USSR STATE COMMITTEE ON THE UTILIZATION OF ATOMIC ENERGY

THE ACCIDENT AT THE CHERNOBYL' NUCLEAR POWER PLANT

AND ITS CONSEQUENCES

Information compiled for the IAEA Experts' Meeting,

25-29 August 1986, Vienna

PART I. GENERAL MATERIAL

DRAFT

August 1986

This material is taken from the conclusions of the Government Commission on the causes of the accident at the fourth unit of the Chernobyl' nuclear power plant and was prepared by a team of experts appointed by the USSR State Committee on the Utilization of Atomic Energy. The members of this team were:

Abagyan A.A.   Mysenkov A.I.
Asmolov V.G.   Pavlovskij O.A.
Gus'kova A.K.   Petrov V.N.
Demin V.F.   Pikalov V.K.
Il'in L.A.   Protsenko A.N.
Izraehl' Yu.A.   Ryazantsev E.P.
Kalugin A.K.   Sivintsev Yu.V.
Konviz V.S.   Sukhoruchkin V.K.
Kuz'min I.I.   Tokarenko V.F.
Kunzevich A.D.   Khrulev A.A.
Legasov V.A.   Shakh O.Ya.
Malkin S.D.

During preparation of this document, material was used from the following organizations: the I.V. Kurchatov Institute of Atomic Energy, the Scientific Research and Design Institute for Power Technology, the V.G. Khlopin Radium Institute, the S.Ya. Zhuk 'Hydroproject' Institute, the All-Union Scientific Research Institute for Nuclear Power Plants, the Institute of Biophysics, the Institute of Applied Geophysics, the USSR State Committee on the Utilization of Atomic Energy, the USSR State Committee on Hydrometerology and Environmental Protection, the Ministry of Health, the USSR State Nuclear Power Supervisory Board, the Ministry of Defence, the Main Fire Protection Directorate of the Ministry of Internal Affairs and the USSR Academy of Sciences.

INTRODUCTION

On 26 April 1986 at 1.23 a.m. an accident occurred at the fourth unit of the Chernobyl' Nuclear Power Plant which resulted in the destruction of the reactor core and part of the building in which it was housed.

The accident took place prior to shut-down of the unit for planned maintenance during operating mode tests on one of the turbogenerators. There was a sudden power surge on the reactor leading to the destruction of the reactor and the release into the atmosphere of part of the radioactive products which had accumulated in the core.

During the accident the nuclear reaction in the fourth unit was stopped. The fire which occurred was extinguished and work was begun to limit and eliminate the consequences of the accident.

The population from the areas in the immediate vicinity of the nuclear power plant and from a 30 km-radius zone around the plant was evacuated.

In view of the extraordinary nature of the Chernobyl' accident, an operational team headed by the President of the USSR Council of Ministers, N.I. Ryzhkov, was organized in the Politburo of the CPSU Central Committee to co-ordinate the activities carried out by the ministries and other state departments to eliminate the consequences of the accident and to assist the population. A government commission was set up to study the causes of the accident and to implement the requisite emergency and rehabilitation measures. The necessary scientific, technical and economic resources of the Soviet Union were mobilized.

Representatives of the IAEA were invited to the USSR and given the opportunity to familiarize themselves with the state of affairs at the Chernobyl' power plant and the measures taken to control the accident. They informed the world community of their evaluation.

Governments of a number of countries and many governmental, public and private organizations and individuals from different countries made offers of assistance to various Soviet organizations to help eliminate the consequences of the accident. Some of these offers were accepted.

During the thirty years of its development, nuclear power has occupied an important place in world energy-production and on the whole has demonstrated a very good record of safety for mankind and the environment. It is impossible to envisage the future of the world economy without nuclear power. However, its further development must be accompanied by still greater scientific and technical efforts to guarantee operational reliability and safety.

The Chernobyl' accident resulted from a combination of several unlikely events. The Soviet Union is drawing the appropriate conclusions from the accident.

Abandonment of nuclear energy sources would require a significant increase in the extraction and consumption of organic fuels. This would undoubtedly increase the risk of disease for mankind, and increase the destruction of waters and forests as a result of the constant release of harmful chemical substances into the biosphere.

In addition to its advantages as a source of energy and as a means of conserving natural resources, the world-wide development of nuclear power also has inherent dangers of an international character. These include transboundary transfers of radioactivity, particularly in the event of serious radiation accidents, and the proliferaton of nuclear weapons, the danger of international terrorism and the specific danger represented by nuclear facilities in the event of war. All this emphasizes the crucial need for close international co-operation in the development of nuclear power and in ensuring its safety.

That is the reality of the situation.

The fact that the contemporary world is full of potentially dangerous industrial production processes significantly aggravating the consequences of military actions gives a new perspective to the senselessness and inadmissibility of war in today's world.

In his speech on Soviet television on 14 May, M.S. Gorbachev said: "For us the indisputable lesson of Chernobyl' is that, with the further development of the scientific and technical revolution, questions of the reliability and safety of technology, questions of discipline, order and organization acquire paramount importance. The strictest possible requirements will have to be applied everywhere and to everything.

"Furthermore we consider that co-operation within the International Atomic Energy Agency should be further enhanced."

1. DESCRIPTION OF THE CHERNOBYL' NUCLEAR POWER STATION WITH RBMK-1000
   REACTORS

1.1. Design data

The design power output of the Chernobyl' nuclear power plant is 6 GW;
as of 1 January 1986 the power of the four operating units of the station was
4 GW. The third and fourth units belong to the second construction stage of
the Chernobyl' nuclear power plant and to the second generation of plants of
that type.

1.2. Description of the reactor in the fourth unit of the Chernobyl' nuclear
     power plant

The chief design features of RBMK reactors are the following:

(1) Vertical channels containing the fuel and coolant, enabling local
    refuelling while the reactor is in operation;

(2) Fuel in the form of bundles of cylindrical fuel elements made of
    uranium dioxide in zirconium tube-type cladding;

(3) A graphite moderator between the channels;

(4) A boiling light-water coolant in the multiple forced circulation
    circuit (MFCC), with direct steam feed to the turbine.

These design features, as a group, determine all the main
characteristics of the reactor and the nuclear power plant both as regards its
merits, which include: the absence of cumbersome pressure vessels which are
difficult to manufacture and limit the reactor's unit power and production
base; absence of a complex and costly steam generator; the possibility of
continuous refuelling and a good neutron balance; a flexible fuel cycle easily
adapted to the fluctuations of the fuel market; the possibility of nuclear
steam superheating; high thermal reliability and durability of the reactor
through channel-by-channel control of coolant flow, channel failure detection,
monitoring of the parameters and coolant activity in each channel and on-load
replacement of leaking assemblies; and as regards its shortcomings: the
possibility that there may be a positive void coefficient of reactivity due to
the presence of a phase transition in the coolant, which governs the behaviour
of the neutron-flux-determined power during accidents; high sensitivity of the
neutron field to reactivity perturbations of different kinds, requiring a
complicated control system to stabilize the power density distribution in the
core; complex branching of the coolant delivery and removal system for each
channel; a large amount of heat energy accumulating in the metal structures,
fuel elements and graphite structure; and slightly radioactive steam in the
turbine.

The RBMK-1000 reactor with a power output of 3200 MW(th) (Fig. 1) is
equipped with two identical cooling loops; to each loop are joined
840 parallel vertical channels containing the fuel assemblies.

The cooling loop has four parallel main circulation pumps (three of which are operational and feed 7000 t/h of water at a pressure of ~ 1.5 MPa, while one is redundant).

The water in the channels is heated to boiling point and partially evaporates. The steam-water mixture with a mean mass steam quality of 14% is led off through the top of the channel and steam-water communication line to two horizontal gravity-type separators. The dry steam (less than 0.1% moisture content) separated in them is fed at a pressure of 7 MPa from each separator via two steam pipes to two turbines with an output of 500 MW(e) each, (all eight steam pipes of the four separators are joined in a common "ring"), while the water, after mixing with the steam condensate, is fed through 12 downcomers to the section header of the main circulation pumps.

The condensate from the spent steam in the turbines is recycled through the separators by feed pumps to the top of the downcomers, thereby subcooling the water to saturation temperature at the main circulation pump inlet.

As a whole, the reactor consists of a set of vertical fuel and coolant channels inserted into cylindrical openings in the graphite columns, and in the top and bottom shielding plates. A light cylindrical cowling encloses the space occupied by the graphite structure.

This structure consists of graphite blocks assembled in the form of columns, with a square cross-section and cylindrical axial openings. It rests on a bottom plate, which transmits the weight of the reactor to a concrete vault.

About 5% of the reactor power is released in the graphite through the slowing-down of neutrons and absorption of gamma quanta. To reduce thermal resistance and prevent oxidation of the graphite, the cavity in the stack is filled with a slowly circulating mixture of helium and nitrogen, which serves at the same time to monitor the integrity of the channels on the basis of variations in moisture content and temperature of the gas.

Below the bottom plate and above the top plate there are spaces for laying the coolant pipes along the routes from the drum separators and distributing headers to each channel.

The robot, i.e. the refuelling machine, after removal of the relevant section of floor and lining up with the channel co-ordinates, couples onto the head of the channel, equalizes its own pressure and the channel pressure, unseals the channel, removes the burnt-up fuel assembly and replaces it with a fresh one, reseals the channel, uncouples and transports the spent assembly to the cooling pond. For as long as the refuelling machine is joined to the fuel channel cavity, a small flow of clean water is fed from it, through the thermohydraulic sealing, into the fuel channel, thereby creating a "barrier" to the penetration of hot radioactive water into the refuelling machine from the channel.

The control and protection system (CPS) of the reactor is based on the movement of 211 solid absorber rods in specially separated channels cooled by water from an autonomous circuit. The system ensures: automatic maintenance of a set power level; rapid reduction in power by the automatic control rods and radial controllers on the basis of signals indicating main equipment failure; emergency stoppage of the chain reaction by the scram rods on the basis of signals indicating dangerous deviations of the unit parameters or equipment failure; compensation for reactivity fluctuations when the reactor is heated up and brought up to power; and control of the power density distribution through the core.

RBMK reactors are fitted with a large number of independent regulators, which are inserted into the core at a rate of 0.4 m/s when the emergency protection system is triggered. The comparatively slow motion of the regulators is offset by their large number.

The CPS includes sub-systems for local automatic control and local emergency protection working on the basis of signals from in-core ionization chambers. The local automatic control system automatically stabilizes the principal harmonics of the radial-azimuthal power density distribution, while the local emergency protection system ensures that the reactor is protected in an emergency against the subassemblies exceeding the set power in different regions of the core. To regulate the vertical fields there are shortened absorber rods, inserted into the core from below (24 rods).

Apart from the CPS, the RBMK-1000 reactor has the following main monitoring and control systems:

(1) System for physical monitoring of the radial power density field (more than 100 channels) and the vertical power density field (12 channels), using direct-charge sensors;

(2) System for monitoring startup (reactivity meters, removable startup ionization chambers);

(3) System for monitoring water flow through each channel by means of ball-type flowmeters;

(4) System for fuel failure detection from the short-lived activity of volatile fission products in the steam-water communication lines at the outlet from each channel; the activity is detected successively in each channel over the corresponding optimal energy ranges ("windows") by means of a photomultiplier moved by a special carriage from one steam-water pipe to another;

(5) System for monitoring channel tube integrity from the moisture content and temperature of the gas flushing the channels.

All the data are fed to computers. The information is issued to the operators in the form of deviation signals, readings (when called for) and recorder data.

RBMK-1000 units are used predominantly for base-load operation (at constant power).

In view of the high power of the unit, the reactor is shut down automatically only when the readings for power, pressure and water level in the separator go outside permissible limits; when there is a total loss of current; when two turbogenerators or two main circulation pumps cut out at once; when there is a drop of more than a factor of two in the feedwater flow; or when a rupture occurs over the whole cross-section of the 900 mm diam. main circulation pump pressure header. In other cases where the equipment fails, provision is made only for an automatically controlled drop in power (to a level corresponding to the power of the equipment still operating).

1.3. Principal physical characteristics of the reactor

The RBMK-1000 nuclear power reactor is a heterogeneous channel-type thermal reactor in which uranium dioxide slightly enriched in ^{235}U is used as fuel, graphite is used as moderator and boiling light water is used as coolant. The reactor has the following principal characteristics:

Thermal power	3200 MW
Fuel enrichment	2.0%
Mass of uranium in fuel assembly	114.7 kg
Number/diameter of fuel elements in a fuel subassembly	18/13.6 mm
Fuel burnup	20 MW.d/kg
Coefficient of nonuniformity in radial power density	1.48
Coefficient of nonuniformity in vertical power density	1.4
Maximum design channel power	3250 kW

Isotopic composition of unloaded fuel:

Uranium-235	4.5 kg/t
Uranium-236	2.4 kg/t
Plutonium-239	2.6 kg/t
Plutonium-240	1.8 kg/t
Plutonium-241	0.5 kg/t

Void coefficient of reactivity α_φ .... 2.0×10^{-6} vol.%
at working point ....   steam

Fast power coefficient of reactivity α_W
at working point .... -0.5×10^{-6}/MW

Temperature coefficient of fuel α_T............ -1.2×10^{-5}/°C

Temperature coefficient of graphite α_C........ 6×10^{-5}/°C

Minimum "weight" of CPS rods, ΔK 10.5%

Worth of manual control rods, ΔK 7.5%

Effect of replacing spent fuel
by fresh fuel (average) 0.02%

An important physical characteristic from the standpoint of reactor control and safety is a quantity known as the operative reactivity margin or excess reactivity. This is defined in terms of a certain number of CPS rods inserted into the core in the region of high differential worth, for fully inserted rods.

The excess reactivity for RBMK-1000 reactors is taken as equalivalent to 30 manual regulating rods. The rate of insertion of negative reactivity, when the emergency protection system is triggered is 1 β/s (β is the fraction of delayed neutrons), which is sufficient to compensate for positive reactivity effects.

The nature of the relationship between the effective multiplication factor and the coolant density in RBMK reactors is largely determined by the different types of absorbers in the core. With the initial loading of the emergency protection system, which comprises about 240 additional absorbers with boron, loss of water draining leads to a negative reactivity effect.

At the same time, a slight increase in steam quality at rated power, with a reactivity margin of 30 rods, results in a reactivity increase ($\rho = 2 \times 10^{-4}$/vol.% steam).

In the case of a boiling water graphite-moderated reactor, the main parameters relevant to operational reliability and thermal safety are the temperature of the fuel elements, the margin to nucleate boiling margin and the graphite temperature.

A series of programs has been devised for RBMK reactors which allow prompt calculations by the plant computers to ensure thermal stability with continuous refuelling and with the valves at the channel inlets in any position. This makes it possible to determine the thermal parameters of the reactor for any channel flow frequency and for any type of control (on the basis of outlet steam quality or the critical power margin) and for any degree of pre-throttling of the core.

To determine the power density fields through the core, the plant relies on physical monitorings based on in-core measurement of the vertical and radial neutron flux. In addition to the physical monitoring system readings, the plant computer also receives data characterizing the core composition, the energy output of each fuel channel, position of the control rods, distribution of water flow through the core channels, and readings from the sensors indicating coolant pressure and temperature. The PRIZMA program calculations carried out by the computer periodically give the operator a digital printout of core configurations, indicating the type of core loading, the position of the control rods, the arrangement of in-core sensors, the power distribution, the critical power margins and margins for the maximum permissible thermal loads on the fuel elements for each fuel channel in the reactor. The plant computer also calculates the overall thermal power of the reactor, the distribution of steam-water mixture flow through the separators, the integral power output, the outlet steam quality from each fuel channel and various other parameters needed to monitor and control the reactor plant.

Experience in operating actual RBMK reactors shows that with the existing means of monitoring and controlling these reactors there is no difficulty in maintaining the temperatures of the fuel and graphite and the critical heat margins at the permissible level.

1.4. Safety systems (Figs 2 and 3)

1.4.1. Protective safety systems

The emergency core cooling system (ECCS) is a protective safety system designed to draw off the residual heat from the core by feeding an appropriate volume of water into the reactor channels in the event of accidents which damage the main core cooling system. Associated with such accidents are ruptures in the large-diameter MFCC pipelines, as well as ruptures in the steam pipes and in the feedwater pipelines.

The system for preventing excess pressure in the main coolant circuit is designed to ensure an acceptable pressure level in the circuit by drawing off steam into a pressure suppression pool where it will condense.

The system for protecting the reactor space is designed to ensure that acceptable pressure within the reactor space is not exceeded in an emergency situation involving the rupture of one fuel channel; it does this by transferring the steam and gas mixture from the reactor space into the steam and gas disposal compartment of the pressure suppression pool and later into the pressure suppression pool itself with simultaneous suppression of the chain reaction by the emergency protection system. The ECCS and the reactor space cooling system can be used to introduce appropriate neutron absorbers (boron salt and ^{3}He).

1.4.2. Localizing (confining) safety systems

The accident localization system as used on the fourth unit of the Chernobyl' nuclear power station is designed to localize and contain

radioactive emissions in accidents involving loss of integrity in any of the pipes of the reactor's coolant circuit, with the exception of the pipework of the steam-water communication lines, the upper parts of the fuel channels and that part of the downcomers which is situated in the drum separator compartment, and the pipework for the steam and gas discharges from the reactor space.

The main component of the localization system is a system of leaktight enclosures, including the following compartments within the reactor compartment:

-   Reinforced leaktight compartments, distributed symmetrically in relation to the reactor axis and designed for an excess pressure of 0.45 MPa;

-   Compartments of the distributing group headers and lower water communication lines; these compartments are designed in line with the strength of the elements used in the reactor construction, not to permit a rise of over 0.08 MPa in the excess pressure level and are calculated to this magnitude.

The compartments containing the reinforced leaktight compartments and steam distribution corridor are connected to the water volume of the bubble condenser by steam discharge channels.

The system of cut-off and sealing devices is designed to ensure leaktightness in the accident localization area by cutting off the pipelines linking the sealed and unsealed compartments.

The bubble condenser is designed to condense the steam formed:

-   In the course of an accident involving loss of integrity of the reactor circuit;

-   Through operation of the main safety valves;

-   By flows through the main safety valves during normal operation.

1.4.3. Safety-assurance systems (service safety systems)

Electricity supply to the plant

The users of electricity at the power plant are divided into three groups, according to the degree of reliability of supply required:

(1) Those unable to tolerate a break in supply lasting from fractions of a second to several seconds under any circumstances, including complete loss of alternating-current voltage from the plant's own working and stand-by transformers, and requiring an assured supply after the reactor's emergency protection system has come into operation;

(2) Those which, under the same conditions, can tolerate a break in supply lasting from tens of seconds to tens of minutes, and which require an assured supply after the reactor's emergency protection system has come into operation;

(3) Those which do not require a supply in the event of loss of voltage from the plant's own working and stand-by transformers, and which, with the unit operating normally, will tolerate a break in supply during the time taken to transfer from the working transformer to the plant's own stand-by transformer.

