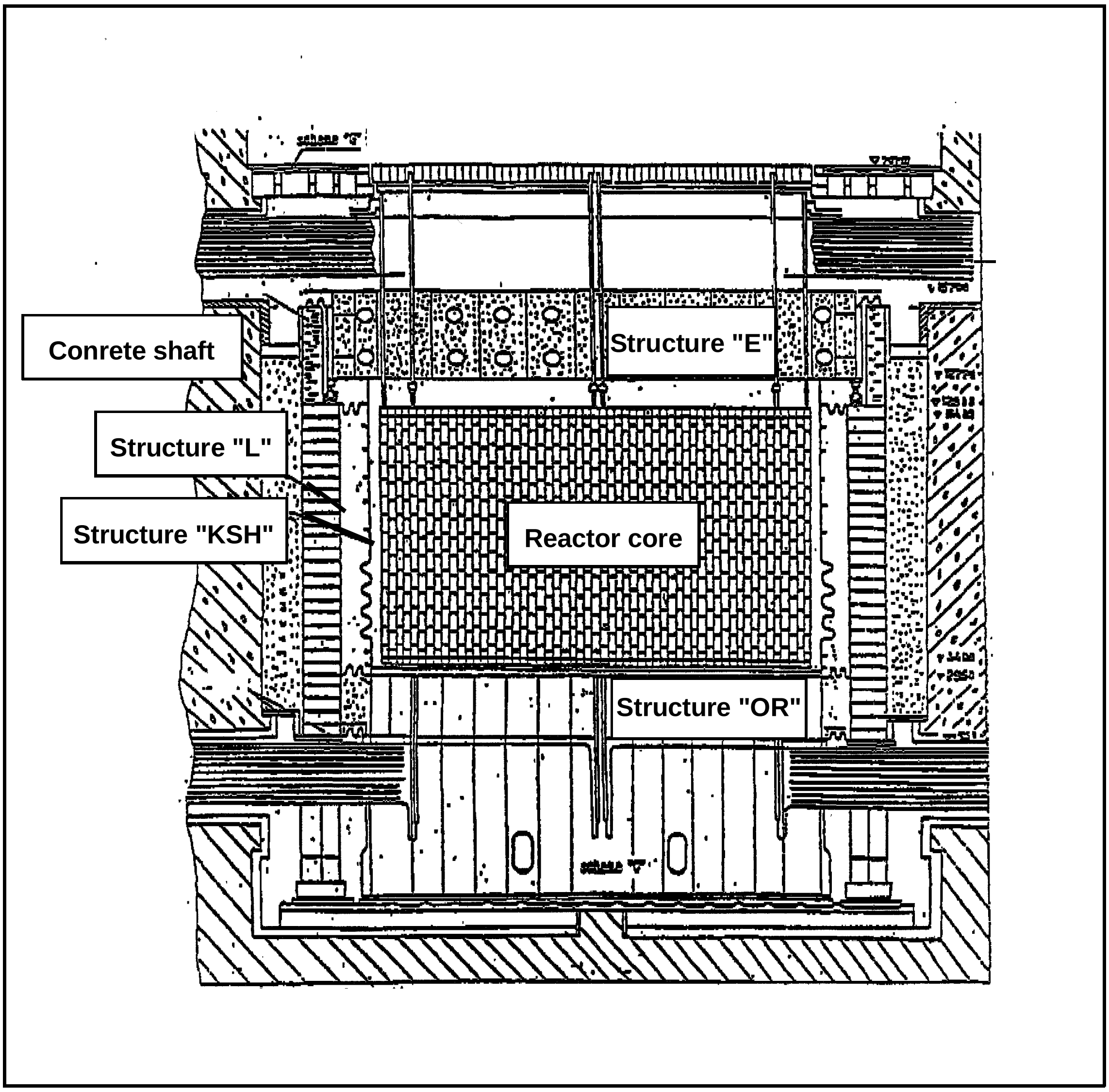


Fig. 1-9 Cross-sectional view of the reactor

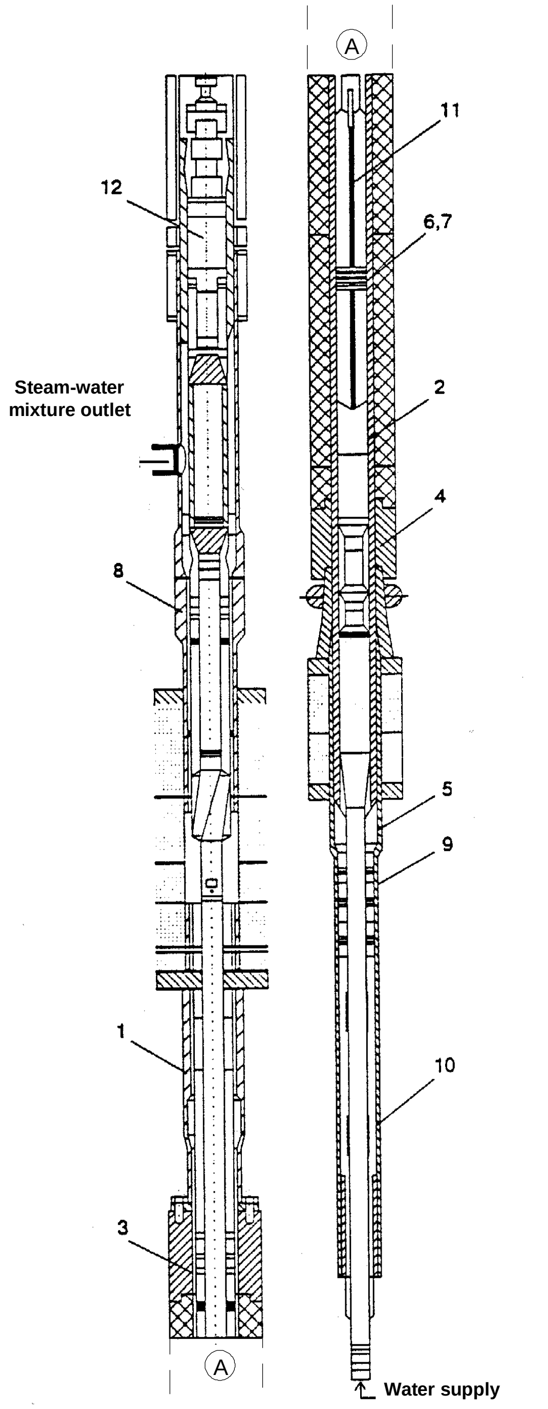
1.3.3 Reactor Tank

The graphite columns are located in a hermetically sealed room - the reactor tank (Fig. 1-9). It consists of a cylinder-shaped metal casing ("KSH"-structure), welded with the upper core plate ("E" structure) and the lower core plate ("OR" structure). All pressure tubes and special channels are firmly connected to the upper core plate. The reactor tank rests on a cylinder-shaped concrete shaft.

The reactor tank makes sure that the graphite does not get in touch with air. During operation the graphite reaches temperatures of up to 750°C. It would oxidize upon the admission of air. To prevent this and to improve heat transition between the graphite and the working and the special channels, a helium-nitrogen mixture (up to 90 volume-% He) flows through the reactor tank.

1.3.4 Pressure Tube with Fuel Element

The pressure tube (technological channel, Fig. 1-10) consists of an upper tube to which steam-water-lines are welded, a centrepart in the core area consisting of a zirconium-niobium-alloy and a lower tube with connections to the water pipes. The upper and lower sections of the pressure tube consist of stainless steel.



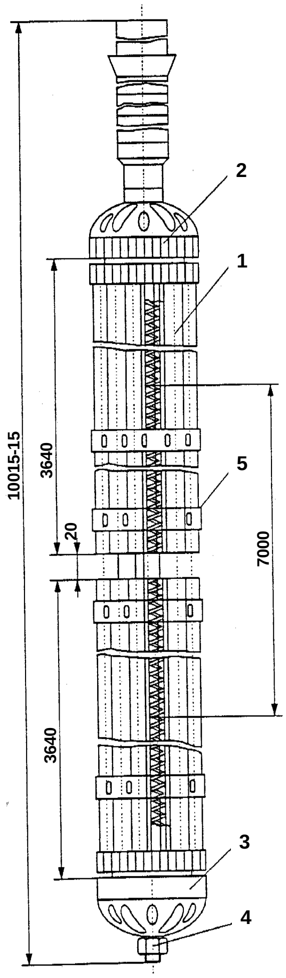
Legend:

1 Upper end part
2 Middle part made of zirconium alloy
3,4 Steel-zirconium transition joints
5 Lower end part
6 Internal surface of blocks
7 Tube
8,9 Ducts
10 Bellows compensator
11 Fuel subassembly, containing fuel elements
12 Suspension

Fig. 1-10 Fuel channel

The pressure tube with the fuel element (Fig. 1-11) serves as the working channel of the reactor. During operation heat is generated in the fuel element by nuclear fission. The coolant flows through the pressure tube from the bottom to the top and partially evaporates in the area of the fuel element.

Each fuel element consists of a suspension device and two fuel rod bundles connected in line. Each fuel rod bundle is 3.5 m long and consists of 18 fuel rods. These fuel rods have been filled with uranium dioxide tablets. One central tube with grids regularly arranged in vertical direction with openings for coolant passage serves for fixing the 18 fuel rods in two concentric circles around the central tube.



Legend:
1 Fuel rod
2 Top filling
3 Fuel element carrier
4 Nut
5 Spacer

Fig. 1-11 Fuel element

For better heat transition from the graphite units to the coolant in the core area, 268 graphite rings of 20 mm height each are arranged around the pressure tube. They alternatingly tightly fit close to the pressure tube or to the bores in graphite units (Fig. 1-12).

The gap between pressure tube and graphite ring or between graphite ring and graphite unit, respectively, for unradiated pressure tubes and graphite is approx. 2 mm. It gets smaller during reactor operation as the graphite shrinks under the influence of radiation and the pressure tube swells. Design mistakes lead to the fact that the gap is closed up after only 15 years. An exchange of the pressure tubes and the graphite rings thus will become necessary during the planned operational period. The bore in the graphite unit will also be reestablished then.

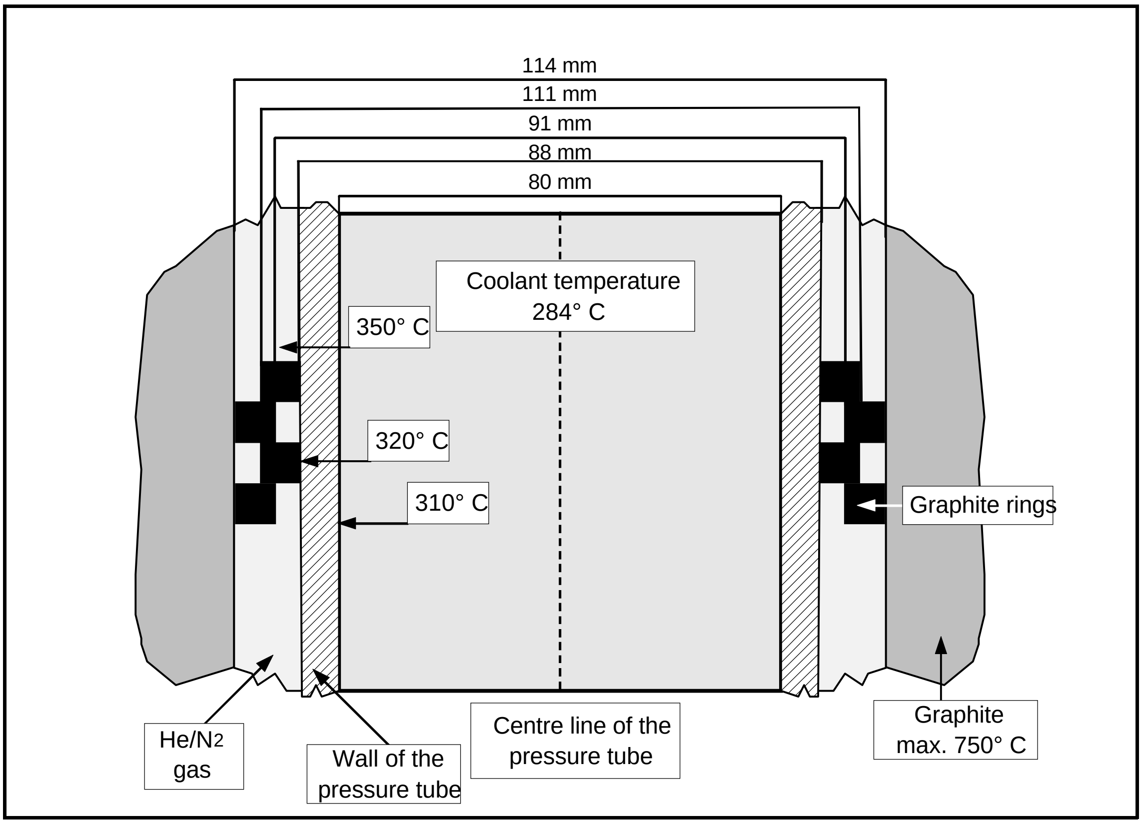


Fig. 1-12 Diagrammatic view of the graphite rings around a pressure tube
(The temperatures indicated apply to normal operation)

Table 1-4 Ratings of a Fuel Element

Ratings	Values
Cladding tube diameter	13.5 mm
Cladding tube wall thickness	0.9 mm
Diameter of UO_2-tablet	11.46 mm
Height of UO_2-tablet	15 mm
Density of tablet	10.4 g/cm^3
Enrichment uranium-235	previously 1.8 %, then 2.0 %, now 2.4 %
Weight of UO_2 in fuel element	3 360 g

1.3.5 Water/Steam System

The cooling system of the reactor (Fig. 1-13) consists of pressure tubes, water/steam lines, steam separator drums (short: drum separators), main coolant pumps (MCP), pressure headers and suction headers of the main coolant pumps, group distribution headers and the respective water inlet pipes.

RBMK plants work with a cooling system according to the boiling water principle. The coolant reaches the reactor core from below in a subcooled way. During passage of the reactor core, a part of the coolant evaporates. At the core outlet the steam content is approx. 14.5 %.

From a fluidic point of view, the reactor cooling system consists of two partial systems (loops), one for each half of the reactor. They are only connected via the main steam system. Each loop contains two horizontal drum separators, connected with each other on the water- and on the steam-side. Four main coolant pumps belong to each loop. During full load three of these pumps operate and one is in stand-by position.

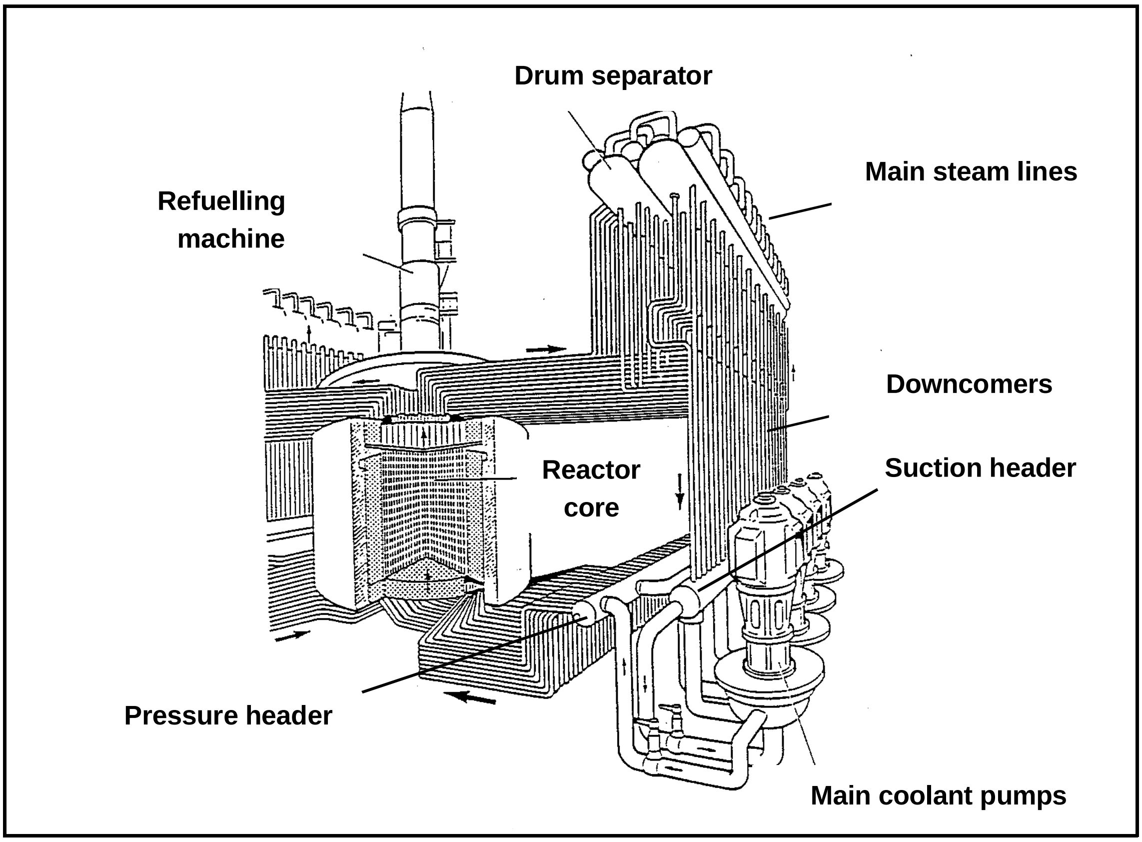


Fig. 1-13 Simplified view of the power producing loop

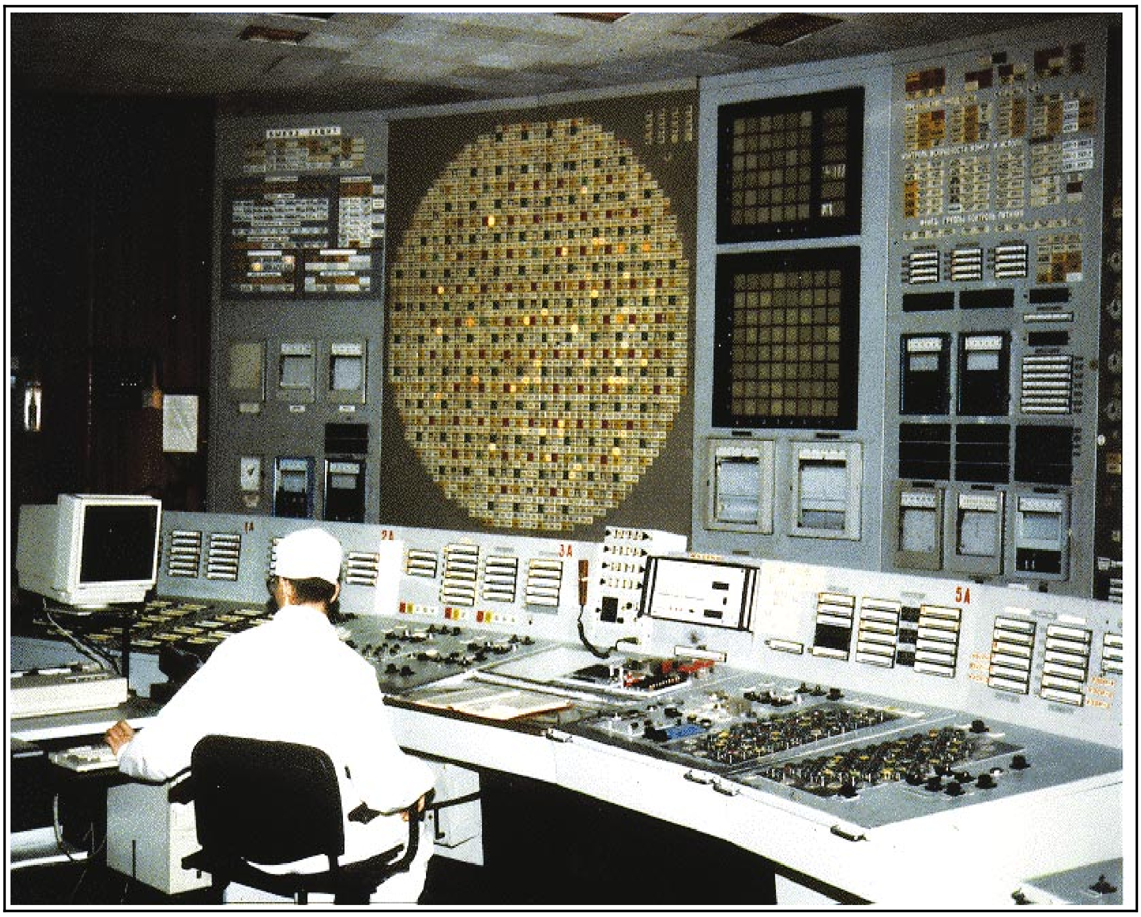


Fig. 1-14 Main control room in the Chernobyl Nuclear Power Plant

Water and steam are separated in the drum separators. The water mixes with the feedwater. Then it leaves the feedwater collector located in every drum separator, and from there it flows back via downcomers to the suction headers of the main coolant pumps.

The steam separated reaches the two turbo-generators via the main steam lines. The condensate from the condenser is transported by the feedwater pumps via the condensate pumps and the degasifier into the feedwater collector of the drum separators where it mixes with saturated water and thus reaches back into the main coolant loops.

The water is transported from the main coolant pumps to a pressure header. The collector is connected to 22 group distribution headers via tubes. 40 - 44 lines which lead to the individual pressure tubes in the reactor branch off each group distribution header.

1.4 Basic Characteristics of RBMK Safety

The safety deficiencies of RBMK plants having caused the accident are to a decisive degree determined by reactor-physical properties.

1.4.1 Basic Concepts of Reactor Physics

Reactivity and its meaning for the control of a nuclear reactor

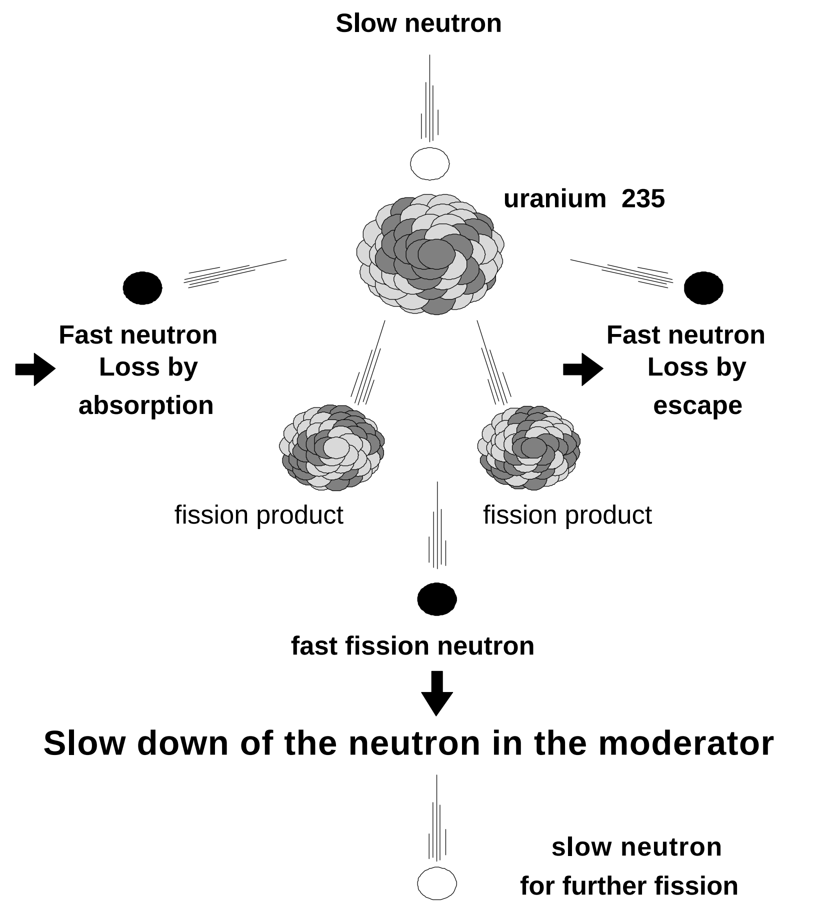
The heat generation in a nuclear reactor is based on the principle that a controlled process of nuclear fissions is maintained. In reactors like the RBMK, these nuclear fissions are mainly actuated by slow neutrons. During each fission two to three neutrons (fission neutrons) are generated in addition to the fragments of the atomic core, the fission products. The fission neutrons are slowed down (moderated) in a moderator (graphite in the case of the RBMK) and can then actuate further fissions. If the nuclear fuel is arranged in a suitable way, a self-sustaining chain reaction will thus develop. By slowing down the fission products in the surrounding fuel heat is generated which is led out of the reactor core by a coolant (water) and which is finally converted into electrical power in the turbo-gernerator. Not all fission neutrons again actuate fissions. Some neutrons are absorbed by non-fissionable atoms or they escape from the core. A stable process of nuclear fission - and thus of heat generation in the reactor core - is reached, when one neutron actuates a further fission after every prior fission. The number of neutrons then remains constant and the reactor is "critical".

It is a basic principle of reactor safety that the number of neutrons in the reactor core may not grow larger than necessary for maintaining a stable chain reaction. Otherwise high amounts of energy would be released quickly. The engineered safeguards could not retroact the temperature and pressure loads thus generated. Parts of the plant would be directly endangered and could not withstand the loads.

The neutron balance in the reactor core which determines the temporal procedure of the reactor power is described by the effective multiplication factor k_{eff} or by the reactivity which is calculated according to the correlation = $(k_{eff} - 1)/k_{eff}$. More than 99 % of the fisssion neutrons are generated directly (promptly) upon fission. A proportion of 0.5 to 0.7 % is released in a delayed way upon decay of unstable fission products.The proportion of the delayed neutrons per fission is referred to by ß. The delayed neutrons

Nuclear fission process

Upon nuclear fission 2-3 fast fission neutrons are generated apart from the fission products. > 99 % of the fission neutrons are released at once (prompt) and < 1 % (fraction β) with a delay.



Effektive multiplication factor k_{eff}	< 1	= 1	$\leq 1 + \beta$	$> 1 + \beta$
Reactivity ρ $\rho = \frac{k_{eff} - 1}{k_{eff}}$	negative	0	positive between 0 and β	positive > β
Reactor state	subcritical, no chain reaction	critical, stable chain reaction	delayed-over-critical, controllable with suitable core design and control	prompt-super-critical
Energy release (power) of nuclear fission	decrease or remain zero	constant	growth can be controlled (e.g. during startup)	growth cannot be controlled during insufficient negative feed-back

Fig. 1-15 Diagrammatic descrition of the nuclear fission process

play a decisive role for the control of the chain reaction in the reactor: If k_{eff} is = 1, i.e. $\rho = 0$, the reactor (taking into account the prompt and delayed neutrons) is critical. If k_{eff} is bigger than 1, ($\rho > 0$), the number of neutrons increases with every "fission generation" and the heat power in the reactor raises. The period in which the number of neutron increases by the factor $e \approx 2.718$ is called reactor period. In the delayed-overcritical sphere ($k_{eff} \leq 1 +$ ß, ρ ; ß) power only increases slowly. But if the reactor gets “prompt-overcritical” ($k_{eff} > 1 +$ ß, $\rho >$ ß), the prompt neutrons already suffice for a power increase. If no sufficient negative feedback mechanisms become effective, the number of fission neutrons will grow very quickly. There is an increase of the chain reaction with a reactor period in the range of milliseconds which cannot be controlled by active countermeasures, like the insertion of control rods. The duration of such a “reactor excursion” and the amount of energy released depends on the reactivity admitted and the strength of the fast-acting negative feedback effects.

Reactivity Coefficients

The reactivity is influenced by several parameters, like fuel temperature, coolant density, coolant pressure and moderator temperature. The influence of these and other parameters on reactivity is described by reactivity coefficients. The reactivity coefficient is the relation between the reactivity change and the change of the respective parameter (e.g.$\Delta\rho/\Delta T_{fuel}$ is the reactivity coefficient of fuel temperature).

The power-related behaviour of the reactor is determined by the cooperation of all reactivity coefficients. Changes of the reactor power generally influence several parameters and thus also reactivity. Accordingly, a “power coefficient” can also be defined as the relation between reactivity change and power change. When reactivity is admitted to the reactor, power increases at first. If the power coefficient is negative, a new stationary state will adjust itself. But if the power coefficient of reactivity is positive, it will only be possible to restrict an increase of power until core destruction by active interferences, e.g. by the insertion of control rods.

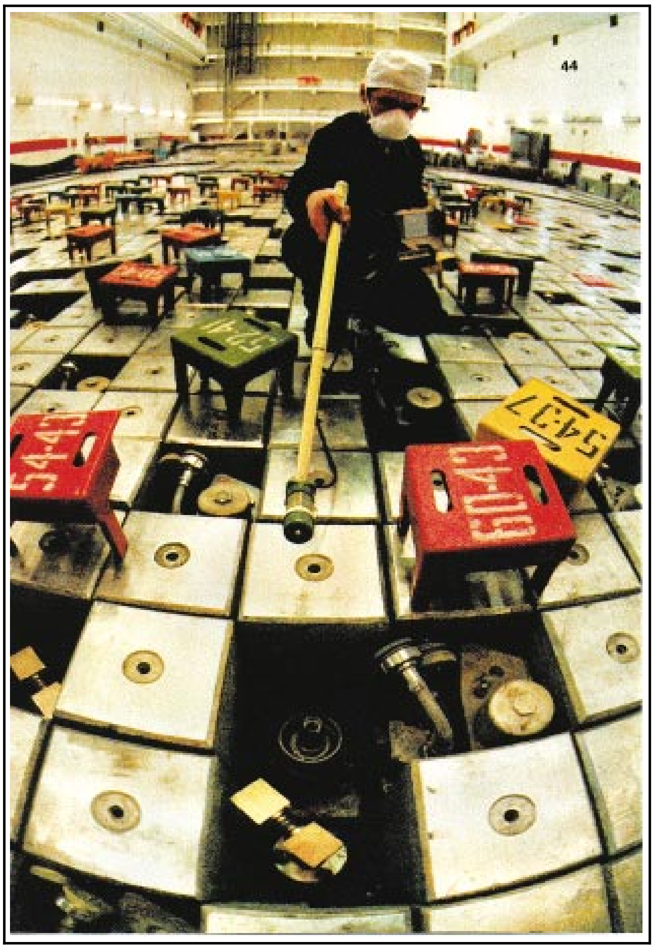


Fig. 1-16 Radiation measurement at the reactor lid

Sufficiently negative feedback effects which can be achieved by a suitable core design therefore represent an essential precondition for the safe operation of nuclear reactors. Reactors with sufficiently negative feedback behave self-regulatingly, as a new equilibrium adjusts by itself after reactivity admission.

Excess Reactivity

(In the long run) the reactivity of the reactor is influenced by the fact that fuel is consumed during nuclear fission (burnup) and fission products absorbing neutrons are generated. Fission products having a particularly strong absorption effect are called neutron poisons. Upon loading the reactor core, more nuclear fuel is employed than initially required for maintaining the chain reaction so that the increasing burnup and the increasing neutron absorption by fission products do not terminate the chain reaction too early. The "excess reactivity" is balanced by additional absorbers brought into the core which are removed from the reactor within the course of the time.

Xenon Poisoning

A neutron poison particularly important for reactor operation is Xenon 135. It mainly results from the decay of the fission product Iodine 135 having a half-life-value of about 7 hours. Xenon 135 is an effective neutron absorber with a half-life-value of about nine hours. During stationary operation of a reactor the generation of Xenon 135 and its removal by neutron capture and decay are balanced. If the power of the reactor decreases, the neutron capture by Xenon 135 will also decrease with the diminishing number of neutrons. As an almost unaltered amount of xenon is at first generated with the decay of Iodine 135, the concentration of the neutron poison in the reactor core increases temporarily. Additional reactivity must be admitted until the xenon concentration decreases again, so that the chain reaction does not end.

1.4.2 Safety Concept

In the reactor of a nuclear power plant (this applies to RBMK in the same way as to other reactors), large amounts of radioactive substances are generated, which have to be kept away from the environment in a reliable way. For this purpose the following basic safety functions have to be ensured during all operating states, including accidents:

- **Reactivity control:** the control of heat generation in the core

- **Core cooling:** heat removal from the reactor core

- **Activity confinement:** the confinement of radioactive substances.

Within the safety strategy for Western-type nuclear power plants, a graded safety concept was developed and implemented in practice. This concept consists of a comprehensive ste of engineered safeguards. On the one hand, there are barriers retaining the radioactive substances arising in the reactor. On the other hand multistage engineered safeguards and design measures protect these barriers against damage.

- **Barriers**

  In Western reactors these activity barriers are fuel rods, the confinement of the reactor cooling system and the containment.

- **Defense in depth**

  Defense in depth represents independent defense lines which are to ensure the integrity of the barriers: high quality requirements to control disturbances, protective devices to restrict disturbances, multiple engineered safeguards to control accidents, technical and administrative measures for plant-internal emergencies. Inherent safety features (e.g. self-regulating behaviour during reactivity disturbances) and automized systems creating the necessary time for intervention represent one basic precondition of this concept. If this precondition is not met, the independence of the lines of defense will be impaired and the applicability of the concept will principally become questionable.

In RBMK plants, defense in depth has only been implemented to a limited extent:

- With the fuel rods and the enclosure of the reactor cooling system there are two barriers enclosing the reactive substances. The "containment" barrier is, however, completely missing in RBMK plants of the first generation and only incompletely exists from the 2nd generation onwards.

- Regarding defense in depth it is significant that the lack of important inherent safety properties (see Section 1.4.3) is not compensated by automized safety features. Accidents simultaneously breaching all defense lines thus become possible. Moreover, the defense line "accident control" is considerably impaired by deficiencies of the protective and engineered safeguards.

1.4.3 Reactor-Physical Properties of the RBMK

Positive reactivity feedback of the RBMK

A special situation for the reactivity behaviour of the RBMK results from the utilization of graphite as moderator and water as coolant. The coolant water at the same time works as neutron moderator and neutron absorber. While the moderator effect of water is of minor importance compared to the one of graphite, the reactivity behaviour of the reactor is considerably influenced by the absorber effect of the water. A reduction of the coolant density, e.g. by evaporation, or a loss of coolant thus leads to a significant reduction of neutron absorption in the reactor core. An increase of the steam content in the pressure tubes thus effects an increase of reactivity. The RBMK has a positive steam void reactivity effect (positive void effect).

The size of the reactivity feedback is strongly dependent on the burnup of the nuclear fuel and the number of absorbers in the core.

As early as in the 70ies, it was demonstrated by measurements that the void effect of RBMK grows strongly positive in the course of operation. The void effect of the reactivity, i.e. the reactivity change upon complete evaporation of the water determined on the basis of the measurements was -0.2 ß in the first core with about 200 stationary absorber rods. For an average burnup of about 10 MWd/kg and without the stationary absorber rods the void effect increased to about +5 ß.

Operational Reactivity Margin (ORM)

An important parameter for the reactivity status of RBMK plants is the operational reactivity margin (ORM). The ORM is the reactivity equivalent of all control rods (completely or partially) inserted into the core. It is stated as a multiple of the reactivity equivalent of an average control rod completely inserted.

The ORM is important for operational and technical safety.

- The operating rules valid in 1986 required that during power operation the ORM had to consist of at least 26 to 30 control rods. This margin is necessary for operational purposes as control rods have to be withdrawn upon changes of the load, e.g. for compensating xenon poisoning, otherwise the reactor would shut down by itself.

- For safety reasons only a limited number of control rods may be withdawn. If the ORM is too low, the positive void effect is intensified and the shutdown effectivity at the beginning of the control rod insertion is reduced. Until 1986 the minimum limit of the ORM permitted was 15 control rods. Experience in Chernobyl has shown that the lower limits of the operating ORM of 26 to 30 control rods were too low from the safety point of view. The importance of the ORM for technical safety had principally been known in the Soviet Union prior to the accident, but it had not been granted adequate attention. The operating staff apparently saw this parameter almost exclusively under operational aspects.

1.4.4 Engineered Safeguards of RBMK

Some systems which are important for the safety of RBMK are described below. Refering to control and shutdown systems this description relates to the status until the accident. The substantial backfitting measures especially for these systems are dealt with in Section 7. For the remaining systems the current state is described as it only slightly differs from the status prior to 1986. The design features of the most important engineered safeguards are comprised in Table 1-5.

Control- and Shutdown System

The function of the control and shutdown system (Fig. 1-17) consists of the operational control of the reactor power and the shutdown of the reactor by termination of the chain reaction. To avoid a disruption of heat generation by "unnecessary" shutdowns, the plant design provided for reactor scrams only upon extreme necessity. Accordingly, there was a reactor protection system which only lowered the reactor power to a certain level (60 %, 50 % or 20 % of the nominal power) depending on the severity of the disturbance and which interrupted the shutdown process as soon as the actuation signal did not exist any longer.