1.4.4. Control safety systems

The control safety systems are designed to automatically bring into operation the protection, localizing and safety assurance systems and to monitor their functioning.

1.4.5. Radiation control system

The power plant's radiation control system, which forms an integral part (i.e. a subsystem) of its automated control system, is designed to collect, process and display data relating to the radiation situation within the plant premises and in the external environment, the condition of equipment and circuits and staff radiation exposure, in accordance with the standards and legislation, in force.

1.4.6. Power plant control points

There are two levels of control at the plant, namely station level and unit level.

All systems related to power plant safety are controlled at unit level.

1.5. Description of the site of the Chernobyl' nuclear power station and of the surrounding region

1.5.1. Description of the region

The Chernobyl' nuclear power station is situated in the eastern part of a large region, known as the Byelorussian-Ukrainian Woodlands, beside the River Pripyat', which flows into the Dnepr. The region is characterized by a relatively flat landscape with very minor slopes down to the river or its tributaries.

The total length of the Pripyat' before it flows into the Dnepr is 748 km, and its catchment area at the point where it passes the power plant is 106 000 km^2. The river is 200-300 m wide, with an average flow rate of 0.4-0.5 m/sec. The long-time average volume flow is 400 m^3/sec.

The water-bearing horizon used for the above region's drinking water supply lies at a depth of 10-15 m in relation to the present level of the Pripyat' and is separated from the Quaternary deposits by relatively impermeable argillaceous marls.

The Byelorussian-Ukrainian Woodland region is on the whole characterized by a low population density (up to the start of construction work on the Chernobyl' power plant the average population density of the region was approximately 70 inhabitants per km^2).

At the beginning of 1986 the total population within a region of 30 kilometre radius around the power plant was approximately 100 000, 49 000 of whom lived in the town of Pripyat', situated to the west of the plant's three-kilometre safety zone, and 12 500 of whom lived in the town of Chernobyl', the regional centre, situated 15 km to the south east of the plant.

1.5.2. Description of the power plant site and its buildings

The first stage of the Chernobyl' power plant, two units with RBMK-1000 reactors, was constructed between 1970 and 1977. Work on the two power units comprising the second construction stage was completed on the same site in late 1983.

In 1981 work was begun on the construction of two more power units using the same reactors (the third construction stage) at a distance of 1.5 km to the south-east of the existing site.

To the south east of the power plant site and directly within the Pripyat' valley, a 22 km^2 cooling water pond was constructed to provide cooling water for the turbine condensers and the other heat exchangers of the first four units. The normal breast-wall level of the water in the cooling pond is taken to be 3.5 m below the design level of the power plant site.

Under the third construction stage, two powerful water-cooling towers (each with a hydraulic capacity of 100 000 m^3/h) are being built; these will be capable of functioning in parallel with the cooling pond.

The area reserved for the construction base and warehouse facilities is situated to the west and north of the site of the first and second stages.

1.5.3. Information on the number of staff at the power plant site at the time of the accident

On the night of 25-26 April 1986 there were 176 duty operational staff and workers from different departments and maintenance services on the site of the first and second construction stages.

In addition to this there were 268 builders and assemblers working on the night shift on the site of the third construction stage.

1.5.4. Information on equipment situated on-site and previously in operation in the complex containing the damaged reactor, and on equipment used in bringing the accident under control

Construction of the Chernobyl' nuclear power station is being carried out in stages, each comprising two power units with common on-site special water purification systems and auxiliary facilities, among which are:

- A storage facility for liquid and solid radioactive wastes;

- Open distributive systems;

- Gas supply unit;

- Stand-by diesel power plants;

- Hydraulic and other facilities.

The liquid radioactive waste storage facility, built as part of construction stage two, is intended for the receipt and temporary storage of the liquid radioactive wastes arising from the operation of the third and fourth units, and also to receive water from washing operations and to return it for processing. The liquid radioactive wastes are channelled from the main vessel through pipes laid along the lower deck of the pipe bridge, while the solid radioactvie wastes reach the storage facility through the upper corridor of the pipe bridge in electric trolley-cars.

The nitrogen-oxygen station is designed to supply the needs of the plant's third and fourth units.

The gas supply unit comprises a compressor unit, electrolysis unit and helium and argon containers; its purpose is to supply the plant's third and fourth units with compressed air, hydrogen, helium and argon. Receptacles for storing the nitrogen and hydrogen are situated in the open.

The stand-by diesel power plant is an independent emergency source of electricity to supply those systems which are important to the safety of each unit. Each stand-by diesel power plant of the third and fourth units is equipped with three diesel generators having a unit output of 5.5 MW. These plants are served by an intermediate and a base diesel fuel depot, fuel transfer pumps and emergency fuel and oil discharge tanks.

The service water for the third and fourth units is supplied by the cooling water pond.

The water for the circulation pumps, which serves both the third and fourth units, enters the pressure basin and from there flows by gravity to the turbine condensers.

In the case of those users requiring an uninterrupted supply of service water, this is provided for by separate pumping stations for the third and fourth units. A stand-by power supply from the diesel generators is available to these pumping stations.

On 25 April 1986, all four units of the first and second construction stages were in operation, as were all auxiliary systems and on-site facilities associated with their normal operation.

2.   CHRONOLOGICAL ACCOUNT OF HOW THE ACCIDENT EVOLVED

The fourth unit of the Chernobyl' nuclear power plant went into operation in December 1983. At the time when the reactor was to be shut down for intermediate maintenance, planned for 25 April 1986, the core contained 1659 fuel assemblies with an average burnup of 10.3 MWd/kg, one additional absorber and one unloaded channel. Most of the fuel assemblies (75%) were first load bundles with a burnup of 12 to 15 MWd/kg.

Before shutdown, tests were to be carried out on turbogenerator No. 8 in a regime whereby the turbine would be supplying plant power requirements during the run down. The purpose of these experiments was to test the possibility of utilizing the mechanical energy of the rotor in a turbo-generator cut off from the steam supply to sustain the unit's own power requirements during a power failure. This regime is in fact used in one sub-system of the reactor's fast-acting emergency core cooling system (ECCS). If carried out in an appropriate way with the requisite additional safety measures, such an experiment would not be forbidden on an operating power plant.

Similar tests had already been carried out at the Chernobyl' plant. At that time it had been found that the voltage on the generator busbars falls off long before the mechanical energy of the rotor is expended during the run-down. In the tests planned for 25 April 1986 the experimenters intended to use a special generator magnetic field regulator to eliminate this problem. However, the "Working Programme for Experiments on Turbogenerator No. 8 of the Chernobyl' Nuclear Power Plant", in accordance with which these tests were to be performed, was not properly prepared and had not received the requisite approval.

The quality of the programme was poor and the section on safety measures was drafted in a purely formal way. (The safety section said merely that all switching operations carried out during the experiments were to have the permission of the plant shift foreman, that in the event of an emergency the staff were to act in accordance with plant instructions and that before the experiments were started the officer in charge - an electrical engineer, incidentally, who was not a specialist in reactor plants - would advise the security officer on duty accordingly.) Apart from the fact that the programme made essentially no provision for additional safety measures, it called for shutting off the reactor's emergency core cooling system. This meant that during the whole test period, i.e. about four hours, the safety of the reactor would be substantially reduced.

Because the question of safety in these experiments had not received the necessary attention, the staff involved were not adequately prepared for the tests and were not aware of the possible dangers. Moreover, as we shall see in what follows, the staff departed from the programme and thereby created the conditions for the emergency situation.

On 25 April at exactly 1:00 hours the staff began to reduce the reactor power (up to then the unit had been operating at rated parameters) and at 13:05 hours turbogenerator No. 7 was switched off with the reactor at 1600 MW(th). The electric power required for the unit's own needs (four main circulation pumps, two electrical feed pumps and other equipment) was switched to the busbars of turbogenerator No. 8.

At 14:00 hours the reactor's emergency core cooling system was disconnected from the multiple forced circulation circuit (MFCC) in accordance with the experimental programme. However, because of control room requirements the removal of the unit from operation was delayed. Thus, the unit then continued to operate with the emergency cooling system switched off, in violation of the operating rules.

At 23:10 hours, the power reduction was resumed. Under the test programme, the rundown of the generator with simultaneous provision of unit power requirements was to be carried out at a reactor power of 700-1000 MW(th). However, when the local automatic regulation system was shut off, which under the operating rules is supposed to be done at low power, the operator was unable to eliminate the resultant unbalance in the measuring part of the automatic regulator quickly enough. As a result of this, the power fell below 30 MW(th). Only at 1:00 on 26 April did the operator succeed in stabilizing it at 200 MW(th). Since the "poisoning" of the reactor was continuing at the same time, a further increase in power was hindered by the small excess reactivity available, which at that moment was substantially below what the regulations called for.

Even so, it was decided to conduct the experiments. At 1:03 and at 1:07 one additional main circulation pump was switched in from either side to join the six pumps already operating, so that when the experiment was finished - during which four main circulation pumps were to be operating through the rundown - four pumps would remain available on the MFCC for safe cooling of the reactor core.

Since the reactor power, and consequently the hydraulic resistance of the core and the MFCC were substantially lower than the planned level and since all eight main circulation pumps were in operation, the total coolant flow rate through the reactor rose to (56 000-58 000 m^3/h, and at some individual pumps to 8000 m^3/h, which meant a violation of the operating rules. An operating regime of this kind is forbidden because of the danger of pump breakdown and the possibility of vibrations arising in the main coolant pipes owing to cavity formation. The switching in of the additional main circulation pumps and the resulting increase in water flow through the reactor brought about a reduction of steam formation, a fall in steam pressure in the drum separators, and changes in other reactor parameters. The operators attempted manually to sustain the main parameters of the system - steam pressure and the water level in the drum separators - but they did not entirely succeed in doing so. At this stage they saw the steam pressure in the drum separators sag by 0.5-0.6 MPa and the water level drop below the

emergency mark. In order to avoid shutting down the reactor in such conditions, the staff blocked the emergency protection signals relating to these parameters.

At the same time, the reactivity continued to drop slowly. At 1:22:30, the operator saw from a printout of the fast reactivity evaluation program that the available excess reactivity had reached a level requiring immediate shutdown of the reactor. Nevertheless, the staff were not stopped by this and began with the experiments.

At 1:23:04, the emergency regulating valves of turbogenerator No. 8 shut. The reactor continued to operate at a power of about 200 MW(th). The available emergency protection from the closing of the emergency regulating valves on two turbogenerators (turbogenerator No. 7 had been shut off on 25 April) was blocked so that it would be possible to repeat the experiment if the first attempt proved unsuccessful. This meant a further departure from the experimental programme, which did not call for blocking the reactor's emergency protection with the switching off of two turbogenerators.

Shortly after the beginning of the experiment the reactor power began to rise slowly.

At 1:23:40, the unit shift foreman gave the order to press button AZ-5, which would send all control and scram rods into the core. The rods fell, but after a few seconds a number of shocks were felt and the operator saw that the absorber rods had halted without plunging fully to the lower stops. He then cut off the current to the sleeves of the servo drives so that the rods would fall into the core under their own weight.

According to observers outside unit 4, at about 1:24 there occurred two explosions one after the other; burning lumps of material and sparks shot into the air above the reactor, some of which fell onto the roof of the machine room and started a fire.

3.   ANALYSIS OF THE ACCIDENT USING A MATHEMATICAL MODEL

The "Skala" centralized control system of the RBMK-1000 reactor has a program for diagnostic parameter recording (DPRP) under which several hundred analog and discrete parameters are periodically examined and stored in accordance with a specified cycle (minimum cycle time 1 second).

In connection with the experiments, only those parameters were recorded with great frequency which were important for an analysis of the experimental results. Therefore, in trying to reconstruct the course of the accident, we used a mathematical model incorporating not only the DPRP print-out but also instrument readings and the results of questioning of the staff.

To perform a rapid analysis of different variants and versions of the accident situation under consideration, we used an integral mathematical computer model of the RBMK-1000 unit in real time. The dependences of reactivity on steam content and on absorber rod movements were determined from calculations based on three-dimensional neutron physics dispersion models.

In reconstructing the course of the accident, it was particularly important to be sure that the mathematical model correctly described the behaviour of the reactor and other equipment and systems in precisely those conditions which prevailed just before the destruction of the unit. As we have already noted in the previous chapter, the reactor was operating unstably after 1:00 hours on 26 April 1986 and the operators were almost continualy introducing new "perturbations" into the controlled system in order to stabilize its parameters. This has made it possible, for a fairly long time interval involving various influences on the reactor, to compare factual data established fairly reliably by the recording systems with the data obtained through numerical modelling. The results of this comparison have proved to be highly satisfactory, which suggests that the mathematical model satisfactorily reproduced the actual plant.

In order to get as clear an idea as possible of the influence of preceding events on the development of the accident, we analysed data beginning at 1:19:00, i.e. 4 minutes before the beginning of the turbo-generator run down experiment (Fig. 4). This movement is convenient in the sense that the operator was then starting one of the operations involved in the drum-separator make up (the second since 1:00 hours) which produced powerful perturbations in the controlled system. At this moment the DPRP recorded the position of the rods of all three automatic regulators - in other words, the initial conditions of the calculation were very clearly established.

The operator began the drum separator make up in order to prevent a radical drop in the water level of the separators. After 30 seconds he succeeded in maintaining the level by increasing the input flow of make up water by a factor of more than three. It would seem that the operator had decided not only to maintain the water level but to raise it. For that reason the water flow continued to increase and after about a minute was already four times the initial value.

As soon as the colder water from the drum separators reached the core, steam generation was substantially reduced, and this in turn reduced the volumetric steam quality, raising the automatic regulator rods. Within about 30 seconds the rods rose to the upper stops and the operator had to "help" them with the manual control rods, thereby reducing the available excess reactivity (this operation was not recorded in the daily operating log, but without it the operator could not possibly have maintained the power at 200 MW). By moving the manual rods upwards the operator brought about an over-compensation and one of the groups of automatic regulator rods dropped 1.8 metres.

The reduction in steam generation brought about a small drop in pressure. Within about a minute, at 1:19:58, the fast-acting steam dump system was closed off, through which excess steam had been slipping to the condenser. This slowed down the rate of pressure drop a little. Even so, up to the beginning of the experiment the pressure continued to fall off slowly. During this period it changed by more than 0.5 MPa. At 1:22:30 the "Skala" centralized control system provided a print-out of the actual power density fields and of all regulatory rod positions. It was for this instant in time that we attempted to correlate the calculated and recorded neutron fields.

The overall neutron field characteristic at this moment can be described as follows: in the radial-azimuthal direction it showed for all practical purposes a smooth convex shape, but in the vertical direction the curve was double-humped, on average, with a greater release of energy in the upper part of the core. A neutron field distribution of this kind would be completely natural for the state prevailing in the reactor at that moment: a burnt-out core, practically all regulating rods up, volumetric steam quality in the upper part of the core much more than lower down, and greater ^{135}Xe poisoning in the central parts of the reactor than on the periphery.

At 1:22:30 the excess reactivity was only 6-8 rods, in other words not more than half of the minimum permissible value laid down in the operating regulations. The reactor was in an unusual and impermissible state, and to assess the subsequent course of events it was extremely important to determine the differential rod worths of the control rods and the scram rods for real neutron fields and real core multiplication characteristics. Numerical analysis showed that the error in determining the control rod worths was extremely sensitive to the error in re-establishing the vertical power density field. Add to this the fact that at such low power levels (approximately 6-7%) the relative error in measuring the field is much greater than in rated power conditions, then it becomes clear that a vast number of calculational variants will have to be analysed before one can be confident of the rightness or wrongness of any given version.

At 1:23 hours the reactor parameters were closer to stable than at any other time in the interval we are considering, and the experiments began. A minute before this the operator had abruptly reduced the flow of make-up water, and this increased the water temperature at the reactor inlet within a time equivalent to that required for the coolant to pass from the drum separators to the reactor. At 1:23:04 the operator closed the emergency regulating valves of turbogenerator No. 8 and the turbogenerator rundown

began. Because of the reduced flow of steam from the drum separators, the steam pressure began to rise slowly (on average at a rate of 6 kPa/s). The total flow of water through the reactor began to fall off owing to the fact that four of the eight main circulation pumps were working off the "running down" turbogenerator.

The increase in steam pressure on the one hand and the reduced flow of water through the reactor together with the reduced input of make-up water to the drum separators, on the other hand, are competing factors in determining the volumetric steam quality and hence the power of the reactor. A point that deserves particular stress is that in the state the reactor had now reached a small change in power would mean that the volumetric steam quality - which has a direct effect on reactivity - would increase much more than at nominal power. The competition between these factors led in the final analysis to a power rise, and this was the circumstance which triggered the pressing of button AZ-5.

Button AZ-5 was pushed at 1:23:40 and the insertion of the scram rods began. At this time the automatic regulator rods, partially compensating for the previous power rise, were already in the lower part of the core, but the fact that the staff were operating with an impermissibly small excess reactivity meant that virtually all other absorber rods were in the upper part of the core.

In the conditions that had now arisen, the violations committed by the staff had seriously reduced the effectiveness of the emergency protection system. The overall positive reactivity appearing in the core began to increase. Within three seconds the power rose above 530 MW, and the total period of the excursion was much less than 20 seconds. The positive void coefficient of reactivity worsened the situation. The only thing that partially compensated for the reactivity inserted at this time was the Doppler effect.

The continuing reduction of water flow through the fuel channels as the power rose led to an intensive steam formation and then to nucleate boiling, over-heating of the fuel, destruction of the fuel, a rapid surge of coolant boiling with particles of destroyed fuel entering the coolant, a rapid and abrupt increase of pressure in the fuel channels, destruction of the fuel channels, and finally an explosion which destroyed the reactor and part of the building and released radioactive fission products to the environment.

In the mathematical model, the destruction of the fuel was simulated by an abrupt increase in effective heat exchange surface when the power density in the fuel exceeded 300 cal/g. It was precisely at that moment that the pressure in the core had risen to the point where an abrupt reduction of water supply from the main circulation pumps occurred (the check valves were closed). This is quite plain from the results obtained with the mathematical model and from the results and measurements recorded by the DPRP. Only the rupture of the fuel channels partially restored the flow from the main circulation pumps; however, the water from the pumps was at this stage no longer directed into intact channels but into the reactor space.

The steam formation and rapid rise of temperature in the core created appropriate conditions for a steam-zirconium reaction and other exothermal chemical reactions. Witnesses observed these reactions in the form of a fireworks display of glowing particles and fragments, escaping from the units.

As a result of these reactions, a mixture of gases was formed containing hydrogen and carbon monoxide, which then led to a thermal explosion upon mixing with the oxygen of the air. This mixing became possible after the reactor space had been vented and destroyed.

4. CAUSES OF THE ACCIDENT

As shown by the analysis presented above, the accident in the fourth unit of the Chernobyl' nuclear power plant belongs to the category of accidents associated with the introduction of excess reactivity. The design of the reactor facility provided for protection against this type of accident with allowance for the physical characteristics of the reactor, including a positive steam void coefficient of reactivity.

The technical means of protection include systems for controlling the reactor and protecting it against a power overshoot, for reducing the examination period, and for self-shielding and protection against malfunctioning in switching operations involving the equipment and systems of the power-generating unit and the emergency core cooling system.

Apart from the technical means of protection, there are also strict rules and instructions for carrying out technological processer at a nuclear power plant, specified in regulations for the operation of each power-generating unit. Among the most important regulations are stipulations referring to the inadmissibility of reducing the operational excess reactivity (reactivity margin) to fewer than 30 rods.

In the process of preparing for and conducting the turbogenerator tests, in which the turbine was to supply the unit's requirements during the run-down, the staff switched off a number of important protection systems and violated the most important provisions of the operating regulations for safe management of technological process.

The table below lists the most dangerous violations of the operating rules committed by the staff of the fourth unit of the Chernobyl' nuclear power plant.

No. 1	Violation 2	Motivation 3	Consequences 4
1.	Reducing the operational reactivity margin sub-stantially below the permissible value	Attempt to emerge from "iodine well"	Emergency protection system of reactor was ineffective
2.	Power dip well below the level provided for by the test programme	Operator error in switching off local automatic control	Reactor proved to be in a condition difficult to control
3.	Connecting of all the main circulation pumps to the reactor, with individual pump dis-charges exceeding the levels specified in the regulations	Meeting the requirements of the tests	Coolant temperature in the multiple forced circulation circuit approached saturation temperature

4.	Blocking of reactor protection system relying on shutdown signal from two turbogenerators	Intention, if necessary, of repeating the experiment with turbogenerators switched off	Loss of possibility of automatic shutdown of the reactor
5.	Blocking of protection systems relying on water level and steam pressure in the drum-separator	Effort to perform tests despite unstable reactor operation	Reactor protection system based on heat parameters was completely cut off
6.	Switching off of the protection system for the design-basis accident (switching off of the emergency core cooling system)	Wish to avoid spurious triggering of the emergency core cooling system while the experiment was going on	Loss of the possibility of reducing the scale of the accident

The chief motive of the staff was to complete the tests as expeditiously as possible. The failure to adhere to instructions in preparing for and carrying out the tests, the non-compliance with the testing programme itself and the carelessness in handling the reactor facility are evidence that the staff was insufficiently familiar with the special features of the technological processes in a nuclear reactor and also that they had lost any feeling for the hazards involved.

The designers of the reactor facility did not provide for protective safety systems capble of preventing an accident in the combination of circumstances prevailing in unit 4, namely the deliberate switching off of technical protection systems coupled with violations of the operating regulations, since they considered such a conjunction of events to be impossible.

Thus, the prime cause of the accident was an extremely improbable combination of violations of instructions and operating rules committed by the staff of the unit.

The accident assumed catastrophic proportions because the rector was taken by the staff into a non-regulation state in which the positive void coefficient of reactivity was able substantially to enhance the power excursion.

5. PRIORITY MEASURES FOR IMPROVING THE SAFETY OF NUCLEAR POWER PLANTS WITH RBMK REACTORS

It has been decided, for existing nuclear power plants with RBMK reactors, to alter the limit stop switches of the control rods in such a way that, in the extreme position, all the rods are inserted in the core to a depth of 1.2 m. This measure will increase the speed of effective protection and eliminate the possibility of a continuing increase in the multiplying characteristics of the core in its lower part as the rods move down from the upper stops. At the same time, the number of absorber-type control rods constantly present in the core will be increased to 70-80, thereby reducing the void coefficient to a permissible value. This is a temporary measure which will be replaced later on by a conversion of RBMK reactors to fuel with an initial enrichment of 2.4% and by the insertion of additional absorbers in the core to ensure that a positive overshoot of reactivity does not exceed 1 β for any change in coolant density.

A number of additional indicators of the cavitation margin of the main circulating pumps are being installed, and also a system for automatic calculation of reactivity with an emergency shutdown signal when the excess reactivity falls below a specified level. These measures will have a somewhat adverse effect on the economic parameters of nuclear power plants with RBMK reactors but they will guarantee safe operation.

In addition to the technical measures, organizational steps are being taken to reinforce technological discipline and to improve the quality of operations.

6.   CONTAINMENT OF THE ACCIDENT AND ALLEVIATION OF ITS CONSEQUENCES

6.1.   Fighting the fire at the nuclear power station

The most important task after the accident at the reactor was to fight the fire. Fire had broken out in over 30 places as a result of the explosions in the reactor which had ejected fragments of its core, heated to high temperatures, onto the roofs above several areas housing the reactor section, the de-aeration stages and the machine hall. Because of damage to some oil pipes, electric cable short circuits and the intense heat radiation from the reactor, focuses of fire formed in the machine hall over turbogenerator number 7, in the reactor hall and in the adjoining, partially destroyed buildings. At 01.30, the firemen on duty with the subsection of the fire division responsible for the power station set out from the towns of Pripyat' and Chernobyl' to the scene of the accident. In view of the immediate threat that the fire would spread along the top of the machine hall to the adjoining third unit, and as it was rapidly increasing in strength, the first set of measures taken was directed towards putting out the fire in this critical area. It was therefore decided that the fires inside the buildings should be put out with fire extinguishers and the fire hydrants installed inside. The main focuses had been overcome by 02.10 for the machine hall roof and by 02.30 for the roof of the reactor section. The fire was out by 05.00.

6.2.   Evaluation of the state of the fuel after the accident

The accident partially destroyed the reactor core and completely destroyed its cooling system. This being the case, conditions in the reactor vault were determined from:

-    Residual heat released by the fuel as a result of the decay of fission products;

-    Heat production from various chemical reactions in the reactor vault (hydrogen burning, oxidation of graphite and zirconium and so on);

-    Heat removal from the reactor vault through cooling by atmospheric air through openings in the previously hermetic compartments around the core.

In order to prevent the accident from spreading and limit its after-effects, significants efforts were directed during the very first hours after the accident towards evaluating the condition of the fuel and any possible change in that condition with the passage of time. To this end, it was necessary to carry out investigations as follows:

-    To evaluate the possible scale of melting (as a result of residual heat production) of the fuel in the reactor vault;

-    To study the interaction between the melted fuel and the reactor structural materials and vault (metals, concrete and so on);

-      To evaluate the possibility that the reactor structural materials
       and vault might melt because of the heat released by the fuel.

       In the first place, calculations were carried out to evaluate the state
of the fuel in the reactor vault, taking into account the leakage of fission
products as a function of the time elapsed since the accident.

       An analysis of the dynamics of fission product leakage from the reactor
in the first few days after the accident indicated that the change in fuel
temperature with the passage of time was not monotonic. It could be assumed
that there had been several stages in the fuel temperature regime. At the
moment of the explosion, the fuel had heated up. An estimate of temperature
based on the relative leakage of the iodine nuclides (that fraction of the
total isotope content of the fuel which was escaping at any one moment)
indicated that the effective temperature of the fuel remaining in the reactor
building was 1600-1800 K after the explosion. During the next few tens of
minutes, the fuel temperature decreased through heat transfer to the graphite
structure and structural materials. There was therefore a corresponding
reduction in the leakage of volatile fission products from the fuel.

       It was considered that the quantity of fission products ejected from
the reactor vault was fundamentally determined during this period by graphite
burning and the related migration processes of the finely dispersed fuel and
fission products embedded in the graphite as a result of the explosion in the
reactor. Subsequently, the fuel temperature began to increase because of
residual heat production. As a result, the leakage of volatile radionuclides
from the fuel increased (inert gases, iodine, tellurium and caesium). When
the fuel temperature had increased further, other, non-volatile radionuclides
began to escape. By 4-5 May the effective temperature of the fuel still in
the reactor had stabilized and then began to decrease.

       The results from the numerical calculation of the condition of the fuel
are shown in Fig. 5. The figure shows the residual radionuclide content of
the fuel, and also the variation in the fuel temperature taking into account
the leakage of fission products as a function of time elapsed since the
accident.

       The calculations show:

-      That the maximum fuel temperature could not have reached the
       melting point of the fuel;

-      That the fission products were coming to the fuel surface in
       batches, which could lead to only local overheating at the
       fuel-cladding interface.

       The fission products leaving the fuel settled on the structural and
other materials surrounding the reactor in the unit, according to their
temperatures of condensation and precipitation. Virtually all the krypton and

xenon radionuclides left the unit, some of the volatile fission products (iodine, caesium) did so, and practically all the rest stayed within the reactor building. The energy from the fission products was thus dispersed throughout the reactor unit.

These factors indicate that melting of the materials surrounding the fuel and movement of the fuel were unlikely.

6.3. Limiting the consequences of the accident in the core

The potential danger that some melted fuel would concentrate, creating conditions in which a critical mass might be reached and a spontaneous chain reaction occur, made it necessary to take appropriate precautions. In addition, the damaged reactor was releasing significant amounts of radioactivity into the environment.

Immediately after the accident, an attempt was made to reduce the temperature in the reactor vault and to prevent the graphite structure igniting by using the emergency auxiliary feed pumps to supply water to the core space. This attempt proved ineffective.

One of two decisions had to be taken immediately:

-   To contain the accident at source by covering the reactor shaft with heat absorbent and filtering materials;

-   To allow the combustion processes in the reactor shaft to come to an end of their own accord.

The first line of action was chosen, as the second carried within itself the danger that a significant area would suffer radioactive contamination and the health of the inhabitants of major cities might be threatened.

A group of specialists began to cover the damaged reactor by dropping compounds of boron, dolomite, sand, clay and lead from military helicoptors. About 5000 t in all were dropped between 27 April and 10 May, mostly between 28 April and 2 May. As a result, the reactor was covered with a friable layer of material which strongly absorbed aerosol particles. By 6 May, the release of radioactivity had ceased to be a major factor, having decreased to a few hundred Ci, and fell to a few tens of Ci per day by the end of the month.

The problem of reducing the fuel temperature was solved at the same time. To bring down the temperature and reduce oxygen concentration, nitrogen was pumped under pressure from the compressor station into the space beneath the reactor vault. By 6 May, the temperature increase in the reactor vault had ceased, and had begun to reverse itself with the formation of a stable convective flow of air through the core into the open atmosphere.

As a form of double insurance against the extremely low risk (although it was a possibility in the first few days after the accident) of the lower levels of the structure being destroyed, the decision was taken to construct,

as a matter of urgency, an artificial heat-removal horizon beneath the foundations of the building. This took the form of a flat heat-exchanger on a concrete slab. This had been done by the end of June.

Experience has shown that the decisions which were taken were basically correct.

A significant degree of stabilization has taken place since the end of May. The damaged parts of the reactor building are stable, and the radiation situation is improving now that the short-lived isotopes have decayed. The exposure dose rate is in the single röntgens per hour range in the areas adjoining the reactor, the machine hall and control and protection areas. Any uptake of radioactivity from the unit into the atmosphere is basically caused by wind removing aerosols. The activity of the releases does not exceed some tens of curies per day. The temperature regime in the reactor vault is stable. The maximum temperatures of the various reactor parts are a few hundreds of degrees centigrade and they have a steady tendency to fall at about 0.5°C per day. The slab at the base of the reactor vault is intact, and the fuel is mostly (~ 96%) localized within the reactor vault, and the compartments of the steam-water and lower water lines.

6.4.   **Measures taken at units 1, 2 and 3**

After the accident in the fourth unit, the following measures were taken at units 1, 2 and 3:

-    Units 1 and 2 were shut down at 01.13 and 02.13 respectively on 27 April;

-    Unit 3, which is closely linked technically with the damaged fourth unit, but which suffered practically no damage from the explosion, was shut down at 05.00 on 26 April;

-    Units 1 to 3 were prepared for a lengthy cold shutdown;

-    After the accident, the power station equipment was placed in the cold reserve state.

Units 1 to 3 and the power station equipment are checked by the staff on duty. Significant radioactive contamination of the equipment and buildings of units 1 to 3 of the power station was caused by radioactive materials coming through the ventilation system, which continued to operate for some time after the accident. There was a significant degree of radiation in some parts of the machine hall, which was contaminated through the damaged roof of the third unit.

The Government Commission ordered that decontamination and other work should be carried out on the first, second and third units with the aim of preparing them eventually for startup and operation again.

Special solutions were used for decontamination. Their composition depended on the material being cleaned (plastic, steel, concrete, various coverings) and the type and level of surface contamination. After decontamination, gamma radiation levels dropped by a factor of 10 to 15. Dose rates within the first and second units were between 2 and 10 mR/h in June. Final decontamination and stabilization of the radiation situation at the first, second and third units can only take place when decontamination work has been completed for the rest of the power station area and when the damaged unit has been entombed.

6.5. Monitoring and diagnosis of the state of the damaged unit

The organization of diagnostic measurements envisaged the resolution of the following basic problems:

- Establishment of reliable monitoring of fuel displacement;

- Determination of the scale of contamination in the area adjacent to the nuclear power plant;

- Evaluation of damage and dosimetric survey inside the unit, and determination of possibilities of work in the surviving premises;

- Determination of the distribution of fuel, fission products etc. in order to work out the basic data for designing structures for entombment.

Apart from evaluation of the radiation situation in and around the plant, the priority measurements included monitoring of the condition of the reactor from the air. Helicopters were used to carry out radiation measurements, an infrared survey of the damaged reactor building and its components with a view to measuring the temperature field distribution, analysis of the chemical composition of gases emitted from the reactor vault and a number of other measurements. After it had been determined that the premises and equipment had survived in the lower part of the reactor building, it became possible to conduct initial measurements and to install emergency monitoring instruments. First of all, instruments for measuring neutron flux, gamma dose rate, temperature and heat flow were installed in the evacuated pressure suppression pool. Redundancy was provided for the thermometric instruments. Evaluation of the situation in the pressure suppression pool showed that there was no imminent danger of melting of structural parts. This afforded the assurance that work on construction of a protective slab beneath the unit could be carried out under safe conditions.

The general measurement strategy was cormulated along the following lines:

- Dosimetric and visual survey inside the damaged unit;

- Radiometric and visual survey from helicopters;

- Measurement of the most important parameters (radioactivity, temperature and air flow) in the surviving structures and accessible premises.

The main measurement efforts at the initial stage were concentrated on monitoring any downward displacement of the fuel that might occur.

Solution of the diagnostic problem was complicated by the following factors:

- The regular measurement system had broken down completely;

- The outputs of any detectors which might have survived were inaccessible to the personnel;

- Information on the condition of compartments and rooms, and on the radiation situation in them, was limited.

At the next stage it was necessary to determine the location in the building of the fuel ejected from the reactor vault and to evaluate its temperature and heat removal.

Conventional or dosimetric survey methods were used to deal with this problem; in addition, some surviving process pipelines were found through which the measurement probes could be inserted. As a result of these investigations, the distribution of the fuel inside the building was largely determined.

The temperature in the compartments under the reactor did not exceed 45°C as from June, indicating good heat removal.

The monitoring and diagnostic methods were refined on the basis of the data obtained.

6.6.   Decontamination of the site

At the time of the accident radioactive materials were scattered over the site and fell on the roof of the turbine hall, the roof of the third unit and on metal pipe supports.

The site as a whole as well as the walls and tops of buildings likewise had substantial contamination as a result of deposition of radioactive aerosols and radioactive dust. The contamination of the site was not uniform.

With a view to reducing the spread of radioactive dust from the site, the roof of the turbine hall and the road shoulders were treated with various polymerizing solutions in order to immobilize the upper layers of soil and prevent dust from rising.

The plant area was divided into separate zones with a view to compehensive decontamination operations. Decontamination is being carried out in the following sequence:

- Removal of refuse and contaminated equipment from the site;

- Decontamination of roofs and outer surfaces of buildings;

- Removal of a 5-10 cm layer of soil and its transfer in containers to the solid waste repository of the fifth unit;

- Laying, if necessary, of concrete slabs on the soil or filling with clean earth;

- Coating of the slabs and of the non-concrete area with film-forming compounds.

As a result of the above measures, it has been possible to reduce the total gamma background in the area of the first unit to 20-30 mR/h. This residual background is due mainly to external sources (damaged unit), indicating that the decontamination of the site and buildings has been sufficiently effective.

6.7. Long-term entombment of the fourth unit

Entombment of the fourth unit should ensure a normal radiation situation in the surrounding area and in the atmosphere and preclude escape of radioactivity into the environment.

For purposes of entombment of the unit it is intended to build the following engineering structures (Figs 6-8):

- Outer protective walls along the perimeter;

- Inner concrete partition walls in the turbine hall between the third and fourth units, in the "B" block and in the de-aerator room along the turbine hall and on the side of the debris by the tank room of the emergency core cooling system;

- A metal partition wall in the turbine hall between the second and third units;

- A protective roof over the turbine hall.

Furthermore, it is planned to seal off the central hall and other reactor rooms and to pour concrete over the debris by the tank room of the emergency core cooling system and over the rooms of the northern main circulation pumps to isolate the debris and to provide protection against radioactive radiation from the reactor sector.

The thickness of the protective concrete walls will be 1 m or more, depending on the design solutions adopted and the radiation situation.

Two variants are considered in the ventilation design:

- An open system with purification of air by aerosol filters and release into the atmosphere through the existing stack of the central ventilation plant;

- A closed system with removal of heat into the heat exchanger located in the upper part of the space to be ventilated and maintenance of negative pressure inside the building to be ensured by pumping of air from the upper part of the space and its discharge through filters and the stack into the atmosphere.

The above activities are to be carried out in the following sequence:

1. The surface layer of soil in the area adjacent to the unit is to be removed to local sites by means of special technology;

2. The area will be covered with concrete and the surface levelled to ensure the movement of self-propelled cranes and other machinery;

3. The roofs and walls of buildings are to be decontaminated.

   At locations where radioactivity is high, special polymer adhesive pastes of various compositions will be used;

4. After the site has been cleaned and covered with concrete, the metal frames for the protective walls will be assembled and then concrete will be provided;

5. As the walls are built, work will proceed with the construction of the main civil engineering structures which are to ensure complete emtombment of the fourth unit.

6.8. <u>Decontamination of the 30 km zone and its rehabilitation for economic use</u>

Significant radioactive contamination of the areas adjacent to the power plant made it imperative to take a number of extreme decisions involving the establishment of surveillance zones, evacuation of the population, bans or restrictions on economic use of land and so on.

It was decided to establish three surveillance zones: a special zone, a 10 km zone and a 30 km zone. In these zones, strict dosimetric monitoring of all transport has been organized and decontamination points have been established. At the zone boundaries there are arrangements for transferring working personnel from one vehicle to another in order to reduce transmission of radioactive substances.

The radiation situation within the 30 km zone will continue to change, especially in areas with a high gradient of contamination levels. There will occur a substantial redistribution of radionuclides over the different parts of the landscape, depending on the characteristics of the topography. The question of re-establishing of the population can be raised only after the radiation situation over the whole contaminated area has been stabilized, by entombment of the fourth unit, decontamination of the plant site and immobilization of radioactivity in locations with a high contamination level.