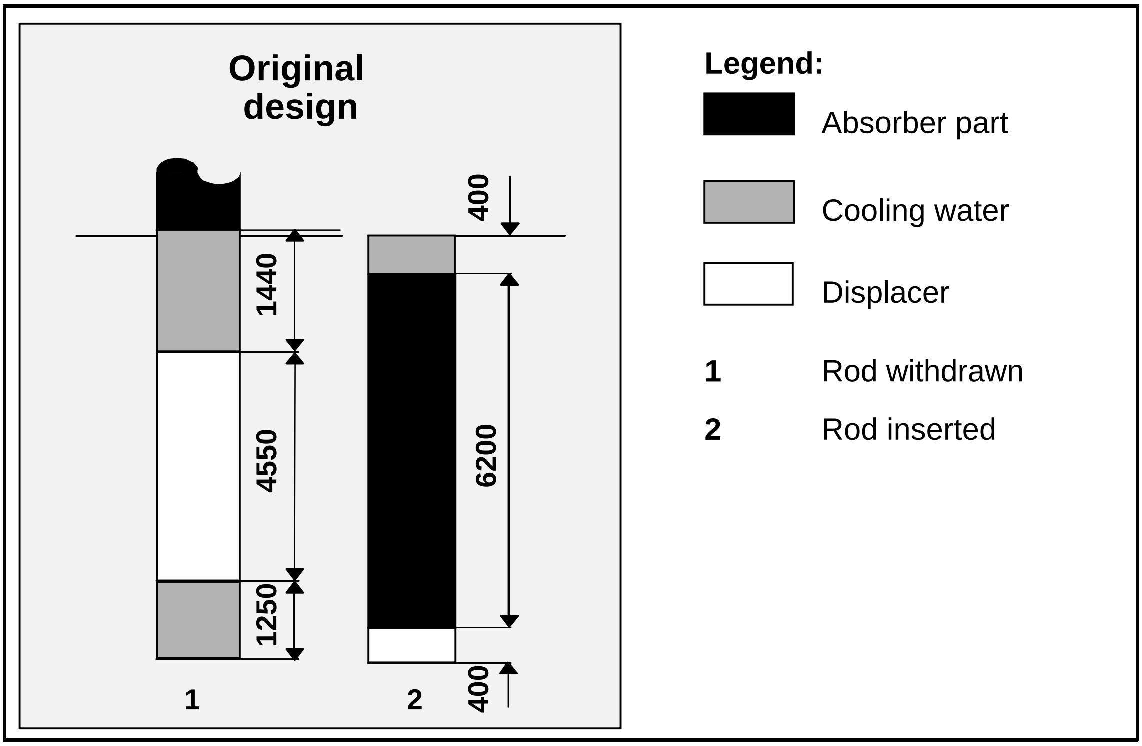


Fig. 1-17 Original design of the control and shutdown system of RBMK plants

There are 211 control rods in the RBMK reactor core belonging to the second generation (179 in plants belonging to the first generation). For shutdown 187 of the 211 control rods are inserted into the core from the top. 24 shortened control rods are inserted into the core from below. They serve the purpose of controlling the axial power distribution. The control rods inserted from below were not incorporated into reactor protection. 163 of the control rods inserted from the top consisted of an absorber part of approx. 6 m length and a displacement part of graphite of 4.5 m length. The total height of the core was 7 m. The other 24 control rods inserted from the top did not comprise a displacement part but an absorber part which is approx. 5 m long. The control rods are cooled with water by their own "control rod cooling system".

One special feature of RBMK plants prior to the accident was a positive reactivity effect of the shutdown system. When the control rod is completely withdrawn, the displacement part is approx. in the centre of the reactor core. Above and below the displacement part the control rod channel is filled by water columns. If a control rod is inserted into the core from this position, the (neutron moderating) displacement part of graphite replaces the lower (neutron absorbing) water column. Thus the opposite of the intended effect is attained at first: The reactor power is not reduced by the admission of negative reactivity, but it is increased by a positive reactivity admission in the lower part of the core. The positive reactivity effect caused by the insertion of completely withdrawn control rods is also called "positive shutdown effect".

In the RBMK-plants there was only one shutdown system. Western reactors, by contrast, apart from their first shutdown system which acts within a few seconds, comprise a second, independent system.

Before the accident the highest control rod insertion speed of RBMK was only 0.4 m/s. Also upon shutdown in an accident the control rods required 18 to 20 s for complete insertion.

Safety Systems for Heat Removal

During normal operation the heat generated in the reactor is removed via the water/steam system.

When the water/steam system is no longer available in the event of disturbance or an accident, there are safety systems for residual heat removal. For disturbances and accidents without loss of coolant this is the emergency feedwater system, for loss-of-coolant accidents the emergency cooling system. If required, these systems are automatically actuated by the reactor protection system.

Emergency Feedwater System

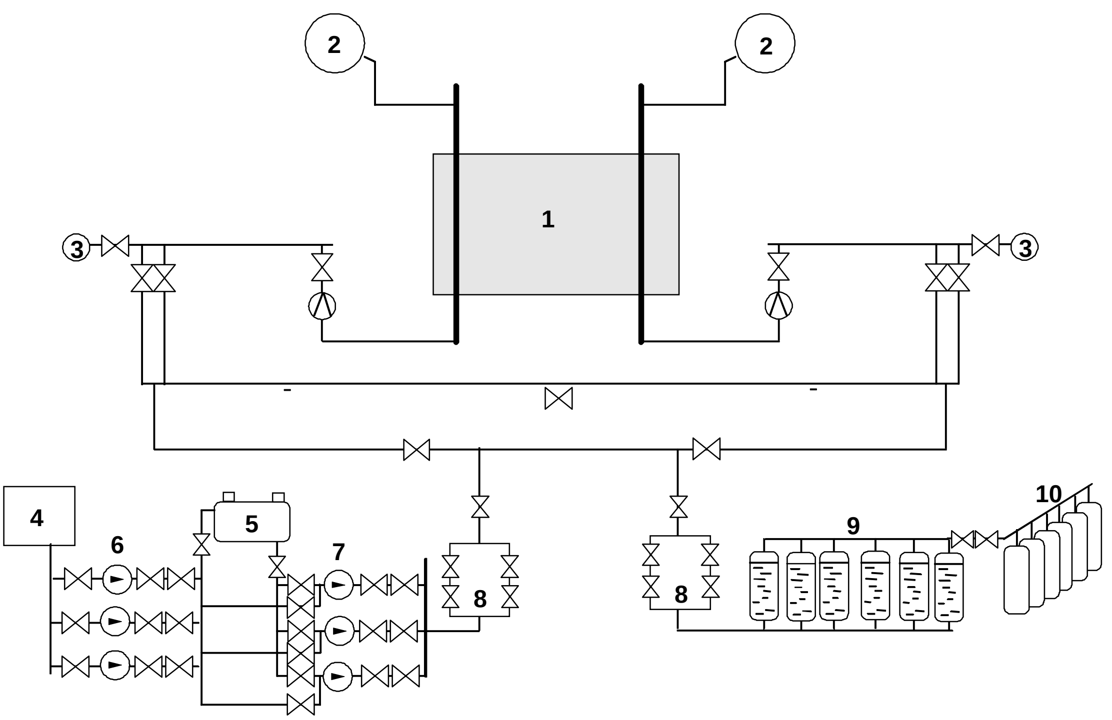
The emergency feedwater system feeds water from the condensate tank via the emergency feedwater pumps with preceding condensate pumps into the drum separators and removes the residual heat after the reactor has been shutdown. The three emergency feedwater pumps are situated in the turbine hall. The emergency feedwater supply system also fulfils operational functions during startup and shutdown, e.g. during filling the reactor cooling system.

Emergency Core Cooling System

The emergency core cooling function of Units 1 and 2 in Chernobyl (1st generation) is carried out by two partial systems (Fig. 1-18). Short-term core cooling is carried out by a system of 6 accumulators with fast opening valves and simultaneous connection with the main feedwater supply system also injecting via fast opening valves.

Long-term core cooling is ensured by the 3 emergency feedwater supply pumps (3 x 50 %) and, if available, by the main feedwater pumps. Theses systems feed into both halves of the reactor core via a common collector. The systems responsible for the emergency core cooling function are designed for the break of a pipe having a nominal width (NW) of 300.

Plants of the first generation which have not been backfitted only have the main feed-water supply and the emergency feedwater supply systems for emergency core cooling. For some plants there are plans to upgrade the emergency core cooling system according to the example of Leningrad, Unit 2, where such backfitting measures are being carried out at the moment. A complete three-train emergency core cooling system shall be backfitted by the installation of one additional redundancy consisting of six accumulators for short-term core cooling and three independent, spatially separated emergency



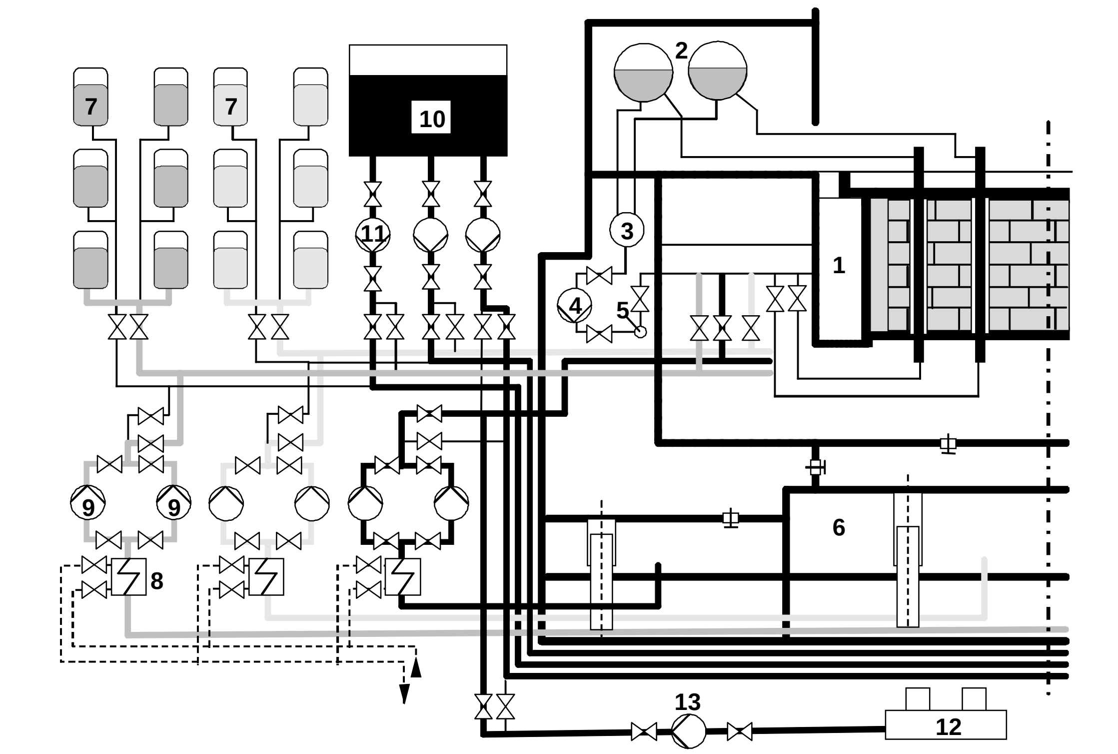
Legend:

1 Reactor core
2 Drum separator
3 Pressure header of the MCPs
4 Condensate tank
5 Feedwater tank
6 Condensate pumps
7 Emergency feedwater supply pumps
8 Fast opening valve
9 Accumulator (Water)
10 Accumulator (Air)

Fig. 1-18 Diagrammatic view of the emergency core cooling system of RBMK plants belonging to the first generation (Chernobyl Unit 1 and 2) core cooling pumps with a redundant water supply. For both halves of the reactor separated emergency cooling collectors are provided for.

The emergency core cooling system in the Chernobyl Nuclear Power Plant, Unit 3 (2nd generation) is designed for the break of the biggest coolant pipe of the reactor cooling system with NW 900. The emergency core cooling system consists of partial systems for short-term and for long-term core cooling. Both partial systems are designed as three-train systems (Fig. 1-19).

The partial system for short-term core cooling consists of two trains having six accumulators each. The third train consists of the main feedwater system. All trains inject into the group distribution header via fast-opening valves. The partial system for short-term core cooling only injects into the reactor half concerned via a selector module.



Legend:

1 Reactor
2 Drum separator
3 Suction header
4 Main coolant pumps
5 Pressure header
6 Pressure suppression pool
7 Accumulator
8 Heat exchanger
9 Emergency core cooling system pumps
10 Condensate tank
11 Emergency core cooling system pumps
12 Feedwater tank
13 Feedwater pump

Fig. 1-19 Diagrammatic view of the emergency core cooling system of RBMK plants of the second generation (Chernobyl Unit 3 and 4)

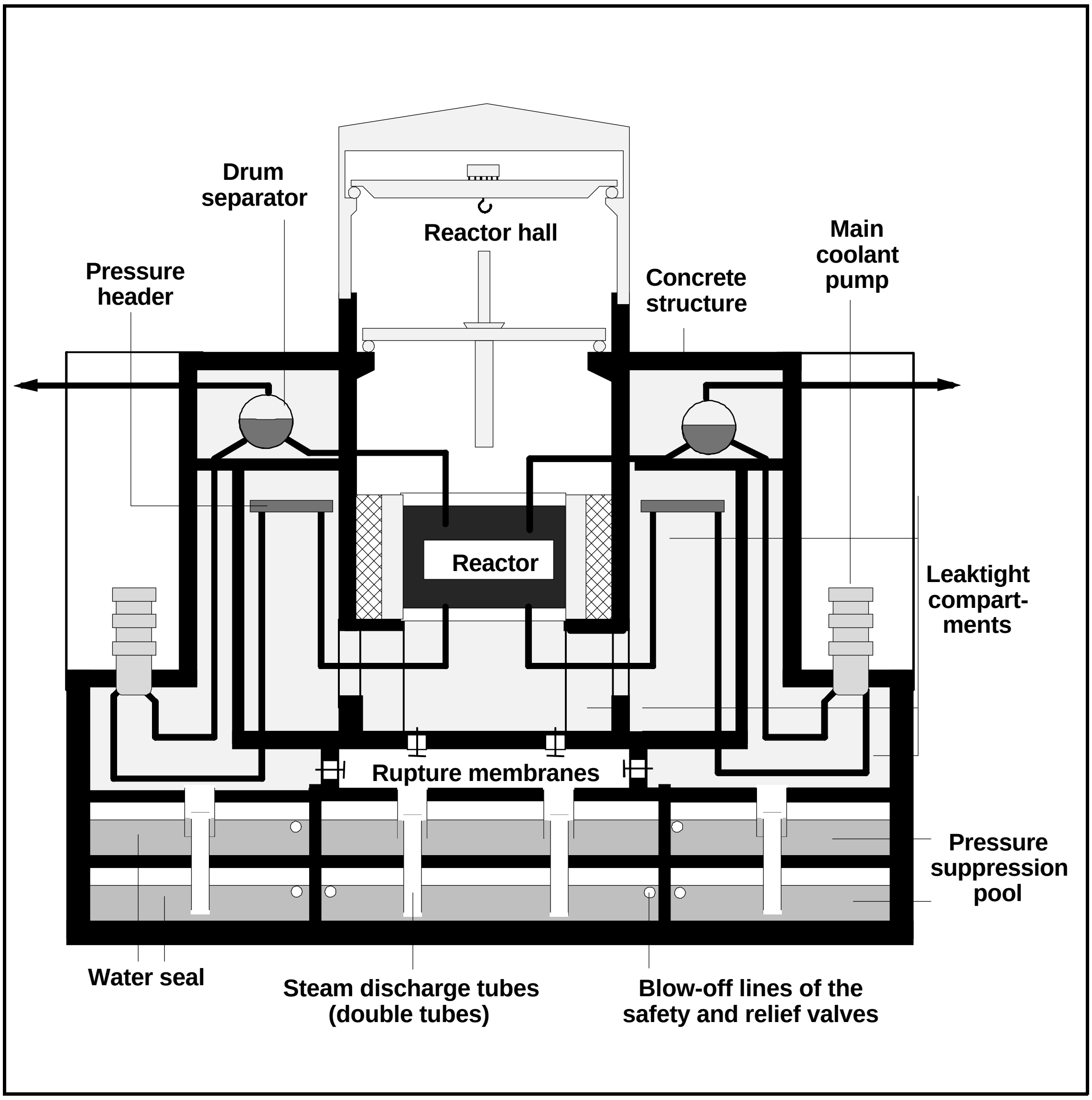


Fig. 1-20 Diagrammatic view of the partial confinement of RBMK plants belonging to the second generation (Chernobyl-4)

The partial system for long-term core cooling consists of 3 x 2 emergency cooling pumps which are assigned to the half of the core with the leak via a selector module and of 3 x 1 emergency cooling pump for the half of the core not affected. All trains possess a uniform separate injection line to the emergency cooling collectors and further into the group distribution headers. All emergency core cooling pumps are emergency power supplied.

Service water system

The service water system is part of the residual heat removal chain and is used to remove residual heat and to cool safety relevant components and operational consumers.

Confinement

RBMK plants do not comprise a confinement comparable to Western light water reactors. To limit pressure after loss-of-coolant accidents RBMK plants of the first generation only have an emergency condensation system of low capacity in the compartments surrounding the lower part of the reactor cooling system. Medium-sized and larger breaks of the reactor cooling system are thus necessarily connected with a release of radioactive substances into the reactor hall, the turbine hall or into the environment, respectively. The reactor building is only designed for loads occuring upon tube ruptures up to NW 300.

From the 2nd generation onwards the plants have an accident localization system which represents a partial confinement with pool-type pressure suppression system. The tank cooling system keeps the water seal of the pool-type pressure suppression system on the required temperature level. Design basis accidents for this system are the break of a pressure header of the main coolant pumps (NW 900), a group collector (NW 300) in the lower hermetically closed compartments of the reactor building as well as the failure of a pressure tube in the reactor.

In all RBMK plants effective provisions to retain radioactive substances in case of medium-sized and larger leaks in the feedwater system, in the upper areas of the water/steam system and in the main steam system are missing.

Table 1-5 Engineered Safeguards of RBMK Nuclear Power Plants

Ratings or systems of the reactor plant, resp.	1st generation (Chernobyl-1 and -2)	2nd generation (Chernobyl-3 and -4)
Control and shutdown systems		
Number of control rods	191	211
Insertion/withdrawal speed	out: 0.2 m/s; in: 0.4 m/s	
Insertion time of fast shutdown rods [1)]	2 - 2.5 s bzw. 7 s, resp.	
Insertion time of control rods in 1986/ today	18 - 20 s/12 s[1)]	
Accumulators		
Accumulators	1 system with 6 tanks	2 syst. with 6 tanks each
Water volume	6.8 m^3 per tank	13 m^3 per tank
Propellant volume	6.8 m^3 per tank	12 m^3 per tank
Pressure	9.5 MPa	
Emergency cooling pumps		
Number for the damaged half of the core		3 x 2 pumps
Number for the intact half of the core		3 x 1 pumps
Capacity		3 x 50 %
Delivery rate per pump		250 t/h
Emergency feedwater pumps		
Number	3	
Capacity	3 x 50 %	
Delivery rate per pump	250 t/h	
Condensation tank cooling pumps		
Number		3
Capacity		approx. 3 x 50 %
Delivery rate per pump		250 t/h
Condensation tanks		
Number		2
Water seal		approx. 3 200 t
Depressurization system		
Design pressure near the collectors of the main coolant pumps		0.45 MPa
Design pressure near the group distribution headers		0.18 MPa
[1)] backfitted after the accident		

1.5 The Situation in Unit 2 of the Chernobyl Nuclear Power Plant

Since the fire in the turbine hall on October 10, 1991, Unit 2 of the Chernobyl Nuclear Power Plant has been shut down. At present the operator is examining under which conditions the reactor can be recommissioned. A decision is to be expected soon. More than half of the fuel elements were removed from the reactor. The remaining 800 fuel elements shall be removed in 1996 after the repair of the spent fuel storage (leak in the bottom of the tank) has been completed.

After diagnosis and repair works, turbines 3 and 4 belonging to Unit 2 are ready for operation. Generator 3 belonging to turbine 3 is also operative. The adjacent generator 4 cannot be repaired because of the damages cause d by the fire.

The main feedwater and emergency feedwater pumps had only slightly been damaged. Nevertheless, many tubes as well as the process control and electrotechnical parts have to be replaced completely.

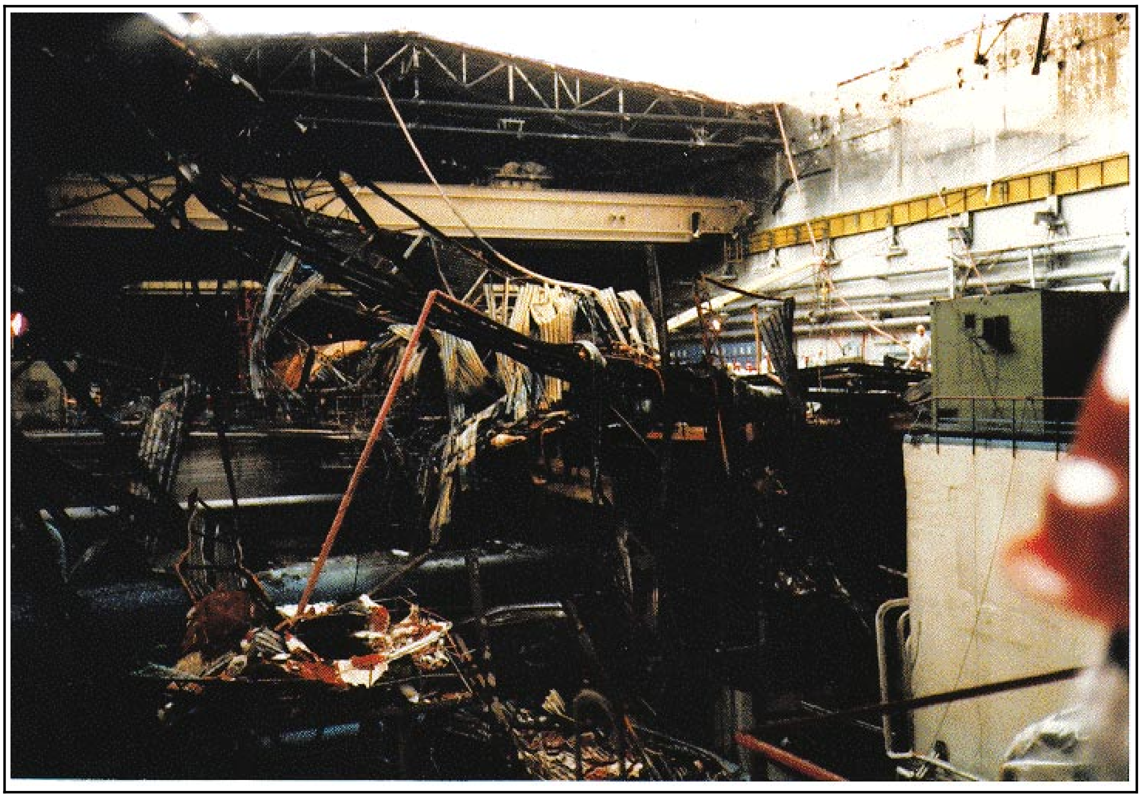


Fig. 1-21 The fire in the turbine hall of Unit 2 at Chernobyl caused substantial damage

In the last two years no repair work has been carried out in Unit 2. At present, the state of the equipment is being examined. Provisional results of the examination show corrosion in the transitional weld seam connections between zirconium and the steel of the pressure tubes. It cannot be excluded that a larger number of these pressure tubes will have to be exchanged, if recommissioning is intended.

According to some experts of the Chernobyl Nuclear Power Plant considerable financial means will be required for recommissioning. According to present prognoses it will not be possible to recommission Unit 2 already in 1996.

2 Development and Causes of the Accident

The accident in Unit 4 of the Chernobyl Nuclear Power Plant on April 26, 1986 occurred when the plant was being shut down as planned. During the shutdown process a test to demonstrate certain safety properties of the plant had been intended. Deficiencies of the test programme, unexpected conditions during the performance of the test as well as several unforeseeable events and unplanned interferences of the operating staff led to an extremely unstable operating condition of the plant in the night of April 25/26, 1986. A prompt, supercritical reactor excursion led to the disastrous failure of the reactor.

2.1 Test Programme

Upon loss-of-coolant accidents during the first phase the core is cooled by injection of water from the accumulators and from the main feedwater supply system. To be able to also operate the main feedwater pumps during a simultaneous failure of the normal power supply (loss of off-site power), the use of the rotational energy of the running down turbo generator was planned for this case. The reliable function of this measure was to be demonstrated. During former tests it had not been possible to provide this proof. Therefore alterations to the generator had been made.

The safe control of a loss-of-coolant accident with a simultaneous loss of off-site power is required by Soviet regulations and was intended for the RBMK design. The function of this design would have had to be demonstrated during trial operation. Unit 4 had started operation in December 1983 without this proof.

The test programme essentially provided for the following:

- At the beginning of the test the thermal power of the plant should range between 700 and 1 000 MW (approx. 20 % to 30 %). In this power range one turbo generator is in operation and the second one is switched off.

- Deviating from normal operation, the test intended to run the six main coolant pumps normally in operation and the two standby pumps.

- Four main coolant pumps (including the two standby pumps) should continue to run during and after the test to ensure core cooling. These pumps therefore were connected to the normal electric network.

- During the test the four remaining main coolant pumps were intended as the load for the turbo generator. Accordingly these pumps were supplied by the turbo generator prior to the test. With the beginning of the test they should phase out in accordance with the decreasing power of the generator.

- The test itself should be started by fast shutdown of the turbo generator in operation. In accordance with the design of the reactor protection system an automatic reactor emergency shutdown should be actuated simultaneously.

2.2 Procedure and Discussion of the Events until Destruction of the Reactor

The plan for the performance of the test could not be observed because of different circumstances. The important events which finally led to the accident are summarized below. A great part of the operational recording equipment had been used to record the essential values for the test measured. The recording of the usual operating parameters before the test was therefore clearly limited. The last minutes until the accident therefore partially had to be reconstructed:

- As planned, the plant was shut down for the annual outage and the planned test on April 25, 1986, at 1:00 o'clock in the morning.

- At 3:47 h the thermal power had been reduced to 1600 MW, i.e. approx. 50 % of the nominal power, and it was kept there.

- At 7:10 h the operational reactivity margin (ORM) was smaller than the permissible value because of instationary xenon poisoning. The reactor would have had to be shut down immediately. This did not happen. In the further course of the test the ORM again increased above the minimum permissible value.

- Until 14:00h the power remained 50 % unchanged. Upon request of the distribution centre in Kiev it was continued to feed this power into the network. The continuation of the test was delayed.

- About nine hours later the shutdown to the power range intended for the test of 20 to 30 % could be continued. But there was a lower deviation from this power range for unknown reasons.

- At 0:28 h, less than one hour before the accident, at a thermal power of 500 MW there were difficulties in the change over of the reactor power control because of a technical dropout or a misaction. The power hereby practically dropped to zero. The thermal reactor power thus about corresponded to the power of the six main coolant pumps. As the ORM with 26 control rods had been smaller than the permitted value of 30 for startup, the reactor would have had to be shut down and the test would have had to be delayed.

- Instead the power was increased as high as possible to carry out the test. By withdrawing the control rods it was possible to increase the reactor power to approx. 7 % and to keep it there.

- About 40 minutes prior to the start of the test, at 0:43 h an important signal which would have led to an automatic emergency shutdown of the reactor upon initiation of the test, was rendered ineffective to be able to possibly repeat the test.

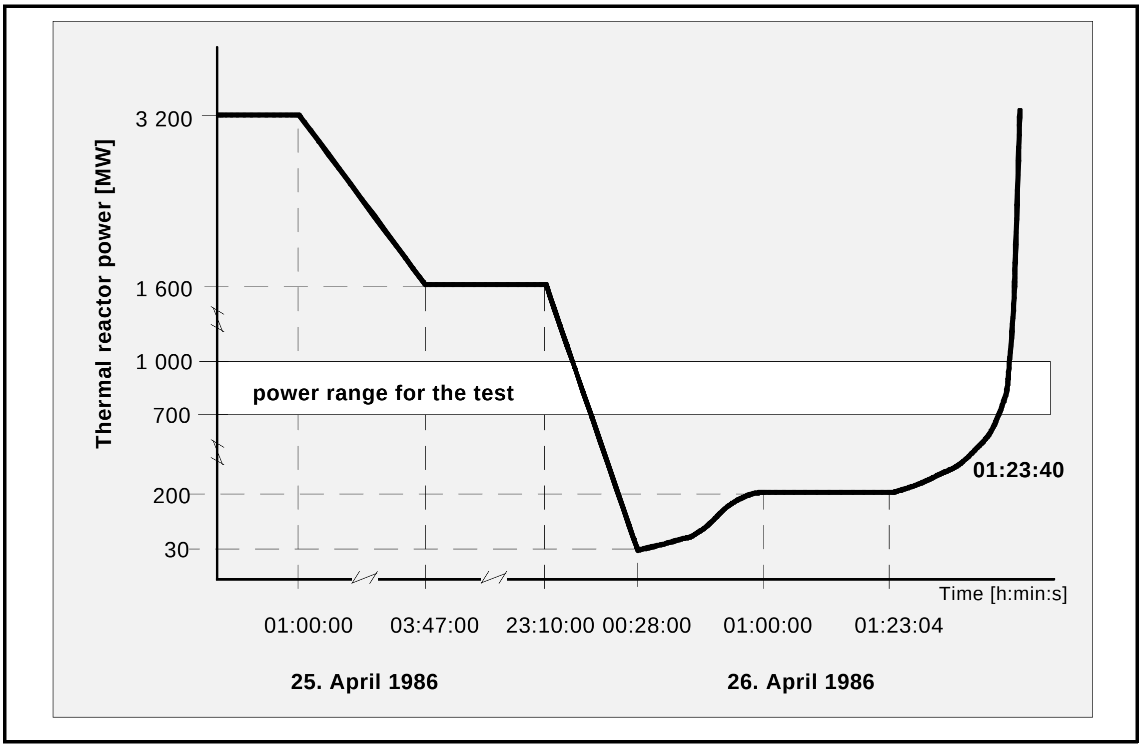


Fig. 2-1 Simplified sequence of the reactor power before the accident

- Immediately prior to the initiation of the test the plant was in an extremely unstable condition, as there were an unfavourable loading condition, a low power level with an unfavourable power density distribution, a high coolant flow rate in the core, a reduced feedwater flow rate with increasing coolant temperature at the core inlet and an instationary behaviour of the spatial xenon poisoning. As recalculations have shown, the ORM at this point of time was only 7 - 8 control rods.

- At 1:23 the test was initiated. As planned, four main coolant pumps ran down. The reduction of the coolant flow rate in the reactor core connected therewith and the shutdown of the reactor actuated a short time later with the present unstable state of the plant at first led to a power increase of more than 15 % of the nominal power and then within a few seconds to a reactor excursion.

- The reactor excursion led to a rapid increase of the energy release in the fuel elements and further to the destruction of the reactor core. The heat stored in the fuel was very quickly transferred to the surrounding coolant which practically evaporated spontaneously. The resulting high pressure increase led to the explosion of the reactor.

Appendix 1 comprises the chronological sequence of the accident and comments on the respective phases of the accident.

2.3 Discussion of the Causes of the Accident

The severe deficiencies in safety-relevant design of RBMK plants represented the main cause of the accident:

- high positive void effect during operational conditions with high burnups.

- positive shutdown effect of fully withdrawn control rods

- insufficient effectiveness of shutdown facilities

- missing incorporation of the ORM into reactor protection.

The accident sequence was determined and aggravated by:

- an unfavourable selection of the time to carry out the test - high burnup with very high void effect of at least 5 ß.

- non-observance of the requirements to be met by reactor safety during preparation of the test programme

- little experience and insufficient participation of the operating staff in the preparations of the test as well as violation of operating regulations by the staff.

The essential aspects which contributed to the accident are more detailedly discussed in the following sections below.

2.3.1 Deficiencies in Core Design

The positive void effect represents a peculiarity of RBMK plants. The principle meaning of the positive void effect is illustrated in Section 1.4.

Immediately prior to the start of the test the void effect, i.e. the reactivity increase with a complete evaporation of the coolant in the pressure tubes, in Unit 4 was at least 5 ß. At this point of time the core was practically completely filled with water, almost all control rods had been withdrawn and the power level was very low. Under these conditions, which clearly deviated from the normal operating conditions, it was possible that the large void effect could practically become completely effective.

Fig. 2-2 shows which consequences such a high void effect can have under accident conditions. The fat curve shows the power increase for the marginal conditions during the accident. A reduction of the coolant flow rate by 0.8 %/s caused by the phasing out of the main coolant pumps was assumed. For the thin curve with the same conditions it was assumed that the ORM of 30 control rods was observed in contrast to the accident. There is a delayed power increase with a lower maximum.

The computations show that with the former design prompt-supercritical reactor conditions were possible in both cases, i.e. upon loss of coolant or coolant flow rate reduction, respectively. They also show that the observance of the ORM limits alone was insufficient to prevent prompt-supercritical reactor excursions.

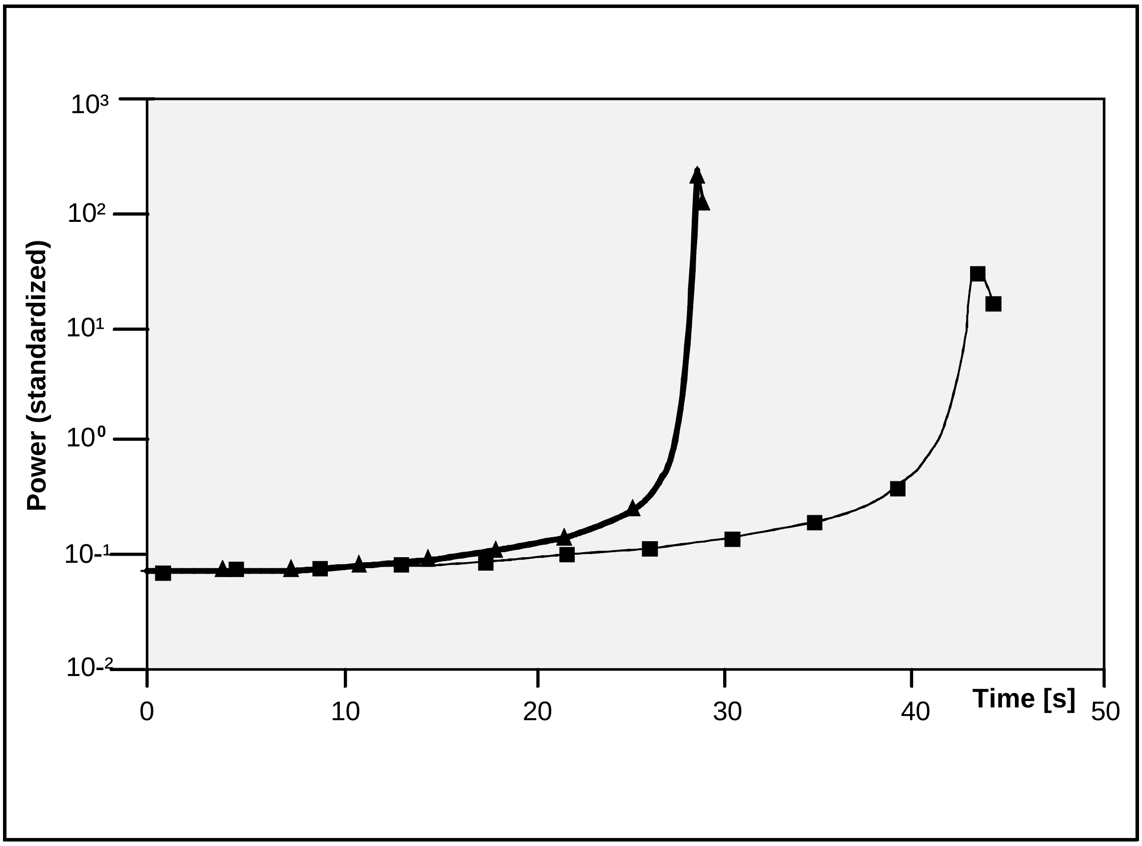


Fig. 2-2 Reactivity transients upon 7% thermal power of an RBMK-1000

2.3.2 Unsuitable Shutdown System

The design deficiencies of the shutdown system (see Section 1.4) made an essential contribution to the accident. On the one hand the fully withdrawn control rods require some seconds to become effective upon request. On the other hand the insertion of fully withdrawn control rods increases the reactivity at first ("positive shutdown effect").

The "positive shutdown effect" was also determined in experiments for commissioning the first unit of the Ignalina Nuclear Power Plant and the fourth Chernobyl unit. It intensifies if the maximum of the axial power density distribution is shifting to the lower part of the core, for example in connection with a power reduction. Estimates made in 1983 showed a strong dependency on the number of completely withdrawn control rods and thus on the ORM. Depending on the type of the plant, a positive reactivity is at first admitted within the first seconds in case of a reactor shutdown with 130 to 160 completely withdrawn control rods and a power maximum in the lower core area.

Such a situation existed immediately prior to the accident. Practically all control rods were completely withdrawn and the lower core area showed a power maximum. The reactor excursion which had slowly developed during the course of the test was intensified by the actuation of the shutdown and could no longer be limited in time.

2.3.3 Insufficient Assumption of Responsibility for Reactor Safety

After commissioning the first unit of the Leningrad RBMK Nuclear Power Plant it showed at an early stage that the void coefficient, contrary to the assumptions during design, took on high, positive values in the course of operation. In 1975 a local reactivity accident which damaged the reactor took place in Leningrad-1. This event represents the forerunner for the Chernobyl reactor accident. Although essential design weaknesses had become apparent at that time, which later contributed to the Chernobyl accident, the authorities responsible officially discarded this event, blaming it an insufficient manufacturing quality.

The experimental determination of the void coefficients of the reactivity at Leningrad-1 carried out after the accident and the instabilities of the reactor core which had thus become visible, led to the decision of increasing the degree of enrichment from the original 1.8 % to 2 % Uranium 235 and of installing an automatic control and protection system. These safety-relevant problems have, however, not been more detailedly assessed. Although the problems connected with the high void coefficient were weakened by the alterations, they have not been removed in principle. This also applies to the more recent RBMK plants.

One decisive reason for the disregard for these problems was that there were no independent safety authorities monitoring that designers, builders and operators completely met their responsibility for reactor safety. Until 1984 this responsibility solely resided with the Ministry for Mechanical Engineering which at the same time was responsible for construction and operation.

The positive shutdown effect was also known to those reponsible for plant design. The plant designers intended to alter the plants to exclude this effect. Nevertheless, the construction of the control rods was not changed, the withdrawal possibilities remained unlimited. In the same way the operational rules and the training of the operational staff were not improved.

All factors decisive for the accident had already been known prior to the accident. The licensing and supervision system and the safety culture of those responsible for reactor safety, however, were generally insufficient. The necessary countermeasures to remove design deficiencies were not carried out.

2.3.4 Deficiencies of the Test Programme

The test programme showed clear deficiencies. The test had only been classified as an electrotechnical test where no reactions on the reactor were to be expected. The test programme was developed by an electrical engineer. Although interferences in the protection and interlock system became necessary to carry out the experiment, safety aspects remained unconsidered. The necessary coordination with the special department responsible for nuclear safety within the power plant, the general project engineer "Hydroprojekt" and the licensing authority "Gosatomenergonadsor" did not take place. The operating staff was practically not prepared for the test.

The assumption that the test only represented an electrotechnical experiment was wrong. The experiment had an immediate influence on the reactivity behaviour of the reactor. This resulted from the fact that unlike the challenge not the main feedwater pumps (as a part of the emergency cooling system) but a part of the main coolant pumps had been chosen as the load for the turbo generator phasing out. Although it was known that the failure of main coolant pumps led to an increase of the steam content in the reactor core and thus to a reactivity increase, the test programme did not contain any special regulations for ensuring safety. The programme also did not comprise any explicit requirement to shutdown the reactor upon start of the test. The test programme only required that deviations from the prescribed programme had to be permitted by the shift supervisor.

One peculiarity of the operating state intended by the test was the increased initial flow rate in the reactor compared to normal operation. There was a minimum steam content with low undercooling below saturation temperature at the inlet to the reactor core. The potential for a high reactivity increase by the void effect was thus given. The factors mentioned had a direct influence on the effects which showed during the test.

The test normally constituted a part of the commissioning experiments. With respect to the burnup state of the reactor the time for carrying out tests connected with reactivity changes was particularly unfavourable. The fourth unit neither had a first load core (with a very low burnup and negative void effect), nor an equilibrium core (with an average burnup of 9 to 10 MWd/kg), but it was in a transitional state from the first load to the equilibrium core (with an average burnup of 10.3 MWd/kg). Here it is significant that the burnup of approx. 75 % of the fuel elements mainly located in the central part of the core was 12 to 15 MWd/kg. The void coefficient in the central area of the core thus clearly ranged above the value of an equilibrium core and was thus higher than usual.

2.3.5 Behaviour of the Staff

An important cause for the accident was the behaviour of the operating staff who violated operating rules before and during the performance of the test.

Insufficient Experience of Operating Staff

Because of the long delay of the test programme, the personnel originally planned did not take part in the test because of the change-over of shifts. The largest proportion of the staff who finally carried out the test on April 26, 1986 had only limited experience in startup and shutdown processes. Only the deputy chief engineer for the operation of units 3 and 4 had many years' experience.

Lower Deviation from the Prescribed Minimum Value of the Operational Reactivity Margin (ORM)

Upon strict observance of the operating rules the test would have had to be discontinued at 7:10 h already and the plant would have had to be shutdown as the minimum ORM of 15 permitted had been deviated from. It is uncertain inhowfar such a decision could have been enforced and which consequences it would have had.

Decrease of the Thermal Power below the Value of 700 to 100 MW provided for by the Test Programme

It can hardly be assessed to which extent the decrease of the thermal power, at first to 500 MW and then to almost zero was caused by technical failures or by misactions of the personnel. The test programme was thus violated but not the operating rules. RBMK in the lower power range tend to an unstable behaviour with respect to xenon poisoning.The initial situation is therefore comparable to the one of the accident in Unit 1 of the Leningrad Nuclear Power Plant on November 30, 1975, from which no sufficient consequences had been drawn.

Lower Deviation of the Prescribed Minimum Value of the Operational Reactivity Margin (ORM) upon Re-Startup of the Reactor

A renewed startup of the reactor after a brief shutdown from a power level of below 50 % was only permitted if the ORM before shutdown had at least comprised 30 control rods. But the ORM on April 25, 1986 prior to the start of the shutdown had only been 26 control rods. After the power had dropped to zero on April 26, 1986 at 0:28 h, it therefore had not been allowed to startup the reactor again.

Because of the xenon poisoning, the reactor power could only significantly be increased again by a manual withdrawal of control rods. It is to be assumed that the minimum ORM of 15 control rods was deviated from. Here it must, however, be taken into account that the importance of the ORM for technical safety had been unkown to the operating staff. The minimum ORM permitted had frequently only been understood as a reactivity margin for compensating the instationary xenon poisoning or as a means to control the power density distribution.

The design of the reactor neither provided for an automatic shutdown nor for an alarm signal upon lower deviation of the minimum ORM. The significance which the ORM plays as a determining parameter for the effectiveness of the shutdown system, was thus not attributed to the ORM during plant design and display in the control room .

Connection of the Standby Pumps to the Main Coolant Systems

The connection of the standby pumps corresponded to the test programme. During the course of the test individual coolant pumps reached flow rates which clearly exceeded the maximum value laid down in the "Limits and Conditions of Safe Operation". There thus was the danger of reactivity admission because of flow rate disruptions in the reactor core by an interruption of the pump delivery.

Blocking of the Actuation of Reactor Shutdown upon Failure of the Second Turbine

For the thermal power level of at least 700 MW provided for by the test programme a blocking of this actuation for reactor shutdown was not permitted according to operating rules. Below a thermal power level of 300 MW this was, however, permitted. The reason for blocking was the performance of additional experiments for measuring vibration properties of the turbo generators. A further reason for blocking was that the test could be repeated, if it had failed in the first place.

Assessment of the Staff Actions:

- Multiple violations by the personnel, especially against the regulations relating to the ORM lead to the assumption that these were tolerated by the leading executives responsible who did not know about their relevance for technical safety.

- The safety-relevant design of the interface between human being and machine did not permit a sufficient tolerance towards operating mistakes in this complex plant and it did not force the operating staff to act in the required safety-oriented way. Especially during operating conditions with a very low power, the plant was particularly unstable. The instrumentation was inadequate and the knowledge about the plant behaviour was limited so that the operating staff frequently had to interfere in a correcting way to handle the consequences of these deficiencies. Determination, display and operational implementation of the ORM were organized like an operating system: The computer for determining the respective ORM was about 50 m from the control desk in the reactor control room. The data were printed out there. The operating staff had to implement the computation results.

- The training of the staff with respect to the physical processes important for the accident was insufficient. Herefor it was essential that no sufficient, comprehensive safety analyses relating to the RBMK existed and important operating experiences, like the forerunner event in Unit 1 of the Leningrad Nuclear Power Plant had not been passed on. A further considerable training deficiency results from the fact that at that time there was no simulator for RBMK plants. For this reason, operating procedures like the startup and shutdown processes, disturbances and accidents could not be trained in a practice-oriented way. In addition, investigations after the accident showed that the training system at the Chernobyl Nuclear Power Plant was insufficient and that examinations of the operating staff were not held in accordance with the regulations.

2.4 Summarizing Assessment of the Causes of the Accident

The decisive causes of the accident had already been known to the planners of the plant responsible for safety as well as to some scientific institutions in the Soviet Union some years before the accident. Measures to remove the design deficiencies of the reactor core and the control and shutdown system were planned and their performance was considered, but they were not implemented.

Considering the severe design deficiencies, the unfavourable burnup condition and the increased void coefficient in the reactor core, such a test should never have been permitted without prior detailed analysis. In addition, the operating staff several times violated operating rules while carrying out the test.

The operating staff was only inadequately supported by suitable information and operating elements, by analytically secured findings on the plant behaviour or a safety-adequate design of reactor protection. To completely assume its responsibility for safety, was asked too much of the operating staff under these conditions.

The short-term planning and performance of measures after the accident to reduce the void coefficient, to increase the necessary operational reactivity margin and the effectiveness of the shutdown system demonstrate that important countermeasures had already been known. If these had been carried out before April 26, 1986, the accident would not have taken place.

3 Destruction of the Reactor and Contamination by Radioactive Substances

The kind and the amount of the radioactive substances released, the temporal sequence of the release and the prevailing weather conditions determining the spreading of the contamination were decisive for the radiological situation at the site of the accident and in the areas affected. Because of the decay of the short-lived radionuclides, the radiological situation has improved today. The measures taken have also partially contributed to this fact. Nevertheless, vast areas are still burdened with long-lived radionuclides, above all with caesium 137, which only slowly decayed (half-life-value 30 years). Vast areas in the Ukraine, Belorussia and Russia are prohibited and will remain that way for many years.

3.1 Destruction of the Reactor Plant

The expolsion destroyed large parts of the reactor building of Unit 4, the turbine hall as well as of the connecting building. The walls of the reactor hall were partially destroyed and the roof was destroyed completely. There were displacements in the drum separator compartments and the walls were damaged. The compartments with drives of the main coolant pumps were completely or partially destroyed. In contrast thereto, the hermetically closed compartments of the main coolant pumps remained intakt. The upper horizontal plate of the reactor ("Structure E") having a weight of approx. 3000 tons was raised and now stands at an angle of 15°. The lower supporting structures of the reactor vessel (Structure OR") lowered by approx. 4 m and crushed the connecting lines to the individual pressure tubes located below (Fig. 3-3 and 1-9). The south-eastern quadrant of the "Structure OR" as well as the emergency core cooling in the north-eastern part of the reactor building were destroyed completely. The reactor shaft in which the reactor was located is practically empty. A large proportion of the nuclear fuel was ejected into the reactor hall and is now below the original reactor position as solidified lava.

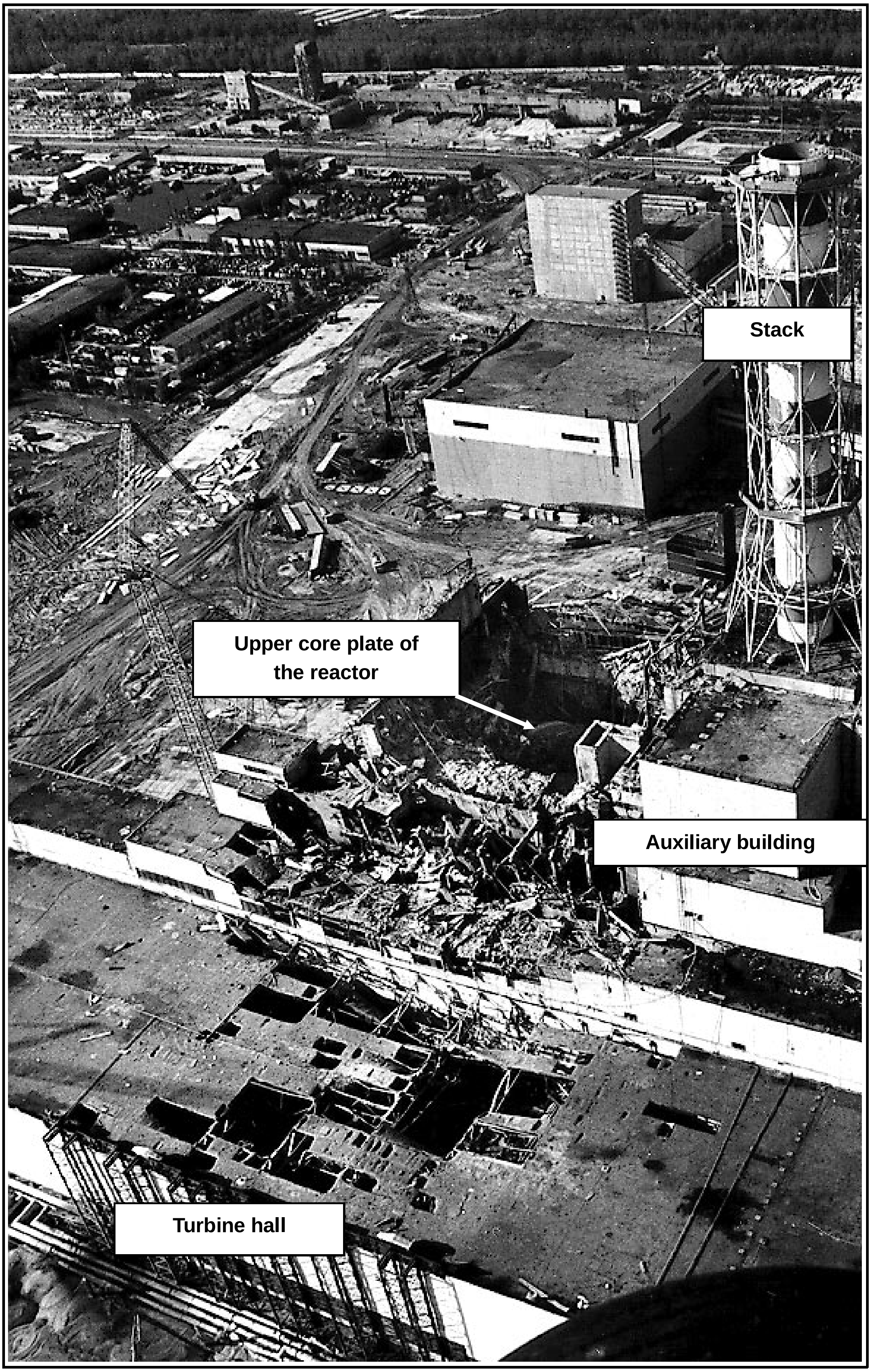


Fig. 3-1 Extent of destruction of Unit 4 at Chernobyl

Table 3-1 Events after the Beginning of the Accident

Time	Event
April 26, 1986	
01:24:00	Recording of the shift supervisor: "Strong impacts, the shutdown systems stop before reaching the lower end position ..." Reactor excursion with more than 100 times of the nominal power. Explosion and destruction of the reactor core. The upper plate of the reactor is hurled up, all pressure tubes break off. Core material and burning graphite parts are ejected. The reactor is burning, further fires start in the surrounding. Massive release of radioactive fission products.
approx. 05:00	Fires extinguished by fire brigade. Shutdown of the directly adjacent Unit 3.
April 27, 1986	
01:13	Shutdown of Unit 1.
02:13	Shutdown of Unit 2.
April 27, to May 10, 1986	
	Filling up of the reactor with different materials (approx. 2400 tons of lead, approx. 2600 tons of boron, dolomite, sand and clay). The release of fission products and direct radiation from the destroyed reactor are restricted by this measure and the burning graphite is covered.
from May 4, 1986 onwards	
	Injection of oxygene into the core area for cooling.
May 6, 1986	
	Far-reaching termination of fission product release from the destroyed reactor.

3.2 Temporal Course of the Release

At the time of the explosion of the reactor there were 1 659 two-part fuel elements in the core. The enrichment of the uranium was 2 %, the average burnup after 715 operating days was approx. 10.3 MWd/kg.

The massive release of radioactive substances lasted for ten days. The intensity of the release and the composition of the radionuclides released can be subdivided into four phases (Fig. 3-4):

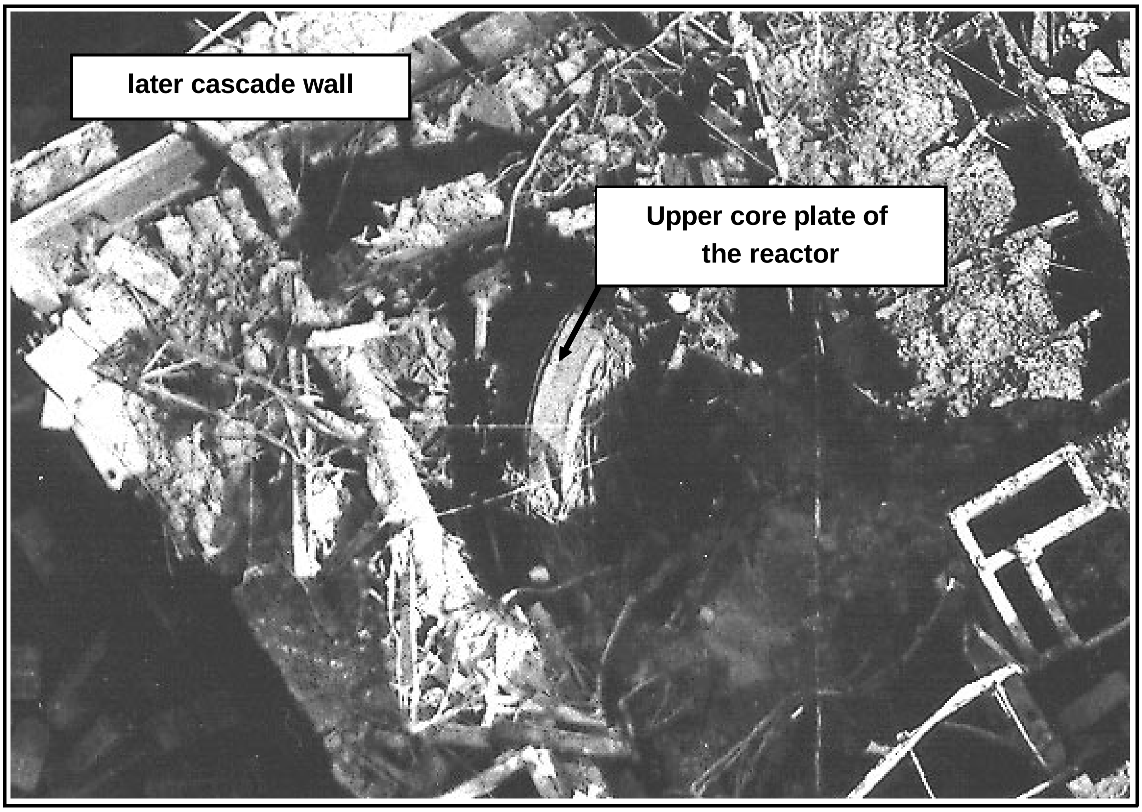


Fig. 3-2 View through the destroyed roof into the reactor hall. The upper core plate of the reactor (weight approx. 3 000 tons) was raised by the explosion and now stands at an angle of 15°.

Phase 1: Upon explosion of the reactor and during the later fire a part of the fuel - partially fractionated into fuel dust or grains - is ejected or discharged. Noble gases and easily volatile nuclides like iodine, tellurium or caesium are released massively. The composition of the least volatile nuclides almost correponds to their proportion in the destroyed reactor core. The hot air stream of the graphite fire transports the radioactive substances into a height of more than 1 200 m.

Phase 2: In the following five days the release steadily decreases because of the measures taken to extinguish the graphite fire and to cover the reactor core. Hot gases and combustion products of the graphite entrain finely dispersed fuel particles. The nuclide composition of the radioactive substances released corresponds to that in the nuclear fuel. The temperature of the hot gases escaping is lower than in Phase 1. The ascending force diminishes and the substances released only reach heights of between 200 and 400 m.

Fig. 3-3 Lower bearing structures of the reactor tank (Structure "OR") which was lowered by about 4 m

Phase 3: The release clearly increases. The materials covering the destroyed core impair heat removal. This leads to heating the reactor up to a temperature exceeding 2 000°C. The remaining iodine is at first expelled out of the hot fuel. The composition of the other substances released almost corresponds to the respective proportions in the nuclear fuel.

Phase 4: On May 6 the release decreases abruptly. This is surprising and until today cannot completely be explaind. Essential influences are ascribed to the countermeasures and to the formation of least volatile compounds of the radionuclides.

In the course of the accident the remaining nuclear fuel in the reactor shaft melts, it mixes with the structure material and flows along the corridors and through the openings into the compartments below the reactor shaft. The molten mass mixes with further substances, especially with the materials thrown down, like lead and sand. A total of

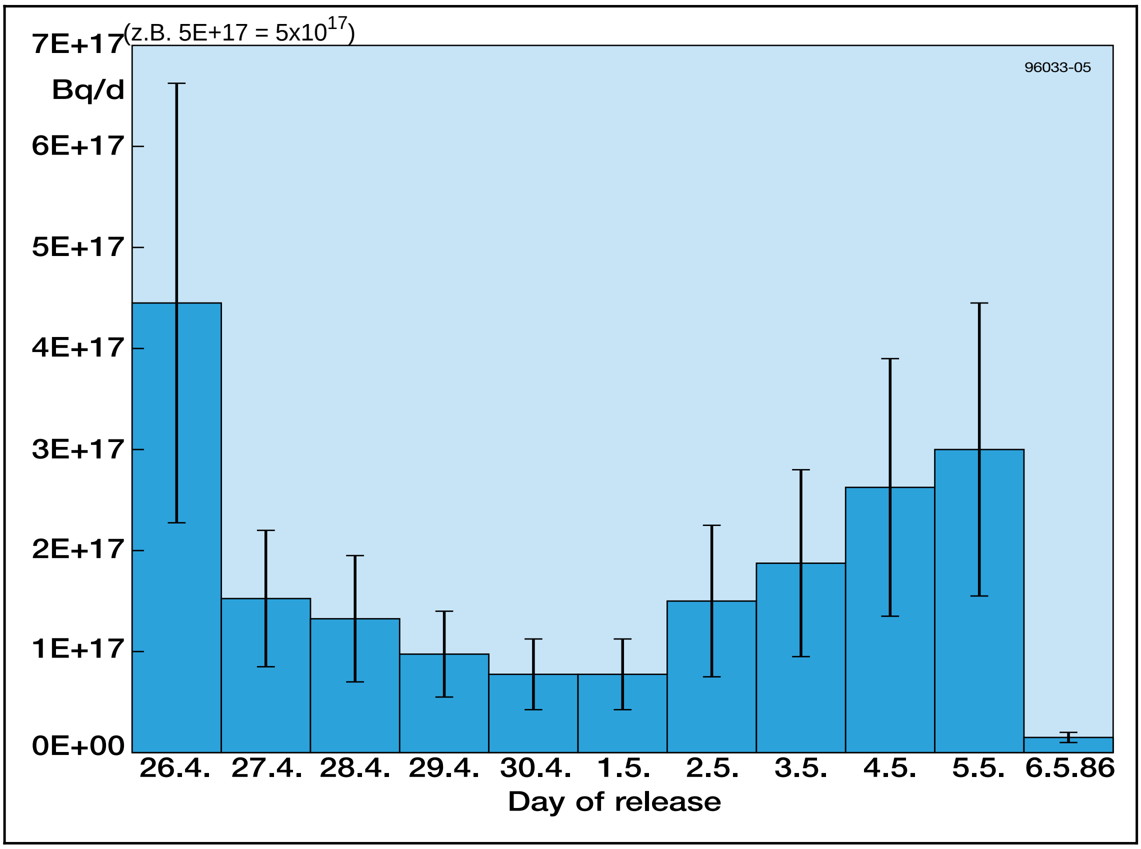


Fig. 3-4 The amount of the radioactive substances released within the first ten days (with ranges of uncertainty)

5 000 tons of material are dropped by helicopters to terminate the release of radioactive substances. The core melting mass finally solidifies.

The amount of radioactive substances released until May 6 in 1986 was estimated to be 2×10^{18} Bq with an uncertainty of +/- 50 % without considering the mostly short-lived noble gases and the tritium. More recent analyses confirm the former estimates. The proportion of nuclear fuel outside the reactor was determined to (3.5 ± 0.5) % of the nuclear fuel mass (190 tons). This value is also confirmed by more recent examinations.

The noble gases krypton and xenon as well as the tritium contained in the core practically escaped completely.

There are still larger uncertainties in estimating the proportions of the easily volatile caesium and iodine isotopes. The caesium 137 release originally indicated with 13 % of the respective core inventory is considered to be too low according to more recent examinations. A more recent account of the caesium 137 release leads to a value of (33 ± 10) % of the respective core inventory. This corresponds to an activity of $(8.5 \pm 2.6) \times 10^{16}$ Bq.

Even more uncertain is the determination of the iodine isotope release. Iodine isotopes can occur as aerosols or in a gaseous state. The relative stability of the relation iodine 131 and caesium 137 in fallout in most European states makes it possible to locate the minimum release of iodine. A released share of 50 % of the idium 131 core inventory is assumed to be the most exact estimate. Taking radioactive decay into account, this corresponds to an activity release of approx 1.3×10^{18} Bq.

Strontium 90 is representative for the group of the least volvative radionuclides with a released share of 4 % of the total inventory. For the release of the largely long-lived alpha-emitting actinides, i.e. in paticular plutonium, a proportion of 3 % is estimated.

Table 3-2 Release Fractions of the most Important Radionuclides

Radionuclide	Half-life value [days]	Core inventory [Bq]	Estimated released fraction [%]
Krypton 85	3 930	3.3×10^{16}	100
Xenon 133	5.27	7.3×10^{18}	100
Iodine 131	8.05	3.1×10^{18}	50
Tellurium132	3.25	3.2×10^{18}	15
Caesium 134	750	1.9×10^{17}	33
Cäsium 137	11 000	2.9×10^{17}	33
Ruthenium 106	368	2.0×10^{18}	3
Strontium 89	53	2.3×10^{18}	4
Strontium 90	10 200	2.0×10^{17}	4
Plutonium 238	31 500	1.0×10^{15}	3
Plutonium 239	8 900 000	8.5×10^{14}	3
Plutonium 240	2 400 000	1.2×10^{15}	3
Plutonium 241	4 800	1.7×10^{17}	3
Curium 242	164	2.6×10^{16}	3

3.3 Spreading of the Radioactive Substances Released

During the entire release period of about ten days the weather conditions in the closer and further surrounding of the site changed considerably. The radioactive substances released by the explosion and the fire on April 26, 1986 were at first transported in a great height in northwestern direction via Belorussia to Finland and to the central and northern part of Sweden. On the following day the wind turned west. The way of the radioactively contaminated air masses led via Poland, Czech Republic and Austria to South Germany where they arrived between April 30 and May 1 (see Fig. 3-5).

After that the radioactive substances spread in north-western direction via the western part of Germany and the north-east France and reached Great Britain and Scotland on May 2. During this time a second wave spreading in Eastern direction formed on the site of the accident causing a weaker contamination which reached to the area south of Moscow. The close city of Kiev remained outside the main spreading pathways.

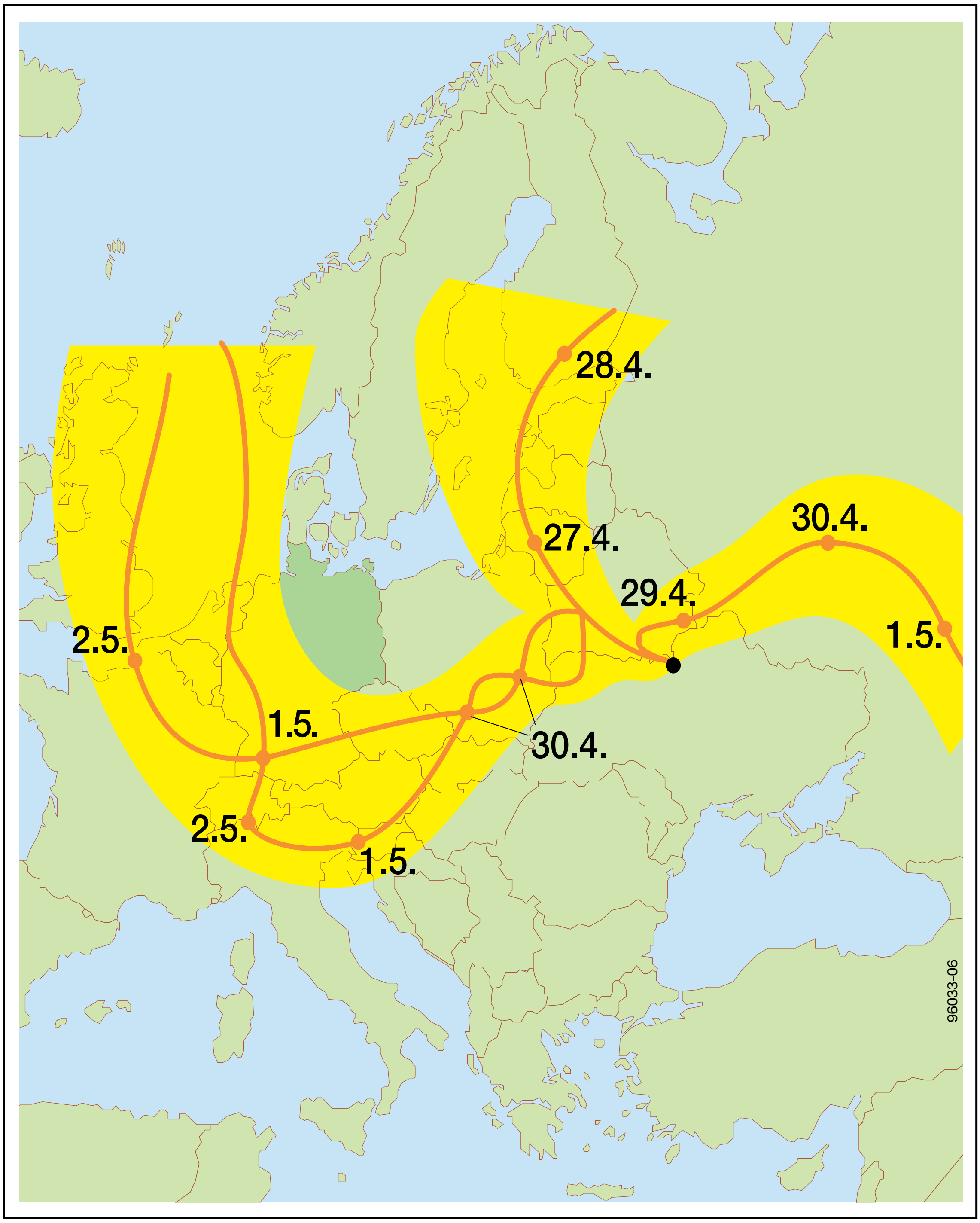


Fig. 3-5 Main spreading directions from April 27 until May 2, 1986

The amount of contamination was not only determined by metereological parameters like wind direction and wind speed. The intensity of the occuring rainfalls by which the radioactive substances were washed out and precipitated was very decisive.

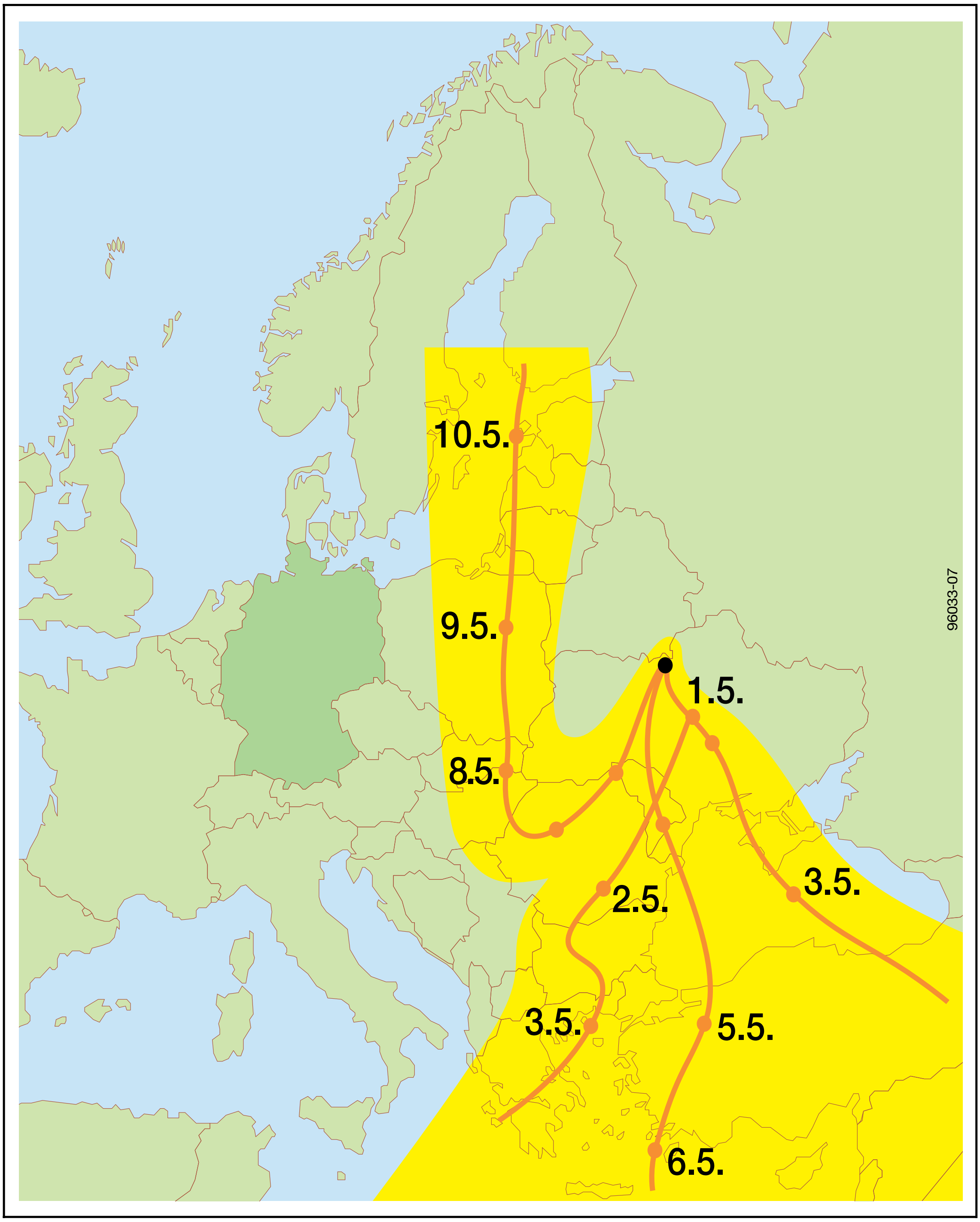


Fig. 3-6 Main spreading directions from May 1 until May 10, 1986

Accordingly there are locally very different degrees of contamination. In addition, ground relief and vegetation, e.g. forest areas, also play a role.

3.4 Radioactive Contamination and Radiation Situation on the Accident Site

The radiation fields existing on the Chernobyl Nuclear Power Plant site today, especially near the destroyed Unit 4, are known. There are tables of measured values and cartograms indicating the dose rates measured in a distance of some metres and from different heights in a tight grid of measured values. Fig. 3-7 shows a cartogram of the local dose rate 1 m above the ground. The determining radionuclide is caesium-137. The dose rate of gamma radiation in the direct surrounding of the Sarcophagus as well as the connecting building and the turbine hall of Unit 4 1 metre above the ground is approx. 0.3 to 0.5 mSv/h. The dose rate in distances of up to about 150 m of the buildings mentioned is about 0.1 to 0.2 mSv/h.

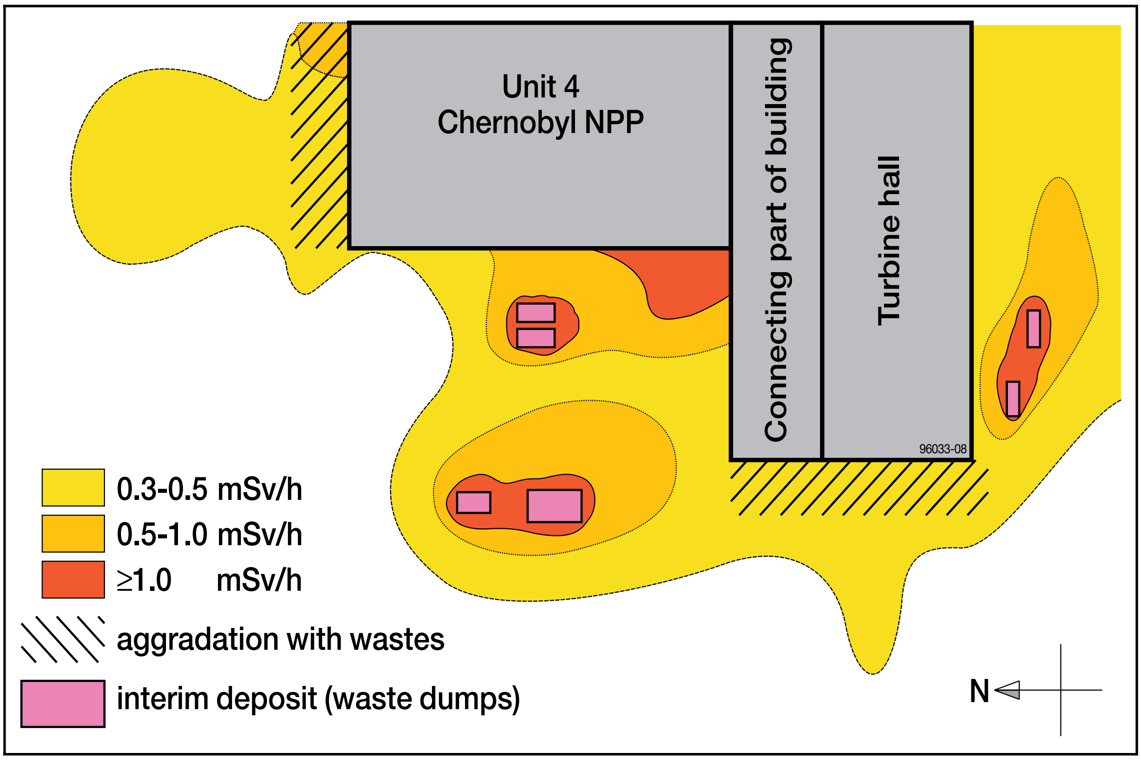


Fig. 3-7 Cartogram of the local dose rate of caesium 137 at a height of one metre above the ground surface

On the site there are about ten depositiories with radioactive substances, above all at the western wall of the Sarcophagus. Highly radioactive wastes, possible fragments out of the reactor core are assumed in at least three of these deposits. Two deposits with a dose rate exceeding 10 mSv/h are located approx. in the middle of the western wall, in a distance of about 20 m, a third with a dose rate exceeding 50 mSv/h in a distance of about 50 m. deposits were also established directly behind the southern wall of the turbine hall (dose rate up to 5 mSv/h).

Several boreholes were put down in the north and the north-east of the Sarcophagus in distances of up to about 100 m to examine the radioactive contamination of the soil and the groundwater. The contaminated material originally distributed in a depth of some 10 cm is thus now located in a depth of about two to three metres below aggradated gravel and concrete layers. The groundwater level is situated about five metres below this radioactive layer.

The deposits were neither established systematically nor sealed by suitable layers. It is thus possible that radionuclides are washed out and migrate into the groundwater.

The contamination of the groundwater by the large, contaminated layer as well as by the radioactive wastes in the deposits seems to be much more problematic than a possible emission of radioactivity from the existing Sarcophagus.

Fig. 3-8 Radiation monitoring at the power plant site from a helicopter

3.5 Radiological Situation inside the 30 km Zone

As far as the large-surface contamination is concerned, the radionuclides are essentially located in a 5 cm surface layer. In 1990 this layer still was about 1.0 to 1.5 cm (progressing migration into depth).