In June, construction of a complex of hydraulic engineering structures began with a view to protecting from contamination the ground water and surface water in the Chernobyl' nuclear power station area. These include:

- A filtration--proof wall in the soil along part of the perimeter of the industrial site of the power plant and wells for lowering the water table;

- A drainage barrier for the cooling pond;

- A drainage cut-off barrier on the right bank of the river Pripyat';

- A drainage interception barrier in the south-western sector of the power plant;

- Drainage water purification facilities.

On the basis of an assessment of the soil and plant contamination in the 30 km zone, special agro-engineering and decontamination measures have been worked out and are now being implemented. Work aimed at restoration of the contaminated land to economic use has yet started, thanks to these measures, which include: changes in the conventional systems of soil treatment in this region, use of special compositions for dust suppression, modification of harvesting and crop processing methods, and so on.

7.   MONITORING OF ENVIRONMENTAL RADIOACTIVE CONTAMINATION AND HEALTH OF THE
        POPULATION

7.1.   Assessment of the quantity, composition and dynamics of the release of
        fission products from the damaged reactor

        The assessment was based on the results of the following:

        -       Systematic analyses of the radioisotopic composition of aerosol
                samples collected at points above the damaged unit from
                26 April 1986 on;

        -       Airborne gamma survey of the plant area;

        -       Analysis of fallout samples;

        -       Systematic measurement data from the country's meteorological
                stations.

        The release of radioisotopes from the damaged unit took place over an
extended period of time which can be divided into several stages.

        In the first stage there was a release of dispersed fuel from the
damaged reactor. The radioisotopic composition at this point corresponded
roughly to that of the irradiated fuel, but enriched by volatile isotopes of
iodine, tellurium, caesium and inert gases.

        In the second stage - from 26 April to 2 May 1986 - the rate of release
from the unit decreased as a result of the measures taken to stop the graphite
burning and to filter the releases. During this period the composition of the
radioisotopes being released was again similar to that in the fuel. During
this stage finely dispersed fuel was being carried out of the reactor by a
flow of hot air and the graphite combustion products.

        The third stage was marked by a sharp increase in the rate of release
of fission products from the unit. In the initial phase of this stage, the
release was composed mainly of volatile components, especially iodine, but
then the radioisotopic composition once more became similar to that of the
irradiated fuel (on 6 May 1986). The reason for this was the heating of the
fuel in the core to a temperature exceeding $1700^{\circ}C$ as a result of the
reactor after-heat. The temperature caused the migration of fission products
and the chemical transformation of uranium oxide, which in turn led to an
escape of fission products from the fuel matrix and their relsease in aerosol
form on the graphite combustion products.

        The fourth and last stage, which began after 6 May, was characterized
by a rapid drop in releases (Table 1). This was a consequence of the special
measures taken, the formation of more infusible fission product compounds as a
result of their interaction with the materials introduced, and the
stabilization and subsequent lowering of the fuel temperature.

The radioisotopic composition of the releases is shown in Table 2.

The fission products in the air and fallout samples were in the form of individual radioisotopes (mainly volatile ones) and were part of the composition of the fuel particles. Particles (associates) with an elevated content of individual radioisotopes (Cs, Ru etc.) were identified, these having formed as a result of the migration of fission products in the fuel and the filling and structural materials and of sorption on surfaces.

The total release of fission products (excluding radioactive inert gases) was approximately 50 MCi, or about 3.5% of the total inventory of radioisotopes in the reactor at the time of the accident. These figures were calculated on 6 May 1986 and take into account radioactive decay. The release of radioactive materials virtually ceased on that day.

The composition of the radioisotopes released during the accident corresponded approximately to that of the fuel of the damaged reactor, the difference being that the former had a higher content of volatile iodine, tellurium, caesium and inert gases.

7.2. Monitoring system

When the accident occurred, the official meteorological, radiation and public health monitoring system began to operate on an emergency footing. As soon as the scale of the accident became evident, the monitoring system was widened to bring in additional groups of experts and technicians. In the first days after the accident, efforts were concentrated on the most urgent radiation, public health and biomedical monitoring tasks.

During ths period the monitoring system began to be extended to cover long-term problems also. Among the organizations involved in the establishment of the system were the State Committee on Hydrometeorology and Environmental Protection, the Ministries of Health of the USSR and of the Union Republics, the Academies of Science of the USSR, the Ukrainian SSR and the Russian SSR, the State Committee on the Utilization of Atomic Energy and the State Agro-industrial Committee.

The help of specialized medical institutions in Moscow and Kiev was enlisted to treat those exposed to radiation.

In addition to setting up a monitoring system, a programme of radioecological, biomedical and other scientific studies to evaluate and predict the effects of the ionizing radiation on man, the flora and fauna was drawn up and began to be implemented.

The priority objective of the monitoring programme were as follows:

- Assessment of the possible internal and external exposures of plant personnel and the population of Pripyat' and the 30 km zone;

- Assessment of the possible exposure of the population of a number of areas outside the 30 km zone, the level of radioactive contamination in which could have exceeded the permissible limits;

- Preparation of recommendations on measures to protect the population and staff from exposures in excess of the established limits.

These recommendations included:

- Evacuation of the population;

- Restrictions or a ban on the use of food products containing increased amounts of radioactive substances;

- Recommendations on what action people at home and in open places should take.

In order to solve these priority problems, systematic monitoring was introduced in respect of the following:

- The level of gamma radiation in contaminated areas;

- The concentration of biologically significant radioisotopes in the air and water of water bodies, particularly those supplying drinking water;

- The degree of radioactive contamination of the soil and vegetation and its radioisotopic composition;

- The amount of radioactive substances in food products, especially I in milk ^{131}

- Radioactive contamination of working and non-working clothes, footwear, means of transport etc.;

- Build up of radioisotopes in internal organs of people etc.

7.3. Main characteristics of the radioactive contamination of the atmosphere and ground and possible ecological consequences

The determining factors in the radioactive contamination of the environment as a result of the Chernobyl' accident were the dynamics of the radioactive releases and the meteorological conditions.

The radioactively contaminated plume moved first to the west and north; during the 2-3 days after the accident - to the north; and, for a few days from 29 April - to the south. The contaminated air masses then dispersed for great distances over the Byelorussian, Ukrainian and Russian Soviet Socialist Republics. The height of the plume on 27 April exceeded 1200 m, while the

radiation levels in it were 1000 mR/h at a distance of 5-10 km from the accident site. The plume and the radioactive track which was forming were regularly surveyed by the airplanes of the State Committee on Hydrometeorology and Environmental Protection, which were equipped with sampling and gamma spectrometry equipment and Roentgen meters, and by the network of meteorological stations.

Fission and induced activity products (^{239}Np and ^{134}Cs) were identified in the air samples.

The main zones of ground contamination after the accident were to the west, north-west and north-east of the Chernobyl' plant, and subsequently - and to a lesser extent - to the south. Radiation levels near the plant exceeded 100 mR/h; on the western track the maximum radiation levels 15 days after the accident were 5 mR/h at a distance of 50-60 km from the accident zone (maximum distances), and the same to the north at a distance of 35-40 km. In Kiev the radiation levels at the beginning of May reached 0.5-0.8 mR/h.

In the zone of the radioactive track near the plant, in addition to the isotopes listed above, plutonium isotopes were identified (their distribution on the ground was insignificant). In this zone isotope fractionation was insignificant, but on the remote radioactive track the radioactive products were considerably enriched by tellurium, iodine and caesium isotopes.

By integrating the contaminated areas it was possible to determine the total activity of the radioactive fallout outside the plant site. In the nearby and remote fallout areas on the European territory of the Soviet Union it amounted to about 3.5% (see subsection 7.1) of the total activity of the fission and activation products accumulated in the reactor (about 1.5-2% on the nearby trail).

Summing the activity (which was determined by taking ground samples) of the radioisotopic fallout on the nearby track yielded an approximate value of between 0.8% and 1.9%.

The plutonium isotope contamination levels in the zones mentioned above were not the determining as regards decontamination work and decisions of an economic nature.

Information on the radioactive contamination of rivers and water bodies was obtained by regularly analysing water samples from the Rivers Pripyat', Irpen', Teterev, Desna and the Dnieper water intake. From 26 April 1986 on water samples were collected from the whole water area of the Kiev reservoir. The highest ^{131}I concentrations were observed in the Kiev reservoir on 3 May 1986, the figure being 3.10^{-8} Ci/L. It should be noted that the spatial distribution of radioisotopes in the aquatic environment was very uneven.

From the first days of the accident, monitoring of the radioisotopic content of sediments at the bottom of water bodies both inside and outside the 30 km zone was organized. The radioisotope concentration in sediments on the bottom of individual parts of the Kiev reservoir adjacent to the accident region was 10^{-7}-10^{-8} Ci/kg and 10^{-10} Ci/L in water during the period 10-20 June 1986.

The radiation dose to which the aquatic organisms in the Kiev reservoir were exposed will not have any serious effect on the population level. Significant radiation effects on the aquatic ecosystem may be observed only in the Chernobyl' plant cooling pond.

The hydrobionts populating the cooling pond were subjected to the highest radiation burdens. For some species of water plant, the internal dose received was as much as 10 rad/h, while near the bottom of the cooling pond the average external exposure was 4 rad/h (at the end of May 1986).

According to expert evaluations, exposure levels of up to 10^{-2} rad/d produce no noticeable effect on terrestrial ecosystems. Inside the 30 km zone around the Chernobyl' plant, higher radiation levels were observed at individual parts of the area contaminated by fallout: this may result in significant changes in the state of radiosensitive plant species at these points.

Radiation levels outside the 30 km zone cannot produce a noticeable effect on the species of which the plant and animal associations are composed.

The results obtained are preliminary in nature. Studies of the effects of the Chernobyl' accident on living organisms and ecosystems are continuing.

7.4. Population exposures in the 30 km zone around the Chernobyl' plant

On the basis of an analysis of the radioactive contamination of the environment in this zone, assessments were made of the actual and future radiation doses received by the population of towns, villages, settlements and other inhabited places. Following of these assessments, decisions were taken to evacuate the population of Pripyat' and a number of other inhabited places: 135 000 people were evacuated.

As a result of these and other measures, it proved possible to keep population exposures within the established limits.

The radiological effects on the population in the next few decades were evaluated. The effects will be insignificant against the natural background of cancerous and genetic diseases.

7.5. Data on the exposure of plant and emergency service personnel. Medical treatment

As a result of their participation in measures to combat the accident in the first few hours after its occurrence, a number of plant and emergency

service personnel received high radiation doses (more than 100 rem) and also suffered burns during their efforts to extinguish the fire. All those affected were given immediate medical attention. By 6:00 hours on 26 April 1986, 108 people had been hospitalized and in the course of the day a further 24 persons out of those examined were admitted to hospital. One person died from severe burns at 6:00 hours on 26 April and one of those working at the damaged unit was not found. It is possible that he was working in the area where structures had collapsed and there was high activity.

As a result of the early diagnosis procedures used in the Soviet Union, within 36 hours persons in whom the development of acute radiation syndrome was diagnosed as extremely likely had been identified for immediate hospitalization. The hospitals selected were the clinical institutes in Kiev closest to the site of the accident and a specialized unit in Moscow, the aim being to provide the maximum amount of assistance and expert analysis of the results of examinations.

One hundred and twenty-nine patients were sent to Moscow in the first two days. Of these, in the first three days 84 were identified as suffering from degrees II-IV of acute radiation syndrome and 27 as degree I of acute radiation syndrome. In Kiev there were 17 patients suffering from degrees II-IV and 55 from degree I.

Details of the methods and results of the treatment of these patients is given in the Annex.
The total number of fatalities caused by burns and acute radiation syndrome among personnel stood at 28 at the beginning of July. None of the population received high doses which would have resulted in acute radiation syndrome.

Table 1. Daily release, q, of radioactive substances to the atmosphere
from the damaged unit (excluding radioactive inert gases)*.

Date	Days after the accident	q, MCi **
26.04	0	12
27.04	1	4,0
28.04	2	3,4
29.04	3	2,6
30.04	4	2,0
01.05	5	2,0
02.05	6	4,0
03.05	7	5,0
04.05	8	7,0
05.05	9	8,0
06.05	10	0,1
09.05	14	~0,01
23.05	28	20.10^{-6}

*Release evaluation error +50%. It is composed of the error
of the dosimetric instruments, of the radiometric measurements
of the radioisotopic composition of air and soil samples and
of the error due to averaging the fallout over the area.

**The values of q were calculated on 6 May 1986 taking into
account radioactive decay. (At the time of the release on
26 April 1986, the activity was 20-22 MCi.) For the
composition of the release, see Table 2.

Table 2. Assessment of the radioisotopic composition of the release from the damaged unit*.

Isotope**	Activity of release, MCi		Amount of activity released from the reactor by 06.05.86, %
	26.04.86	06.05.86***)	
^{133}Xe	5	45	Possibly up to 100
^{85m}Kr	0,15	—	..
^{85}Kr	—	0,9	..
^{131}I	4,5	7,3	20
^{132}Te	4	1,3	15
^{134}Cs	0,15	0,5	10
^{137}Cs	0,3	1,0	13
^{99}Mo	0,45	3,0	2,3
^{95}Zr	0,45	3,8	3,2
^{103}Ru	0,6	3,2	2,9
^{106}Ru	0,2	1,6	2,9
^{140}Ba	0,5	4,3	5,6
^{141}Ce	0,4	2,8	2,3
^{144}Ce	0,45	2,4	2,8
^{89}Sr	0,25	2,2	4,0
^{90}Sr	0,015	0,22	4,0
^{238}Pu	$0,1.10^{-3}$	$0,8.10^{-3}$	3,0
^{239}Pu	$0,1.10^{-3}$	$0,7.10^{-3}$	3,0
^{240}Pu	$0,2.10^{-3}$	1.10^{-3}	3,0
^{241}Pu	0,02	0,14	3,0
^{242}Pu	$0,3.10^{-6}$	2.10^{-6}	3,0
^{242}Cm	$0,3.10^{-2}$	$2,1.10^{-2}$	3,0
^{239}Np	2,7	1,2	3,2

*Evaluation error +50%. For explanation, see footnote on Table 1.

**Data on the activity of the main radioisotopes measured in the radiometric analysis.

***Total release by 6 May 1986.

8. RECOMMENDATIONS FOR IMPROVING NUCLEAR POWER SAFETY

8.1. Scientific and technical aspects

In 1985 the Consultative Council for Co-ordination of Scientific Research on Nuclear Safety approved a "List of Priority Tasks", which constitutes the basis for planning experimental and theoretical studies on nuclear safety in the USSR aimed at providing a more detailed justification for safety specifications, evaluating the actual level of nuclear safety and enabling nuclear power plants commissioned before 1985 to be brought up to that level in accordance with the specifications laid down.

After the accident at the Chernobyl' nuclear power plant, the status of theoretical and experimental research on nuclear safety has been reviewed and evaluated, and measures for extending, improving and intensifying it have been developed.

Computer programs for analysing the safe behaviour of nuclear power plants in all possible transient and accident regimes - including conditions not anticipated at the design stage - are being improved, and modelling systems and complexes are being developed.

Research on the possibility of building reactors with passive safety systems - so called "intrinsically safe" reactors, the cores of which cannot be destroyed in any type of accident - is being expanded.

There will be an expansion of research on quantitative probabilistic analysis of safety, on the analysis of risks from nuclear power and on the development of a conceptual and methodological basis for optimizing radiation safety and for comparing radiation hazards with other industrial hazards.

8.2. Organizational and technical measures

The system of monitoring and technical standards in force in the USSR covers all the basic questions of nuclear safety and is continually improving. In 1985 a Summary List and Development Plan for USSR nuclear power regulations and standards was drawn up under the auspices of the State Nuclear Power Supervisory Board (Gosatomehnergonadzor); this co-ordinates and directs the activities of all official bodies involved in the development and co-ordination of the corresponding scientific and technical documents.

A comparison between the existing Soviet document relating to nuclear power station design and operation with similar foreign documents does not reveal any major differences. In general, the nuclear safety standards in force do not require revision. However, more careful verification of their implementation in practice is necessary. The quality of training and retraining of staff needs to be improved and design and construction staff must verify more carefully the quality of plant components during manufacture, assembly and adjustment during commissioning; their responsibility for the subsequent effectiveness and safety of operating nuclear power plants must be increased.

Since the Chernobyl' accident, organizational measures have been taken to improve the safety of nuclear power plants. These can be divided into two stages.

The first stage, which was carried out before a detailed scientific and technical analysis of the course of the accident had been made and in the light of preliminary information from the site, relates to operating nuclear power plants with reactors of the RBMK type and involves operational measures at those plants. The main purpose of these measures is to prevent any recurrence of operating conditions such as those which immediately preceding the accident.

The second stage relates to measures arising from the scientific and technical analysis of the accident and includes steps aimed at improving the safety of nuclear power plants of all types.

The measures that are planned should be adequate to ensure the safe operation of nuclear power plants with reactors of the RBMK type.

For power plants with other types of reactor, the intention is to carry out safety enhancement measures foreseen earlier, which relate mainly to the latest advances in science and technology, operating experience, the possibility of diagnosing the condition of metal in piping and other plant components, automatic process control systems, and so on.

With a view to raising the level of leadership and responsibility for the development of nuclear power and to improving the operation of nuclear power plants, an All-Union Ministry of Nuclear Power has been established.

A whole range of measures to improve State monitoring of nuclear safety is also to be carried out.

8.3. International measures

In the light of the Chernobyl' accident, the Soviet Union, paying due regard to the international nuclear safety work currently being done and desiring to strengthen international security further, has put forward some proposals about the establishment of an international regime of safe nuclear power development and the expansion of international co-operation in this sphere. These proposals are contained in statements by the General Secretary of the Central Committee of the Communist Party of the Soviet Union, M.S. Gorbachev, on 14 May and 9 June 1986.

An international regime of safe nuclear power development would take the form of a system of international legal instruments, of international organizations and structures and also of organizational measures and activities to preserve the health of the public and protect the environment in the context of world-wide nuclear power activities. The establishment of such a regime could be achieved by drawing up international agreements, signing the corresponding international conventions and supplementary agreements, carrying

out joint co-ordinated research programmes on nuclear safety problems, exchanging scientific and technical information, setting up international data banks and banks of material resources needed for safety purposes, and so on.

Funds could be set up, with the direct participation of international organizations, for providing emergency assistance, including that required with the urgent provision of the necessary special medical supplies and dosimetric and diagnostic equipment and instruments and with the supply of food, fodder and other material assistance. It is also necessary to set up a system of early notification and provision of information in the event of accidents at nuclear power plants - in particular, those with transboundary consequences. Attention needs to be paid, moreover, to the question of the material, moral and psychological damage associated with such accidents.