Another problem is connected with the changing chemical condition of the wastes. Humid and organic components in the soil mobilize the radioactive substances.

The area with a plutonium contamination (Pu-239 and PU-240) above 3.7×10^{10} Bq/km^2 within the 30 km-zone comprises about 360 km^2. The specific plutonium activity of the soil in the area exceeds 370 Bq/kg.

In the 30 km-zone there are deposits with radioactive wastes from the operation of Units 1, 2 and 3 as well as with radioactive wastes originating from the accident in Unit 4. Because of the circumstances, the latter was conditioned in an inexpert way and disposed of at different locations. To these locations belong the Sarcophagus (e.g. utilization of the wastes as filling material for newly erected walls), places for an easy intermediate storage (graveyards of wastes) as well as final deposits. The wastes have very different specific activities and frequently contain long-lived alpha-emitters. Some wastes are highly radioactive. The composition of the wastes is often insufficiently known or not known at all.

In the 30 km-zone there are several monitored intermediate and final deposits which do not meet the requirements of long-term, final deposition of radioactive wastes. To these deposits belong: "Komplexnij" (concentre steel tank covered with a clay layer located on the construction site of Units 5 and 6 of the nuclear power plant, content 11500 containers with solid radioactive waste), "Burakovka" (trench-type with 30 trenches in a distance of 12 km from the nuclear power plant, with 200 000 m^3 low- and medium-radioactive wastes with a total of 5.5×10^{14} Bq) and "Podlesnij" (module type in a distance of 1.5 km from the nuclear power plant, designed for 5 million m^3 highly radioactive wastes). This division of the wastes into low-, medium- and highly radioactive does not correspond to the internationally common classification.

The wastes are very different, they are enclosed by different kinds of soil and they are partially exposed to an increase of the groundwater level. A large part of the wastes with a total volume of 1.1 million m^3 and a total activity of 1.4 x 10^{16} Bq is deposited in ditches and basins which are not protected against the admission of water. The activity in the groundwater currently measured in the groundwater near these deposits is mainly determined by strontium 90. The concentration there partially exceeds the limit for drinking water to be consumed by the population by more than 100 times. According to expert assessments about 15 % of the strontium 90 contamination at these places pass into the groundwater as mobile compounds. The caesium 137 and plutonium concentrations in the groundwater are about one size lower than the strontium concentration. In other contaminated areas, however, the caesium 137 contamination outweighs the strontium 90 contamination.

3.6 Large-Surface Contamination in the Ukraine, in Belorussia and Russia

Already immediately after the accident extensive measurements of the air exposure (aerogamma measurements) and of the soil contamination were carried out. Later soil, water and biosamples were taken and examined with respect to radiological substances. A great number of institutes of the former Soviet Union participated in more than a hundred thousand of these measurements. The data acquired were used to describe the radioactively contaminated areas in cartograms, on the basis of which protective and decontamination measures were taken.

In the first months after the release, the radioactive iodine which leads to an exposure of the thyroid, was particularly important. But because of the short half-life-value, the effect of the radioactive iodine remained restricted to this period. Now caesium 137 with its half-life-value of about 30 years is the critical nuclide. It was spread over vast areas (Fig. 3-9).

Apart from the close area of the prohibited 30 km-zone around the Chernobyl Nuclear Power Plant and the areas around Gomel, the strontium 90 nuclide with a half-life-value of about 28 years is less significant. Although a pure beta-emitter does not contribute to external radiation exposure, it is particularly dangerous because of its accumulation in vegetable food and because of its properties as a substance which lodges in bones.

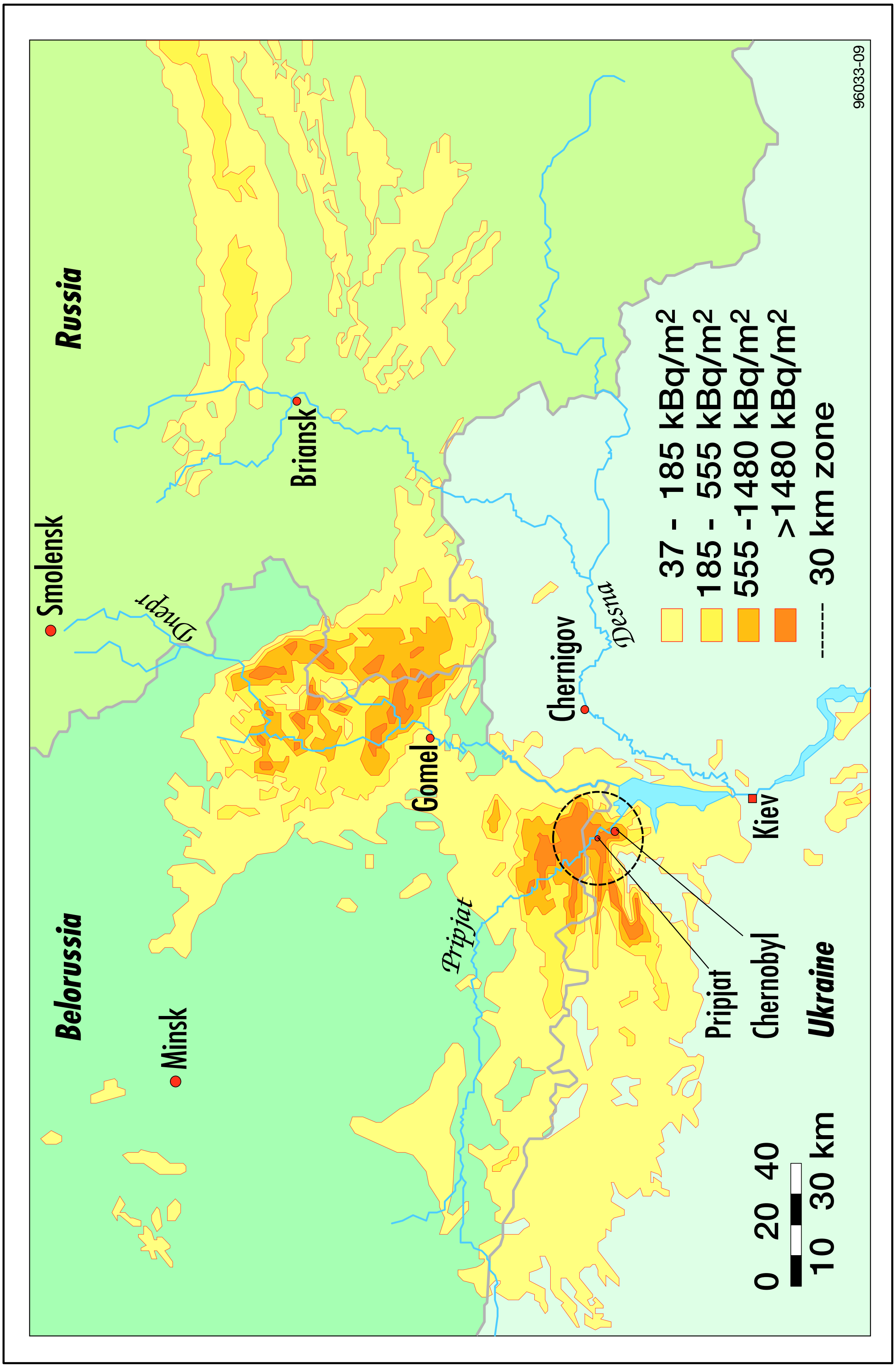


Fig. 3-9 Caesium 137 contamination in the Ukraine, Belorussia and Russia

The overall strontium activity released is much lower than the caesium activitiy and it was spread over shorter distances.

The areas in Russia, the Ukraine and Belorussia contaminated with caesium, strontium and plutonium are illustrated in Fig. 3-9 to 3-11. The contaminations in West-European countries were much lower.

The former Soviet authorities divided the contaminated areas into three different zones according to the degree of contamination:

- **Zone 1: Zone with occasional controls**
  Areas with a Cs 137 contamination ranging between 37 and 555 kBq/m^2
  (1-15 Ci/km^2)

- **Zone 2: Zone of permanent control**
  Areas between 555 kBq/m^2 and 1 480 kBq/m^2 (15-40 Ci/km^2)

- **Zone 3: Zone of strict control**
  Areas with a contamination of more than 1 480 kBq/m^2 (more than 40 Ci/km^2).

Zones 2 and 3 are referred to as "closer control zones" below.

In Belorussia the closer control zones cover 7 000 km^2, in Russia 2 000 km^2 and in the Ukraine 1 000 km^2. As a comparison, the caesium contamination caused by the Chernobyl accident in locally tightly restricted areas in Southeast-Bavaria reached 100 kBq/m^2 and around Munich 20 kBq/m^2.

In Belorussia there are still about 440 settlements with 109 000 inhabitants in the closer control zone. In the Russian Federation in the area of Brjansk 112 000 inhabitants live in 274 places, in the Ukraine 52 000 inhabitants in 73 places in the closer control zone. About one third of this total of 273 000 inhabitants are children. These figures are subject to permanent change, on the one side because of unplanned resettlements and migration and on the other side by incorporation of additional places into the closer control zone.

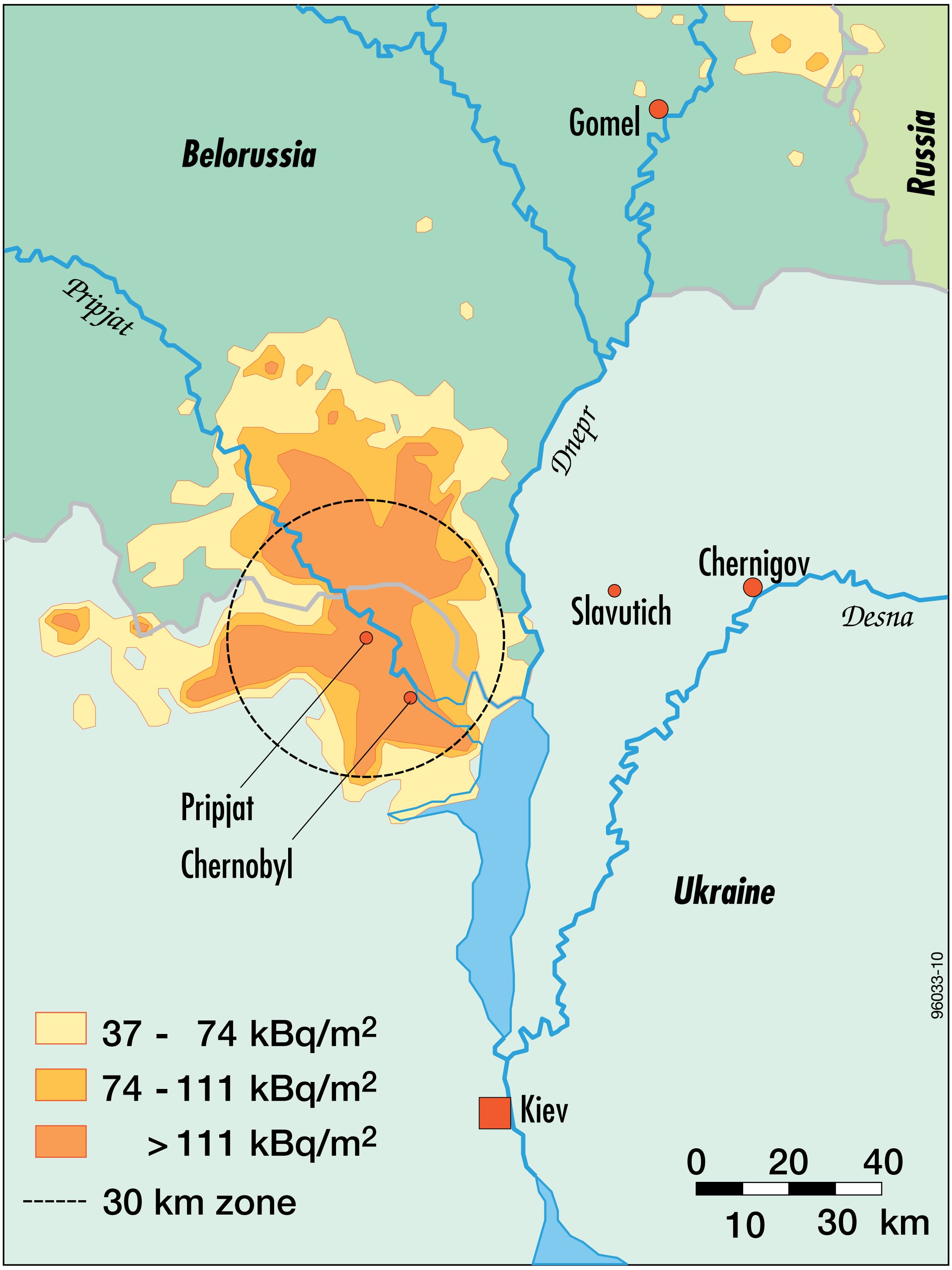


Fig. 3-10 Strontium 90 contamination in the larger surrounding of the Chernobyl plant

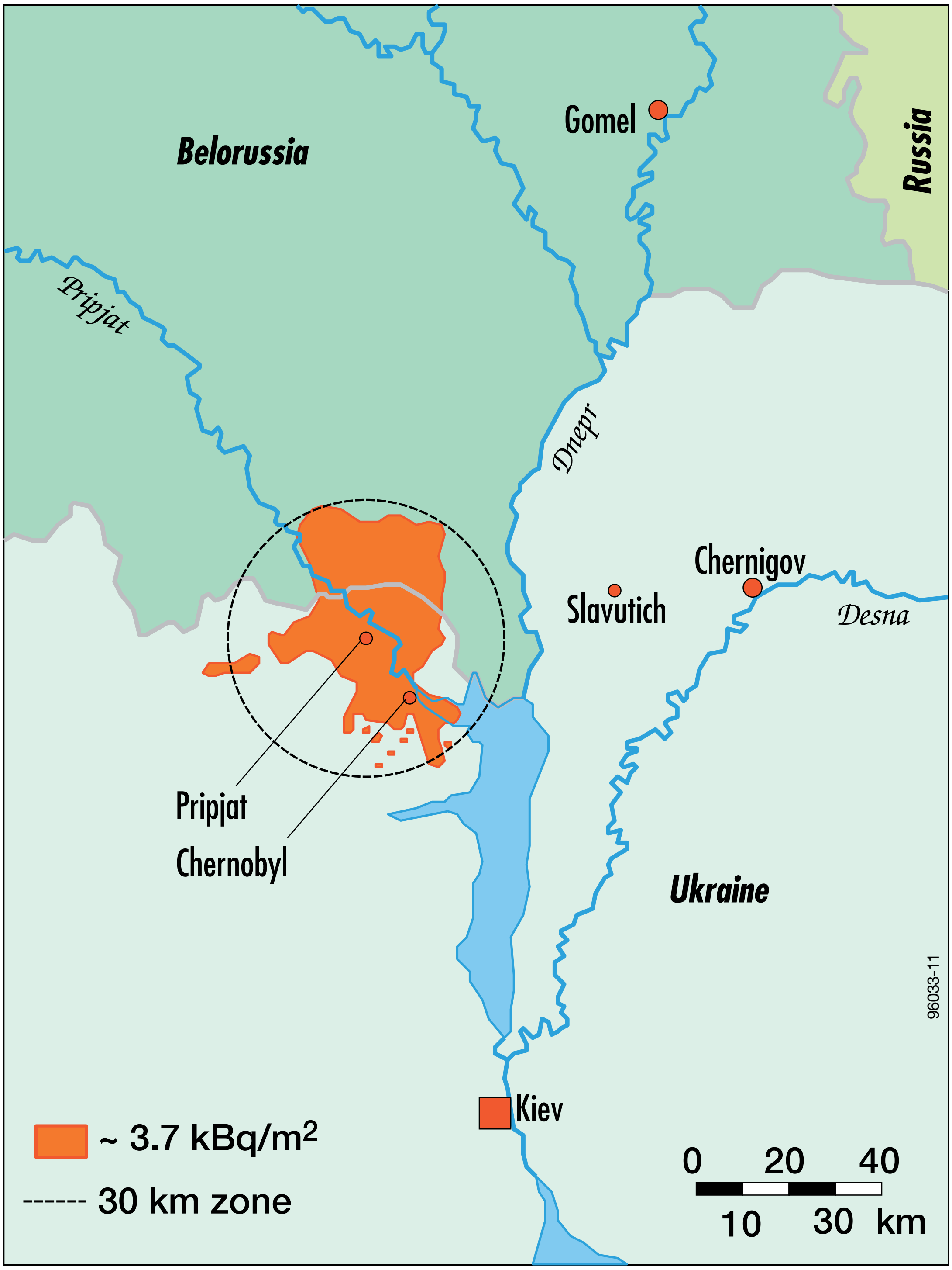


Fig. 3-11 Plutonium 239 und 240 contamination the larger surrounding of the Chernobyl plant

The radiation protection commission of the former Soviet Union recommended a series of measures to limit the radiation exposure of the population in the most contaminated areas. The dose for an individual person in the first year thus should be limted to a maximum of 100 mSv, in the following year to 30 mSv and then to 25 mSv per annum. The respective limits for food were derived thereform. Soviet scientists state in an estimate that the 273 000 persons in the closer control zone on average received a total body dose of more than 50 mSv in the period until the end of 1989 by the reactor accident. The population affected thus on average received about 10 mSv per year which is four or five times the annual dose compared to the natural radiation dose in Germany.

As a criterion for resettlement the radiation protection commission of the former Soviet Union introduced the concept of an accident-dependent lifetime dose of 350 mSv. According to this concept some further 10 000 people would have to be resettled in the future, in addition to the people already resettled. In the areas of zone 1 a life without radiation-related restrictions is generally possible.

4 Sarcophagus

4.1 Erection of the Sarcophagus

After the explosion in Unit 4 at Chernobyl, the isolation of the destroyed reactor from the environment represented a priority to prevent a further release of radioactive substances. For this purpose the construction referred to as "object shelter" or "Sarcophagus", consisting of concrete and steel was built around the destroyed reactor. Because of the urgency, there was no time for detailed planning.

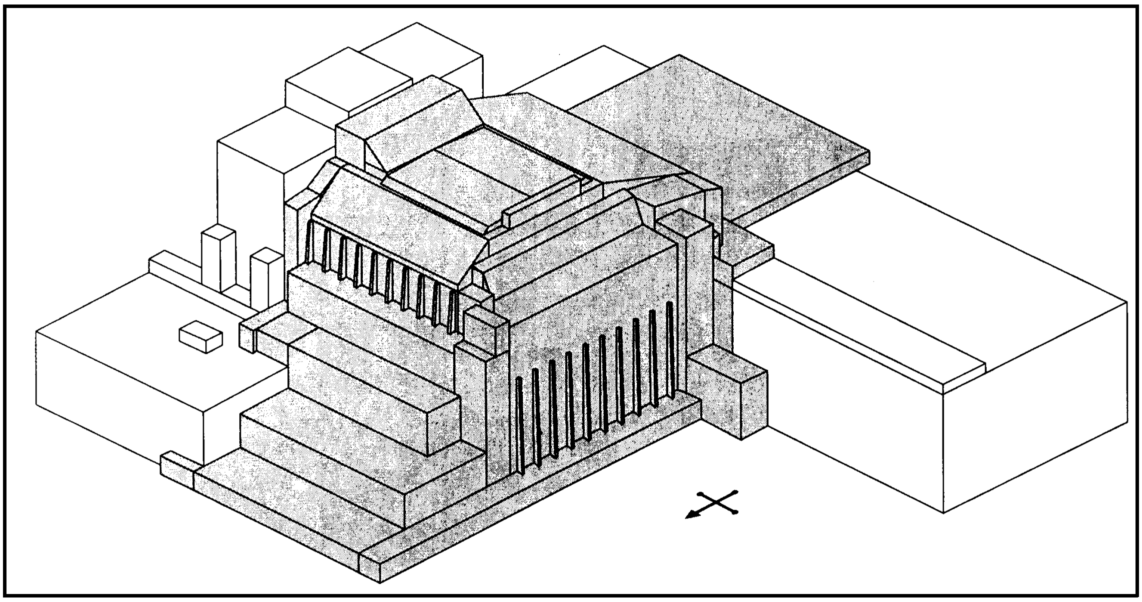


Fig. 4-1 Diagrammatic view of the Sarcophagus built from May until October 1986

Special requirements resulted from the objective to further operate the third reactor unit of the nuclear power plant, which among other things was connected with the destroyed reactor via the common tubine hall and the auxiliary building. This necessitated a constructional separation of the two units.

In the turbine hall a separation wall was erected between the area of Units 3 and 4. In the auxiliary building located between the two reactor units (Fig. 1-8) compartments near the fourth unit were completely filled with concrete so that a strong barrier of up to 6 m was created.

On the northern side a protection wall of concrete about 50 m high leading upwards in four cascades was erected (Fig. 4-2). A considerable part of the radioactive debris ejected out of the reactor during the explosion is said to have been encased with concrete in this cascade wall which is about 20 m thick at its the lower end. On photos taken at the time of erection it can be seen that even larger units were encapsulated here. In front of the western wall of the reactor building which largely remained intact a hollow steel wall with buttresses was erected.

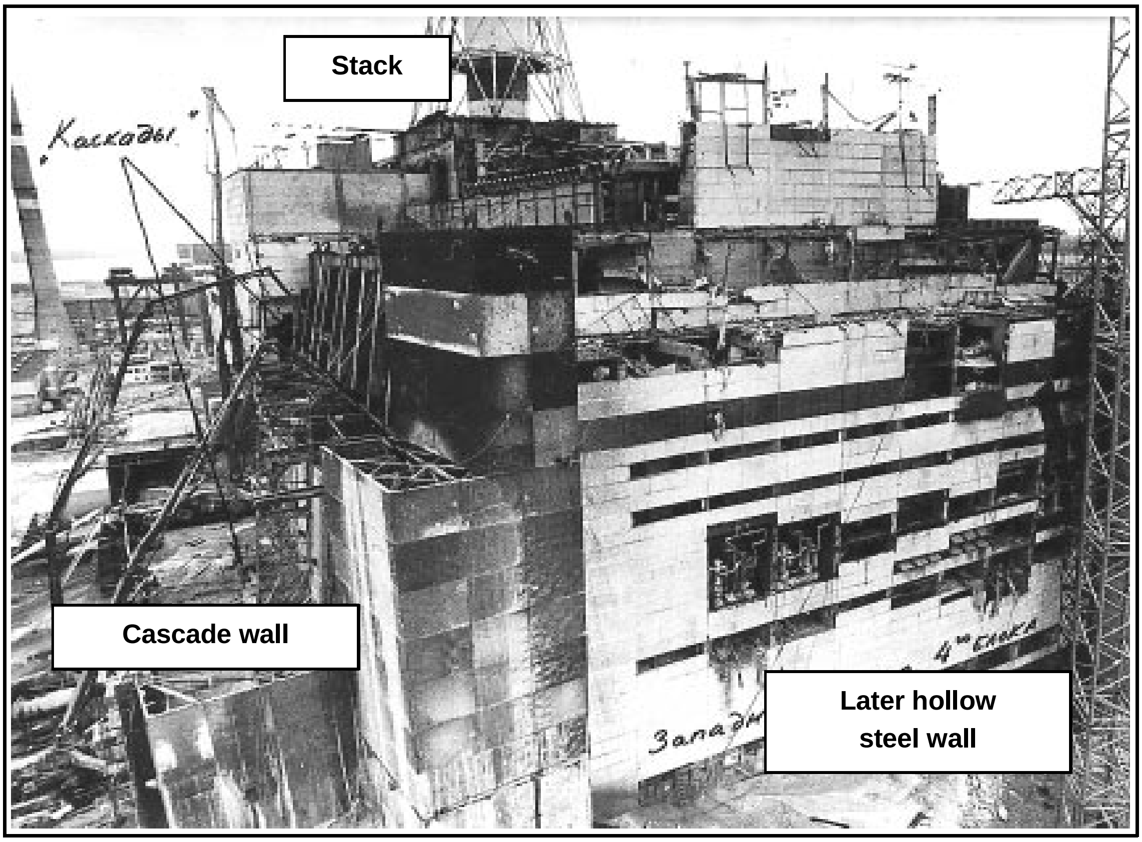


Fig. 4-2 View on the "cascade wall" under construction and the western wall in front of which the hollow steel wall was erected

The intact western wall of the reactor building and two intact concrete steel air shafts on the eastern side were used as the supporting construction for the roof of the Sarcophagus. Two steel girders B1 and B2 (Fig. 4-3) rest on these structures as main support of the roof of the Sarcophagus. Steel tubes having a diameter of 1.2 m were laid onto these two steel girders and a roof construction of steel and profiled roofing plates were put onto these steel tubes. Today this ceiling structure covers the former reactor hall to the top.

At the northern side, the cascade wall was practically led to the roof. On the southern side two big steel girders "Mamont" and "Osminok" were built in (Fig. 4-4). These rest

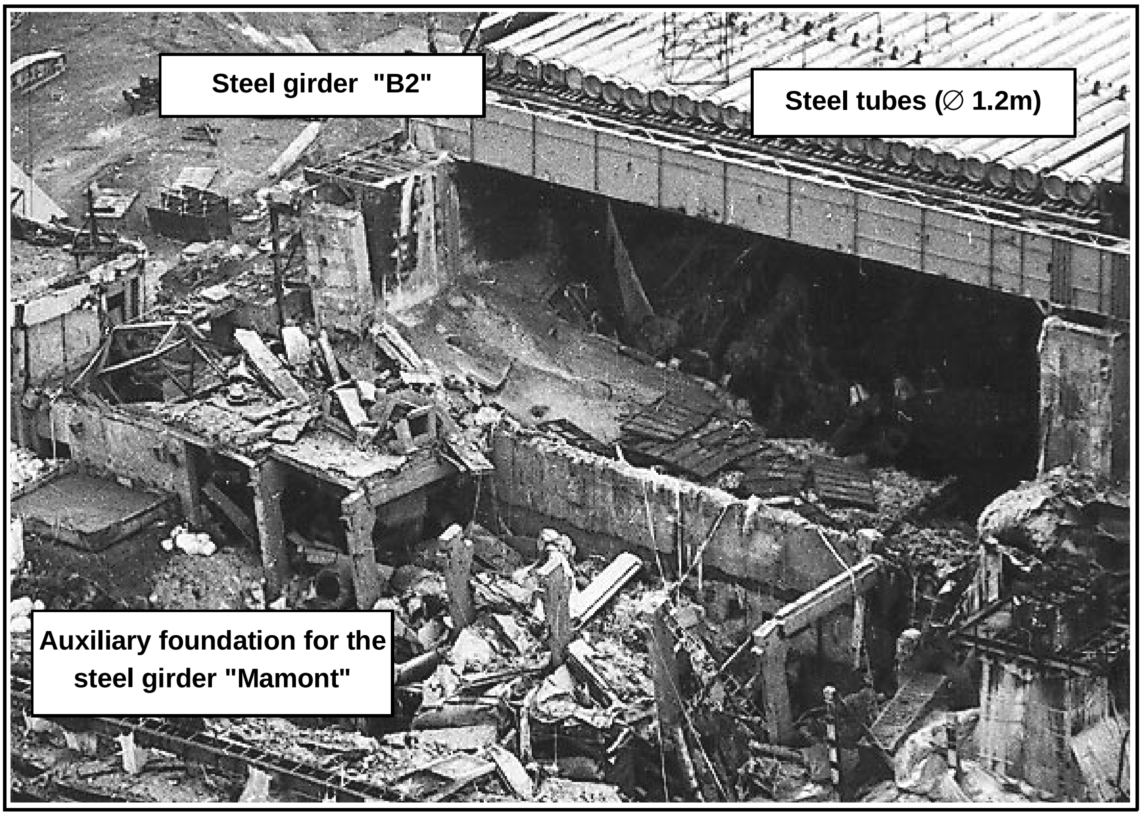


Fig. 4-3 Destroyed Unit 4 during the construction phase of the Sarcophagus

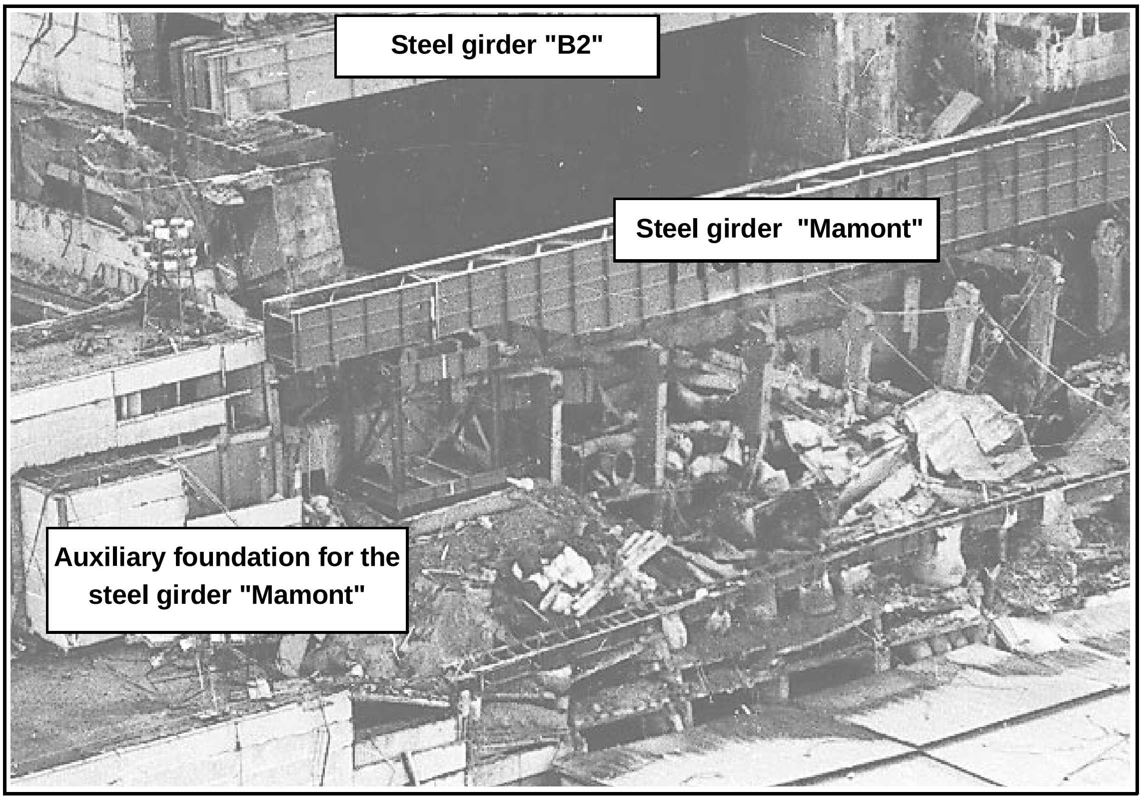


Fig. 4-4 Steel girder "Mamont" on the southern side of the destroyed unit which rests on auxiliary foundations

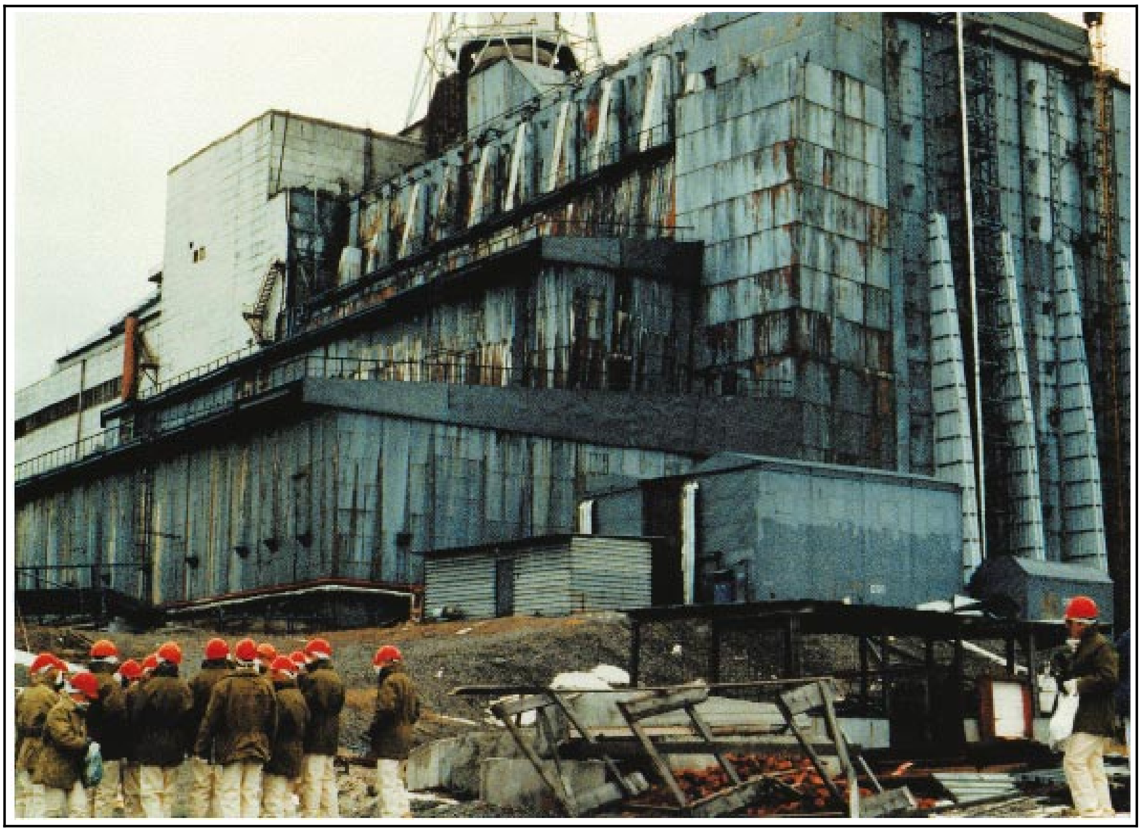


Fig. 4-5 Task group meeting with the Sarcophagus still being under construction; on the right the hollow steel wall with buttresses

on auxiliary foundations or on the remaining parts of the fourth Unit destroyed, respectively. The roof construction was extended beyond these girders to the south, where it is connected to the roof of the turbine hall.

4.2 Nuclear Fuel in the Sarcophagus

The examinations on the whereabouts of the nuclear fuel indicate that approx. 95 % of the fuel originally in the reactor core are inside the Sarcophagus today. These are about 180 tons of nuclear fuel.

The largest proportion of the nuclear fuel which had remained in the reactor shaft melted at first after the accident because of the decay heat and then flew through openings into lower compartments. It mixed with other substances and solidified to a glass-like mass, “lava”, which in the course of the time and under the influence of radiation, heat and humidity turned into a porous state. Today the surface temperature of the lava is close to room temperature.

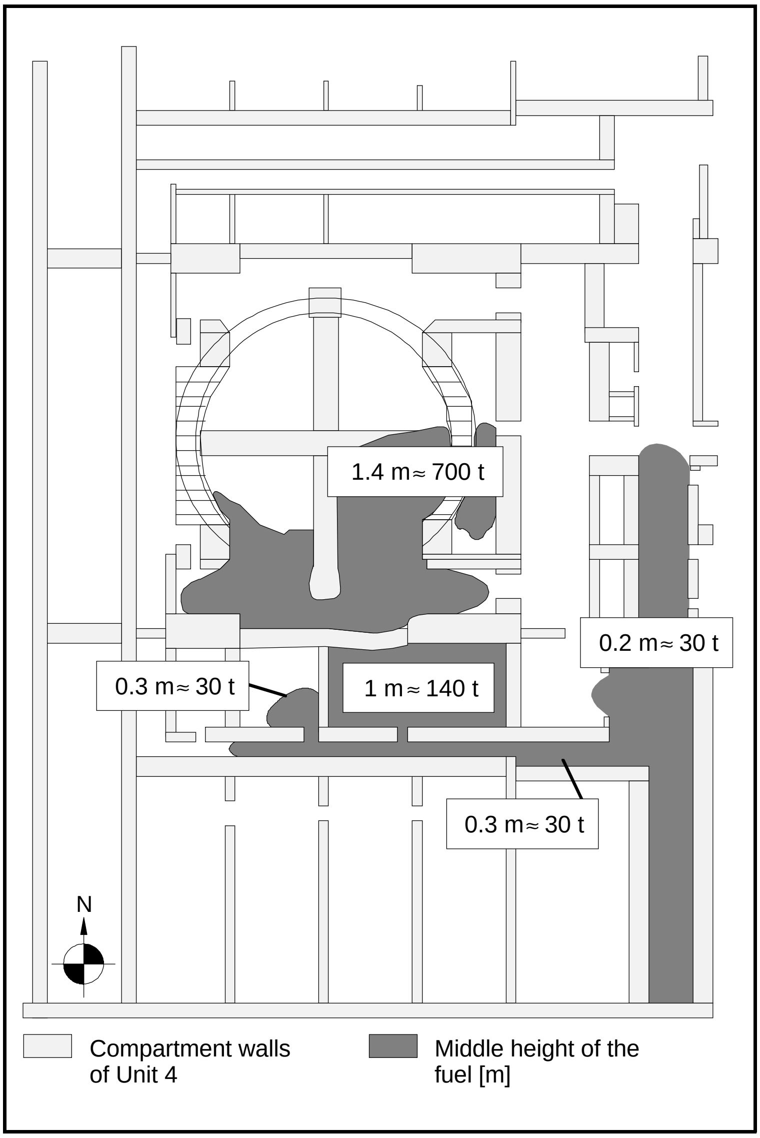


Fig. 4-6 Horizontal distribution of the molten nuclear fuel (lava) inside the Sarcophagus

The spatial distribution of the nuclear fuel is roughly known. In the lower compartments there are between 100 and 130 tons. A more exact determination is difficult, as many of these compartments were partially or completely filled up with concrete. 50 to 80 tons of fuel are presumed in the destroyed reactor hall and in the northern cascade wall. In addition, there are about 20 tons of spent fuel elements which were stored in spent fuel pits outside the reactor at the time of the accident.

In the lower compartments of the Sarcophagus there are approx. 3000 m^3 water consisting of extinguishing water and rainwater which intruded from outside. A question important for technical safety is whether the contact of this water with the fuel-containing lava could lead to a chain reaction of nuclear fissions because of the moderation effect of the water. The possibility of such a recriticality has been assessed to be very unlikely.

In the Sarcophagus there is a considerable amount of radioactive dust. As this dust can escape from the Sarcophagus in the form of aerosols, its amount and its composition are of great interest. The total mass of the radioactive dust in the Sarcophagus has been estimated to amount to 1 ton, its activity of 4.3 x 10^{15} Bq. This activity in particular originates from strontium 90 (about 47 %) and caesium 137 (about 30 %). A latex

Fig. 4-7 "Elephant foot" having a diameter of about 2 m formed of molten fuel and sand

solution is periodically sprayed into the Sarcophagus via a spraying system installed in the Sarcophagus to bind the radioactive dust. However, not all areas of the Sarcophagus are reached in that way. In addition, this binding does not last forever. New dust permanently develops from the progressing erosion of the reactor building and the disintegration of the lava. The total amount of unbound dust almost remains unchanged.

The release of radioactive aerosols from the Sarcophagus by natural air circulation is low. According to Ukrainian sources it is 1.1 x 10^{10} Bq/a at present. During certain accidents, e.g. a crash of larger parts, the aerosols could be whirled up and released into the environment, which could lead to an exposure of the personnel employed on the power plant site. Estimates do, however, show that even upon collapse of the Sarcophagus, the nearest populated site, Slavutich, would practically not be affected.

The presence of radioactive substances in the Sarcophagus also represents the risk of groundwater contamination. But at present this risk is assessed to be low.

4.3 Radiation Situation Inside the Sarcophagus

Most compartments of the Sarcophagus are accessible for a short period or at least accessible by robots. The intensity of the radioactive radiation is well known there. It strongly varies depending on the presence of fuel-containing masses and radioactive dusts, on the degree of destruction as well as on the filling with substances like concrete or sand.

The contamination of the buildings adjacent to the destroyed reactor unit varies considerably. The degasifier floor, for example, is only relatively weakly contaminated, as most of its walls remained intact. For this reason hardly any radioactive material could intrude. In contrast thereto, parts of the nuclear fuel ejected during the accident contamianted extinguishing water and radioactive dust reached into the turbine hall, the roof of which had been destroyed. Today the local dose rate in the turbine hall is about 10 to 20 mSv/h, in the roof area above the destroyed reactor the dose rates are up to 390 mSv/h.

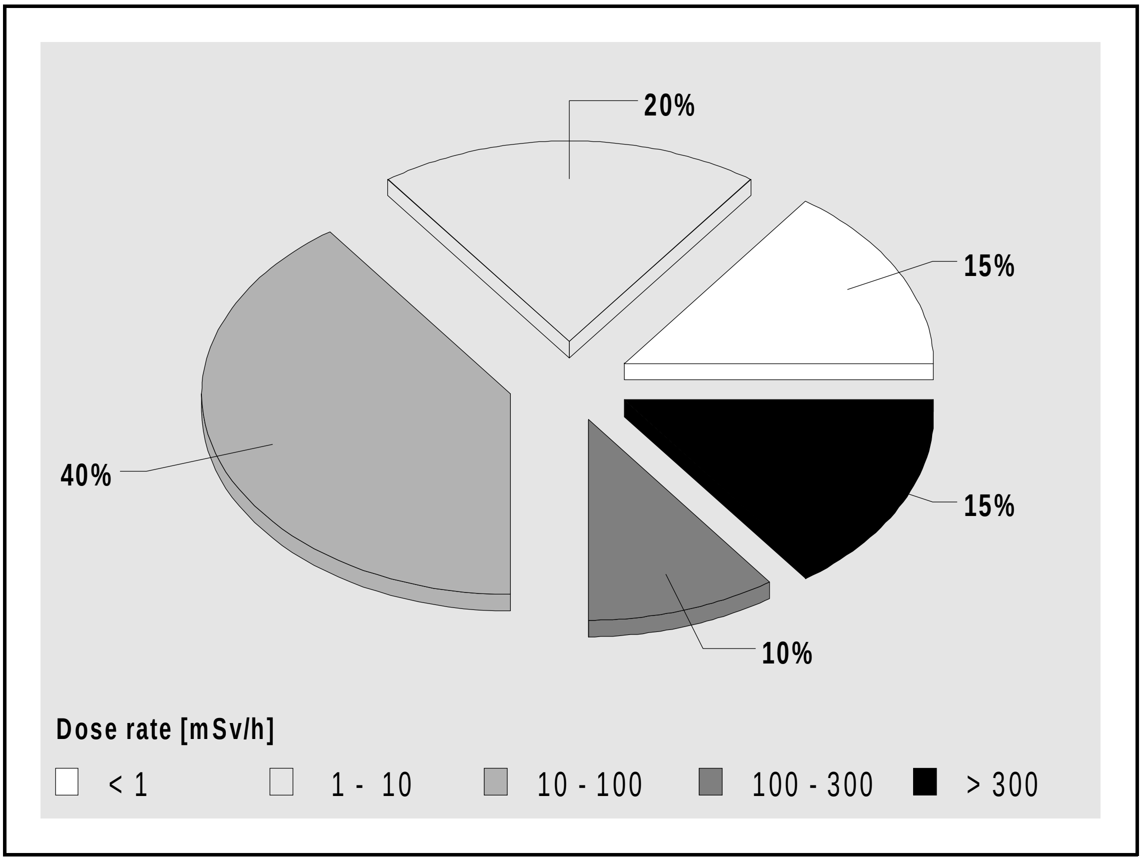


Fig. 4-8 Fraction of rooms inside the Sarcophagus having a specified dose rate

Fig. 4-9 Inside the Sarcophagus: supports twisted out of their position can be seen on the left. The southern external cover of the Sarcophagus can be seen on the right.

4.4 Stability of the Sarcophagus

During its erection a part of the components of the Sarcophagus was designed and manufactured in accordance with standard engineering criteria. There is little reason to doubt the carrying capacity of these building components. Restrictions do, however, result from the installation conditions determined by the high radioactive radiation. Thus many components were installed in a remote-controlled way so that building components could not always precisely be placed in the planned position. In addition, some essential supporting structures could not be screwed or welded, as usual, but only be placed on top of each other. This does not create severe problems for the accommodation of vertical loads, but upon horizontal stress these connections only function via frictional resistance, so that the carrying capacity may be lowered considerably.

During the construction of the Sarcophagus building components of the destroyed reactor building were also used as long as these still seemed to be useable after the

Fig. 4-10 The Sarcophagus shortly before completion

accident. Such building components, especially air shafts at the eastern side which had remained intact and the western wall of the reactor building represent essential supports for the upper part of the Sarcophagus and have to accommodate the respective loads. The assessment of their strctural perfomance is not easy as a more detailed examination of their quality prior use was not possible because of the high radiation. Such building components could at least partially have been damaged.

A part of the newly erected building structures is based on the debris of the destroyed unit. The procedure contained steps like rough levelling of the area concerned, remote-controlled placement of an encasement, filling with concrete and placement of a steel contruction forming the support for newly erected building components. Unfortunately, little is known about the conditions below these foundations. Hollow spaces with water access in the long-term could lead to a weighing down and thus impair the support.

Internal and external impacts are to be considered in an assessment of the stability of the Sarcophagus:

- Inside the Sarcophagus corrosion processes damaging concrete surfaces as well as steel constructions and uncovered reinforcing steel, for example of components damaged earlier, are important. The water present in the Sarcophagus, the rainwater intruding through joints and gaps and the humidity connected therewith promote these processes.

- From outside, the stability of the Sarcophagus may be affected by horizontal loads. To these especially belong storms and earthquakes. Chernobyl is situated on the "Russian Plate". It forms a large tectonic unit and is characterized by a low seismic activity in its central part. Earthquakes here hardly exceed magnitude 5 on the Richter scale. Only in the Carpathian Mountains about 700 km from Chernobyl larger earthquakes have to be taken into account. In the last 50 years several earthquakes with magnitudes between 6.3 and 7.4 on the Richter scale have occured here. The seismic centres of these earthquakes were partially in a very high depths. Ukrainian considerations to base the safety assessment of the Chernobyl site on earthquakes of the intensity 7 have recently become known. But the probability of such an event is very low.

- Storms are nothing unusual in the area of Chernobyl. Hurricanes with extreme wind velocities are, however, very seldom. According to one Ukrainian study, for example, the probability of a strong storm of up to 170 km/h is 1:10 000 per year. How reliable such statements relating to earthquake and storm endangerments are and which actions are required as a consequence still remains to be examined in more detail.

The Sarcophagus had originally been designed for a period of approx. 30 years. It withstood the external impacts of the last ten years. To these impacts also belong earthquakes, like the earthquakes of May 30 and 31, 1990, for example, the seismic centre of which was located in the Carpathian Mountains (with magnitudes of 6.8 or 6.3, resp. on the Richter scale). The earthquake did not cause any visible changes to the outside of the Sarcophagus. But there were transformations at the gaps of some walls inside the Sarcophagus. The stability analyses carried out by Ukrainian research institutes identified deficiencies, especially with respect to the quality of the constrctuion works. But finally no facts were identified according to which a collapse of the Sarcophagus in the next years seems to be likely. Today the assessment of the stability for the entire period of 20 years implies considerable uncertainties. Concrete technical concepts for upgrading measures are already being discussed at different places and they should permit a reduction of the endangerments with reasonable efforts. The next years must show whether and inhowfar the uncertainties in the assessment of the stability of the Sarcophagus can be limited in the future.

Concrete steps for the reconstruction of the Sarcophagus are, however, more important than improved analyses, especially as a reconstruction cannot be avoided in the long-term. One important question here is which steps should be taken in which sequence.

In its considerations the Ukrainian government has so far concentrated on the construction of a new, structurally independent enclosure which encapsulates the Sarcophagus existing today (Sarcophagus 2). A possible retreat of the ruins of the fourth reactor unit and the existing Sarcophagus for such a concept would be carried out within the new enclosure. A feasibility study commissioned by the European Union considers the superstruction of the entire double unit, i.e. of the destroyed fourth and the third reactor unit still operating. The costs for implementing this demanding concept were estimated to amount to about 2 billion DM (prices of 1995).

Fig. 4-11 The completed Sarcophagus

For such considerations it is also important that the suitability of the procedure during reconstruction of the Sarcophagus is also closely connected with the solution of several other problems:

- The radioactive material provisionally buried mainly close to the present Sarcophagus aggravates the foundation works for a second enclosure and impairs the working conditions by radiation.

- During the construction phase for a second enclosure above the existing Sarcophagus, this latter Sarcophagus can be damaged. This implies risks for the construction personnel which can hardly be overseen and which could be reduced by a prior reconstruction of the existing Sarcophagus.

- The required size and the costs of the new enclosure largely depend on two factors, i.e. whether a collapse of the old Sarcophagus is still to be expected after the construction of Sarcophagus 2 and whether the ruin of the fourth reactor unit shall still be demolished then. A prior, possibly also only partial demolition of the fourth reactor unit with the disposal of radioactive substances, e.g. of the dust or the lava in the Sarcophagus would permit a more compact type of construction.

On the whole it therefore seems to make sense to step-by-step deal with the reconstruction issues in one integrated overall concept. The first step should be to upgrade the existing Sarcophagus as this relatively cost-effective measure in any case represents the precondition for further reconstruction steps. With this step which could be completed within three to five years, it should be possible to ease the stability problem of the present Sarcophagus for 15 to 20 years. The time required for a careful overall planning of the in any case expensive solution of all problems connected with each other could thus be won.

5 Protection of and Provisions for the Population

5.1 Evacuation of the Population

In the morning of April 26, 1986 a government commission to coordinate the technical and medical functions in the three republics affected, i.e. the Ukraine, Belorussia and Russia were summoned upon order of the Council of Ministers of the USSR. This government commission worked under extreme conditions. Many decisions had to be taken under extreme time pressure. There were no precautions for accidents of this severity. Priority was granted to the health of the population, in particular to the health of children and pregnant women. At the beginning of its work, the government commission operated from the town of Pripjat and after the evacuation of this town it moved to Chernobyl on April 29, 1986.

Parallel to this commission, a so-called operative group was established which should clarify questions relating to the removal of the consequences of the accident. Leaders

Fig. 5-1 This building compelx was erected after the accident to accommodate the government comission in Chernobyl.

of ministries and authorities, chairmen of local Soviet party organs, scientists and experts participated in this operative group. Particularly important decisions were taken in the politbureau of the central committee of the Communist Party and the government of the Soviet Union.

The operative group was supported by a medical commission, which determined the criteria for the evacuation measures in the 30 km zone. In the first weeks of the evacuation it was primarily tried to protect the inhabitants, especially children and pregnant women, against radiation exposure.

The dose rate measured was taken as the decision criterion for an evacuation in 1986. Today the contamination zones are subdivided according to the Caesium 137 contamination (Table 5-1).

116 000 persons were affected by the short-term evacuation of zone 3. In the following years the population of zone 2 was also partially resettled.

Table 5-1 Categorization and criteria for evacuation and control measures

Zone	**Cs-137-Contamination [kBq/m^2]**	**Radiation dose [mSv/a]**	**Measures**
1	37 - 555	up to 2	• no evacuation • regular monitoring of the radiation situation
2	555 - 1 480	up to 5	• evacuation of the area for longer periods • possibly return • permanent monitoring of the area • consumption of cultivated food prohibited
3	über 1 480	more than 5	• immediate evacuation of the area • permanent resettlement of the population • access prohibited and strict control

Fig. 5-2 Evacuation of the population from the 10 km prohibited zone on April 27, 1986

The town of Pripjat had to be evacuated completely as the dose rate in the town was some hundred milliröntgen per hour and thus more than ten thousand times the normal value. The evacuation took place in the evening of April 27, 1986. Within three hours all inhabitants of Pripjat, among these 17 000 children and 80 patients confined to bed were evacuated. All inhabitants were allowed to leave town with the most necessary things only.

Fig. 5-3 The evacuated town of Pripjat (in the background the Chernobyl Nuclear Power Plant)

On May 2 and 3, 1986 the second evacuation phase followed. About 10 000 people living in additional settlements were evacuated from the 10 km-zone around the accident reactor and were taken to unaffected areas. From May 4 and 5, 1986 onwards the 30 km-zone around the reactor was also evacuated. In addition to the inhabitants of the town of Chernobyl, the inhabitants of 50 villages in the Gomel region in Belorussia were also resettled. About 273 people still live in areas where the contamination exceeds 555 kBq/m^2. According to a United Nations report a total of 400 000 people (150 000 in Belorussia, 150 000 in the Ukraine and 75 000 in the Russian Federation) were resettled by force or on their own initiative. A part of these people has been able to return to areas of zone 2 in the meantime. Figures relating hereto are not available.

The situation in the city of Kiev at no time after the accident was radiologically critical.

The inhabitants of Chernobyl were mainly transported to Kiev and Chernigov. Some thousand families were evacuated to regions outside the Ukraine to Moldavia, the Baltic Provinces and the Russian Federation. Later the town of Slavutich was built 45 km east of Pripjat as a replacement for this latter town where the operating staff of the Chernobyl Nuclear Power Plant had mainly been living.

To quickly provide the resettled inhabitants with a new space for living and to ensure the energy supply, housing and social facilities had to be created, roads had to be built,

Fig. 5-4 View of the newly built town of Slavutich

gas and oil pipes had to be imbedded as well as power supply had to be ensured. So far about 66 000 flats and houses and schools for approx. 30 000 children, preschool facilities for more than 12 000 children as well as several hospitals have been built in Belorussia, for example.

Nevertheless, these efforts are not enough. Until today the living conditions of the resettled population are unsatisfactory. Since the aggravation of the economic situation at the beginning of the 90ies there have been great problems to carry out and finance the necessary measures. It has also shown that many of the newly built houses have not been moved into, because the quality of the buildings was bad, an insufficient number of places of work in the new settlements had been created, or because of unfavourable living conditions.

A special problem is the psychosocial situation of the resettled population. A part of the former inhabitants returned to the contaminated zones. According to Ukrainian sources about 2 000 persons have returned to the 30 km-zone.

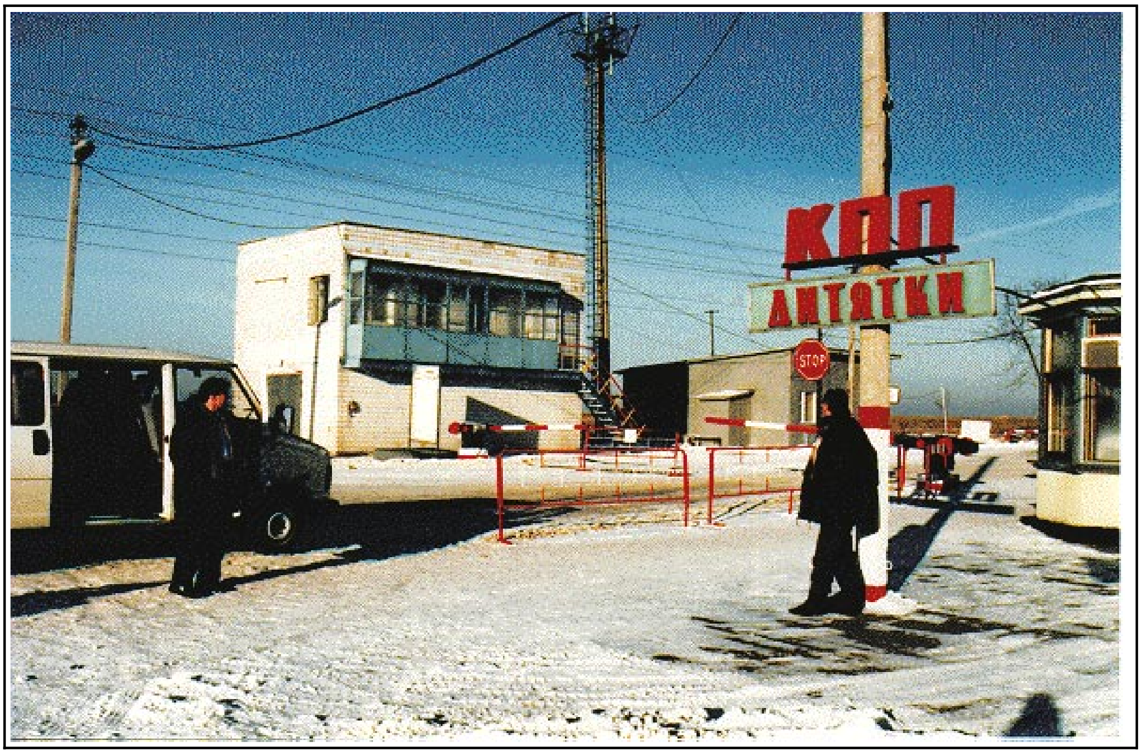


Fig. 5-5 Entrance to the 30 km control zone

Fig. 5-6 View of the abandoned town of Pripjat

5.2 Medical Care

Immediately after the accident iodine tablets were distributed to about five million people for thyroid prophylaxis. The inhabitants of the 30 km-zone were supplied with priority. The Russian Health Ministry determined provisory limits for radionuclides in milk (3 700 Bq/l) and daily food. Food exceeding these limits was excluded from consumption. In rural areas these restrictions were, however, only partially observed or not at all.

In the period immediately after the accident an effective care for the population was aggravated by contradictory information and the politically enforced minimization of the situation. In the following period mass examinations for thyroid dysfunction were carried out among the population affected. These examinations have been continued as a part of the national health programmes until today.

The medical care for the population has been intensified, but it still suffers from the adverse economic situation. In Gomel a radiation medical centre was opened. A central state Medical and Radiological Register to collect data of radiation victims was established in Obninsk. In addition, further radiation medical centres were established in the areas exposed to radiation.

As early as in July 1986 the Health Ministry of the Ukraine had estimated the future annual external and internal radiation exposure. In addition, a series of protective measures was implemented to reduce radiation exposure. Hospitals in Kiev took care of the collection of data of persons affected by radiation and of their medical treatment. Moreover, a joint research centre and a scientific "information centre for radiological medicine" were opened.

The international support and cooperation for medical supply and the evaluation of the consequences of the accident at first started very hesitantly. Only when the political climate became more open, the countries concerned accepted the help offered from abroad. Since then international cooperation has intensified. In 1991 the health authorities of the Ukraine, Belorussia and Russia established epidemiological registers, where the results of radiological examination and health monitoring programmes are collected, within the framework of the IPHECA Programme run by the WHO.

But after the collapse of the former Soviet Union, the cooperation of the countries affected in the field of preventive medicine has become weaker and weaker. To portray an objective picture of the situation is thus getting more difficult.

5.3 Food Supply

The supply of the population in the contaminated areas with food which had not been exposed to radiation was and is one of the main problems after the accident. In these regions there are numerous factories belonging to food industry, in particular milk and grain processing as well as sugar production. In 1992 these food factories produced about 30 % of the goods in the region corresponding to 6 % of the overall production in the Ukraine. The agricultural products are frequently radioactively contaminated and thus not always have the quality required.

To keep the activity of the food low, special technologies and processing methods are employed. But with many of these processing methods the vitamin content is reduced drastically and the quality of the food is impaired. This is even more problematic as the weakened health of the population in the areas affected urgently requires vitamins to strengthen the defensive powers of the body.

Despite all the measures taken, it is still not possible to supply the population in the areas affected with sufficient quantities of uncontaminated food.

5.4 Economic Effects

Fig. 5-7 The contamination of grain is examined

The removal of the consequences of the Chernobyl accident requires substantial material and financial resources. It is almost impossible to estimate the total damage incurred, as almost all sectors of the national economies in the three states concerned are affected directly or indirectly. In the former Soviet Union more than 15 billion dollars were spent to remove the social, economic and health consequences.

The political collapse of the former Soviet Union has intensified the economic difficulties in the countries concerned. They spend a considerable part of the state finances on the removal and mitigation of the accident consequences. In Belorussia and in the Ukraine these expenses were more than ten percent of the state budget in the early 90ies.

6 Health and Ecological Consequences of the Accident

There are very controversial opionions on the health effects of the reactor accident in Chernobyl. This applies to a particular extent to the amount of current and future health detriments. Since 1986 the national organizations in the three mainly affected countries, the Ukraine, Belorussia and Russia as well as many international organizations have strived for proper clarification. The International Atomic Energy Agency, the World Health Organization, the European Union and the United Nations are to be mentioned here in the first place. The main object was to clarify which measures are suitable and appropriate to ensure an adequate medical supply of the human beings affected. The overall picture of the health and ecological consequences which actually occured is slowly getting clearer by the studies carried out by the national and international organizations. It must, however, be taken into account that owing to the long latency period most of the late health effects can only be prognosted. Systematic examinations on the long-term health effects therefore continue to be necessary.

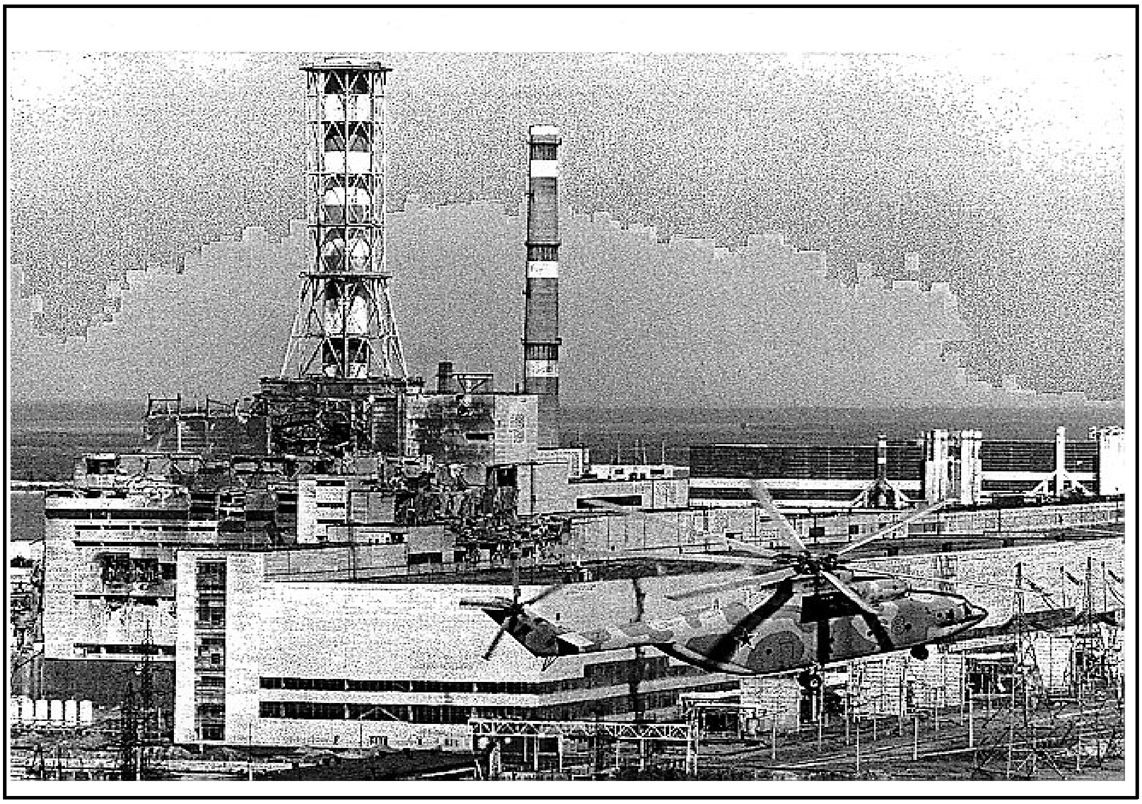


Fig. 6-1 Spraying of decontamination liquids by helicopter

The following kinds of health and ecological consequences have to be considered:

- Acute radiation injuries resulting from emergency activities as well as delayed health effects of persons who were involved in fire fighting and removal works.
- Health effects in the population in most severely affected regions of the Ukraine, Belorussia and Russia.
- Health effects outside the former Soviet Union.
- Ecological effects in the contaminated area.

6.1 Health Effects caused by Emergency Acitivities

The operating staff of the reactor, firemen as well as members of the army, e.g. helicopter pilots, were employed to immediately fight the fire and to cover the open reactor core. A part of this group of persons received very high dose rates. About 300 persons were taken to hospital. 134 persons showed symptoms of an acute radiation sickness with weakness, vomiting and dizziness as well as skin burns. Despite intensive medical efforts, partially including transplantations of bone marrow in specialized hospitals in Moscow and Kiev with the help of American surgeons, 28 persons died of radiation sickness and the fire injuries. The total body doses were up to 13 Gy. (With a body dose of 4 Gy the chance to survive is about fifty percent).

Two members of the operating staff died directly by the impact of fire and explosion.

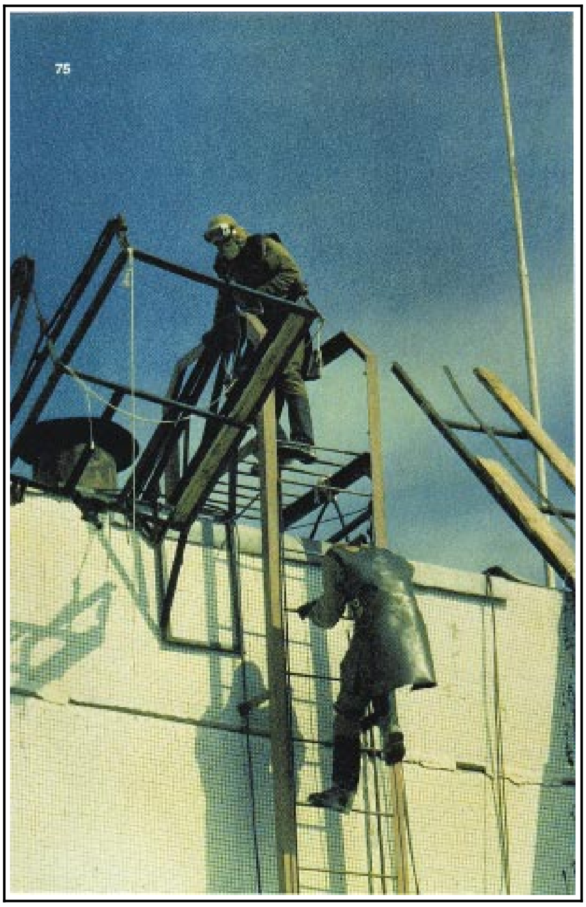


Fig. 6-2 Liquidators involved in construction work of the Sarcophagus

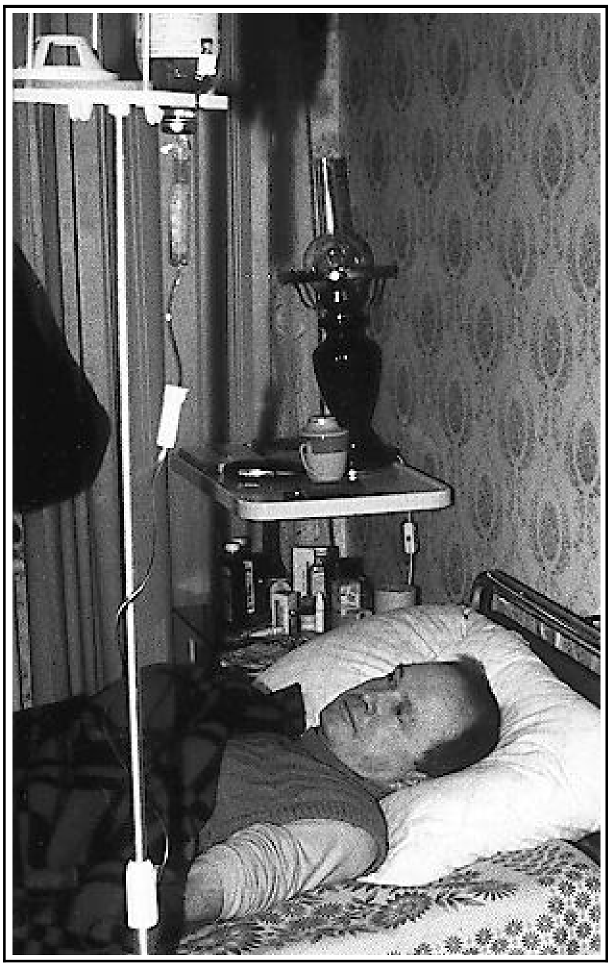


Fig. 6-3 Kiev Institute for Radiation Hygiene: This engineer was in the turbine hall at the time of the accident. He suffered severe radiation injuries and has to undergo stationary treatment.

In addition, 14 of the patients with an acute radiation sickness died in the Ukraine until 1995 according to Ukrainian statistics.

Members of the army and civilists from many parts of the Soviet Union were employed for the decontamination and removal works in the region surrounding the accident reactor. The number of this group of persons which is generally referred to as “liquidators” is difficult to determine and, according to Soviet figures, consisted of about 600 000 persons. The latest reports of the World Health Organization and of the United Nations speak of about 800 000 persons.

A central radiation epidemiological register for this group of people was established in Obninsk in 1986. At the end of 1991 it contained the data of 285 000 individuals. Although these registers are continued in the Ukraine, Belorussia and in Russia, the collection of data does not seem to be complete and consistent. Individuals from the Baltic states and the Caucasus regions outside the Russian Federation are not comprised in these registers.

According to preliminary analyses of the radiological data collected, the individual doses of the liquidators in many cases range from 50 to 250 mSv. The reliability of the dose determination is questionable here. During their first days of the recovery work the liquidators presumably often received higher doses than 250 mSv. So far there have been no findings on an increase of typical secondary effects such as leukemia, thyroid cancer or other malignances. But there are many hints, especially from Russia, that suicides, other forms of violent deaths, invalidity and neurological and psychosomatic diseases among liquidators can be observed more often. Although these secondary effects cannot directly be attributed to radiation exposure, they are to be connected with the reactor accident in a broader sense. The World Health Organization is going to analyze the extent and the causes for the impairment of the liquidators' health situation in its international IPHECA programme.

6.2 Health Effects of the Population

The radiation exposure of the population caused by the reactor accident can essentially be attributed to the short-lived iodine 131 and the long-lived caesium 137. Immediately after the accident the Soviet authorities ordered emergency protective measures. The most severely affected areas, like the town of Pripjat, for example, were evacuated within a short period. Further evacuations followed later, when additional, exposed areas were found by monitoring programmes. In addition, restrictions limiting the consumption of food were ordered. With the help of these measures, the authorities wanted

Fig. 6-4 Belorussian children after thyorid operation treated in the Clinic of the Institute for Radiology at Aksakovchina

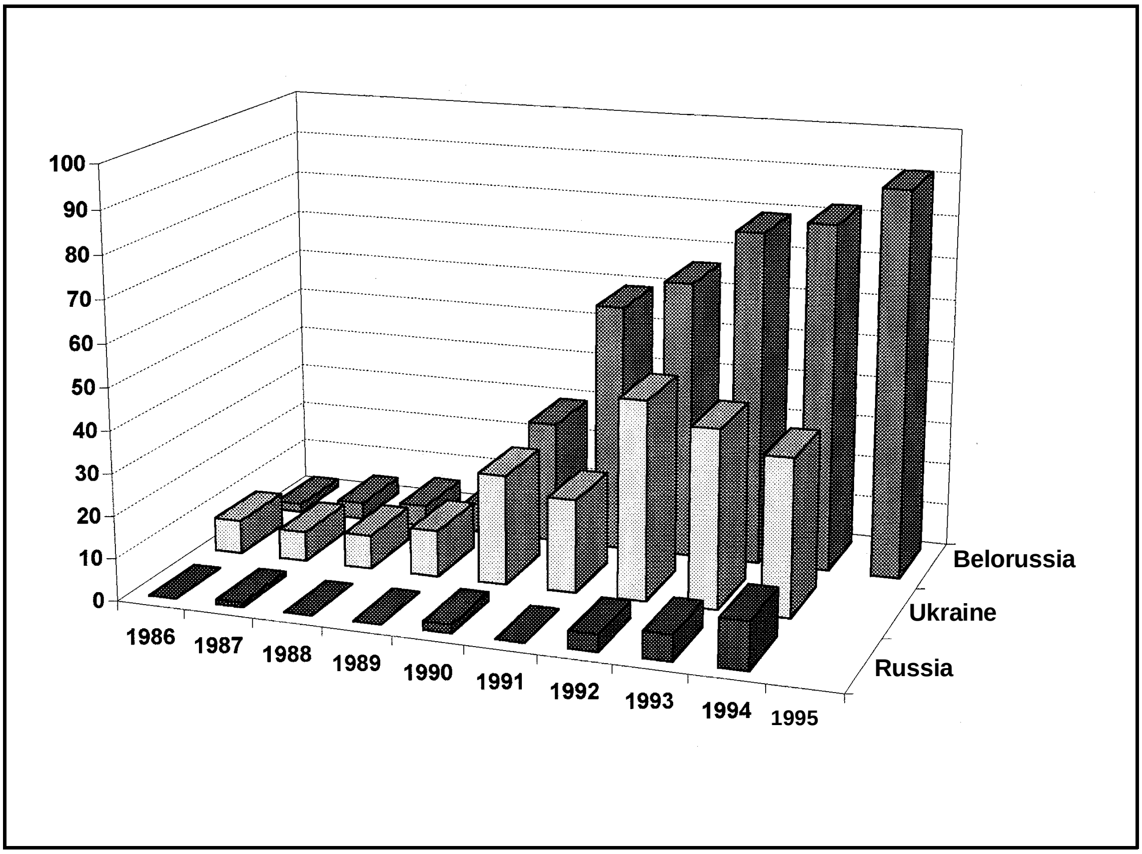


Fig. 6-5 Thyroid cancer incidence of children in the Ukraine, Belorussia and Russia from 1986 through 1995 (1995 data based on Ukrainian statistics)

to achieve that even the population of the highly exposed areas normally did not receive a total dose exceeding 250 mSv. Immediate radiation injuries could thus largely be prevented. In some cases, however, reports on visual imparment lens of the eye and inflammable eye diseases have been reported.

Particularly important was the intake of iodine 131 with the food. Iodine 131 has a half-life of eight days and accumulates preferably in the thyroid subsequent incorporation via the consumption of fresh milk. In the areas most severely affected there were very high iodine concentrations in the milk. Thyorid exposures of up to 50 Gy were the consequence for children. Although stable iodine tablets were distributed to the population affected to block off the intake of radioactive iodine, this measure was only partially successful.

Thyroid cancer of children owing to natural causes is very seldom. Examination of the victims of the nuclear bomb in Hiroshima and Nagasaki have shown that radiation leads to a increase of the frequency of thyroid cancer of children. These findings are confirmed by increasing numbers of children with thyroid cancer in the areas most severely affected by the accident. The World Health Organization (WHO) determined the figures for the occurence of thyroid cancer in the age group of up to 14 years in the comparative period of 1981 to 1985 and 1986 to 1994 (Table 6-1).

Table 6-1 Thyroid Cancer of Children up to 14 Years according to WHO Statistics of 1995

Countries	**Number of thyorid cancer cases in the given period**	
	1981 - 1985[1)]	**1986 - 1994**
Belorussia	12	333
Ukraine	26	208[2)]
Russian Federation (Brjansk and Kaluga area)	1	24

1) Figures calculated from annual incidence and number of children according to WHO 1995
2) Until mid-1994

The number of thyorid cancer cases per year has been increasing since 1986 until today. A total of 565 cases of thyroid cancer occured until 1994 with more than two million children examined. Most of these cases can be attributed to radio-iodine intake after the accident. The thyroid cancer cases predominantly occur in the most severely affected regions. In the strongly affected Belorussian region of Gomel the frequency of thyroid cancer increased from 1 case among one million children before the accident to more than 100 per one million children in 1994. Infant thyroid cancer can generally be treated successfully, but it requires long-term therapy. In some cases the medical treatment had to be repeated. Nevertheless, some children died in Belorussia.

Despite intensive surveys an increase of other tumour diseases and of leukeamia of children or adults owing to radiation has so far not been determined. This also applies to genetic defects. The latest reports issued by the WHO and the United Nations also confirm these results. Nevertheless, a premature evaluation must be warned of. The latency periods for many cancer types are longer than the period which has passed after the accident. It cannot be concluded from the survey results which do not disclose a statistical increase that there are no additional cases of cancer caused by radiation.