There is yet another aspect of nuclear safety, that of the prevention of nuclear terrorism. A task of overriding importance in this connection is the development of a reliable system of measures to prevent nuclear terrorism in any form.

An important role in the establishment of an international regime of safe nuclear power development must be played by the IAEA.

It is gratifying to note that initial steps have already been taken to carry out the proposals in respect of the establishment of an international regime of safe nuclear power development. Intensive work has begun on preparations for the conclusion of two international conventions, relating to early notification of nuclear accidents and to assistance in the event of nuclear accidents and radiological emergencies. Certain aspects of the expansion of international co-operation, in particular, the IAEA's research programmes on nuclear safety, are being actively discussed.

The proposals for establishment of an international regime of safe nuclear power development are inextricably linked with problems of military détente and nuclear disarmament. The Chernobyl' accident has demonstrated once again the danger of nuclear energy getting out of control and has made people aware of the devastating consequences which would ensue from its military application or from damage to peaceful nuclear installations in the course of military action. It is absurd, at the same time as discussing and solving problems of the safe utilization of nuclear energy, to develop ways and means of applying it in the most dangerous and inhuman way possible.

9.   THE DEVELOPMENT OF NUCLEAR POWER IN THE USSR

Owing to the extremely rapid development of nuclear power, a reduction in the consumption of organic fuel by thermal power plants in the European part of the country is planned in the Soviet Union's energy programme. The contribution of oil to electric power production is to be cut by more than half. Nuclear power should then cover most of the economy's increased electricity requirements. There are plans for the maximum possible use of nuclear fuel for centralized heating and industrial heat supply, and for the creation of nuclear industrial complexes.

The Soviet Union is a pioneer in the peaceful uses of atomic energy. The world's first nuclear power plant, with a uranium-graphite channel-type reactor, has been operating for thirty-two years. The subsequent programme for the establishment in the USSR of so called demonstration power reactors for nuclear power plants with relatively low power capacities made it possible to select the most promising of these for further development and improvement.

The three types of reactor adopted in the USSR for the needs of the country's growing nuclear power programme allow great flexibility and reliability of energy supply, more efficient use of nuclear fuel resources than would otherwise be possible, and are also well adapted to the special requirements of a developing power engineering infrastructure.

The nuclear power plants being built in the USSR are based on the WWER, RBMK and fast breeder reactors. The first two are thermal reactors with light-water coolant. The fast breeder reactors use liquid sodium as coolant and are being built at present with a view to full-scale industrial testing of the technical solutions which have been adopted and the gradual future development of a closed fuel cycle based on plutonium.

At present, nuclear power plants with WWER and RBMK reactors provide the basic nuclear power production in the USSR. The country's installed capacity has reached nearly 30 million kilowatts. The Soviet nuclear power plants are characterized by high operational availability. The utilization factor of the installed capacity at nuclear power plants during recent years has been relatively high.

In accordance with the "Main Lines of Economic and Social Development of the USSR for 1986-1990 and up until the year 2000", it is expected that nuclear power will be developed extremely rapidly in the European part of the country and in the Urals. In 1985, power generation at nuclear plants reached nearly 170 000 million kWh and by the year 2000 it will increase by 5-7 times.

This development means that it will be primarily nuclear plants that provide the additional capacity needed for the energy systems of the European part, relieving us of the need to build new thermal plants burning organic fuel for base load operation.

The Soviet Union is also developing nuclear sources of heat supply based on high-temperature gas-cooled reactors. The construction of safe plants with such reactors will make it possible to produce high-temperature heat for a number of industrial technological processes.

The Soviet Union is actively participating in international collaboration in the nuclear power field, co-operating effectively in the competent bodies and commissions of the United Nations, in the TAEA, the World Energy Conference and others.

The development of nuclear energy in the USSR is being carried out in close co-operation with CMEA countries.

List of principal installations of the main block of the plant

| No.	Installation or item	Measurement unit	Unit weight in tons	No. per NPP unit
	Reactor section			
1	Graphite stack	Assembly	1850	1
2	System "S" metal structures	"	126	1
3	System "OR" metal structures	"	280	1
4	System "E" metal structures	"	450	1
5	System "KZh" metal structures	"	79	1
6	System "A" metal structures	"	592	1
7	System "D" metal structures	"	236	1
8	Drum-type steam separator	pc	278	4
9	Main circulation pump TsVN-8	"	67	8
10	Main circulation pump electric motor	"	33	8
11	Main isolating gate valve (diameter 800)	"	5.7	8
12	Intake header	"	41	2
13	Pressure header	"	46.0	2
14	Distributing group header	"	1.3	44
15	Lower water communication lines	Set	400	1
16	Steam-water communication lines	"	450	1
17	Downcomers (diameter 300)	"	16	1
17a	Primary coolant circuit pipes (diameter 800)	"	350	1
18	Refuelling machine	"	450	1
19	Overhead crane of central hall Q50/10ts	pc	121	1
20	Overhead crane of main circulation pump room Q50/10ts	"	176	2
21	Supply fan, type VDN at level + 43.0	"	3.5	30
22	Exhaust ventilator at level + 35.0	"	3.5	50
23	Controlled leakage tank	"	1.4	2
24	Controlled leakage heat exchanger	"	0.2	2
25	Scheduled preventive maintenance tank	"	25	4
26	Metal structures and pipes of the accident confinement zone	Set	270	1
27	Check valves of the lower water communication line room	"	2.5	11
28	Accident confinement system release valve	pc	2	8
29	Accident confinement system condensers	"	3.7	36
30	Carriage container	"	146	1
31	Crane in gas activity reduction system room Q30/5ts	"	45	1
	Carbon steel pipes	Set	1170	1
	Stainless steel pipes	"	760	1
	Machine room			
32	Turbo-unit K-500-65/3000	pc	3500	2
33	Moisture separator/reheater SPP-500	"	15	8
34	Low-pressure heater	"	37.5	4
35	First stage condensate pump units	"	2.5	6
36	Overhead crane of machine room Q 125 ts	"	211	1
	Carbon steel pipes	Set	3825	1
	Stainless steel pipes	"	1300	1
37	De-aerator	pc	4.5	2
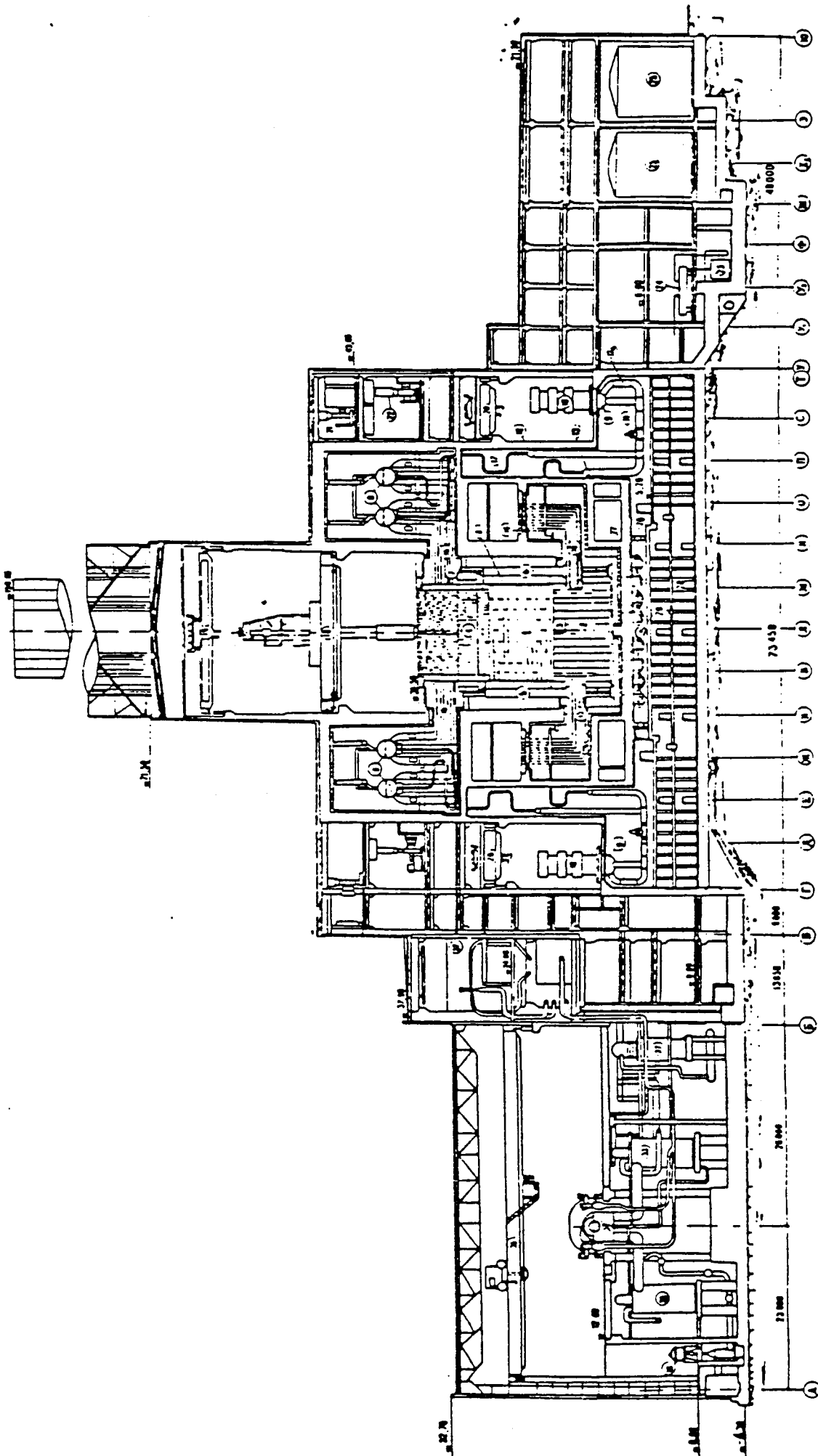
Fig. 1. Cross-section through the main structures of a power plant with an RBMK-1000 reactor (with localization zone)
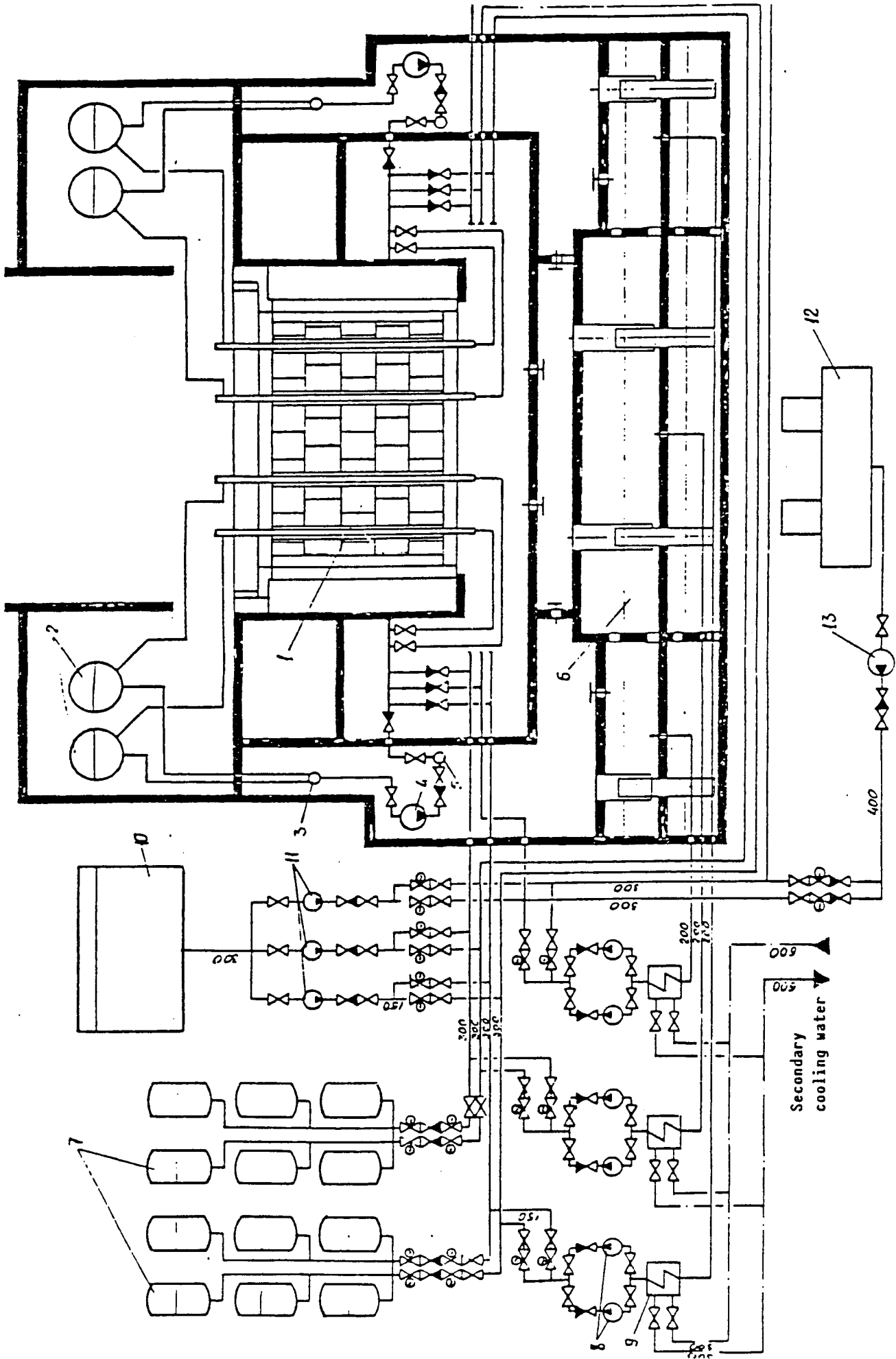
Fig. 2. Schematic diagram of the emergency core cooling system (ECCS):

1. Reactor; 2. Steam separator; 3. Suction header; 4. Main circulation pump; 5. High pressure header; 6. Pressure suppression pond;
7. ECCS vessels; 8. ECCS pumps for cooling the damaged half of the reactor; 9. Heat exchanger; 10. Clean condensate tank;
11. ECCS pumps for cooling the undamaged half of the reactor; 12. Deaerator; 13. Feed pump.
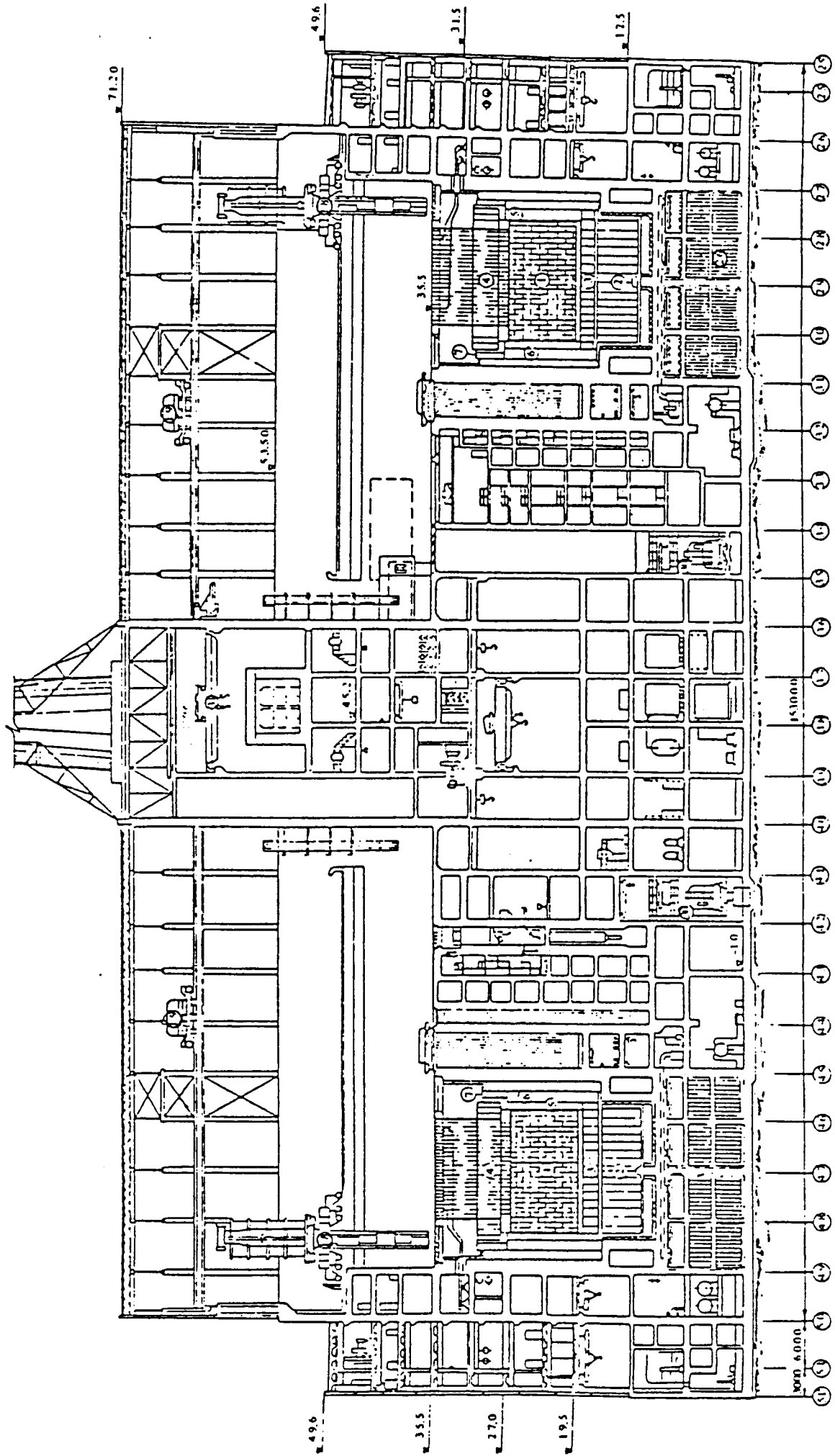
Fig. 3. Cross-section through the reactor sector of a nuclear power plant with an RBMK-1000 reactor (with localization zone)

Fig. $\frac{4}{1.}$

Note: Legend from left side
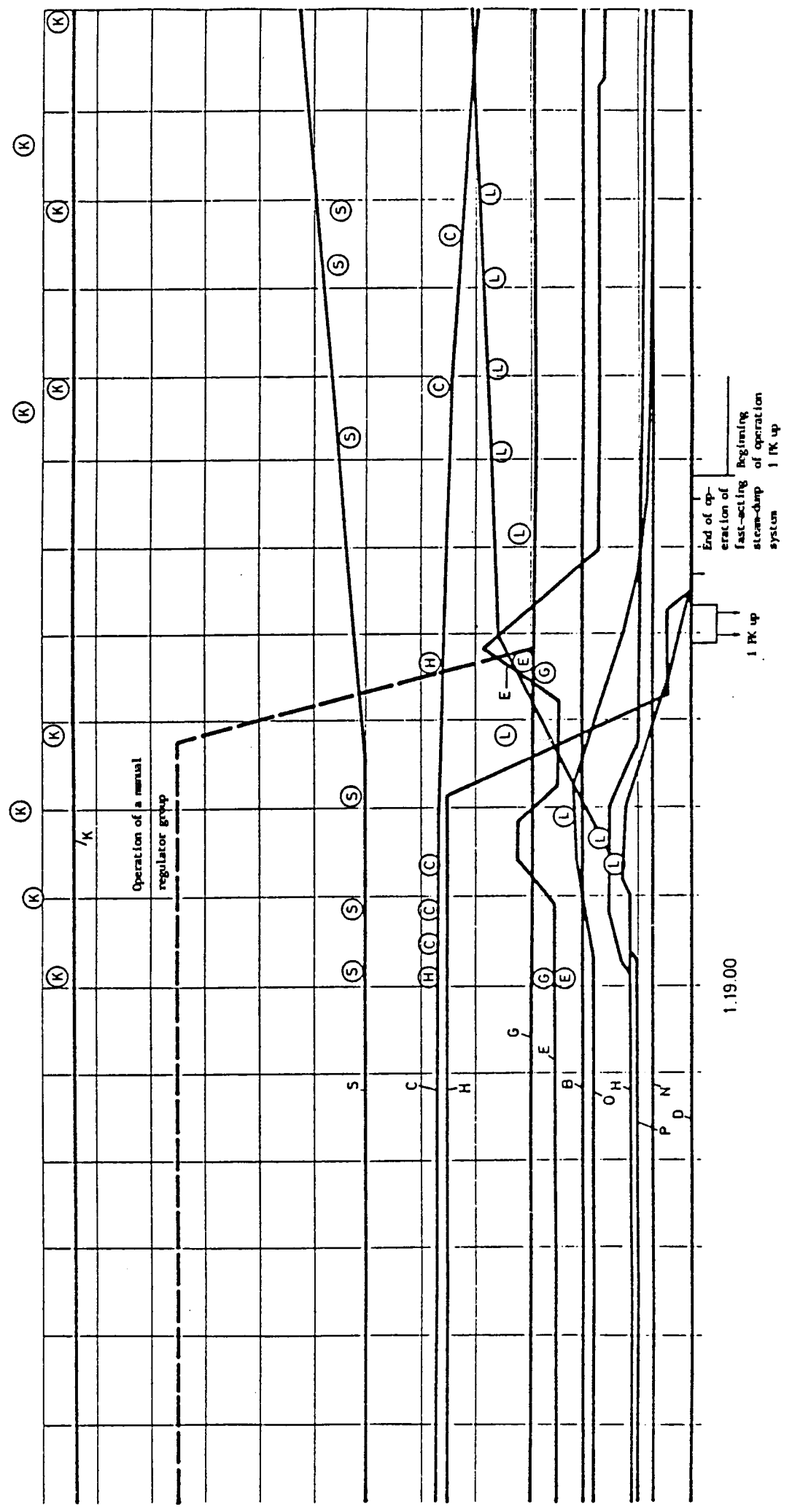of printout missing
because of illegibility
of original.

Fig. 4

2.

1.22

Emergency
1.23 stop valve
closed

Automatic reg-
ulator fault
corrected
Butterfly emer-
gency valve
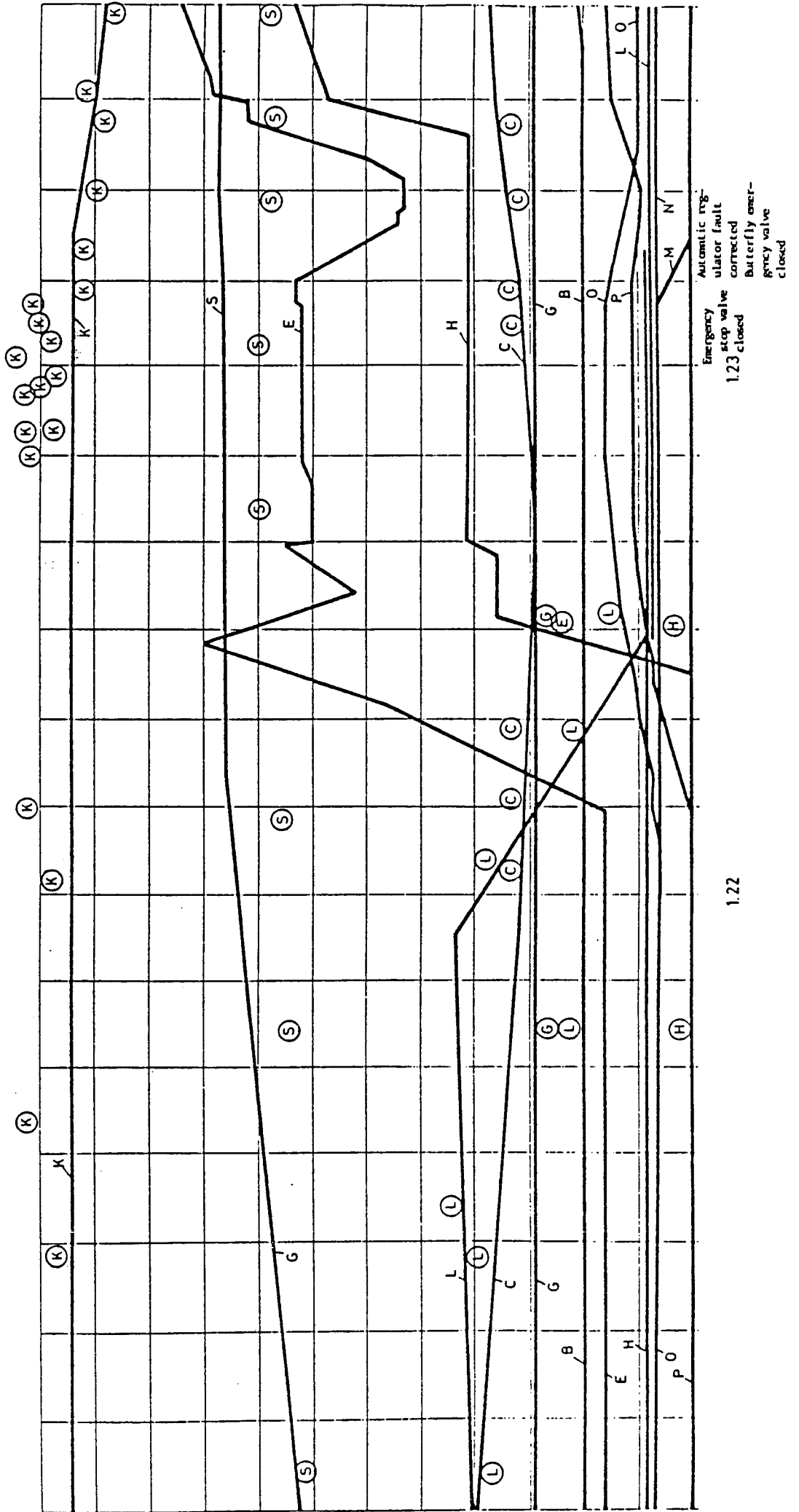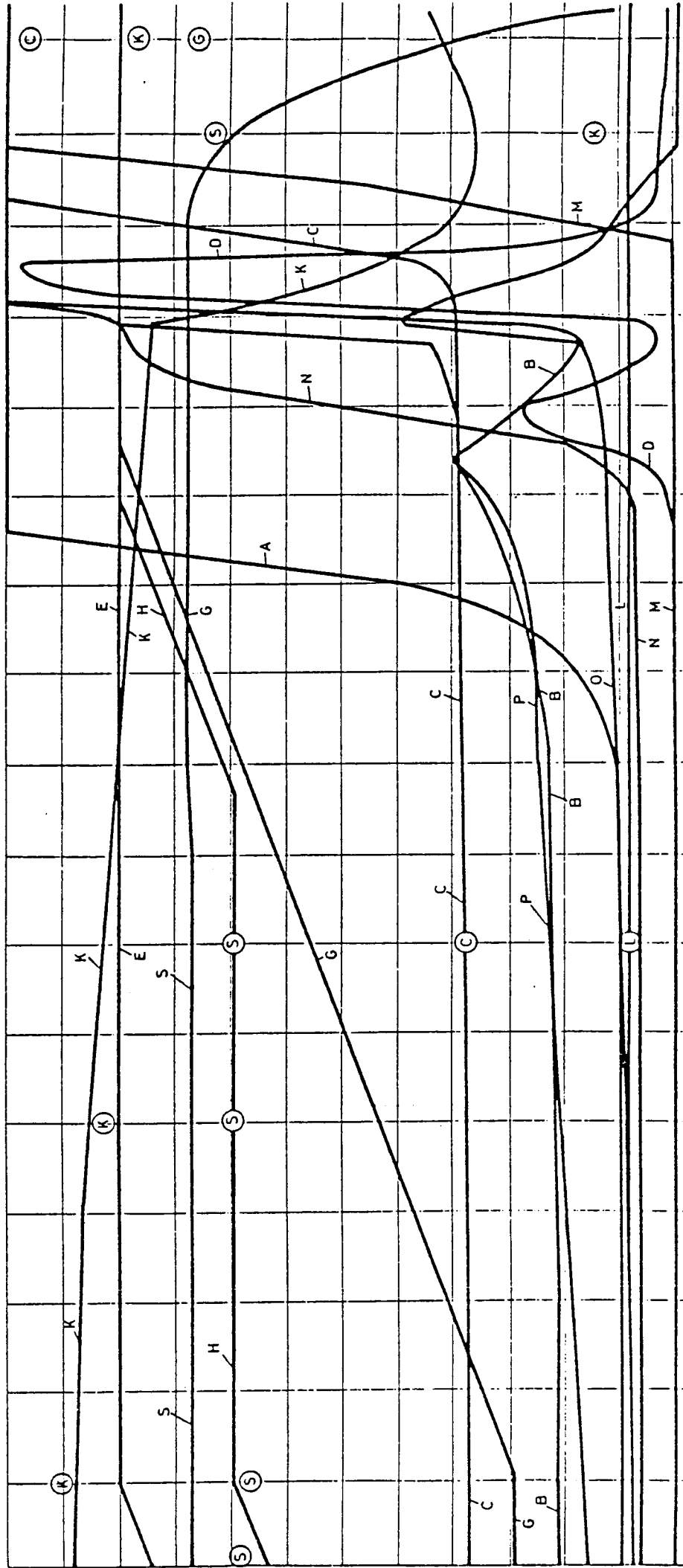closed

Fig. $\frac{4}{3}$

End of
operation
1 PK up

1,23'40"
A3-5

Fault in measurement section of
automatic regulators AR1, AR2
Overpressure in drum separator
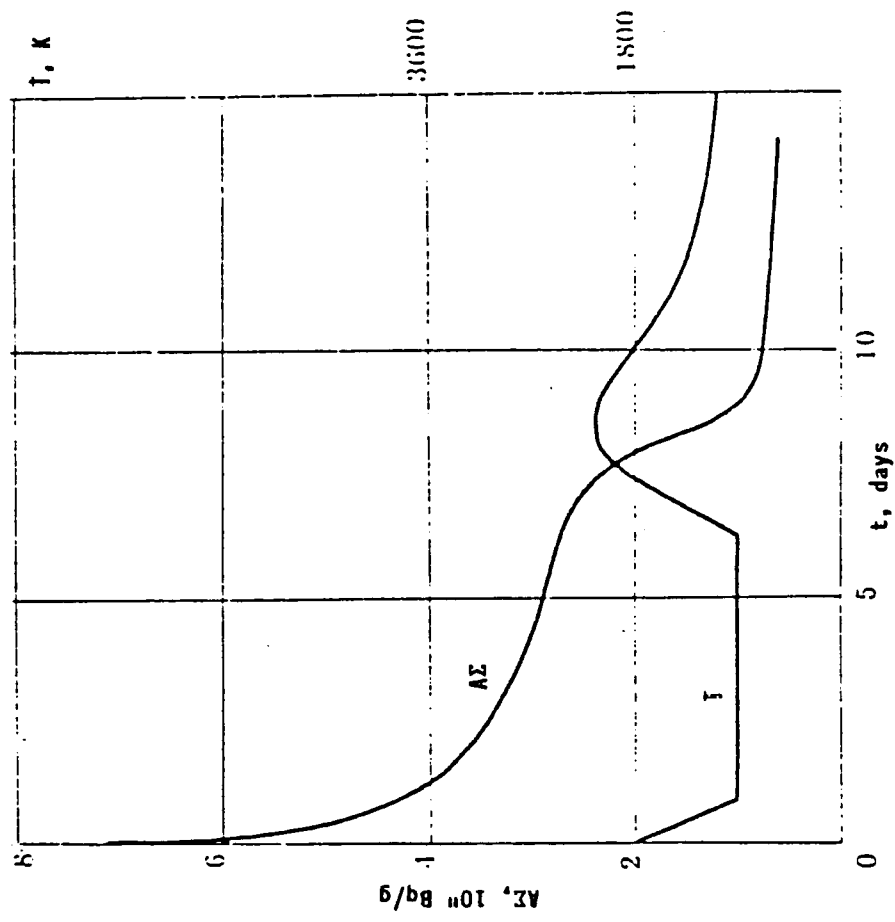Triggering of fast-acting steam-
dump system

Fig. 5. Variation of activity and temperature of the fuel with time

Unit II | Unit III | Unit IV

Metal dividing wall

Engineer's wall

Burial structures

Zone of destruction of
principal structures

Concrete dividing wall - Principal structures

Fig. 6. Diagram showing one scheme for the isolation and
encasement of unit 4 (horizontal cross-section)

71,30

50,00

50,00

37,90

41,15

30,90 29,35

17,15

12,00

5,75

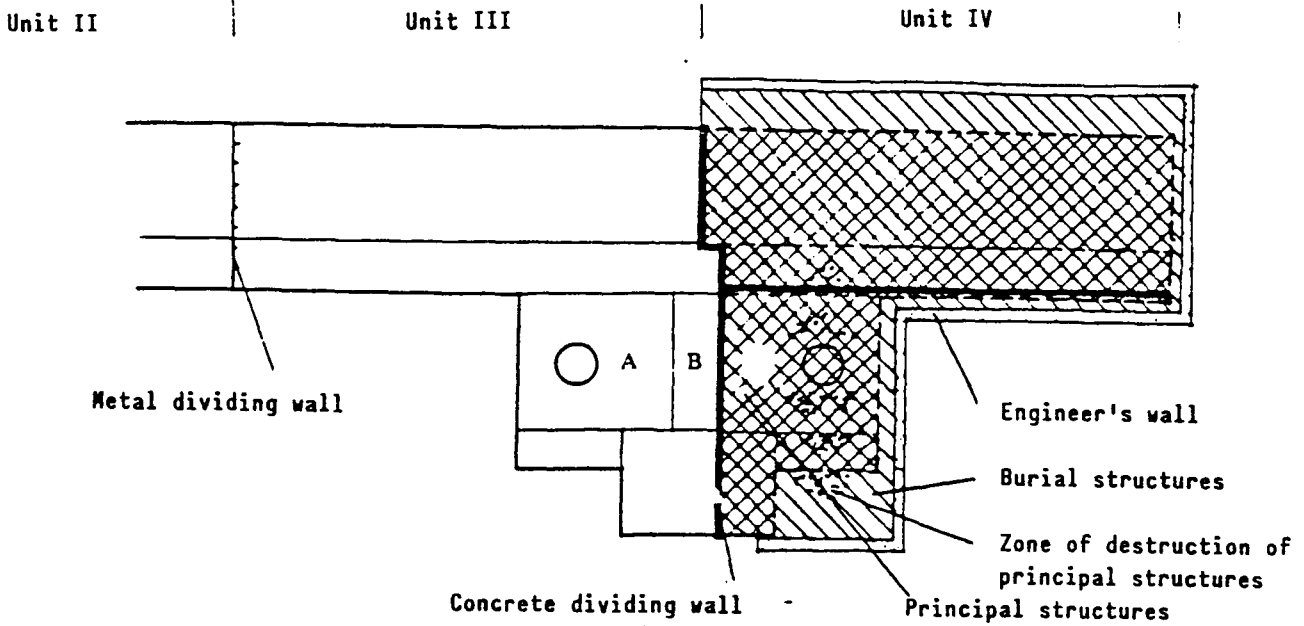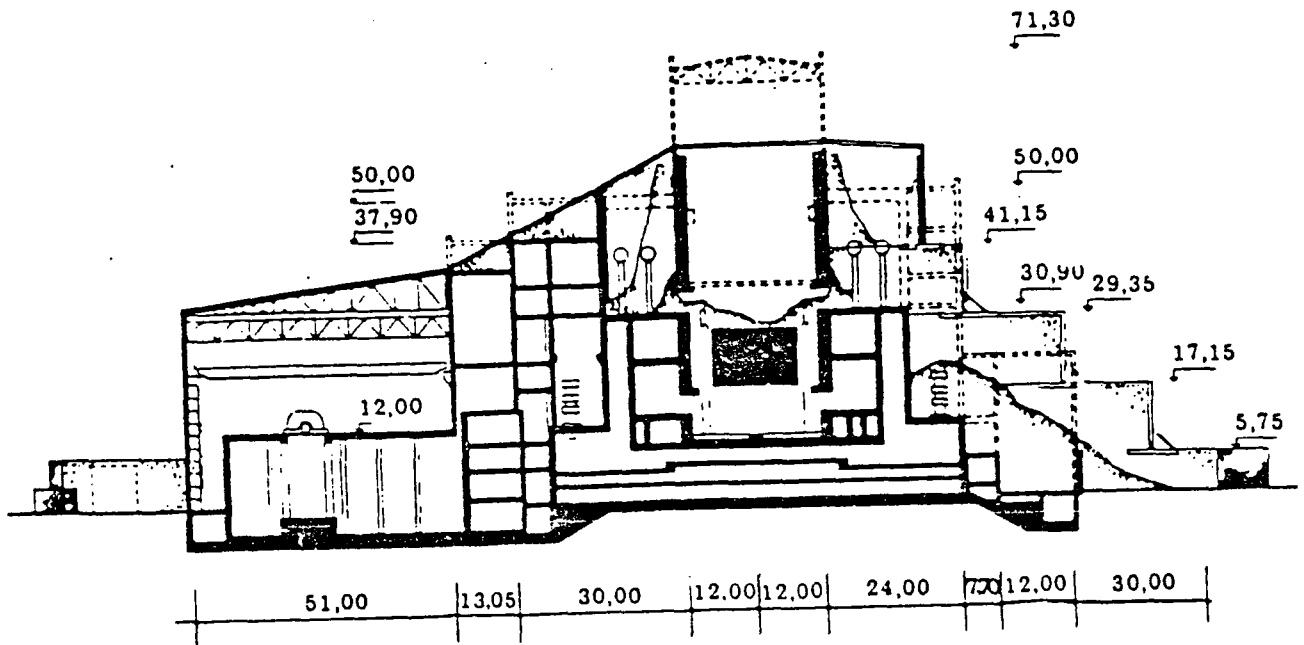| 51,00 | 13,05 | 30,00 | 12,00 | 12,00 | 24,00 | 12,00 | 30,00 |