On the other hand, it has not yet been verified that an increased occurence of lung and stomach cancer as stated in the United Nations' report carried out for the Gomel region must be attributed to radiation exposure, as the latency periods for these types of cancer are longer than the period which has passed since the accident.

Recently (in April 1995), the press reported about 125 000 cases of death due to the Chernobyl reactor accident. This figure mentioned by the Ukrainian government was misinterpreted and represents the total number of deaths among the affected population of about 2.5 million people in the period between 1988 and 1994. This figure comprises deaths for all reasons and cannot be attributed to radiation exposures by the reactor accident. This figure more or less corresponds to the overall death rate of the Ukrainian population. Even without these exaggerations and misinterpretations the actual health consequences caused by the accident is grave enough.

The areas in the Ukraine, Belorussia and Russia affected by the reactor accident report about a general increase of diseases among the population. Especially stress-related illnesses like depressions, anxieties, psychic excitation but also chronic bronchitis, high blood pressure, coronary diseases and diabetes are more and more often diagnosed. According to present findings, these diseases cannot directly be attributed to a radiation exposure. But they are, nevertheless, considered as indirect consequences of the accident and the expulsion of many thousands of people from their familiar circumstances of life. One reason for a part of these diseases may also be the general impairment of the social and economical situation after the collapse of the Soviet Union and the uncertainties connected therewith. The increase of contagiuos diseases, e.g. diphteria and tuberkulosis, might also be connected with this impairment of the general living conditions and the insufficient medical treatment.

The radiobiological effects of the Chernobyl reactor accident will continue to be a subject of intensive international cooperations and research activities. A systematic and conclusive analysis of the extensive data and examination results already existing in the three countries affected represent the most important task. But apart from this research work the affected population may not be forgotten. They require intensified help. The states concerned cannot solve this task all by themselves. Further efforts of the international community of states and the respective financial resources are reqiured herefor.

6.3 Health Effects in Germany

Because of the meteorological spreading conditions at the time of the accident large parts of Europe were radioactively contaminated, while the distribution largely depended on the local weather conditions. The caesium 137 contamination in Germany was thus very different (Berlin 2.3 kBq/m^2, Munich 19 kBq/m^2, Alp region partially up to 100 kBq/m^2). The radiation exposure caused thereby in South Bavaria was up to 1 mSv effective dose by external radiation and about 0.5 mSv by ingestion (the average natural radiation exposure in Germany is 2.3 mSv per year). Although a late effect risk can be calculated on the basis of these doses, this is very low compared to the existing general cancer risk.

On the whole, there is no scientific evidence for an impairment of health conditions in Germany owing to the additional radiation exposure caused by the Chernobyl reactor accident.

6.4 Ecological Effects

The external radiation and the intake of radionuclides into the organism as well as the varying radiation sensitivity of the different species determine the effects of radiation on flora and fauna.

Close to the power plant large amounts of radioactive particles were deposited in an adjacent forest. This forest was damaged massively. The pinetrees in the closer sourrounding of the accident site died within weeks and months after the accident (so-called "red wood"). Radiation doses exceeding 10 Gy were estimated for this area.

In other areas, where radiation doses ranged between 3 and 10 GY, there were clearly perceivable damages to pines. Other types of trees, like aspen-trees, birches and oaks in the neighbourhood of the damaged pines did not show any or only few symptoms. Many of the damaged pine-trees died in the following years. As a precaution against soil erosion and carrying away contaminated dust, the damaged areas should be reforested.

Herbal plants hardly show any visible damages. Examinations of these plants did, however, disclose increased gene mutation rates which normalized when their descendants were replanted into in lower contaminated areas.

A large fraction of the radioactive substances accumulated in the spruce needle layer of the forest soils. The number of insects and their larva living in this stray layer in the summer of 1986 decreased to one percent of the normal value. There was a decrease in the population density by about two thirds for types living deeper in the soil. Because of the disturbed ecological balance in the dead forests there were more parasitic insects, like pine lappet moths, powder-post beetles, and weevils which also threatened the less damaged forests in the neighbourhood. To prevent a further spreading of these parasitic insects the dead parts of wood were stubbed.

The number of vertebrate animals also decreased in the damaged areas. Mice suffered from pathological changes of their blood and their inner organs as well as reduced fertility. But the damaged areas were soon reinhabited by immigrating animals. Thus, a tenfold increase of rodents compared to the population density before the accident was determined in 1987. The grain harvest which had not been cropped and the low number of wild animals is considered to be the reason for this increase. Since 1989 the conditions normalized. Living conditions without human influence have developed for wild animals in the prohibited areas.

There are only few reports about the effects on birds and water animals. For birds there are indications for an increased embryo death rate in the eggs. In the tissue of fish increased contents of caesium 137 were found. The contamination in the Denjepr, Pripjat and Desna rivers as well as in the Dnjepr-storage reservoir have not led to contamination doses where impairment of the population density of water organisms is to be expected.

7 The Safety of RBMK Plants

After the accident in Unit 4 of the Chernobyl Nuclear Power Plant great efforts were made to clarify its sequence and its causes. In the Western world the RBMK technology and thus also the safety-relevant properties were largely unknown. It was the priority of the Soviet side to improve the safety of RBMK in such way that a distastrous accident caused by a reactor excursion was avoided.

In the meantime the design deficiencies and the circumstances which led to the accident are sufficiently known. The basic deficiencies of the reactor physical design (also see Section 1.4) of the shutdown facilities and the operating rules of RBMK plants were decisive. Explosion-like reactor excursions thus became possible during certain operating states. In all RBMK plants improvements relating to these deficiencies have been carried out in the meantime.

Starting out from the knowledge acquired during accident analysis, safety issues of RBMK plants have been more and more systematically analysed in the Soviet Union and later in Russia as well as within the framework of international cooperation. These examinations disclosed a series of further safety deficiencies which can lead to severe accidents.

The upgrading measures which have been carried out since the Chernobyl accident are described below and the improvement of the safety thus achieved is discussed. In addition, further measures are dealt with which are still to be carried out.

7.1 Reactivity Control

The safety of RBMK is decivisely determined by the reactivity behaviour of the reactor core. It is the essential aim of the measures already implemented or still planned to exclude the possibility of great, fast reactivity increases.

Important upgradings are:

- reduction of the positive void effect
- removal of the "positive scram effect"
- limitation of reactivity insertion during loss-of-coolant in the coolant system for the control rods
- installation of a fast shutdown system.

7.1.1 Positive Void Effect

A short time before the accident the positive void effect of reactivity in the Chernobyl Nuclear Power Plant, Unit 4 in a state of low power and with an operational reactivity margin (ORM) of about 7 control rods was at least 5 ß. This positive void effect was decisive for the initiation of the accident and the disastrous procedure and it can be

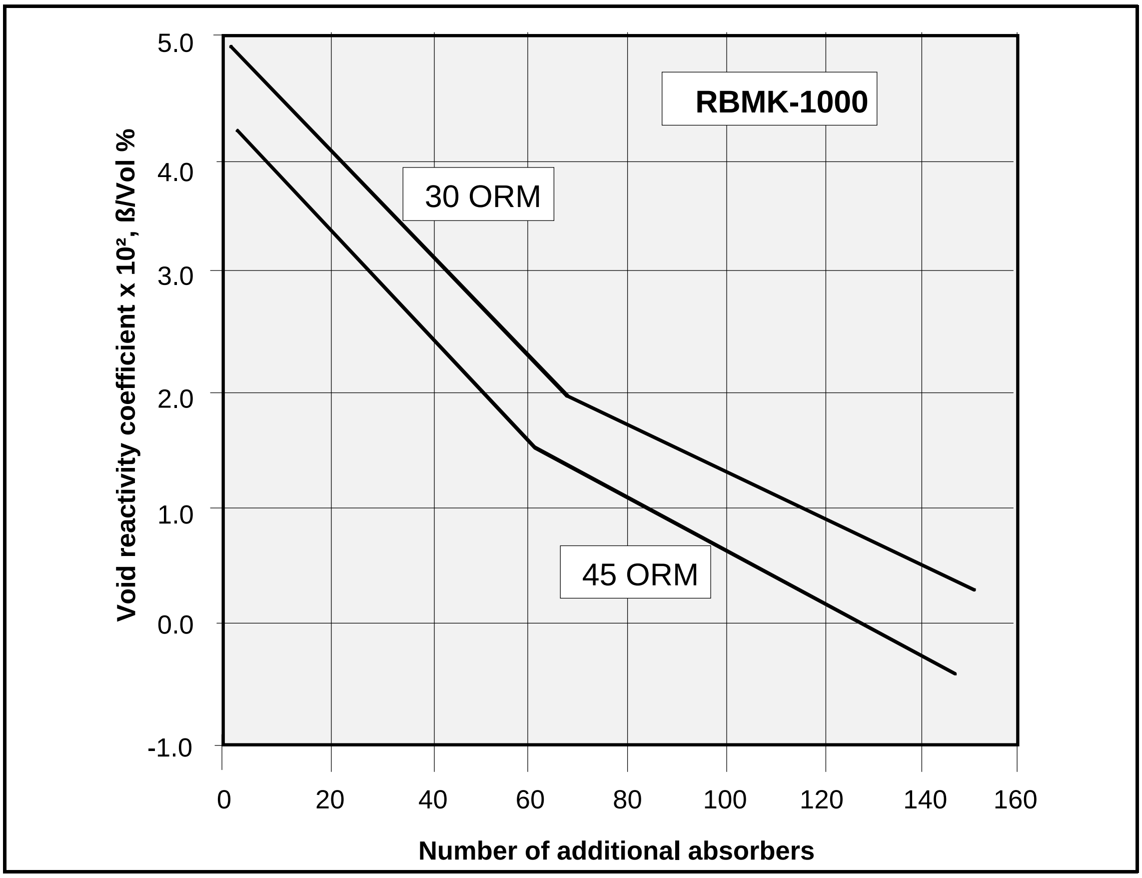


Fig. 7-1 Void reactivity depending on the number of additional absorbers

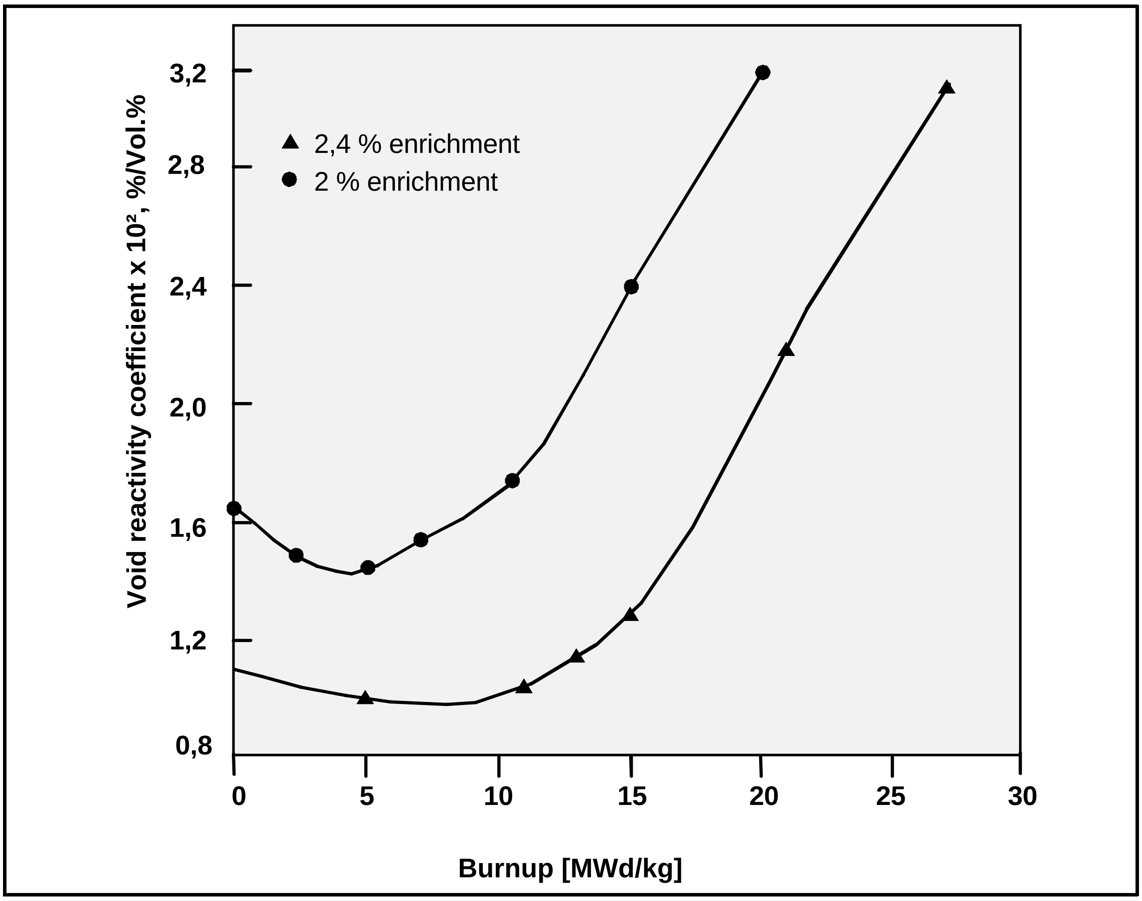


Fig. 7-2 Dependecy of the void coefficient on the burnup and the initial enrichment without consideration of the absorbers in the core

regarded as the greatest safety deficiency of RBMK plants at the time of the accident. Its reduction became very important for a further operation of the RBMK plants.

Already a short time after the accident constructive measures were taken to reduce the positive void effect, in particular by additional stationary absorber rods in the reactor core. About 80 of these absorbers were installed per reactor (Fig. 7.1), in some plants even more. The additional absorbers have limited the usability of the fuel, i.e. lowered the fuel burnup achievable. To compensate this effect, the fuel enrichment of uranium 235 was increased, namely from 2.0 to 2.4 % in most plants (Fig. 7-2) leading to a further reduction of the positive void effect. This increase effects a further, though smaller reduction of the positive void effect. The burnt-up fuel elements are continuously replaced by new ones with an enrichment of 2.4 %. This process has not yet been completed in all RBMK plants. In Units 1 and 3 of the Chernobyl Nuclear Power Plant, for example, about 1200 each of the about 1600 fuel elements in the core are loaded with an enrichment of 2.4 %.

In addition thereto the operating rules were modified. They now require a larger number of control rods inserted into the reactor than before. While the former ORM during normal operation was 30 control rods, it is now 43 to 48 control rods (53 to 58 in RBMK-1500). A smaller value of ORM than 30 today is not permitted in any event. In the past the minimum ORM permitted was 15. The observation of the minimum ORM permitted still today is only regulated by operating rules. But in the meantime the ORM is displayed well visible in the control room. In addition thereto, some plants were backfitted with an alarm signalling a lower deviation from the ORM permitted.

Table 7-1 Current values for the void effect and the power coefficients of RBMK plants (according to Russian statistics)

Plant	**Date of measure-ment**	**Average burnup [MWd/kg]**	**Addi-tional absorbers**	**Fuel element with 2.4 % enrichment**	**Void effect [β]**	**Power coefficient [10^{-4} x β/MW]**
Leningrad-1	06.02.94	11.7	80	1 520	0.8 ± 0.2	-2.8 ± 0.2
Leningrad-2	23.12.94	11.5	80	1 474	0.4 ± 0.1	-2.5 ± 0.2
Leningrad-3	31.07.94	11.4	81	1 579	0.8 ± 0.1	
Leningrad-4	16.03.94	11.4	80	1 579	0.8 ± 0.2	-2.1 ± 0.2
Kursk-1	11.04.94	9.6	99	1 102	0.8 ± 0.1	-2.3
Kursk-2	18.05.95	8.7	108[1)]	848	1.0 ± 0.1	-1.8
Kursk-3	03.03.95	9.6	87[2)]	1 075	0.6 ± 0.1	-2.3
Kursk-4	16.12.94	10.2	84	1 210	0.8 ± 0.1	-2.1
Smolensk-1	21.04.94	11.6	81	1 536	0.6 ± 0.2	-2.8
Smolensk-2	29.03.95	11.5	81	1 546	0.7 ± 0.2	-2.1
Smolensk-3	24.01.95	10.4	93	1 329	0.1 ± 0.2	-2.7
Chernobyl-1	28.04.95	10.6	84	1 168	0.7 ± 0.2	-2.7
Chernobyl-3	14.04.95	10.3	93	1 262	0.7 ± 0.2	-3.5
Ignalina-1	18.03.95	7.7	52	0	0.8 ± 0.2	-2.3 ± 0.2
Ignalina-2	17.03.95	7.7	53	0	0.8 ± 0.2	-1.8 ± 0.2

[1)] including 34 additional absorbers of stainless steel
[2)] including 25 additional finger absorbers of boron carbide

The current values of the void effect and the power coefficient after the improvements are illustrated in Table 7-1. The figures represent the results of Russian measurements which were carried out in the power regime near rated power, at mean burnup and with ORMs of 42 to 48 control rods. The table shows that in the meantime the positive void effect ranges between (0.8 ± 0.2) ß in most plants. The size of the void effect during reactor operation is regularly determined and examined every 200 operating days.

If the power or the ORM, respectively, get smaller, the positive void effect increases, for example during the transition from full power to zero power by about 0.7 ß. At present, the positive void effect of most RBMK during plant conditions with a thermal reactor power of 700 MW still being just permissible according to the current operating rules and the minimum permissible ORM would be up to 1.6 ß depending on the burnup condition of the reactor core. In a preaccident plant condition, into which the plant in principle still could get today upon violation of the operating rules, the void effect would be considerably lower than in the past, but it would still clearly range above 2 ß. In contrast to the time prior to the accident, the fast shutdown system has now been backfitted in the meantime. If, in addition, the negative reactivity reaction effect caused by the fuel temperature increase is taken into account, a repetition of the former explosion-like accident procedure seems hardly possible today. But there still exists a need for examination with respect to the series of detailed questions.

The observation of operating conditions which are of utmost importance for safety principally would have to be ensured by overlapping measures. Automation is highly important in this context. An essential improvement could, for example, be reached by the introduction of an actuation "ORM low" initiating automatic shutdown.

At present Leningrad-1 and -2 work on the introduction of such an actuation criterion.

7.1.2 Positive Scram Effect

The original RBMK control rod construction caused a "positive scram effect" during the insertion of control rods from their upper final position to shut down the reactor (see Section 1.4.4) This unusual property which does not exist in Western reactors, initially inserted positive reactivity at the beginning of the control rod movement into the core. The size of the effect can substantially be reinforced by an axial power distribution with an excessive maximum in the lower core area. The "positive scram effect" together with the positive void effect contributed to the severe effects of the accident.

One of the first measures after the accident was to limit the withdrawal of the control rods. Later the control rod design was changed to remove this design deficiency. Fig. 7-3 shows a schematic comparison of the old control rod design, the intermediate solution and the new control rod design. By limiting the withdrawal of the control rods the water column in the lower core area responsible for the positive shutdown effect can no longer occur, see version B on Fig. 7-3. The new control rod design, version C, permits the complete withdrawal of the absorber part, as the absorber part was extended and the distance between the graphite displacer and the absorber part was enlarged. This modification of the control rod design removed the "positive scram effect". It was carried out in all RBMK plants.

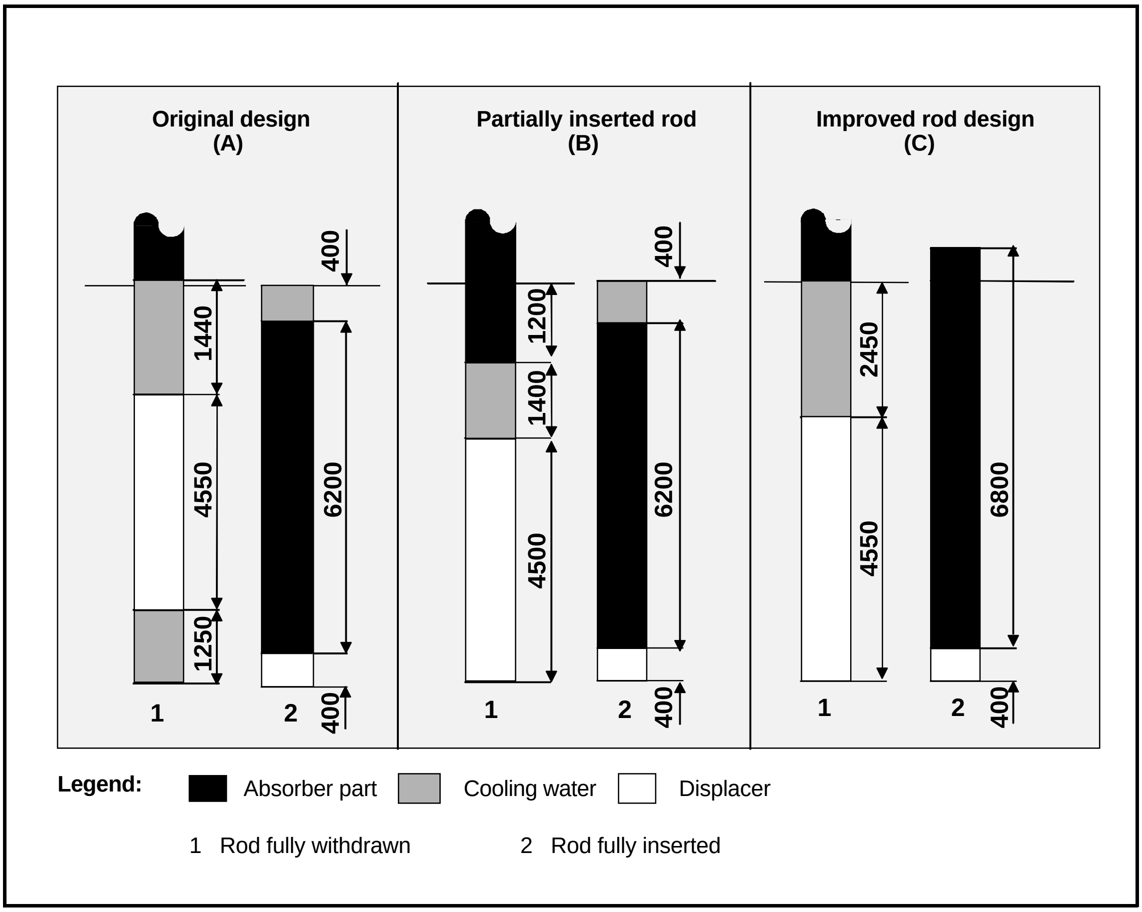


Fig. 7-3 Change of RBMK control rod function to prevent the positive scram effect

7.1.3 Reactivity Insertion during Loss of Coolant in Control Rod Cooling System

The control rods in the RBMK core are cooled with water by a separate system. An admission of gas or a loss of coolant from this cooling system have the potential for a high reactivity insertion.

The size of the reactivity effect is clearly dependent on the number of control rods currently in the core. This was demonstrated by GRS-recalculations of operating measurements in Smolensk-1 upon startup of the reactor. The results are shown in Table 7-2. During shutdown condition with the control rods inserted, the reactivity effect of the control rod cooling system is almost zero or slightly negative, respectively. With an increasing number of control rods withdrawn the reactivity effect increases. An evacuation of the system with 84 control rods withdrawn (critical condition of the reactor) can thus already effect a reactivity insertion of 4.3 ß.

Table 7-2 Reactivity change by voiding of the control rod cooling system depending on the number of control rods withdrawn

Number of control rods withdrawn	Reactivity effect upon voiding of the system [β]
all control rods completely inserted	- 0.1
46 control rods completely withdrawn	+ 3.1
84 control rods completely withdrawn	+ 4.3

Planned measures to reduce this reactivity effect provide for an improvement by dividing the control rod cooling system into two or more separate systems. In addition thereto, changes of the control rod design are planned to reduce the water inventory in the control rod channels.

Monitoring of the control rod cooling system has already been improved by additional measurements of the flow rate and the filling level in most RBMK plants. A shutdown is actuated upon deviation from the minimum limits. Rules on the deaeration of heat exchangers and pumps in the control rod cooling system were established on the basis of operating experience. Possible causes for a reduction of the filling level or gas admission shall thus largely be excluded.

Reactivity disturbances caused by evacuation of the control rod cooling system can either be avoided completely or their potential effects can be reduced substantially by backfitting measures relating to the division of the cooling system and the improved control rod design. The respective measures should be carried out in all plants as soon as possible.

7.1.4 Control and Shutdown System

Operational reactivity control and shutdown of the reactor to the subcritical state represent the function of the control and shutdown system. In RBMK plants this system plays a particularly important role, as RBMK plants in a number of incidents and accidents do not shut down by themselves via reactivity feedback effects. Examples are coolant flow rate reductions, depressurization procedures and large loss-of-coolant accidents. It is international practice to provide for two diversitary shutdown systems which each for itself can shut down the reactor. At present RBMK plants do not yet meet this requirement.

The existing RBMK control and shutdown system comprises a total of 211 control rods (plants of the first generation, however, only comprise 191 control rods) which are either moved manually or automatically and which are inserted or dropped simultaneously upon shutdown. Until the accident the shutdown speed for fast accidents was too slow. The upgrading measures were therefore directed at reducing shutdown times. Thus 24 control rods were changed to a fast shutdown system. These control rods now fall into the reactor core within 2 to 2.5 s. For most of the other control rods the insertion time was shortened to 12 to 14 s.

The control and shutdown system consists of the following control rod groups (the figures in brackets apply to plants belonging to the first generation):

- 24 (21) fast shutdown rods, insertion time: 2.0 - 2.5 s,
- 12 (8) control rods of local automatic power control (LAR),
- 8 (16) control rods of the local automatic protection (LAP)
- 119 (114) manual and automatic control rods for reactor power control,

- 32 (32) shortened control rods (USP) which are inserted into the core from below and which serve to flatten the power distribution.

The short insertion time of the fast shutdown rods is achieved by a changed cooling. In the new construction a water film provides for cooling so that water does no longer have to be displaced upon insertion or dropping of the control rods, respectively, which is the case for the other control rods.

The number of the shortened control rods which are inserted into the reactor core from below was increased from 24 to 32. In contrast to the past, these control rods were integrated into reactor protection.

The following reactivity effects are attained for the shutdown system of RBMK of the second and the third generation with 211 control rods: The reactivity effectiveness of the fast shutdown rods is about 2 ß, while the reactivity effectiveness of all control rods of manual and automatic control amount to about 12 ß. These values refer to a rod-free reactor core. For an ORM of 45 control rods common during power operation, the shutdown reactivity is reduced to about 9 to 10 ß. Upon reactor shutdown all control

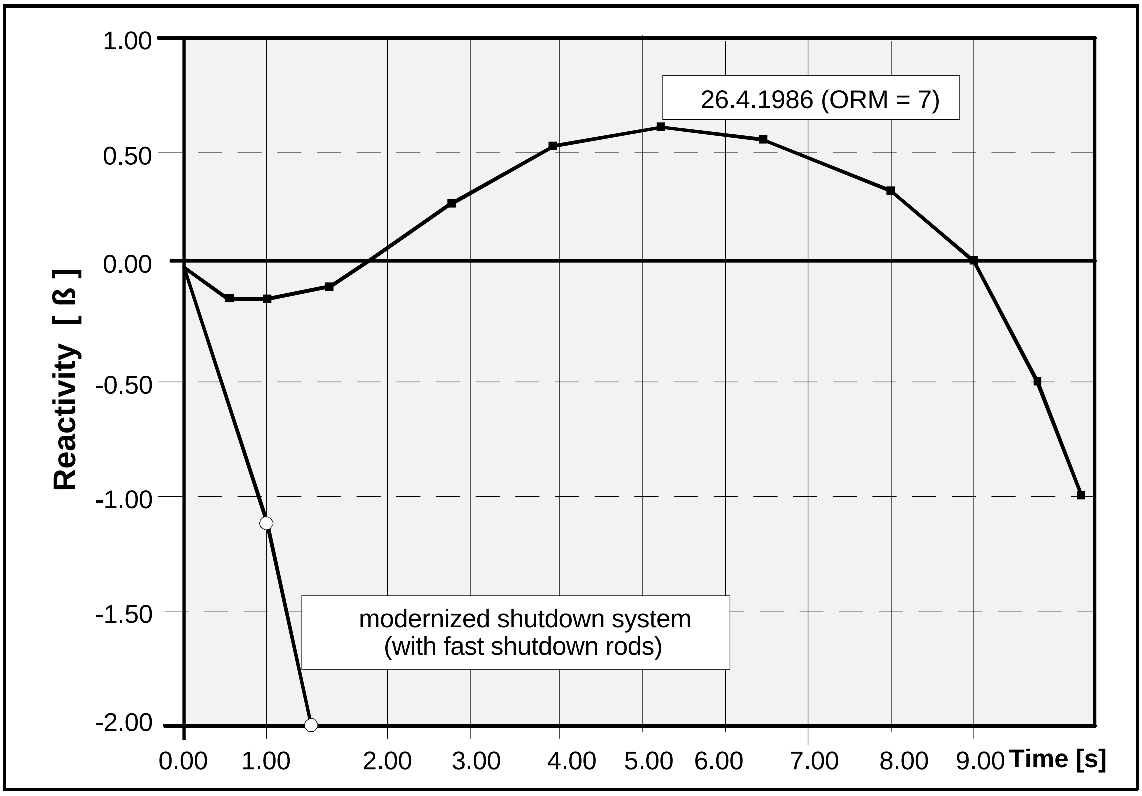


Fig. 7-4 Effectiveness of the shutdown system with respect to reactivity in RBMK plants as a function of time

rods are actuated simultaneously so that the other control rods drop with the 24 fast shutdown rods which results in a reactivity effectivity of about 1.5 ß/s at the beginning of the fast shutdown.

The essential deficiencies in this sector have generally been removed with the improvements of the control and shutdown system. There are restrictions applying to plants of the first generation. Because of the reduction of the positive void effect and the increase of the ORM, the subcriticality in the shutdown state is lower. This effect brings along special consequences in the plants of the first generation having 191 control rods now. Additional safety verifications and possibly upgradings are required here.

The problem that RBMK plants do not have a second, diverse shutdown system still remains. Considering the peculiarities of the core design, it is important to backfit such a system to ensure a high reliability of the shutdown function. A second, independent shutdown system with control rods, the injection of fluid absorbers like gadolinium nitrate or boron acid as well as the insertion of boron carbide balls into special cooling channels are being discussed.

7.1.5 Improvements in the Reactor Protection System

When predetermined criteria are reached, the reactor protection system automatically actuates shutdown or a power reduction on six different levels. On the two highest levels an automatic reactor shutdown is actuated. The following levels today cause a power reduction to 50 or 60 %, respectively.

A number of upgradings was carried out. They had above all the aim to earlier and more reliably detect a fast increase of power. The changes among other things concerned the following actuation signals: The value of the actuation "reactor period low" was changed from 10 s to 20 s, the value of the actuation "reliable, fast power change" was reduced to 10 % of the set value. To monitor the reactor period, a three-leg system was introduced. The reactor period is not continuously monitored on all load levels. In addition thereto the signal can no longer be suppressed. A blocking of the shutdown function by manual interference is now largely prevented.

In addition, different plants were backfitted with further actuation signals for shutdown, like the signals upon disturbances in the control rod cooling system described above.

Further improvements are necessary. One example is the introduction of a shutdown signal "low coolant flow rate in a group of working channels" as a contribution to the prevention of a simultaneous failure of a larger number of pressure tubes.

For certain actuating events protective measures now as before are still actuated by one single actuation criterion, although there should principally be two actuation criteria derived from different physical parameters for all accidents. Here a systematic analysis is still required.

7.1.6 Core Monitoring

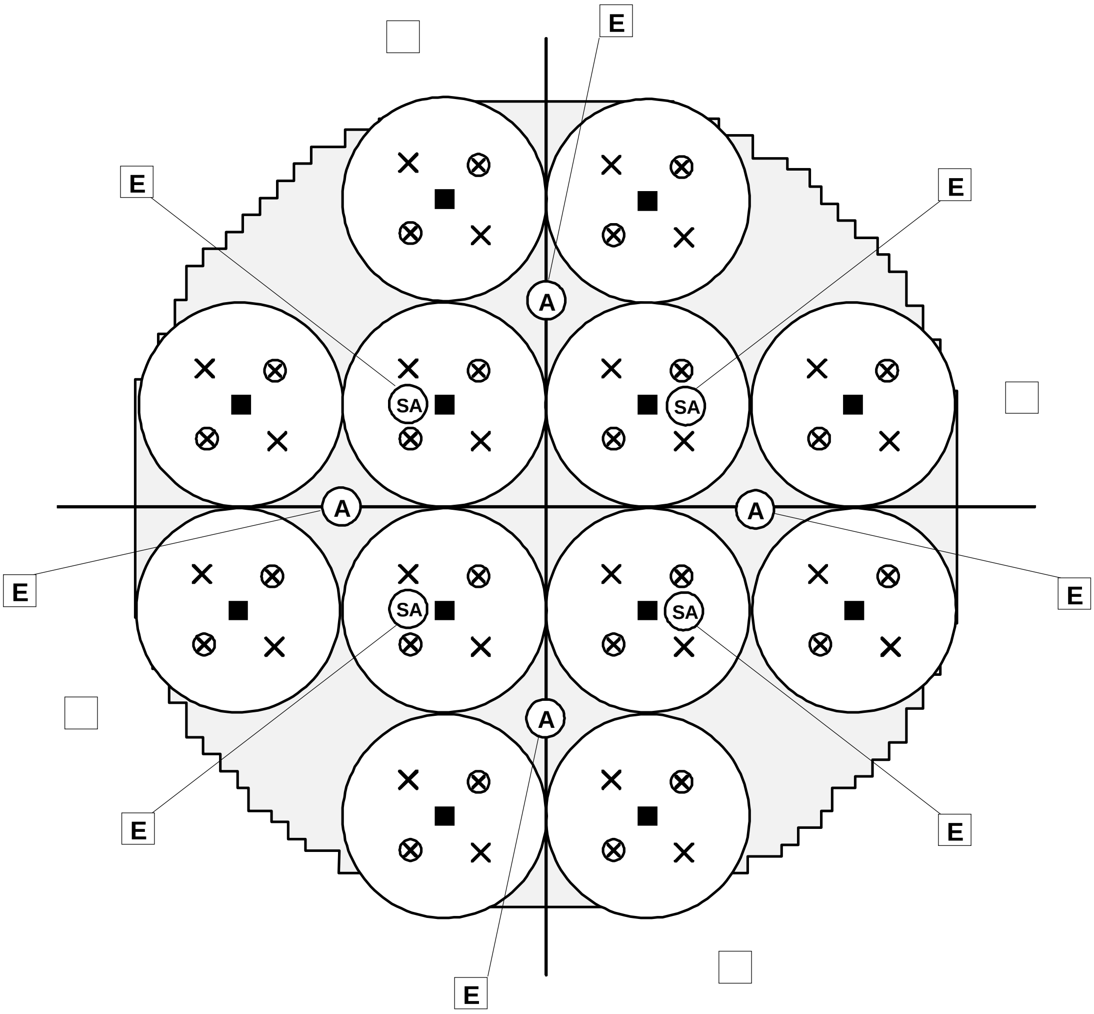
The core monitoring system provides the necessary measurement data for reactivity and power control of the reactor core. There are detectors for core monitoring outside as well as inside the reactor core.

During most operating conditions (power 5 %) core monitoring is assumed by a so-called "local" system, i.e. largely by in-core instrumentation.

For this purpose the core is divided into zones. To each zone belong one control rod and four to six local detectors. During each local power change of more than 1 % the control rod is moved within the respective zone for automatic compensation. During a power increase of more than 2 % one to two additional control rods are inserted. To avoid the possibility of a fast control rod withdrawal, the control rod withdrawal speed was limited to 0.2 m/s. In addition, control rods can manually be withdrawn only step-wise and in several steps.

Local monitoring of the reactor core requires a minimum number of zones to ensure sufficient control of all core areas. The present standard configuration comprises 12 zones (Fig. 7-5) which is considered to be sufficient. Most plants have in the meantime been equipped with this configuration. The remaining plants shall be backfitted with it. Chernobyl-1 is still equipped with the inadequate 7-zone system.

The radial and axial power distribution in the reactor core is recorded and analysed by an on-line computer (SKALA). First improvements have been carried out in all SKALA systems. Instead of the past maximum of every 30 minutes, the core condition is now displayed in intervals of five minutes. This also applies to the ORM value. But these



Legend:

- ■ Rod of local automatic power control (LAR)
- A Rod of global automatic power control (AR)
- SA Shortened control rod (USP)
- × In-core detector (control system)
- ⊗ In-core detector (control and protection system)
- E Outside-core detector (control and protection system)
- □ Outside-core (protection system)

Fig. 7-5 Control and protection system of the Chernobyl-3 plant (12-zone-system) measures do not suffice yet. The SKALA system is outdated and its capacity is too restricted. Here further improvements are necessary and possible, as the concepts for modernizing Leningrad-1 and -2 show.

7.1.7 Summarizing Evaluation of Reactivity Control

The measures for reducing the high positive void effect and for removing the positive shutdown effect as well as speeding up of the shutdown process were the most important changes to remove the severe deficiencies of the nuclear design. These backfittings were implemented in all plants in a comparable way.

Examinations on the dependency of the void effect on the operating condition show, however, that it clearly increases upon partial load and small ORMs. Still today, it is therefore very important that the minimum ORM permitted and the minimum reactor power permitted are kept. The observance now as before is regulated by operating rules.

A voiding of the control rod cooling can lead to a high reactivity insertion. In the meantime monitoring of the system has been improved to more reliably shutdown the reactor during such disturbances. In addition thereto, changes of the design are planned to lower the amount of the possible reactivity insertion.

The possibility of reactivity accidents was clearly reduced by the total number of the measures taken. A repetition of the former explosion-like accident procedure today hardly seems possible. Nevertheless, further improvements of reactivity control are necessary.

7.2 Core Cooling

To remove the heat generated in the reactor during normal operation there is the water-steam system and upon disturbances or accidents the emergency feedwater supply and the emergency core cooling system. Emergency feedwater supply and emergency core cooling comprise substantial deficiencies, in particular in plants belonging to the first generation (Fig. 7-6). A further weakness refers to the coolant supply of the individual pressure tubes.

7.2.1 Coolant Blockades of the Pressure Tubes

Due to a design deficiency, a damage at the control and isolating valves in the feeding pipes of the presssure tubes was possible which could block off coolant supply. Such an event on March 24, 1992 in the Leningrad-3 plant led to the destruction of the fuel element with subsequent pressure tube failure. According to the operator countries the control and isolating valves of all plants have been replaced by an improved design in the meantime which now comprises a minimum opening for ensuring cooling. The deficiency was thus removed.

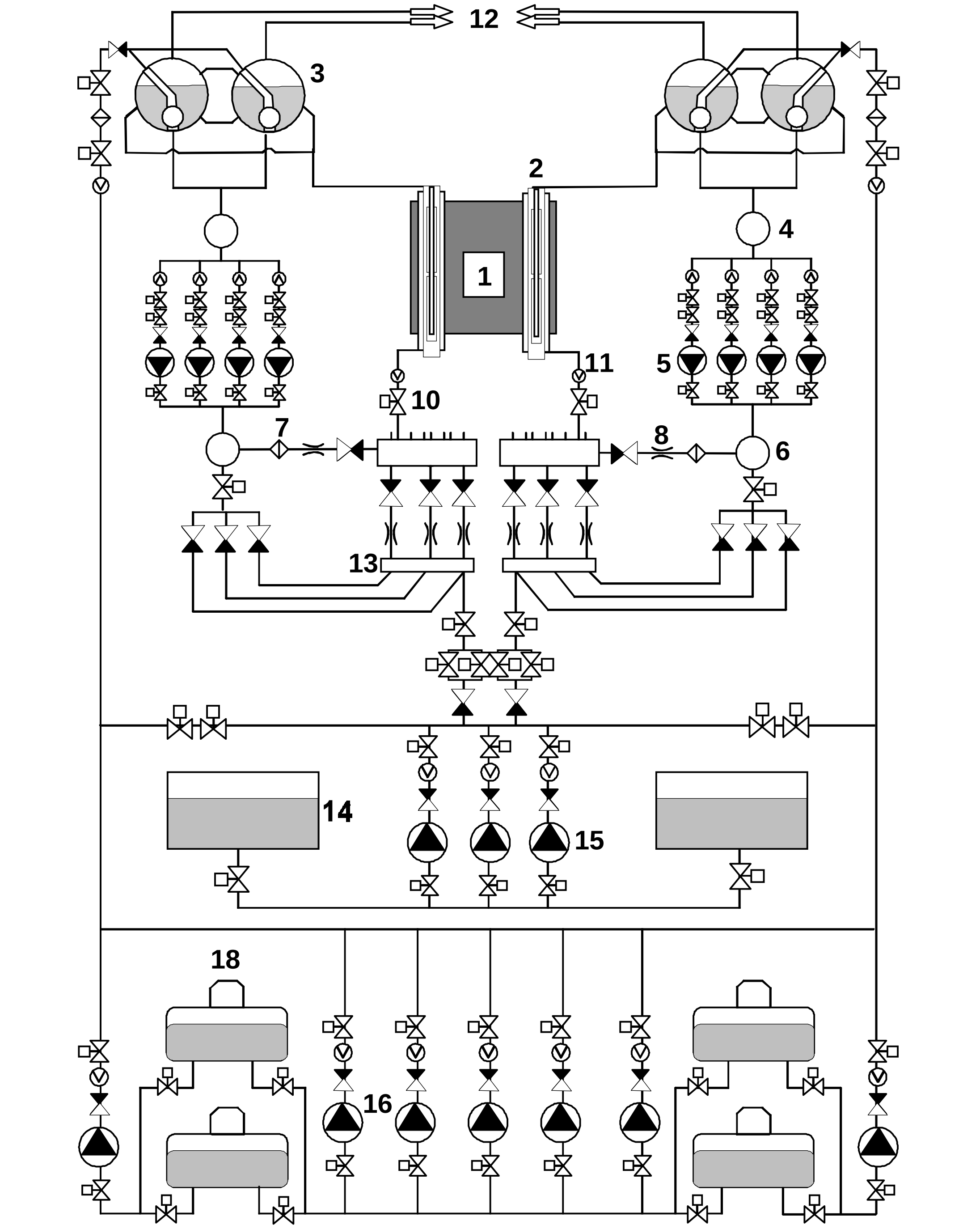
7.2.2 Emergency Feedwater Supply System

The emergency feedwater supply system was not designed as a safety system. Its main components and pipes are arranged in close neighbourhood to the main feed-water supply system in the turbine hall. The legs of the emergency feedwater supply system are not spatially separated from each other. It is practically not protected against spreading impacts. Operating experience has shown that it thus is not sufficiently re-liable. The fire in Chernobyl, Unit 2 on October 11, 1991, which led to the collapse of the roof of the turbine hall, put the main feedwater pumps as well as the emergency feedwater pumps out of action. This led to a substantial endangerment of core cooling. The reactor core was temporarily only cooled by the sealing water pumps of the main coolant pumps.

Considering the design deficiencies and the operating experience, improvements of the emergency feedwater supply seem to be of great importance. But emergency feed-water supply and emergency cooling systems have to be regarded in combination.

7.2.3 Emergency Core Cooling System

The emergency core cooling systems of RBMK plants are structured in different ways (see Section 1.4.4 and Fig. 1-18 as well as 1-19). The first generation does not possess an independent emergency core cooling system. The emergency feedwater supply system is used for core cooling. The deficiencies of the emergency feedwater supply



Legend:

1 Reactor core
2 Pressure tube
3 Drum separator
4 Suction header
5 Main coolant pumps
6 Pressure header
7 Mechanic filters
8 Flow rate control
9 Group distribution header
10 Control and isolating valve
11 Flow rate meter
12 Main steam lines
13 Emergency core cooling collector
14 Storage tank 500 m^3
15 Emergency injection pump
16 Main injection pump
17 Auxiliary injection pump
18 Feedwater tank

Fig. 7-6 Emergency core cooling system of the first generation with backfittings (Unit 1 and 2 of the Leningrad Nuclear Power Plant) system thus also fully apply to emergency core cooling. It is urgently required to upgrade the emergency core cooling function in plants belonging to the first generation .

In Leningrad-2 an independent emergency core cooling system is being established. For other nuclear power plants of the first generation similar plans exist. Even after this backfitting measure there remain two weaknesses. The emergency cooling pipes for each half of the reactor still continue to be one-legged in certain areas and the emergency core cooling capacity continues to be restricted to breaks of pipes with a nominal width of 300. The significance of the limitation to loss-of-coolant accidents NW 300 strongly depends on whether a complete break is to be assumed for larger pipes or not. This needs to be examined further.

The emergency core cooling system in nuclear power plants of the second and third generation, like Chernobyl-3 is designed for the break of the largest coolant pipe of the reactor cooling system having a nominal width of 900. This largely corresponds to current requirements to be met by safety systems. It is designed as a three-leg system. All legs have continuous separate injection lines to the emergency cooling collectors and further into the group distribution header. There are, however, restrictions caused by the one-leg arrangement of certain passive components and by the design of certain auxiliary systems.

7.2.4 Service Water System

The service water system is part of the residual heat removal chain. It serves to remove residual heat and to cool components important for technical safety. The basic deficiencies of other safety systems, like the spatial separation partially missing and the missing redundant structure, are also found in the service water system.

7.2.5 Summarizing Evaluation of Core Cooling

The safety systems relating to core cooling of RBMK plants belonging to the first generation show substantial deficiencies. The emergency feedwater supply system over large areas is not redundant and not designed against spreading impacts, like fire or flooding. The plants of the first generation further do not comprise an independent emergency core cooling system. Comprehensive upgradings, like the ones currently

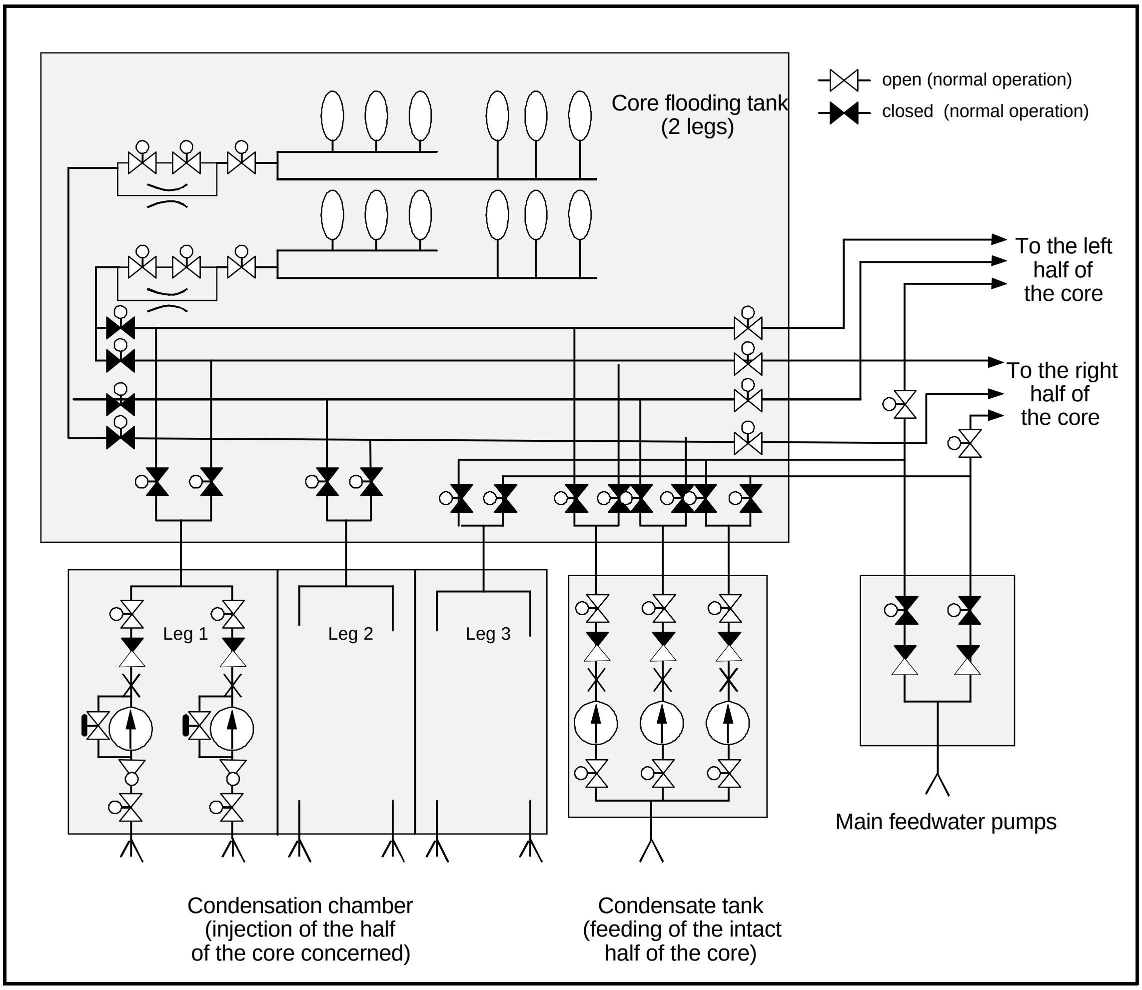


Fig. 7-7 Subsystems of the emergency core cooling system at Smolensk-3

carried out at Leningrad-1 and -2, for example, are urgently required here to achieve a sufficient level of reliability.

For RBMK of the second and third generation the situation relating to systems engineering is generally more favourable. The plants have an independent emergency core cooling system and the redundancies of the safety systems have been arranged in a spatially separated way to a larger extent.

With respect to the emergency feedwater supply system and the service water system, the conditions are, however, similar like to those of the first generation. Here upgradings are also required for the second and third generation.

7.3 Confinement Function

7.3.1 Confinement

The first generation of RBMK plants does not comprise a confinement - an accident localization system, as it is called in Russian - to keep the coolant with the radioactive substances emerging through potential leaks away from the environment. To precipitate steam and to limit pressure in the reactor building after loss-of-coolant accidents there is only an accident localization system of a low capacity. Medium and larger breaks in the area of the reactor cooling system are thus necessarily connected with radioactive releases into the reactor hall or into the environment, respectively. In addition thereto, the reactor building of old plants is only designed for line breaks of up to NW 300 inclusively.

At present, Leningrad-1 and -2 are backfitting partial confinements, comparable to RBMK of the second and third generation. Separated buildings are built for pool-type pressure suppression systems. At the moment there are no definite projects for such backfitting measures for most of the other plants of the first generation. Such backfitting measures would, however, be useful for all old plants.

RBMK plants of the second and third generation have a partial enclosure with pool-type pressure suppression system. Design accidents are the break of a pressure header of the main coolant pumps (NW 900), a group distribution header (NW 300) in the lower hermetically sealed compartments of the reactor building as well as the failure of a pressure tube in the reactor vessel. But the confinement only comprises parts of the reactor cooling system. Thus, no RBMK generation has a confinement for breaks in the upper compartments. This concerns main steam lines and upper sections of the down-comer and feedwater lines. Backfitting measures practically do not seem possible. But according to Russian reports the radiological limits for the respective accidents are observed.

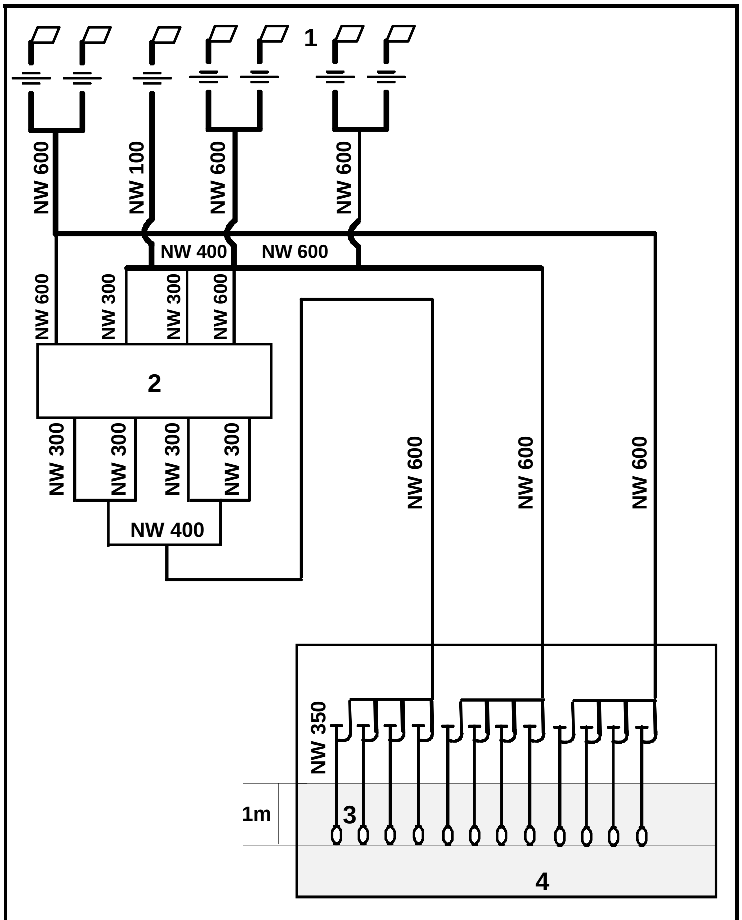
7.3.2 Reactor Overpressure Protection System

The reactor vessel in which the reactor core is located has to be secured against inadmissibly high pressure to prevent a rise of the upper cover plate. The raise of the cover plate would lead to the rupture of all pressure tubes and control rod channels.

This would have disastrous effects. As the design basis accident for protection against pressure the break of one pressure tube was originally assumed. The simultaneous failure of several pressure tubes was not taken into account. According to Russian analyses the simultaneous break of three to four pressure tubes can, however, be controlled.

So far three events including failure of one single pressure tube have occured. These experiences and analyses prove that a propagation leading to multiple failure is unlikely. Other realistic scenarios with multiple failures of pressure tubes are not known. Independent hereof, it still urgently remains to be clarified whether there is a plausible initiator for multiple failures of pressure tubes and which number of pressure tubes failing simultaneously would have to be assumed.

Measures to improve pressure protection primarily aim at the improvement of material testing with respect to the pressure tubes and the increase of the depressurization capacity of the reactor vessel. In Smolensk-3 and Leningrad-2 the depressurization capacity of the reactor pressure vessel was increased to the technically feasible value. The simultaneous failure of nine pressure tubes is thus controlled. In most of the other RBMK plants the pressure relief capacity was increased in a first step corresponding to four pressure tubes failing simultaneously. Here too, it is intended to reach the technically feasible status in the longterm.



Legend:
1 Rupture facility (NW 450)
2 Reactor vessel
3 Condensation tubes (NW 400)
4 Pressure suppresion tank

Fig. 7-8 Simplified diagram of the pressure protection system of the reactor vessel

Considering the possible consequences of a respective accident this is also necessary.

7.4 Common Design Requirements

The safety concepts for nuclear power plants generally comprise safety-relevant precautions which ensure that the protective targets are also kept in case of spreading impacts. Such impacts are fire, flooding and earthquakes, for example. Redundant safety systems, in particular, are arranged in spatially and functionally separated way and are emergency power supplied. These precautions have not been taken in all safety-relevant RBMK systems. There are also important deficiencies relating to fire protection.

7.4.1 Instrumentation and Control

Instrumentation and control show similar weaknesses like other engineered safeguards. Operational and safety-related functions have not consequently been separated functionally and spatially. Thus damages can spread because of the spatial closeness of high-potential current and control current cables or failures by fire or flooding. Such deficiencies can also be found in plants of the second and third generation, although to a more restricted extent. In these plants the redundancies of reactor protection are connected via a common ventilation system. Further important weaknesses are:

- resistance to jamming of the instrumentation
- quality of the instrumentation and control components
- protection of electrotechnical components
- capacity of the floating batteries
- emergency control station in plants of the first generation

The specification of the instrumentation and the measuring transducers is oriented on the operational conditions of the environment. But for a safe detection and control under accident consitions it has to be ensured by all means that the instrumentation also functions under the conditions prevailing then. According to one recent examination there is no qualification for accident conditions for a larger number of instrumentation channels.

The deficiencies in quality of the instrumentation and control components lead to high maintenance efforts and frequent readjustments and thus to possible misadjustments.

There are considerable deficiencies with respect to the fuse protection of electrotechnical components which can lead to extensive failures of subdistributions or entire power supply busbars.

The supply time of batteries is only 30 minutes. Upon failure of the emergency power supply the battery-run instrumentation and the measurement and control equipment are no longer supplied after that time.

Some RBMK of the first generation do not possess an emergency control station to lead the plant into a safe condition even upon failure of the control room. This is important because larger pressurized tubes are located near the control room and the break of these tubes could endanger the accessibility of the control room.

Fig. 7-9 October 1991: The fire in the turbine hall of Unit 2 caused considerable damages

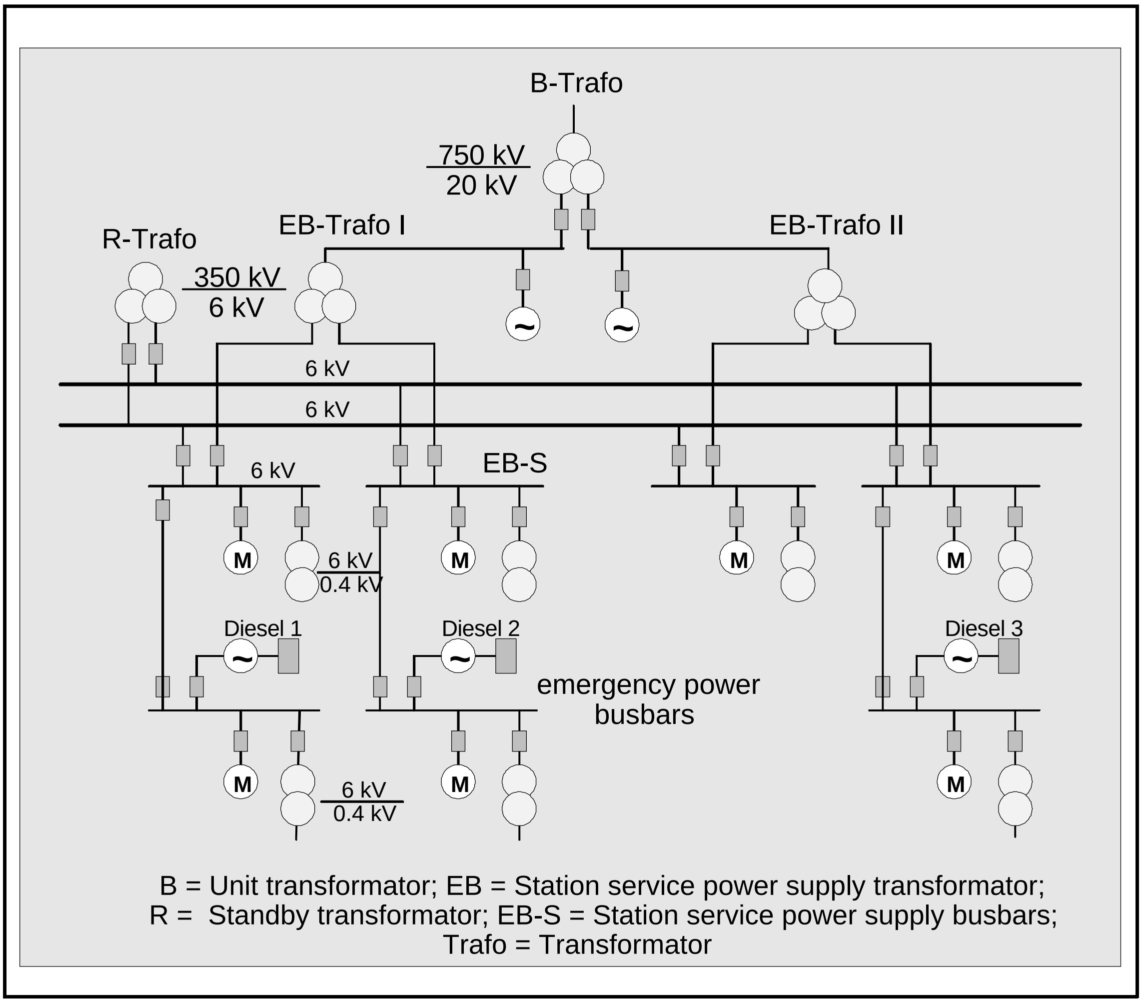


Fig. 7-10 Block diagram of the station service power supply and emergency power supply of the Chernobyl-4 plant

In the meantime improvements have been carried out in the field of instrumentation and control. Thus the safety instrumentation at Leningrad-2, for example, was exchanged completely. But in other plants only selective backfitting measures have been taken.

Eastern and Western experts therefore largely agree that further and comprehensive backfitting measures relating to the instrumentation and the control of RBMK plants are necessary. There is a number of support programmes or these are being planned. But different measures, e.g. for spatial and functional separation are expensive. Such measures at Leningrad-2 could thus only be implemented, when parts of the switch-board building were newly constructed.

7.4.2 Fire Protection

The fire protection of the RBMK corresponds to old Russian standards. It emphasizes fire protection by the plant fire brigade. Modern concepts are above all aimed at fire prevention and spatial and fire protective separation of safety systems, possibly supplemented by automatic extinguishing systems.

In accordance with the great importance of fire protection, numerous backfitting measures have been carried out. These, for example, comprise the use of fire-resistant paints, fire-proof doors, protection doors, fire-resistant cables as well as the introduction of a spatial or fire-protective separation of the safety and auxiliary system, respectively. The present status of fire protection still continues to be regarded as being unsatisfactory.

Further upgradings are necessary. This applies to the 1st generation to a much greater extent than to the second and third generation. A fire protection concept is required which provides for fire prevention, reporting, extinction of fires, the limitation of fire loads

Fig. 7-11 Battery plant of the emergency power supply (example: RBMK-1500 at Ignalina, Lithuania)

as well as the restriction of the effects of fires as prime elements of fire protection before fire fighting by plant fire brigades. In addition thereto, systematic fire hazard analyses, e.g. for cable routings, are to be carried out to identify local or fire protective weaknesses.

7.4.3 External Impacts, in particular Earthquakes

RBMK plants were not designed against air plane crashes or blast waves caused by explosion. In accordance with the Soviet rules and regulations of the 60ies, plants of the first generation and a part of the plants belonging to the second generation were also not designed against earthquakes. The technical rules for the seismic design were only elaborated at the beginning of the 80ies which were then partially applied to more recent plants (Smolensk-3, Ignalina-2).

In the meantime recalculations have been carried out for the older RBMK plants. These recalculations showed that the loads to be assumed for earthquakes can be accommodated with the exception of a small number of important components, e.g. the supports of the drum separators. Backfittings are being discussed.

In this context it must also be taken into account that all RBMK plant locations are situated in seismologically relatively inactive areas of the Russian Plate. Although this also applies to the Chernobyl site and although this is far away from areas with an increased seismic activity, higher seismic load assumptions than those assumed for the remaining RBMK plants are currently being discussed in the Ukraine. It must still be examined in more detail, how reliable the examination referred to in this context are and which actions are required.

Fig. 7-12 View into the reactor hall of an RBMK plant

7.5 Accident Analyses

Computer simulations of accidents represent an important basis of the safety design of nuclear power plants. They serve the purpose of precalculating the plant behaviour for all disturbances and accidents to be assumed and thus provide the basis for dimensioning the engineered safeguards. For RBMK plants such accident analyses could only be carried out to a very limited extent, as

- there were no suitable computation programmes available to the plant designers, and as
- they did not have access to powerful computers.

This deficiency is particularly disadvantageous, as the RBMK has a very complex plant behaviour which can hardly be realistically simulated with simplified models. The multi-dimensional computations which are decisive for reactivity behaviour thus could not be performed prior to the accident at Chernobyl, for example.

After the Chernobyl accident more powerful computer codes were increasingly employed for accident analyses of RBMK, among these also western accident codes developed for conventional light water reactors. But these computation codes required a further qualification of the underlying models for RBMK-specific conditions.

Important improvements of safety and safety assessment are expected of the systematic use of such computation codes for important design issues, like the transient plant behaviour during accidents.

Due to the numerous alterations to the plants, the assumptions and the initial data of the existing accident analyses do no longer correspond to the current status of the plants. This applies to the void reactivity coefficient, for example, as well as to the actuation criterion for reactor scram and to emergency core cooling. A great number of the accident analyses therefore has to be repeated using plant-specific data.

7.6 Operation

The safety of nuclear power plants is considerably determined by operation. The safety concept of Soviet reactors placed great confidence into the correct actions of the staff. Among other things this had an influence on accident control procedures. The comparatively great importance of manual interferences carried out by the operating staff during normal operation and accident control as well as significant room for action granted to the operators are characteristic here. One example for the operator's stress during normal RBMK operation is the stabilization of the spatial power density distribution. (Table 7-3).

Table 7-3 Manual actions of the operator to stabilize spatial power density distribution

Generation of RBMK-Anlagen	Normal operation [actions/h]	Replacment of fuel elements [actions/h]	State of development
First RBMK plants with equilibrum load (Leningrad-1, end of 70ies)	180	500	high positive void effect (α_φ), α_φ = (4-5)β x10^{-2}/Vol% no LAR system
RBMK plants in the period between 1980 - 1986	20	50	void effect still high, α_φ = (4-5)β x10^{-2}/Vol% with LAR system
Smolensk-3 plant, 1993	2	50	current design with reduced void effect $\alpha_\varphi \approx$ 0,3 β x10^{-2}/Vol% LAR system
LAR: Local automatic power control			

7.6.1 Management and Responsibility

In the countries operating RBMK plants there was no strict division of the responsibilities for nuclear safety between builder, operator and the state as well as within the power plants themselves until recently. In addition thereto, the situation was characterized by authority-oriented structures and substantial communication and decision problems. The responsibility for safety issues could locally, where concrete safety functions were to be solved, only be dealt with within the framework of prescribed structures and procedures. A competent, independent licensing and supervisory authority and independent expert organizations doing preliminary work which take care that all important safety issues are paid the necessary attention were also missing.

Today several cooperation projects support the establishment of competent, independent and strong licensing and supervisory authorities. Important legal bases (Atomic Act) for the activities of the authorities have recently been created in Russia and the Ukraine. In Lithuania these are being elaborated at the moment. But the financial means are partially missing to refer to competent expert organizations to the necessary degree.

7.6.2 Operating Rules

The Chernobyl accident demonstrated the significance and the limitations of operating rules. Although the operating staff had to carry a great responsibility for safety and accident control, they were not sufficiently supported by clearly structured directives and a distinct human-machine interface. Until today, operating rules have been partially inconsistent with the technical content of safety reviews and they do not correspond to the current state of plant technology and safety analyses.

7.6.3 Backflow of Experience

Up to the recent past the analysis of operational experiences as well as the processes of passing on and implementing the findings acquired were insufficient. The analyses were carried out by special departments. Important information was partially treated like a classified document and was neither passed on within the own organization nor to other organizations. In many aspects, also owing to West-Eastern cooperation, the conditions have improved in the meantime. But on the other hand, new difficulties have arisen after the dissolution of the Soviet Union.

7.6.4 Documentation

A complete, continuously updated plant documentation in the nuclear power plant is necessary for operation. Even more so, if, like in the case of Chernobyl, there is a considerable fluctuation of personnel connected with a loss of know-how.

In RBMK plants there have been instruments for filing, updating and distributing necessary documents in an orderly manner for a long time. These instruments have, however, been used with a very different commitment. This also shows its effects in an insufficient accessability of the files. In some cases, like in Lithuania, for example, the improvement of plant documentation is currently being worked on with international support.

7.6.5 Maintenance

Maintenance must ensure the function of the safety-relevant facilities required according to the design. It comprises testing, service and repair.

RBMK plants require comparatively extensive maintenance. On the one hand, this is due to the complex structure of the plant, on the other hand important components were not sufficiently reliable and had to be replaced earlier than originally intended.

A series of deficiencies was shown by examinations of maintenance practice carried out in international cooperation. These deficiencies, for example, refer to the determination of the extent and the intervals of inspections, to the technical equipment with testing devices and the quality of the inspections. Because of the difficult economic situation the recruitment of qualified replacement parts has also again and again created problems.

Despite the fact that many components were designed with increased factors of safety, substantial safety losses will have to be expected if these deficiencies in the field of maintenance continue for a longer period.

7.6.6 Training and Instruction

Training programmes run by RBMK plants are practically only aimed at operators. Seminars for the technical staff and for executives in conceptional safety issues, like design basis, accident analysis or backflow from operating experience, for example, hardly exist. The scope and the frequency of the operators' simulator trainings are also insufficient. The reason herefor is the lack or the restricted capacity of RBMK simulators. Not least because of the low degree of automation of RBMK plants and their complex behaviour this deficiency is particularly important.

7.6.7 Summarizing Assessment of Operation

In the sphere of operation there are many opportunities for improving the safety of RBMK plants. Many things developed slowly in the past, as the required means were missing in the difficult economic situation. But in principle it would be possible to achieve a lot within a comparatively short period and with little efforts according to Western standards.

The experience of the last years has shown that international cooperation can be very effective here. The beginnings of a systematic analysis of operation have, for example, been initiated by the project "RBMK Safety Review" financed by the European Union and incorporating RBMK operators and have led to extensive recommendations of different urgencies. These analyses are, however, only performed for few plants.

8 Necessary Measures to Ensure the Function of the Sarcophagus

In 1986 the Sarcophagus was mainly built in a remote-controlled way and under great time pressure. The destroyed reactor unit was enclosed and a furhter release of radioactive substances into the environment was largely prevented. The existing Sarcophagus has fulfilled this essential protective target for ten years now. The release of radioactive substances is very little. But the Sarcophagus does not represent a permanent enclosure, especially as its stability is questionable. This, above all, refers to the accommodation of loads upon external impacts, like wind, snow and earthquake loads, for example. Further safety concerns are directed at a possible release of radioactive dust upon mechanical loads inside the Sarcophagus. Although very unlikely, it cannot completely be excluded that the existing nuclear fuel mass could again reach a critical state by water streaming in. In the longterm, there also is the danger that radioactive substances could escape from the reactor into the groundwater.

The Ukrainian authorities have also raised the problem of the far-reaching consequences upon collapse of the Sarcophagus. An evaluation of this risk shows, however, that such an event would result in great radiation exposures for the power plant staff, but already the next bigger place named Slavutich would hardly be affected. Even if the nuclear fuel became critical, neither large releases nor mechanical effects would have to be anticipated.

Nevertheless, measures for improving the safety of the Sarcophagus cannot be renounced. Ensuring stability of the existing Sarcophagus represents the main priority. In particular those load-bearing structures and their foundations which are possibly predamaged have to be reinforced.

The stability towards earthquakes can thus also be increased. The status of the building structure as well as possible loads and impacts have to be examined and specified in detail to be able to plan and implement safety measures for improving the stability of the Sarcophagus. An improvement of the stability of the Sarcophagus is also required to exclude harmful impacts to the adjacent Unit 3 which is still operating.

An overall concept on the enclosure of the radioactive substances is to be developed to ensure long-term safety at the plant site. This concept has to take all essential safety and environmental aspects into account. To these also belong radiation protection during the construction and reconstruction measures to be carried out, the treatment and final deposal of radioactive wastes as well as the protection of the groundwater.

In 1992 the Ukrainian government issued an international request for tenders to solve this problem. As a result of this request for tender the erection of a new, larger Sarcophagus 2 has been proposed by a group of contractors. This project is technically demanding and starts out from a phase-out of Unit 3. It requires great financial resources, the financing of which is not yet secured. The project of erecting a second Sarcophagus by no means renders the improvement of the stability of the existing Sarcophagus superfluous. On the contrary, this improvement is necessary to be able to build a second Sarcophagus at all. It will have to be examined during the stabilization of the existing Sarcophagus whether the required level of protection could thus already be achieved without having to build a further expensive Sarcophagus. In this connection the possibilities to render the situation inside the Sarcophagus harmless should also be examined. To these measures belong a partial recovery of the nuclear fuel containing masses, improved techniques for binding radioactive dusts and a renewal of the antiquated measuring techniques for monitoring the Sarcophagus, for example. For construction measures and possible interferences in the existing Sarcophagus remote-controlled or automated technical procedures have to be designed and employed.

Effective decontamination measures, temporary shieldings and a comprehensive control of the radiological situation have to constitute integral parts of the concept. To achieve a long-term ecologically satisfactory situation on the site of the accident, sufficient possibilities for treatment, intermediate and final deposal of the radioactive wastes are still to be created.

The destroyed reactor unit will have to remain enclosed and isolated from the biosphere for many decades, perhaps even centuries. Only in international cooperation the Ukraine will succeed in achieving a solution of the problem which is safe in the long-term. It is highly important to bundle the knowledge on Chernobyl-related issues splintered into more and more different organizations in Russia, Belorussia and the Ukraine after the dissolution of the Soviet Union. This requires an intensified technical and scientific cooperation of these countries with each other and with the West to create the reliable data and information base necessary for the development of a good safety concept.

9 Future Radiation Protection Measures

Ten years after the reactor accident the main objective of radiation protection measures today is to be prevent the intake of long-lived radionuclides with food and drinking water. Now as before vast areas are radioactively contaminated, especially by caesium 137 and strontium 90. Parts of the population have returned to prohibited areas and largely live on food which they produced themselves. Experiments to decontaminate contaminated food with special treatment procedures showed little success. It is useful to advise the population with respect to the consumption of woodland fruit to prevent the intake of high amounts of radionuclides with certain products. The food supply for these people, and especially for the children, with vitamin-rich, non-contaminated food would represent a substantial improvement of radiation protection and of the general health situation.

In the countries concerned, the economic situation has further aggravated during the last years, especially for the population evacuated. This may also contribute to the impaired health situation of the population, even if the causes for the health problems cannot be determined individually. Comprehensive and reliable help to improve the food supply and the employment situation is an urgent need.

The medical care provided to the population also requires the support of other nations. Better equipment, medicine and better treatment methods are particulary required. But this alone is not enough, if the population in rural areas is not reached or does not own any financial means. Particularly effective is the commitment of Western surgeons and research centres who do not only work scientifically, but also help locally.

The scientific analysis of radiation protection aspects and of the health consequences continues to represent a central function of the states concerned and of the international expert world. This is necessitated by the long latency periods of many types of radiogenic cancer alone. The continuation of the cancer register and its analysis in epidemiological studies is an essential task. In this connection it is important to harmonize the work carried out in the Ukraine, Russia and Belorussia and to jointly use the national data existing so that consistent results can be derived therefrom. The belated determination of the radiation exposure received, which in return has to be known for epidemiological studies and for the derivation of risk factors, represents a problem.

Studies on the health condition of clearly defined and carefully monitored groups of persons who were employed as liquidators during the accident are also important.

A further emphasis of future scientific analyses relates to researching possibilities that radiation influences diseases or can partially be blamed for diseases which are generally not regarded as radiation-related.

Apart from the permanently prohibited areas belonging to zone 3, the ground contaminationin the settled areas is increased, but it is not considered to represent an significant radiation protection problem. Although these increase dose rates will last for a long time, especially since decontamination measures of soils and wood areas are either little effective or not feasible at all. One important radiation protection measure is reforesting to prevent spreading of the contamination from the radiated soil areas by the wind. Within the 30 km zone there are some spots with high dose rates. These are prohibited and must be recultivated. Radiation monitoring programmes of soils, flora and fauna must be continued. Sediments in surface waters and the groundwater must also be monitored regularly. Preventive measures should be taken against washing out radioactively contaminated sediments during floods.

10 Summary and Conclusions

10.1 Causes of the Accident

The events which led to the accident in Unit 4 of the Chernobyl Nuclear Power Plant on April 26, 1986 have essentially been clarified during the past ten years. Although there are still some gaps of knowledge relating to some details of the accident procedure, the knowledge available in the meantime suffices to identify the causes and to take effective measures to prevent a repetition of such an accident.