Fig. 7. Diagram showing one scheme for the isolation and
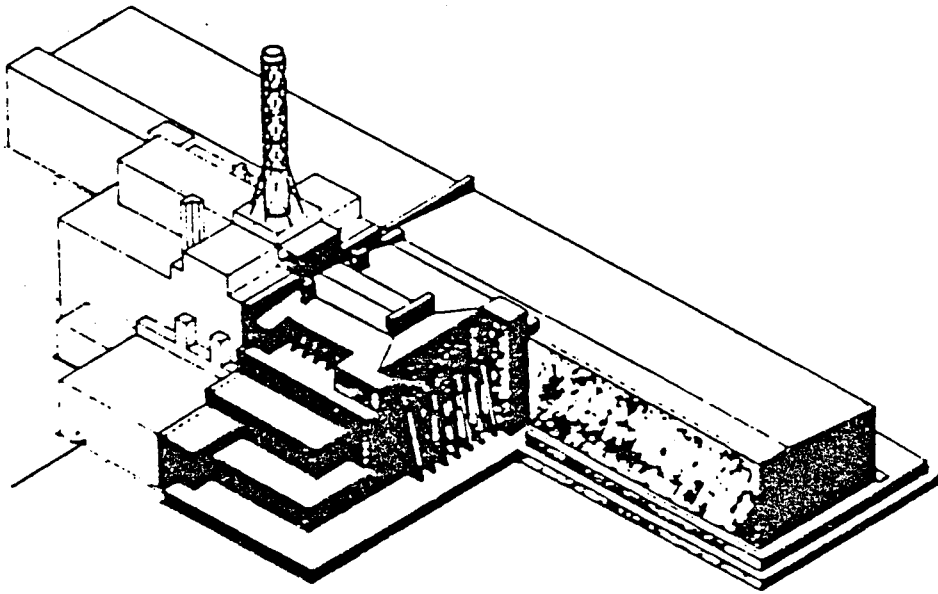encasement of unit 4 (vertical cross-section)

Fig. 8. General view of one scheme for the isolation and encasement of unit 4

USSR STATE COMMITTEE ON THE UTILIZATION OF ATOMIC ENERGY

THE ACCIDENT AT THE CHERNOBYL' NUCLEAR POWER PLANT

AND ITS CONSEQUENCES

Information compiled for the IAEA Experts' Meeting,

25-29 August 1986, Vienna

PART II.   ANNEXES 1, 3, 4, 5, 6

D R A F T

August 1986

A N N E X   1

WATER-GRAPHITE CHANNEL REACTORS AND OPERATING
EXPERIENCE WITH RBMK REACTORS

1.   Water-graphite channel reactors and operating experience with RBMK reactors.

1.1.   Water-graphite channel reactors use ordinary water as a coolant and graphite as a moderator.   The distinctive features of channel reactors are: the absence of a pressure vessel, the relative simplicity of the design, the extensive scope for channel-by-channel inspection and control, the possibility of refuelling while the reactor is operating, the flexibility of the fuel cycle, and the practically unlimited potential for increasing the power by means of standard structural elements.

        The first power reactor in the USSR was a channel-type reactor – the water-graphite reactor of the First Atomic Power Station, which had an electrical capacity of 5 MW and was started up in June 1954 at Obninsk, near Moscow.

        The experience accumulated in the construction and operation of the First Atomic Power Station was utilized in planning the Beloyarsk Nuclear Power Plant (NPP) (1964, 300 MW).

        The further development of the water-graphite reactor concept in the USSR led to the construction of the high power channel-type boiling-water reactor RBMK-1000 with an electrical capacity of 1000 MW, which, along side the WWER-1000 reactor, became the basic reactor for large-scale nuclear power production in the USSR.

        The commissioning of the first RBMK-1000 reactor at the Leningrad NPP in 1973 marked the inception of a series of reactors of this type.

        The broad programme of construction of RBMK-1000 reactors carried out in the 1970s led to the commissioning, over the period 1973 to 1985, of 14 reactors (4 reactors each at the Leningrad, Kursk, and Chernobyl' NPPs and 2 at the Smolensk NPP) with a total installed electrical capacity of 14 GW. In each new generation of reactors, improvements aimed at increasing their reliability and safety were introduced.

The knowledge and experience gained from operating generating units with RBMK-1000 reactors revealed their intrinsic safety margins and made it possible to design, on the basis of this type of reactor, the even more powerful RBMK-1500 reactor, with an electrical capacity of 1500 MW, which was brought into service in 1983 at the Ignalinsk NPP and by early 1985 reached its design output.

Channel-type reactors have advantages which facilitate the solution of safety problems. These advantages include:

- their convenience for carrying out individual checks on the state of the fuel elements and fuel assemblies and on channel integrity;

- the possibility of operationally exchanging failed fuel assemblies without shutting down the reactor;

- the reduced hazard from primary circuit pipe breaks due to the increased number of coolant loops and the corresponding reduction in tube diameters;

- the design option of increasing the unit power of the reactor without making the emergency core cooling system more complicated.

On the other hand, certain specific features of channel-type graphite reactors cooled with boiling water call for fundamentally new solutions to be found in developing the safety systems. These features include, in particular:

- the large steam volume in the coolant circuit, which considerably slows the rate of coolant pressure reduction after an accidental pipe break;

- the potential occurrence of a positive void reactivity effect, which to a large extent governs the behaviour of the neutron-flux-determined power of the reactor in emergencies due to interruptions of the coolant circulation through the core;

- the large amount of thermal energy accumulated in the metal structures and graphite stack of the reactor, which affects the decline in thermal power after a response of the safety system (scram).

1.2. As of now, the cumulative service life of RBMK reactors within the nuclear power system is approaching a total of 100 reactor-years.

On the basis of analysis and generalization of this operating experience, the various reactor components and plant systems and operating regimes are continually being updated and improved. As a result, a large number of measures have been developed and introduced with a view to increasing the reliability and operating safety of nuclear power plants. The most important of these measures are the following:

- modernization of the design of the isolating and regulating valves, the ball detectors of the flowmeters and the fuel channel shut-off plugs;

- optimization of the routing of the steam/water piping and the steam discharge tubes of the drum separators;

- improvement of the drum separator internals;

- improvement of the main circulation pumps and their auxiliary systems;

- introduction of prognostic programmes for operational calculations, of programmes for recording the state of equipment during emergencies and of diagnostic programmes for monitoring the process systems;

- development and introduction of local automatic control systems and local emergency protection systems based on in-core sensors;

- justification and experimental operation at one of the generating units of fuel assemblies with an initial enrichment of 2.4%;

- development of afterheat removal systems allowing extended continuous repairs of reactor equipment and components.

These measures and others carried out at the generating units have ensured the reliable and safe operation of nuclear power plants with RBMK reactors, some statistics on which are given in Table 1.2 showing the production of electrical energy by nuclear power plants over the operating period 1981-1985 and the installed capacity factor for 1985.

The maximum values obtained for the installed capacity factor in 1985 were 91% at unit 4 of the Leningrad NPP, 90% at unit 2 of the Chernobyl' NPP and 87% at unit 1 of the Leningrad NPP.

Generalization from the operating experience accumulated and from the scientific research and development work carried out has indicated some ways of increasing the effectiveness of RBMK generating units, including:

increasing the power of existing generating units, improving and optimizing the operating regimes of the units, introducing automatic reactor and equipment protection systems, improving the conditions under which repairs are carried out on the reactor plant and increasing the maintainability of its individual components.

As is well known, the limiting parameters for the power of RBMK reactors are the fuel temperature, the temperature of the graphite stack and metal structures, and the burnout ratio of the fuel channels. At existing reactors, these parameters are lower than the maximum permissible. For example, at the nominal thermal power of the reactor the maximum power of a fuel channel is about 2600 kW, where 3000 kW would be permissible, and the maximum temperature of the graphite stack is 923 K (650°C), where 1023 K (750°C) would be acceptable; the maximum temperature of the metal structures is 573 K (300°C), where 623 K (350°C) would be allowed, and the burnout ratio is not less than 1.35. The main items of equipment in the turbine room of RBMK generating units (turbogenerators, unit transformers, de-aerators, condensate and feed pumps) also have a safety margin of ~10% with respect to power.

These demonstrated safety margins have made it possible to justify operating the generating units at a higher power level, while the full-scale tests carried out in several generating units at powers of up to 107% of nominal have confirmed this possibility.

Table 1.1. The main technical characteristics of nuclear power plants (NPPs) with RBMK-type reactors are given in Table 1.1.

Characteristics	RBMK-1000	RBMK-1500
Electrical power (MW)	1000	1500
Thermal power (MW)	3200	4800
Steam output (t/h)	5800	8800
Steam parameters before turbines:		
Pressure (kgf/cm^2)	65	65
Temperature (°C)	280	280

Table 1.2. Performance data for the operation of NPPs with RBMK-1000 reactors.

Performance data	Leningrad NPP	Kursk NPP	Chernobyl' NPP	Smolansk NPP
Installed capacity as of 1/1/86 (MW)	4000	4000	4000	2000
Electricity production for the period 1981-1985 (10^9 kW.h)	140.4	82.4	106.6	23.4
Installed capacity factor for 1985 (%)	84	79	83	76

ANNEX 3

ELIMINATION OF THE CONSEQUENCES OF THE ACCIDENT AND DECONTAMINATION

3.   ELIMINATION OF THE CONSEQUENCES OF THE ACCIDENT AND DECONTAMINATION

3.1.   Progress and prospects for decontamination and startup of the first, second and third units

    The surfaces of the equipment and compartments of the nuclear power plant were contaminated mainly through the ventilation system which continued to operate for some time after the accident at the fourth unit and also as a result of the spread of radioactive dust from the site of the plant. The highest levels were recorded for separate horizontal sections of the surfaces in the turbine building (up to 10^6 β-part/(cm^2/min), since it was contaminated for a prolonged period through the damaged roof.

    The γ-radiation dose rate in the contaminated compartments of the first and second units on 20 May 1986 was 10-100 mR/h and in the turbine building 20-600 mR/h.

    The washable nature of the materials (plastic, steel, concrete and various coverings) and the nature and levels of the surface contamination were taken into account when choosing the composition of the decontaminating solutions.

    The spraying decontamination method was widely applied in the washing process making use of washing machines and fire hydrants. Some of the compartments were washed manually by wiping with a rag soaked in decontaminating solutions. The steam ejection method was also employed as well as dry decontamination methods using polymer covers.

    The decontamination processes were monitored by direct measurement of the gamma background from the washable surfaces and by the smear method. As a result of decontamination, the contamination levels of the surfaces of the compartments and equipment were on the whole reduced to the norms established by the Radiation Safety Standard No. 76 and the Basic Health Regulations No. 72/80:

    For service compartments - 2000 β-part/(cm^{2}min);

    For semi-service compartments - 8000 β-part/(cm^{2}min).

    After decontamination, the gamma radiation levels dropped by a factor of 10-15 and the γ-radiation dose rate for the compartments of the first and second units was 2-10 mR/h.

3.2. Progress and prospects for decontamination of the power plant site

During the accident, radioactive material was scattered over the site of the plant and also fell on the roof of the turbine building, the roof of the third unit and on metal support pipes.

The plant site, the walls and the roofs of the buildings also had considerable contamination as a result of the fallout of radioactive aerosols and radioactive dust. However, the overall gamma background at the site consisting of radiation from the destroyed fourth unit greatly exceeded the radiation levels from the contaminated site and buildings. It should be noted that the contamination of the site was uneven.

In order to reduce the spread of radioactive contamination in the form of dust, the site, the roof of the turbine building and the sides of the roads were treated with rapid polymerizing solutions to reinforce the upper layers of the soil and to prevent the formation of dust.

In view of the complex nature of the work the nuclear power plant site was divided into zones for the purposes of decontamination.

The sequence of work carried out for each zone was based on the following criteria:

- The need for staff to work at facilities inside the zones;

- The principle "from dirty to clean" and taking account of wind roses;

- The need for subsequent work involved in startup of the units.

Decontamination in each zone was carried out in the following order:

- Removal of debris and contaminated equipment from the site;

- Decontamination of roofs and external surfaces of the building;

- Removal of a layer of soil, 5-10 cm thick, and transportation of it in containers to repositories (the solid waste storage vault of the fifth unit);

- Laying, where necessary, of concrete slabs or filling in with clean soil;

- Covering of slabs and non-concreted parts of the site with film-forming material;

- Restriction of access to the treated site.

The total number of sites treated ranged from 15 000-35 000 m^2 per 24 hours. As a result of these measures the overall gamma background in the area around the first unit was reduced to 20-30 mR/h. The fact that the residual background was caused mainly by external sources demonstrates that the decontamination of the site and buildings was fairly effective. However, significant improvement in the radiation conditions over the whole site of the nuclear power plant and particularly in the areas around the third and fourth units will be possible only after the destroyed reactor has been enclosed.

3.3. Progress and prospects for decontamination of the 30-km zone and its return to economic activity

The formation of the radioactive trail following a single release of effluent ends after about a year. After this period there is a significant redistribution of the radionuclides among the elements of the landscape in accordance with the characteristics of the relief. The most intensive redistribution of radioactivity (secondary transfer) occurs during the first 3-4 months after the release, particularly during the course of active biological and atmospheric processes (growth, development and drying off of plants, rains and winds). The loosely attached part of the radioactive substances which have settled on the surface of the soil and vegetation are subject to considerable redistribution. In coniferous forests such redistribution ends only after 3-4 years (after complete renewal of the needles).

For these reasons the radiation conditions within the 30-kilometre zone will continue to change significantly for 1-2 years particularly in regions with a high contamination level gradient.

Therefore the measures taken to decontaminate populated areas generally result only in a temporary improvement in the radiation conditions.

All this leads one to conclude that the evacuated population can only return to the area after the radiation conditions over the whole territory of the contaminated zone have stabilized (when releases from the reactor have ceased, the industrial site has been decontaminated and the radioactivity has been fixed over the territory where there is an increased contamination level). Conditions will stabilize most rapidly in regions of the zone with a low contamination level gradient (for example in the northern and southern projections of the radioactive path).

In order to decide whether agricultural production can be resumed and the evacuated population can return, it is necessary to have reliable information about the concentrations of long-lived radionuclides (strontium-90 caesium-137) in the soils and the crops cultivated on those soils. Soil samples have now been taken from all the fields at the collective and state farms in the region. When these samples have been analysed, cartograms will be drawn up showing the contamination of the agricultural lands and indicating the radionuclides.

Other radionuclides making up the contamination (zirconium-90, niobium-95, ruthenium-103 and 106, cerium-141 and 144, caesium-134, barium-140, strontium-89) and accounting for more than 90% of the total activity will not be limiting factors in the future either because they have short half-lives or because they are not easily absorbed from the soil by plants.

In principle the contaminated lands could be reused for agricultural purposes. General organizational and technical principles for agricultural management under such conditions have been worked out and numerous recommendations established for specific aspects. Since the agricultural conditions of Poless'ye are very specific and the nature of the radioactive contamination has not yet been studied in detail, specific evaluations can be made only when the specific data have been obtained. Resumption of agricultural activity in these areas requires:

(a) The re-organization of agricultural specialization in accordance with the contamination levels of the lands used; exclusion of production and produce from directly entering human food; primary seed production, industrial production and animal fodder production;

(b) The implementation of special measures aimed at the durable fixation and consolidation of radionuclides in a form which is inaccessible to plants for a prolonged period with subsequent cultivation by applying sorbents (clayey suspension, zeolites) to the upper contaminated layer of soil;

(c) The implementation of special decontamination measures involving the removal of the contaminated surface layer of turf directly by mechanical means or after consolidation using chemical agents (latex emulsion SKS-65 gp).

The measures taken to enable the land to be reused for agricultural purposes will be differentiated according to the time and level of contamination of the territory.

In the evacuation zone and in the strict control zone, agricultural harvesting work is being carried out as normal in accordance with the special measures worked out together with the State Agricultural Programme of the USSR and Ukranian SSR and the USSR Ministry of Health.

With regard to the surface contamination of vegetation and soils in 1986, the basic special requirements for the organization and the technological aspects of the work can be summarized as follows:

(a) To reduce to a minimum the mechanical cultivation of soils with increased dust formation;

(b) Grain and industrial crops are being harvested by direct combine harvesting and depending on the actual contamination levels of the produce are being used (after being stored) for food purposes, fodder, seed and industrial reprocessing;

(c) A compulsory requirement after the harvesting of perennial grasses and winter crops is the introduction of lime, mineral fertilizers and sorbents to increase soil fertility and reduce the entry of radionuclides into agricultural production.

When considering the fate of the contaminated forests one has to bear in mind their well-known role as absorbents and accumulators and conservers of moisture in forest-steppe and steppe regions.

Research has also shown that in conditions of radioactive contamination, forests also act as accumulators of radioactive substances, first in the crown then in the forest litter. The radionuclides fixed in the litter will for a long time be excluded from the radiation chains.

Therefore at present, the majority of experts believe that the best way of dealing with the contaminated forests is to increase the fire-prevention service.

At present, special agrotechnical and decontamination measures, which are designed to enable the contaminated lands to be reused for economic purposes, have been developed and are being implemented based on the evaluations of the contamination conditions of the soil and vegetation cover in the 30-km zone. These measures include changing the traditional system of soil cultivation in this region, the use of special dust-suppression compounds, changing the harvesting and crop processing methods and so on.

The level of radioactive contamination of houses and buildings in the countryside in the 30-kilometre zone fluctuates within significant limits. Typical building materials are bricks, wood (boards) both unpainted and painted, where the condition of the paint varies, slate and roofing iron.

Decontamination was carried out by spraying the surfaces with decontaminating solution at a flow rate of 10-15 L/m^2. Automatic filling machines were used.

As a result of decontamination, the radiation dose rate from the buildings dropped to the background levels for this region generally, the β contamination did not exceed 1000 β-part./(cm^2 min).

After washing the buildings, the radioactive contamination of the earth along the walls increased by 2-2.5 times and therefore this earth was dug over or removed with bulldozers and taken away.

The transport vehicles were decontaminated by the spraying and steam ejection methods using the above solutions.

ESTIMATE OF THE AMOUNT, COMPOSITION AND DYNAMICS OF THE DISCHARGE OF RADIOACTIVE SUBSTANCES FROM THE DAMAGED REACTOR

4.1   Amount of radioactive substances discharged from the reactor

The initial information for estimating the amount of these substances discharged from the damaged reactor consisted in the material obtained from aerial gamma-ray photography of the region of the Chernobyl' plant and the national territory carried out by the UNKhV with helicopters of the Air Force and the USSR State Committee on Hydrometeorology and Environmental Protection (Gaskomgidromet) as from 1:05 a.m. on 25 June 1986.