In the beginning the Soviet Union emphasized misactions and failures of the personnel as the real cause of the accident. The deficiencies of the technical design of the RBMK reactor type used in Chernobyl were played down, sometimes by misleading information. With the more exact information the West received within the framework of its co-operation with Eastern Europe, the serious technical deficiencies of the RBMK design and the inadequacies of the political and administrative system in the Soviet Union became more evident. This led to a modified view on the individual guilt of the operating staff.

From today's viewpoint the main causes of the accident were:

- severe deficiencies in the reactor core design and in the design of the shutdown facilities,
- a political and administrative system unable to remove these deficiencies, even though they had been known long before the accident,
- an insufficiently reasoned and examined test programme with respect to technical safety,
- operation and operating equipment asking too much of the staff when assuming their responsibility.

10.2 Safety of RBMK Plants

10.2.1 Core Design

Soon after the accident the Soviet Union initiated measures to remove the deficiencies of the reactor physical design and the shutdown system. The upgradings served the purpose of reducing the high positive void effect, removing the positive shutdown effect and speeding up the shutdown process. These backfitting measures were carried out in all plants in a similar way. The worst deficiencies of the nuclear design have thus been removed. A repetition of the former explosion-like accident seems to be hardly possible today.

Examinations of the dependency of the void effect on the operating condition show, however, that it increases considerably upon partial load and small values of the operational reactivity margin (ORM). The observation of the minimum permissible ORM and the minimum permissible reactor power is still only controlled by operating rules. For operating conditions which are of such a vital significance for safety, this does not suffice. Further improvements are necessary here, for example by backfitting an automatic shutdown before inadmissible values are reached.

Relating to core design, it is also known that incidents with an evacuation of the control rod cooling system can lead to a high reactivity admission. Monitoring of the system has been improved in the meantime to a more reliable shutdown of the reactor during such incidents. Technical measures to considerably lower or completely remove the amount of a possible reactivitiy admission are being planned. An early implementation of such backfittings is highly important.

10.2.2 Shutdown Systems

Because of the unfavourable nuclear properties of the reactor core, increased requirements have to be met by the shutdown system of RBMK plants. The relatively slowly acting shutdown system did not fulfil these requirements. After the accident the shutdown systems in all RBMK plants were improved essentially. A considerably faster shutdown system with quickly dropping control rods (approx. 2 s) was introduced.

The shutdown upon certain initiating events is, however, still actuated by one single criterion. Here further backfittings are necessary so that there are essentially two diverse actuation signals for accidents. To ensure the particularly high reliability of the shutdown required, RBMK plants would generally also have to be equipped with a second diverse shutdown system. Such a backfitting is technically viable.

10.2.3 Engineered Safeguards

The engineered safeguards of RBMK plants belonging to the first generation have considerable deficiencies. The emergency feedwater supply system is not redundant in large areas and it is not designed against hazards, such as fire or floods, for example. Other important systems, like instrumentation and control, are also similarly vulnerable to hazards. The plants of the first generation further do not comprise an independent emergency core cooling system. Comprehensive upgradings are urgently necessary here. The respective backfittings are at present only carried out in Leningrad-1 and -2.

The situation of RBMK plants of the 2nd and 3rd generation with respect to system engineering is more favourable on the whole. The plants have an independent emergency core cooling system and the redundancies of the safety system are largely arranged in a spacially separated way. But relating to the emergency feedwater supply system and the service water system, the conditions are similar to the ones of the 1st generation. Here backfittings are urgently required for the 2nd and 3rd generation.

RBMK plants of the 2nd and 3rd generation comprise a partial containment. The first generation does not possess such a facility. Leningrad-1 and -2 are backfitting a partial containment which can be compared to the one of the 2nd and 3rd generation at the moment. This backfitting measure would be advisable for all other old plants.

A great weakness of all RBMK plants is fire protection, the first generation being more strongly concerned than the 2nd and the 3rd generation. In all plants backfitting measures have been carried out to a different degree. But nevertheless, the present status of fire protection is still unsatisfactory. Further upgradings are inevitable.

Fig. 10-1 The Chernobyl Nuclear Power Plant with the cooling water reservoir in the foreground

10.2.4 Reactor Tank

The break of pressure tubes leads to a pressure build-up in the reactor tank. If the carrying capacity of the reactor tank is exceeded, the upper cover plate can raise. This would have disastrous consequences.

The break of a single pressure tube was originally assumed as the design accident for the protection of the reactor tank against pressure. The simultaneous failure of several pressure tubes was not taken into account. But according to Russian analyses the reactor tank is supposed to withstand a simultaneous break of three pressure tubes.

Although no plausible scenarios with multiple failures of pressure tubes are known, all RBMK plants take efforts to improve protection against overpressure. This improvement is necessary considering the possible consequences of a respective accident. The measures are above all aimed at the improvement of material testing of the pressure tubes and the increase of the depressurization capacity of the reactor tank. In

Smolensk-3 and Leningrad-1 and -2 the depressurization capacity was increased to such extent that a simultaneous failure of nine pressure tubes can be controlled. A further improvement is practically impossible.

At present, a simultaneous failure of three to four pressure tubes is controlled in most of the other RBMK plants. Further improvements are intended. Independent thereof, it urgently remains to be clarified whether there are plausible accident sequences with a simultaneous failure of several pressure tubes and how many pressure tubes could fail hereby.

10.2.5 Accident Analyses

Computer simulations of accidents represent the unrenouncable basis for the safety design and for the safety assessment of nuclear power plants. In the past such analyses in the Soviet Union could only be carried out to a very limited extent, as neither suitable computer codes nor powerful computers were available. This was particularly disadvantageous for RBMK plants, as they show a very complex behaviour which can hardly be simulated in a realistic way with simplified models.

After the Chernobyl accident, powerful computer codes for accident analysis of RBMK have been used increasingly. These codes which partly come from the West do require, however, a further qualification of the underlying models for RBMK-specific conditions. Further findings on the safety of these plants as well as concrete opportunities for improvement are expected from their systematic use for the examination of the plant behaviour upon accidents.

10.2.6 Operation

The safety concept of Soviet reactors strongly emphasizes correct and timely actions carried out by the operating staff. This essentially still applies today. Operation in RBMK plants is therefore particularly important for safety. More recent examinations on the operation of RBMK plants showed considerable weaknesses. This in particular applies to the unclear assignment of responsibility, insufficient analysis and implementation of operating experience, deficiencies in maintenance as well as contents and frequency of trainings for the operating staff. Improvements are urgently required here. This is also recognized by the operators.

On the whole, there is a large variety of possibilities for improving the safety of RBMK plants in the field of operation. A lot could be achieved within a comparatively short period of time and with relatively small efforts. The experience of the last years has shown that international cooperation can effect a lot here.

10.3 The Safety of Units 1, 2 and 3 at Chernobyl

Unit 1 as well as Unit 3 directly adjacent to the destroyed unit 4 of the Chernobyl Nuclear Power Plant still operate. Unit 2 has remained shutdown since the fire in the turbine hall in 1991. The operator of the plant has been working on recommissioning for several years now.

In the units of the Chernobyl Nuclear Power Plant similar technical backfittings have been carried out like in most other RBMK plants. But the uncertainty about the further operation and the lack of suitable equipment and financial means have sometimes led to delays. In addition, there were significant problems with personnel due to the emigration of experienced reactor technicians to Russia. Whether and to which extent the safety of unit 3 is impaired by the close neighbourhood to the destroyed unit 4 is to be further examined.

10.4 Further Operation of RBMK Plants

The responsibility for the safety of RBMK plants solely resides with the respective states operating them. Western organizations cooperate with the responsible authorities in these states to support them in fulfilment of their responsibility, but the opportunities of the West to exert an influence are very limited. In addition, the knowledge of Western experts referring to the details of RBMK technology is still very limited.

In their decisions on the further operation of RBMK plants the respective states, apart from safety requirements, also consider their economic and social needs. Merely asking to shutdown the reactors without consideration of this trade-off would be counterproductive for safety.

Despite the significant safety improvements after the Chernobyl accident, there still are important safety deficiencies in RBMK plants. The analyses carried out during the last years even showed new problems. They did, however, also show that greater safety improvements have been made on some locations and that the individual RBMK plants show significant differences. Today they can only adequately be assessed in a plant-specific way.

Experts in East and West agree that at least the essential points of the safety deficiencies still existing today have to be removed by upgrading the design and improving operation. The necessary measures have largely been defined in an international co-operation, but they have only partially been implemented in few plants. Further progress definitely has to be achieved in the time to come. Essential upgradings are technically viable. They do, however, require substantial financial means and effective planning. International cooperation and support are very important here.

10.5 Safety of the Sarcophagus

The sarcophagus hurruiedly built around the destroyed reactor has fulfilled its protective function during the last ten years. In the longterm its retaining power and stability is, however, questionable. Internal or external loads could lead to damages or even a col-

Fig. 10-2 The Sarcophagus

lapse of the sarcophagus and thus to a release of radioactive substances into the closer surrounding. The staff on the site, for example the operating staff of Unit 3 would be endangered. Wide-spread effects are, however, not to be expected. The new town of Slavutich which was build for the operating staff about 50 km east of the site, would practically not be affected.

Upgrading stability of the sarcophagus represents a priority. This measure is also necessary to prevent a possible impairment of the safety of the adjacent Unit 3.

Within the framework of an overall concept which, among other things, means that the destroyed reactor is permanently secured and that the site is reconstructed, realistic targets have to be developed which take into account the radiological conditions on the site and the priorities of the safety and disposal functions. The concept has to be implemented step-by-step. The suggested construction of a second enclosure which is to enclose the existing sarcophagus has to be examined within the framework of such an overall concept.

In this connection it is vitally important to bundle the knowledge splintered more and more into different organizations in Russia, Belorussia and the Ukraine after the dissolution of the Soviet Union. This requires an intensified technological and scientific cooperation of these countries with eachother and with the West to create a reliable data and information base necessary for the development of a prospective overall concept.

10.6 Contamination and Radioactive Wastes on the Site

Type and extent of the contamination on the power plant site are well known by measurements. Although the local dose rate is significantly increased, most areas are accessible. At some points highly radioactive material, like the nuclear fuel ejected out of the accident reactor, was digged in. These provisionary depositories represent an obstacle for construction and reconstruction measures. In addition, radioactive substances get into the groundwater there. At present contamination is still low, on the long-term there is, however, a considerable endangering potential. An orderly disposal of the provisionary depositories is therefore imperative.

In addition, safe and sufficient intermediate storage capacities have to be provided for the spent fuel elements of the units still operating. The stores available are practically exhausted.

10.7 Radiological Situation in the Areas Concerned

About 10 000 km², 7 000 thereof in Belorussia, 2 000 in the Russian Federation and 1 000 in the Ukraine are prohibited because of the high contamination, above all by caesium 137. About 116 000 persons were resettled from these areas. They will remain inaccessible for many further decades. Contamination and radiation rates are quite detailed known by measurements. There is a regionally, even locally, complex picture with very different levels of contamination. Many of the almost 400 000 people who left their homes could return. Today about 273 000 people live in areas with increased contamination which is, however, not directly endangering health. The annual radiation dose is about five times as high as the natural level. As this radiation exposure mainly results from the consumption of contaminated food, the supply of the population concerned with sufficient, uncontaminated food is preeminent. The uncontrolled

Fig. 10-3 Deserted Ukrainian farmhouse

return of the population into highly contaminated areas represents a special problem. Thus, about 2 000 people have returned to the 30 km zone. A few areas subsequently turned out to be highly contaminated. Some further 10 000 people would have to be re-settled from these areas.

Agricultural and forest measures to reduce contamination proved to be hardly effective. Nevertheless, the continuing advise of and care for the population in this field is important to decrease radiological contamination by a target-oriented agriculture.

10.8 Consequences of the Accident for Health

28 people, mainly firemen and members of the operating staff, died of the radiation and burns they suffered while fighting the fires and bringing the catastrophe under control. 134 persons were strongly irradiated, so that they developed symptoms of acute radiation sickness. Two members of the operational staff died of the immediate effects of the explosion.

Only few corroborated informations are available about the health situation of the temporary workers recruited from all parts of the Soviet Union to work in Chernobyl. There are about 800 000 of these so-called liquidators. They partially received considerable radiation doses which presumably frequently ranged above 250 mSv during the first days. It is frequently reported about an increased rate of illnesses of different kinds among these group of persons. The World Health Organization sees one emphasis of its further activities in the closer examination of these aspects.

The increase of thyroid cancer of children in Belorussia and in the areas affected in the Ukraine and the Russian Federation is statistically highly significant. In the period between 1986 and 1994 565 children in these areas contracted thyroid cancer. This means that the case rate has increased by up to 1000 percent. Provisory figures for 1995 do not yet show a decrease of the illness. Thyroid cancer of children can generally be operated with good success, but it does require long-term therapy. Despite operation, some children died in Belorussia.

An increase of the case rate of leukemia due to radiation has so far neither been determined for children nor for adults. For most types of cancer the period until the onset of the disease is very long, however. It therefore continues to be necessary to provide medical care to the population and to carry out long-term analyses of the health situation. A harmonization of the current studies performed in Belorussia, Russia and in the Ukraine within the framework of international programmes is very important in this context.

In addition to these studies the immediate help for the population affected remains important. It will, however, only be effective, if all relevant causes and symptoms of the problem are worked on. The exclusive concentration on measures for reducing radia-tion exposure is insufficient. Improvements of the nutrition on the whole, of the possibilities of medical therapy (e.g. thyroid cancer therapy) as well as programmes improving the social and economic perspectives of the population affected by the accident are most urgent.

10.9 Consequences of the Accident for Reactor Safety in Germany

The concept, construction and management of German plants are totally different from RBMK plants. Moreover, the reactor accident in Chernobyl did not bring along any technical or scientific phenomena which, in principle, had not already been known before.

Considering the disastrous consequences of the accident it was, nevertheless, a requirement of precaution to carefully assess the safety of German nuclear power plants. For this purpose the Reactor Safety Commission advising the BMU carried out a comprehensive review of the safety and operation of all German nuclear power plants. This review showed that there are no consequences for German plants from the technical viewpoint.

Nevertheless, the circumstances which led to the reactor accident in Chernobyl have proven, how important it is to permanently check the nuclear power plants and to further develop safety technology and operation. This had been common practice in Germany long before the accident. The accidents did, however, lead to considerations, how these examinations could be intensified and systemized. The result is that in Germany, like in all other states, all nuclear power plants will be subject to comprehensive safety reviews about every ten years.

Under the impression of the consequences of the accident, efforts already existing at that time were speeded up to take additional preventive measures against extremely unlikely simultaneous failures of several engineered safeguards in German nuclear power plants.

An accident management concept was introduced, which for many of these extreme cases, still permits the prevention of reactor core melting or to limit its effects. The proof that even an accident with core melting does not lead to severe consequences outside the nuclear power plant has become a precondition for licensing new nuclear power plants in Germany.

The accident in Chernobyl reminded people in a drastic way that a big nuclear accident can have considerable consequences across state boundaries and that reactor safety represents last but not least an international function. Since 1991 the Federal Republic of Germany has advocated worldwide, international binding regulations for ensuring

Fig. 10-4 The Chernobyl Nuclear Power Plant from the east. Unit 4 is in the background on the left.

high safety levels of the nuclear power plants. In 1994 a nuclear safety convention was passed which in the meantime has been signed by almost all states operating nuclear power plants. This convention comprises basic requirements to be met by the safety of nuclear power plants as well as regulations on how the individual states document fulfilment of these requirements within their territories. At present the procedures for an effective implementation of these regulations are coordinated internationally.

10.10 Consequences of the Reactor Accident in Chernobyl for Radiation Protection in Germany

During the first days and weeks after the accident people in the Western countries affected were disconcerted about the extent of the contamination with radioactive substances and the radiological consequences. The insufficiently coordinated and partially contradictive measures of the authorities responsible in the individual states considerably contributed to this situation. There was particularly great uncertainty with respect to the determination of contamination limits of food.

In the meantime the early assessments of the consequences of the accident provided by radioecologists and the German Radiation Protection Commission have largely been confirmed. Considering the recommended activity limits, no negative health consequences were to be expected.

The European Union established uniform standard values. An internationally uniform decision basis for emergencies was created with the Basic Safety Standards of the International Atomic Energy Organization and with the Recommendation No. 63 of the International Radiation Protection Commission.

Within the framework of the Radiation Protection Prevention Act better possibilities were created to detect and follow the effects of radioactive substances upon accidents in nuclear plants at an early stage, to determine areas potentially affected, to give warnings and to recommend rules of action or protective measures. The computer-based early detection system IMIS (Integrated Measurement and Information System) was introduced, for example. Its effectiveness has been tested and checked in regular exercises.

11 Glossary

Absorber
Materials absorbing neutrons and thus influencing the chain reaction.
Strong neutron absorbers, like boron, hafnium and cadmium are used in control rods of reactors. Some fission products also have a particularly high absorption effect, e.g. xenon 135. They are called neutron poisons.

Accident localisation system
The accident localisation system of RBMK of the 2nd and 3rd generation consists of pressure tight compartments which enclose the lower part of the reactor cooling system with the largest coolant tubes (e.g. suction-side and pressure side collectors of the main coolant pumps and group distribution headers). The design pressures of the individual compartments differ. They are connected with the water seal in the pool-type pressure-suppression system via downcomers.

Accumulator
In RBMK plants the accumulators are part of the short-term emergency core cooling system. They are filled with water which is kept at a pressure of 9.5 Mega-Pascal (MPa) by a nitrogen blanket. The accumulators have the function of bridging the first period after the break of a larger coolant line until the injection pumps of the long-term emergency core cooling system are availabe after run-up of the emergency power diesel.

Activity
It indicates the number of atomic cores decaying in a radioactive substance per second. The measuring unit is becquerel. The former measuring unit was "curie" (Ci). One Ci = 37 billion becquerel. But the effect of radiation connected therewith cannot be derived from activity. Type of radiation, radiation energy, biological circumstances, etc. have to be taken into account herefor.

Actuation criterion
The total of all measured physical variables actuating reactor protective actions.

Actuation signal	Measured values of physical variables actuate actions for reactor protection after the signal has been processed.
Barrier	Device in nuclear plants enclosing radioactive substances and, moreover, possibly shielding off radiation. Normally there are several barriers behind each other.
Becquerel (Bq)	Variable for measuring activity. There is an activity of 1 becquerel when 1 atomic core decays per second in a certain amount of a radionuclide.
Biosphere	All parts of the earth settled by living creatures.
Burnup	The burnup of nuclear fuel is a measure for the energy gained by nuclear fission. It is measured in megawatt days per kilogram fuel (MWd/kg). The amount of the burnup also determines the amount of fission products (e.g. caesium and iodine) and of activiation products, i.e. isotopes generated by neutron capture (e.g. plutonium and other actinides). In RBMK plants burnups of 10 to 20 MWd/kg, in pressurized and boiling water reactors 30 to 50 MWd/kg are common. When these burnup values are reached, the share of fissionable uranium 235 has reduced to such extent that the fuel elements have to be exchanged by new ones.
Chain reaction	Reaction which continues by itself. In a fission chain reaction a fissionable core absorbs a neutron, fissions its and thus releases several neutrons (in case of uranium 2.5 on average). These neutrons again can be absorbed by other fissionable cores, initiate fissions and release further neutrons.
Contamination	Pollution caused by radioactive substances.
Coolant	Every substance which serves the removal of heat from a nuclear reactor. Common coolants are water, carbon dioxide, helium and fluid sodium.
Criticality	State of a nuclear reactor in which a self-sustaining chain reaction is taking place. A reactor is critical when the number

of fissions remains constant. This is the normal operating state. For startup the reactor is rendered slightly overcritical, upon shutdown subcritical, accordingly (the chain reaction ceases).

Decontamination Removal or reduction of a radioactive contamination with the help of chemical or physical procedures (e.g. washing or cleaning with chemicals). The decontamination of substance flows, like air or water, is carried out with the help of filters or by evaporation and precipitation, respectively.

Design accident The design of a nuclear power plant is based on a broad range of accidents. These so-called design accidents must be controlled by the engineered safeguards so that the effects in the environment remain below the predetermined limits of the Radiological Protection Ordinance.

Dose The dose is the measure of a radiation effect

- **Equivalent dose**
  Product of the energy dose and the assessment factor. The unit is Sievert (Sv) 1 Sv = 1 J/kg.

- **Effective dose**
  The effective dose, or more precisely effective equivalent dose represents the sum of the average organ doses multiplied by weighing factors. The effective dose is the unit for assessing the radiation-dependent risk for late genetic and somatic effects.

- **Energy dose**
  Quotient of the energy which is transferred to the material in one volume element by ionizing radiation and the mass in this volume element. The unit is Gray (Gy) 1 Gy = J/kg

- **Individual dose**
  Whole or partial body dose accumulated by a person.

- **Sievert (Sv)/Millisievert (mSv)**
  Measuring unit for the radiation dose; millisievert replaced the former unit millirem (mrem).
  Conversion: 1 Sv = 100 rem; 1 mSv = 100 mrem. The millisievert considers the radiation of the organism by different types of radiation. Thus all types of ionizing radiation, e.g. cosmic radiation, X-rays and the radiation of a radioactive substance can be assessed with respect to their biological effects (artificial and natural radiation can also be compared).

Downcomer lines The downcomer lines in the RBMK connect the steam separators with the suction-side collectors of the main coolant pumps.

Energy dose see Dose

Enrichment Process by which the share of the fissionable isotope, e.g. uranium 235, in the nuclear fuel is increased.

Excess reactivity Reactivity of the reactor core which is needed to compensate the burnup between fuel element replacement periods.

Equilibrium core Core load which adjusts itself by a continuous replacement of burnt-up fuel elements by fresh fuel elements and thus practically remains unchanged.

Equivalent dose see dose

Fission products Nuclides which are generated directly by fission or the subsequent radioactive decay by fission; e.g. krypton 85, strontium 90, caesium 137.

Group distribution header The group distribution headers in the RBMK are connected with the pressure-side collectors of the main coolant pumps via tubes. There are 22 group distributors in each half of the reactor cooling system. 40 to 44 lines which lead to the individual pressure tubes of the reactor branch off every group distribution header.

Individual dose see Dose

Isotope Atoms differ by the different number of neutrons and protons in the atomic core. If atomic cores have the same number of protons, they belong to one certain element. If an atomic core has the same number of protons, but a different number of neutrons, one speaks of different isotopes of the elements concerned. Example: All uranium atoms have 92 protons in the atomic core. There are, however, several uranium-isotopes depending on how many neutrons the core contains. For uranium 238 there are 146 neutrons: 238 = number of the protons (92) + number of the neutrons (146).

Lava Here: mixture of molten fuel element particles and structural parts

Main feedwater system The main feedwater system essentially consists of tubes, collectors, valves and the main feedwater pumps. The main feedwater system is an operational system. During full load four of five main feedwater pumps operate and one is in standby position.

Main steam system System of tubes, collectors and valves connecting the nuclear steam generation system with the turbine.

Megawatt (MW) One million times the measured variable Watt (W). 1MW = 1000 kW = 1000 000 W. Measured variable for the (electrical) power of power plants. 1 MW corresponds to 1 359 Ps.

Millisievert (mSv) see Dose

Neutrons, delayed Neutrons are released upon nuclear fission. More than 99 % are created immediately (promptly). A share of 0.5 to 0.7 % is released in a delayed way. The share of the neutrons released in a delayed way is referred to by beta (ß). The delayed neutrons play a very important role for controlling the chain reaction in the reactor core.

Nuclear fission Fission of the atomic core mainly into two fragments (fission products) and 2 - 3 fast neutrons. Large amounts of energy are released here. The nuclear fission is initiated by a slow neutron which is slowed down by a moderator. Example: Uranium 235 + neutron = barium 144 + krypton 90 + 2 fast neutrons + approx. 200 MeV.

Outside core and inside core detector Outside and inside core detectors are radiation detectors measuring induced radioactivity created as a consequence of radiation in a radiation field to determine particle flow density or particle fluency.

ORM value An important rating of the reactivity behaviour of RBMK plants is the ORM (operational reactivity margin). The ORM is a reactivity equivalent for all control rods entirely or partially inserted. It is calculated as the multiple of the reactivity contributed by an average, fully inserted control rod.

Plutonium Radioactive element which is generated from the non-fissionable uranium 238 by absorption of a neutron released by nuclear fission. A "Fast Breeder" uses this process in a target-oriented way to produce new fuel. In reactors plutonium can be used as fuel.

Pool-type pressure suppression system The pool-type pressure suppression system in RBMK of the 2nd and 3rd generation is connected with the pressure-tight compartments where the lower tubes and the components of the reactor cooling system are located. It serves the limitation of pressure in these compartments after the break of a coolant line by condensation of the steam/water mixture streaming out in a water seal.

Power excursion A power excursion is a quick increase of the reactor power beyond the normal operational level which can lead to core damages.

Radiation exposure Effect of ionizing radiation on the human body. Total body exposure is the effect of ionizing radiation on the whole body, partial body exposure is the effect of ionizing radiation on individual parts of the body or organs. External radiation exposure is the radiation exposure outside the body, internal

	radiation exposure is the radiation exposure by radiation sources inside the body.
Radioactivity	Properties of many atomic cores which convert by themselves: The decay of atomic cores with an emission of radiation of the different types (alpha, beta and gamma radiation) as a process existing in nature as well as by artificial processes (e.g. nuclear fission). The gamma radiation which is used for X-rays has the highest power of penetration.
Reactivity	Measure referring to the deviation of a reactor from the critical state. It is described by the numerical value and results from the effective multiplication factor $k_{eff:= keff}$ -1/k_{eff} $_{keff}$ here describes the neutron balance, i.e. the relation of two consecutive neutron generations (current and previous). If k_{eff} = 1, the reactor - taking into account the prompt and the delayed neutrons - is critical. If k_{eff} is ; 1, the number of neutrons increases with every "fission generation" and the heat generated in the reactor increases. Upon negative reactivity the power level decreases.
Reactivity effect	The change of reactivity upon alteration of the operating condition.
Reactor core	The "heart" of the reactor. Here the chain reaction takes place. The core essentially consists of fuel elements, control rods, circumflowing coolant and the moderator. The reactor core is located inside the reactor vessel.
Reactor period	The time T in which the neutron flux density in a reactor changeds by the factor e = 2.718 (e: basis of the natural logarithms), when the neutron flux density in- or decreases exponentially.
Reactor protection system	A safety system containing information of different measuring devices monitoring safety-relevant operational variables of a nuclear reactor and which is able to activate one or several safety functions automatically to keep the reactor in a safe condition or to shut it down.

Reactor shaft In the RBMK reactor building the reactor shaft contains the entire core arrangement including the biological shield.

Reactor shutdown The reactor shutdown is the process by which a reactor is transferred into the subcritical state.

Release Escape of radioactive substances from an area limited by one or more barriers (for example from a nuclear power plant or a waste package)

Residual heat Heat generated by the decay of radioactive fission products in a nuclear reactor after shutdown of the reactor. In the first seconds after the shutdown the residual heat still is about 5 % of the power before the shutdown.

Sievert see Dose

Spent-fuel pool A tank filled with water, where burnt-up fuel elements are stored until their activity and heat development has reduced to the desired value.

Steam separators Cylindrical containers in RBMK plants approx. 30 m long, with a diameter of 2.5 to 3 m, in which steam and water are separated. About 1600 water/steam lines which are connected with the pressure tubes in the reactor lead into a steam separator. In addition, the steam lines branch off from it which lead the main steam via collectors to the turbine as well as the so-called downcomer lines which lead the water separated from the steam and mixed with the feedwater to the suction-side collectors of the main coolant pumps. In the steam separators there are feedwater collectors which mix the feedwater injected with the water separated from the steam.

Transients Each essential deviation of the operational parameters of a nuclear power plant (power, pressure, temperature, coolant flow rate, etc.) from the set values which can lead to an imbalance between heat generation and heat removal in the reactor, unless this deviation is caused by leaks in tubes or containers.

Subcriticality	Reactor state where less neutrons are produced than needed, i.e. the power decreases to zero.
Void coefficient	The power change of a reactor is dependent on different parameters, the so-called reactivity coefficients. One of these parameters is the void coefficient describing the reactivity change and thus the power change dependent on the void content in the reactor core. A negative void coefficient effects that a negative retroaction occurs upon power increase by the increasing void content and the power increase is limited. In the German licensing procedure it must be demonstrated that the void coefficient is always negative. In Soviet RBMK plants this void coefficient is positive.

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Appendix Chronological Sequence of Events leading to the Reactor Accident at the Chernobyl Nuclear Power Plant on April 26, 1986

Chronological Sequence of Events leading to the Reactor Accident at the Chernobyl Nuclear Power Plant on April 26, 1986		
Time	**Operational Mode, Operational Condition**	**Comment**
April 25, 1986		
01:06	100 % power; start of shutdown ORM - 31 control rods	Shutdown for the planned revision and performance of test
03:45	Start to replace nitrogen-helium mixtures in the cooling system of the graphite by nitrogen	This generally leads to a reduction of the absorption in the gas mixture by 1 - 1.5 ß and to a reduction of the stability of the axial power density distribution.
03:47	The thermal reactor power is 1 600 MW (50% of nominal power)	
04:13 to 12:36	Measurements of parameters of the control system and the vibration properties of the turbo generators No. 7 and 8 upon constant thermal power of 1 500 MW	
07:10	The ORM is 13.2 control rods	Consequence of instationary xenon poisoning. Continued operation represents a violation of the limits and conditions of safe operation. (The operational limit for ORM according to these conditions was 26 - 30 control rods. An operation with ORM values below 26 control rods required the permission of the chief engineer of the power plant. If the ORM dropped below 15 control rods, shutdown was to be initiated immediately.)
13:05	50 % power; interruption of shutdown; shutdown of a turbo generator (No. 7). Switch-over of the respective consumers to the remaining turbo generator No. 8	After the switch-over there was the following energy supply of the main coolant pumps (MCP): • 4 running MCP of turbo generator No. 8 • 2 running MCP of the network • 2 standby pumps for which a supply from the network was intended upon later connection

Chronological Sequence of Events leading to the Reactor Accident at the Chernobyl Nuclear Power Plant on April 26, 1986 (continued)		
Time	**Operational Mode, Operational Condition**	**Comment**
14:00	Clearing of the emergency core cooling system. Delay of the further shutdown upon request of the load distributor in Kiev. Further operation of the plant with 50 % power.	This measure is carried out in accordance with the test programme. The test programme in this point violates the operating rules. For the further operation of the plant the emergency core cooling system was not rendered ready again.
15:20	The ORM is 16.8 control rods.	Violation against the conditions of safe operation, if not explicitly permitted by the chief engineer.
18:50	Station service power consumers which were not incorporated into the test, were connected with transformer of turbo generator No. 6.	
23:10	50 % Power; power reduction continued, set value 700 - 1000 MW thermally, equivalent to 20 - 30 % accord. to test programme.	
April 26, 1986		
00:05	The thermal reactor power is 720 MW.	
00:28	The thermal reactor power is 720 MW. Switch-over from local power control to medium power control. Drop of the reactor power below the set value to 30 MW thermally (approx. 1 %). Rise of the reactor power by manual withdrawal of the control rods in the time following.	The reason for this lower deviation from the set value is unknown. Switch-over in accordance with a recommendation of the operating rules. The strong decrease was caused by a mistake of the operator upon switch-over of control and belated manual countercontrol. Re-startup violates limits and conditions of safe operation, as ORM had been too low prior to the shutdown. (Immediately prior to shutdown reactor power was approx. 15 % and latest ORM recorded was 26 control rods. Accord. to limits and conditions of safe operation a re-startup after a brief shutdown of a power of below 50 % is only permissible if ORM prior to shutdown at least 30.

Chronological Sequence of Events leading to the Reactor Accident at the Chernobyl Nuclear Power Plant on April 26, 1986 (continued)		
Time	**Operational Mode, Operational Condition**	**Comment**
00:28 (ff.)		Reactor power which had been kept for a sufficient time before the shutdown, was 50 %. Starting out from this power level as the criterion for minimum value of ORM, number of control rods must at least be 45.
00:34:03	Unexpected fluctuation of the level in the drum separators.	
00:36:24	Change of actuation value for reactor protection with respect to pressure drop in drum separators from 55 to 50 kg/cm^2.	
00:39:32 to 00:42:35	DREG.programme out of operation. Blocking of reactor protection with respect to failure of 2nd. turbo generator.	 Blocking of reactor protection represents a violation of limits and conditions of safe operation.
00:41 to 01:16	Separation of the 8th turbo generator from the network to measure the vibration properties without load.	Not part of the test programme.
00:52:35 to 00:59:54	The DREG programme is out of operation.	
01:03	Stabilization of the thermal load upon 200 MW (approx. 7 %).	A further increase of reactor power was practically impossible because of xenon poisoning, esp. as there was a lower deviatation from minimum permissible excess reactivity.
01:03 and 01:07	Connection of the two standby pumps in the two main core cooling systems.	Connection of standby pumps corresponds to test programm. After connection of standby pumps 8 MCP in operation.
01:06	Increase of feedwater injection and drum separators to 1 200-1 600 t/h.	Water level in the drum separators should be increased again with this measure.
01:09	Sudden decrease of feedwater flow rate to 90 t/h in right and to 180 t/h in left core cooling system. Core flow rate is 56000 to 58 000 m^3/h. As a consequence the temperatures on the suction side of the MCP increase to 280.8°C (left side) and 283.2°C (right side).	There was a sudden decrease of feedwater flow rate to approx. 75 t/h in the right core cooling system and to 130 t/h in the left core cooling system at 01:22:45. During phase-out of MCP feedwater flow rate fluctuate around 150 t/h in right loop and 110 t/h in left loop.
01:12:10 to 01:12:49	DREG Programme out of operation.	

Chronological Sequence of Events leading to the Reactor Accident at the Chernobyl Nuclear Power Plant on April 26, 1986 (continued)		
Time	**Operational Mode, Operational Condition**	**Comment**
01:18:52	DBA signal is DREG Programme. (A special DBA switch was installed for this test actuating start of diesel generators and phase-out of turbo generator. This switch was turned when turbine tripping valves closed).	Different times indicated for DBA signal.
01:22:30	The parameters were recorded on tape. Later computations showed that ORM at that time had been 6-8 control rods.	Violation of limits and conditions of safe operation. It is unclear whether lower deviation of permissible ORM (being a consequence of prohibited re-startup) had been known to staff.
01:23:04	Instruction: "turn on oscillograph". Turbine tripping valves of turbine No. 8 closed. Phase out of turbine with 4 MCP (MCP 13, 23, 14, 24) started.	Reactivity admission as a consequence of the decrease of coolant flow rate and pressure, increase of coolant inlet temperature and power increase thus started.
01:23:10	DBA switch pressed.	Different times indicated for DBA signal.
01:23:10 to 01:24:40	Automatic control rod groups AR-1 to AR-3 (total of 12 control rods without displacement part) are completely inserted.	Automatic control tries to oppose an power increase.
01:23:40	Reactor protection AZ-5 was actuated. The shutdown rods and the manual control rods dropped into core.	AZ-5 actuation manually or automatically? Additional power increase owing to positive shutdown effect initiated.
01:23:43	Actuation of reactor protection owing to signals: • reactor period < 20s • high reactor power. Thermal reactor power exceeded 530 MW.	Consequence of power increase.
01:23:46	Separation of first pair of phasing-out MCP from power supply.	Reason for further coolant rate and pressure reduction.
01:23:46,5	Separation of 2nd pair of phasing-out MCP from power supply.	Reason for further coolant rate and pressure reduction.
01:23:47	Strong flow rate heatup (by 40 %) of the MCP not phasing out. Inadmitted flow rate measurement of phasing out MCP. Sudden increase of drum separator pressure and level. The signals "defective measuring unit" are displayed for boths automatic power controllers in ground area (No. 1 and 2).	A power increase is connected with an increase of hydraulic resistance of pressure tubes.

Chronological Sequence of Events leading to the Reactor Accident at the Chernobyl Nuclear Power Plant on April 26, 1986 (continued)		
Time	**Operational Mode, Operational Condition**	**Comment**
01:23:48	Re-establishment of flow rate of MCP not phasing out. Re-establishment of flow rate of the MCP of left side participating in phase-out, 15 % below the initial flow rate. Re-establishment of flow rate of phasing-out MCP 24, 10 % below initial flow rate. Unreliable measurements at phasing-out MCP 23. Further pressure and level increase in drum separators (left side: 75.2 kg/cm^2, right side: 88.2 kg/cm^2). Opening of valves of fast-acting reducing station in the condensers.	The different pressures in drum separators of right and left side correspond to differences in coolant flow rates during phase-out of MCP. (01:23:22: left side 27 900 m^3/h; right side: 27 000 m^3/h) and of feedwater flow rates immediately prior to phasing out of MCP (01:23:00 left side: 130 t/h; right side: 75 t/h).
01:23:49	Occurence of accident signal "pressure increase in reactor vessel" "No voltage = 48 V" (no power supply of the control rod drives); failure of the two automatic power controllers in the ground area (No. 1 and 2).	Break of pressure tubes.
01:24:00	Strong impacts, the shutdown rods stop before reaching their final position. Power supply for sleeves and control rod drives fails.	Destruction of the reactor.
gegen 05:00	Fires extinguished	
April 27, 1986		
01:13	Shutdown of Unit 1	Units 1 and 2 are only shut down one day after the accident.
02:13	Shutdown of Unit 2	
from 27/04/86 to 10.5.86	Covering of reactor with different materials (approx. 2 400 tons of lead, approx. 2 600 tons of boron, dolomite, sand and clay)	Fission product release and direct radiation out of destroyed reactor should be limited and fire of graphite in core area which had occured in meantime should be extinguished.
from 04/05/86	Injection of nitrogen into core area.	Cooling of reactor core.
from 06/05/86 onwards	Termination of fission product release from destroyed reactor.	Strong decrease in fission product release presumably due to covering core area and reduction of core temperature by nitrogen cooling.

Photos

"Tschernobyl-Reportage", Planeta Verlag: Photos of pages 25, 84, 89 and 91

Photostudio Jürgens Photo, Berlin: Photos of pages 62, 80, 85, 87, 123, 135, 138 and 143