In order to determine the amount of radionuclides, the data from the aerial gamma-ray photography were plotted on a map of the district, isodose lines were drawn and the areas encompassed by these curves were calculated. The results of the estimates of this amount, as at 26 June 1986, are given in Table 4.1 in absolute and relative values.

The data of this table show that the total radioactivity of the fission products discharged from the damaged reactor and which had settled on the ground in a 30-km zone, amounted to 8-14 MCi. An analysis of the findings obtained showed that at the time the intense discharge of fission products from the reactor ceased on 6 June 1986, the amount of radionuclides present in the 30-km zone was approximately 20 MCi. It should be noted in particular that more than half of this activity is found in a zone with $R > 20$ mR/h, in an area consisting all told of 17% contaminated land and including the grounds of the Chernobyl' plant.

According to an analysis of Goskomgidromet's aerial gamma-ray photography, beyond the limits of the special zone, the activity of the radionuclides settling on the ground was 10-30 MCi. It follows from an analysis of the data that the total activity of the radionuclides released from the disabled reactor to the environment does not exceed 50 MCi, i.e. it represents approximately 3-4% of the total activity of the fission products in the reactor of the fourth unit of the Chernobyl' plant on 6 May 1986.

An independent estimate of the amount of fission products discharged from the damaged reactor was made by experts of the V.G. Khlopin Radium Institute. The amount of fuel present in these zones was determined on the basis of scanning with a collimated detector from a helicopter flying over the production area at a height of 300 m, analysis of samples taken in the 30-km zone and use of correlation ratios between the gamma activity of Ce and the alpha activity of Pu. This value is somewhat higher than the one obtained from the analysis of the isodose data. The relative values for the distribution of fission products over the production area and on the roof of the Chernobyl' power plant building are given in Fig. 4.1.

4.2. Composition of fission products of uranium and other radionuclides released from the damaged reactor

As the initial information for estimating the composition of the radionuclides released by the damaged reactor, use was made of radiometric investigations of aerosol samples and soil specimens carried out by the V.G. Khlopin Radium Institute and the I.V. Kurchatov Atomic Energy Institute in the period from 6 to 30 May 1986. These data led to the conclusion that the composition of the fission products (except for gaseous I, Te, Cs) discharged by the damaged reactor is similar to that of the fission products in the fuel in the reactor itself. This is confirmed, in particular, by the averaged data from studies of the soil and grass cover in the zone from 1.5 to 30 km from the reactor. These are shown in Table 4.2.

In the 30-km zone, dozens of soil samples were examined for their content of transuranium elements with respect to alpha radiation. The radioactivity of the samples ranged from 2 to 2000 Bq/g and was dependent on 90% ^{242}Cm. Approximately 10% of the alpha radioactivity was associated with isotopes of masses 238, 239 and 240. The radioactivity of ^{238}Pu is about 40-70% relative to the sum of the radioactivities of the nuclides ^{239}Pu and ^{240}Pu.

The soil sample in a radius of 1.5 km having the relatively largest concentration of transuranic elements may be considered one found in a discharge in a south-western direction at the end of a sector with a contaminated forest. The results of an analysis of this sample, taken on 8 May 1986 on the surface of a road, are shown in Table 4.3. The total alpha radioactivity of the sample is 1.3 x 10^4 Bq/g.

The radioactive composition of alpha emitters in the air samples (filters) and soil samples, according to the data of the I.V. Kurchatov Atomic Energy Institute are shown in Tables 4.4 and 4.5, and according to the data of the Khlopin Radium Institute in Table 4.6.

Investigations of the aerosol composition of air samples (with pumping through a filtering tissue) also confirm the transport via airborne dust of both volatile and slightly volatile chemical elements without distinct fractionation, with the exception of iodine, ruthenium and tellurium. The aerosol samples were taken at a height of 200 m above the damaged reactor and at a height of 3 m above the earth at 10 fixed points in the production area. Table 4.7 shows the results of the aerosol measurements at a height of 200 m, and Table 4.8 at a height of 3 m. Points 3 and 10 of Table 4.8 refer to the northern direction from the Chernobyl' power plant building and points 8 and 9 to the southern direction. All four points are located on a line running approximately 150 m more to the east of the damaged reactor (see Fig. 4.1).

The data of Table 4.7 indicate a sharp drop in specific aerosol activity after 6 May 1986, which is evidence of the dynamics of fission product discharge from the damaged reactor with time. Up to 7 May 1986, the reactor was a source of elevated release of radionuclides, but after 6 May 1986 it ceased being in any degree the determining factor in the formation of aerosol radioactivity above the production area. This formation was determined initially by processes of dust formation and secondary wind transport of radionuclides over the production area as a whole (Table 4.9).

The concentration of radioactive aerosols at a height of 200 m was the same as that at a height of 3 m (data of 9 and 11 May for 200 m and of 12 May for 3 m). After 12 May, the concentrations of aerosols at a height of 200 m become approximately 100 times lower, but at 3 m above the production area they subsequently showed little change. This can be seen by comparing the data of Table 4.8 with those of Table 4.9. The latter gives the results of a determination of aerosol concentrations at a height of 3 m above the production area, carried out on 22 May 1986 at points located relatively close to the points referred to in Table 4.8 (see Fig. 4.1).

The compositions of the air and fallout samples showed the presence of "hot" particles enriched primarily in radionuclides of one type. Fig. 4.2 and 4.3 show the results of measurements of the radionuclide composition of such particles. As can be seen, there are particles containing practically nothing but Cs or Ce. There is a tenfold increase in the content of ^{140}Ba over the theoretical value.

4.3. Dynamics of radionuclide discharge from the damaged reactor

The material used as initial information for analysing the dynamics of the discharge of radionuclides from the damaged reactor was data from systematic studies of the radionuclide composition of aerosol samples taken above the fourth unit of the Chernobyl' plant on 26 April 1986. The results of the investigations are shown in Table 4.10 and in Fig. 4.2.

Analysis of these data led to the conclusion that the release of radionuclides beyond the limits of the damaged nuclear power plant unit was a process extended over time, consisting of several stages. The dynamics of the discharge process are characterized especially prominently by the data of Table 4.11, whch presents non-dimensional values of fission-product release (normalized in terms of ^{131}I) in time.

In the first stage, the mechanical discharge of dispersed radioactive fuel took place as a result of an explosion in the reactor. The composition of radionuclides at this stage of discharge corresponded approximately to the composition of fission production in spent fuel, but enriched n volatile nuclides of iodine, tellurium and caesium.

In the second stage, from 26 April to 2 May, the capacity for discharge beyond the limits of the damaged unit decreased owing to the measures undertaken to terminate the burning of graphite and the filtration of substances emerging from the core. In a first approximation, the reduction in the power of discharge in this period can be represented in the form

$$Q(\tau) = Q_0 e^{-0.5\tau} \qquad , \qquad\qquad (4.1)$$

where Q_0 is the power of discharge immediately after the explosion (Ci/d);

τ is the time after the beginning of the damage (days).

In this period the composition of radionuclides in the discharge was also similar to their composition in the fuel. At this stage, finely disperse fuel escaped from the reactor directly with a flow of hot air and with products from the burning of graphite.

The third stage of release was characterized by a rapid increase in the power of radionuclide discharge beyond the limits of the reactor unit. In the initial part of this stage it was primarily the escape of volatile components, especially iodine, that was observed; subsequently, the composition of the radionuclides again resembled that of their composition in spent fuel (on 6 May 1986). The power of fission product discharge in the third stage can be described by the expression

$$Q(\tau) = const.\ e^{\alpha\tau}, \qquad\qquad (4.2)$$
where $\alpha = (6-8) \times 10^{-2}$ 1/h.

The fact that the discharge was of this nature was apparently caused by the heating of the fuel in the core to a temperature above 2000°C due to residual heat release. As a result of temperature-dependent migration of fission product, and also possible carbidization of uranium dioxide, there was a leak of fission products from the dioxide and their escape either in aerosol form or in products of the burning of graphite (graphite particles).

The final – fourth – stage, starting on 6 May, is characterized by a rapid decrease in the escape of fission products from the fuel and virtual termination of discharge (Table 4.13), which was a consequence of the special measures taken, by the formation of more refracting fission products as a result of their interaction with the materials introduced.

Main conclusions:

1. The total release of radioactive substances (not including radioactive noble gases) was about 50 MCi, which represents 3.5% of the total amount of radionuclides in the reactor at the time of the accident. These data were calcualted on 6 May 1986, with allowance for radioactive decay.

2. The composition of radionuclides in the discharge due to the accident was notable for its elevated content of volatile iodine and tellurium.

3. Generalized quantitative information concerning the variation in power of discharge with time and composition of the radionuclides released from the damaged reactor are given in Table 4.13 and 4.14 and in Fig. 4.4.

Table 4.1 Estimate of tne amount ot radionuclides on the ground in a
30-km zone of the region of the Chernobyl plant as of 26 June 1986

Point No.	Zone with R, mR/h	Area, KM^2	Activity	
			Absolute, MCi	Relative, %
1	R > 20	870	5-8,7	63,0
2	10 < R ≤ 20	480	0,8-1,4	10,2
3	5 < R ≤ 10	1100	1÷1,7	10,8
4	3 < R ≤ 5	2780	1,3÷2,2	16,0
	Total:	5230	8÷14	100,0

№ 2B
⊗

№ 4B
⊗

№ 3
⊛

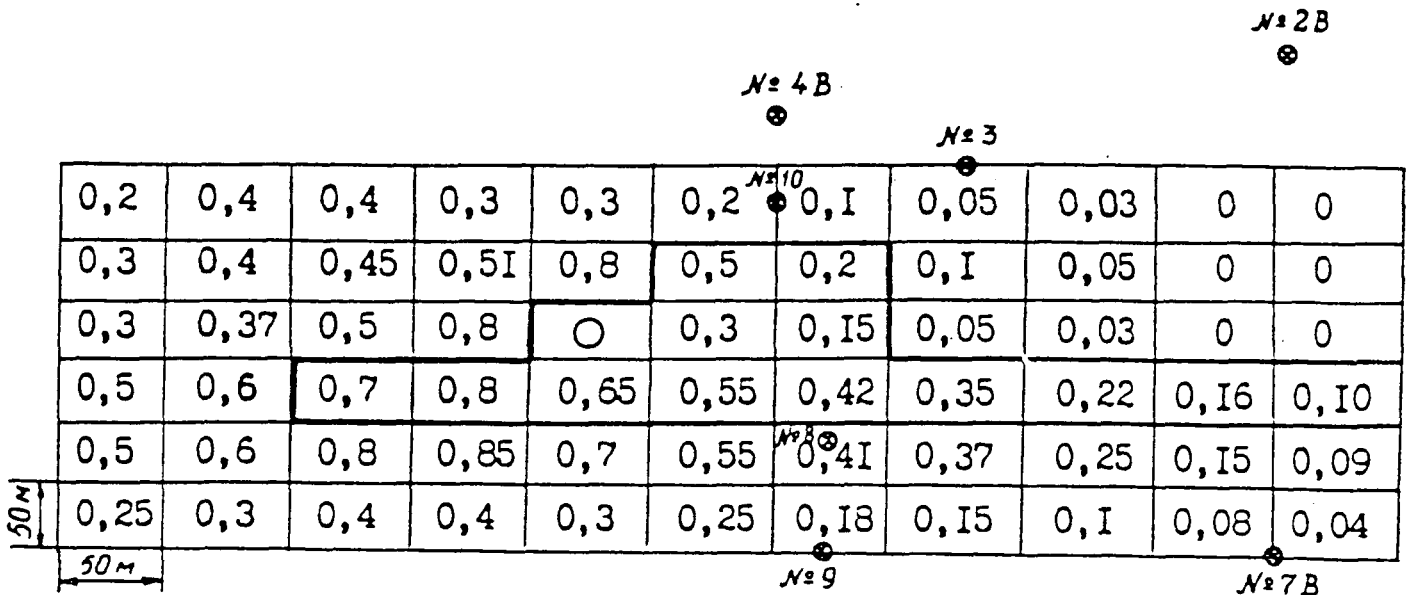| 0,2	0,4	0,4	0,3	0,3	0,2 №10 0,I		0,05	0,03	0	0
0,3	0,4	0,45	0,51	0,8	0,5	0,2	0,I	0,05	0	0
0,3	0,37	0,5	0,8	○	0,3	0,15	0,05	0,03	0	0
0,5	0,6	0,7	0,8	0,65	0,55	0,42	0,35	0,22	0,16	0,10
0,5	0,6	0,8	0,85	0,7	0,55	№8 ⊗ 0,41	0,37	0,25	0,15	0,09
0,25	0,3	0,4	0,4	0,3	0,25	0,18	0,15	0,I	0,08	0,04

50м

№ 9

№ 7B

Fig. 4.1 Relative distribution of gamma-emitting fission products over the
production area ot the Chernobyl nuclear power plant

4.2

Table 4.2   Data from radiometric measurments of soil samples on

17 May 1986 on the northern path of fallout within the

limits of the 30-km zone

Radionuclide	Specific activity		Content in sample %	Content in irradiated reactor fuel, %
	Bq/g	Ci/km^2		
^{141}Ce	$3,2.10^3$	$5,1.10^2$	15,8	18,3
^{132}Te	$3,4.10^2$	$5,4.10^1$	1,7	0,22
^{131}I	$3,1.10^3$	$5,1.10^2$	15,8	2,8
^{103}Ru	$3,5.10^3$	$5,6.10^2$	17,3	21,4
^{106}Ru	$9,6.10^2$	$1,5.10^2$	4,6	16,9
^{134}Cs	$1,6.10^3$	$2,5.10^2$	7,7	4,5
^{137}Cs	$1,7.10^3$	$2,7.10^2$	8,3	3,4
^{95}Zr	4.10^3	$6,4.10^2$	19,8	23,0
^{140}Ba	$1,8.10^3$	$2,9.10^2$	9,0	9,6

$$1 \text{ Ci} = 3,7.10^{10} \text{ Bq}$$

4.3

Table 4.3 Composition of radionuclides in a soil sample of
           8 May 1986 at a distance of 1.5 km from the reactor

Nuclides	Specific activity, 10^5 Bq/g
^{95}Zr	36
^{103}Ru	1,7
^{131}I	6,3
^{140}Ba	21
^{141}Ce	28
^{144}Ce	17
^{239}Np	6,4
Alpha-radioactive nuclides	0,13

Note: $1 \text{ Bq} = 2{,}7 \cdot 10^{-11}$ Ci

4.4

Table 4.4   Radionuclide composition ot alpha-emitters in the air and
some reference nuclide ratios

Nuclide	Atmospheric activity, Ci/L	$\dfrac{\text{Nuclide}}{^{144}\text{Ce}}$	$\dfrac{^{239+240}\text{Pu}}{^{242}\text{Cm}}$	$\dfrac{^{238}\text{Pu}}{^{239+240}\text{Pu}}$
^{238}Pu	$3 \cdot 10^{-14}$	$4 \cdot 10^{-4}$		
^{239}Pu	$2{,}2 \cdot 10^{-14}$	$2{,}9 \cdot 10^{-4}$	$7{,}8 \cdot 10^{-2}$	$0{,}55$
^{240}Pu	$3 \cdot 10^{-14}$	$4 \cdot 10^{-4}$		
^{242}Cm	$6{,}7 \cdot 10^{-13}$	$8{,}7 \cdot 10^{-3}$		

4.5

Table 4.5   Radionuclide composition of alpha-emitters on soil samples and
some reference nuclide ratios

Nuclide	$\dfrac{\text{Activity of soil, Ci}}{\text{Sample}}$	$\dfrac{\text{Nuclide}}{^{144}\text{Ce}}$	$\dfrac{^{234+240}\text{Pu}}{^{242}\text{Cm}}$	$\dfrac{^{238}\text{Pu}}{^{239+240}\text{Pu}}$
$^{239+240}\text{Pu}$	$2{,}5 \cdot 10^{-10}$		$3{,}5 \cdot 10^{-2}$	$0{,}72$
^{238}Pu	$1{,}8 \cdot 10^{-10}$			
^{242}Cm	$7{,}1 \cdot 10^{-9}$			

4.6

Table 4.6   Radionuclide composition of alpha-emitters in soil samples, according to measurement data of the Radium Institute

Nuclide	Activity, Bq/h		Nuclide$/^{144}Ce$		$^{239+40}Pu/^{242}C$		$^{238}Pu/^{239+40}Pu$	
	I	II	I	II	I	II	I	II
$^{239+240}Pu$	790	5,2	$6,3 \cdot 10^{-4}$ $5,2 \cdot 10^{-4}$		$8,1 \cdot 10^{-2}$ $7 \cdot 10^{-2}$		0,44	0,38
^{238}Pu	348	2,0	$2,8 \cdot 10^{-4}$ $2 \cdot 10^{-4}$					
^{242}Pu	9784	74	$7,8 \cdot 10^{-3}$ $7,4 \cdot 10^{-3}$					
^{144}Ce	$1,23 \cdot 10^{6}$ $1,0 \cdot 10^{4}$		I	I				

4.7

Table 4.7 Radionuclide composition of aerosols at a height of 200 m, Bq/L

Nuclides	Measurement data			
	09.05.86	II.05.86	I3.05.86	24.05.86
^{95}Zr	8,9	I0	0,68	0,06
^{95}NB	5,8	II	I,2	–
^{99}Mo	3,8	–	–	–
^{99}Tc	I6	7,5	0,28	–
^{103}Ru	36	3I	0,94	I,2
^{131}J	58	45	I,0	0,6
^{132}Te	23	8,5	0,I9	–
^{137}Cs	–	2,0	0,37	0,I
^{134}Cs	–	–	–	0,05
^{140}Ba	I0	4,8	–	–
^{140}La	I2	5,6	0,23	–
^{141}Ce	6,0	8,4	0,4I	0,2
^{144}Ce	–	8,0	0,4I	0,4

4.8

Table 4.8   Radionuclide composition of aerosols at a height of 3 m, Bq/L

Nuclides	Concentration on 12 May 1986 at points			
	3	10	8	9
^{95}Zr	44	7,5	3,3	I,8
^{95}Nb	–	9,8	3,7	2,0
^{103}Ru	I55	67	I,6	I,3
^{131}J	I95	I00	I,0	2,9
^{132}Te	42	24	0,25	0,2
^{140}Ba	7,5	2,8	2,4	I,8
^{140}La	7,5	4,4	2,3	I,2
^{141}Ce	–	6,0	3,0	I,3
^{144}Ce	–	6,6	2,8	–

4.9

Table 4.9   Concentration of radioactive aerosols on
20 May 1986 at a height of 3 m, Bq/L

Nuclides	Points		
	2C	4C	- 7C
^{95}Zr	I,7	I,8	4,I
^{95}Nb	2,0	2,I	3,7
^{103}Ru	I,0	I,2	29,2
^{106}Ru	0,6	0,9	I0,0
^{132}Te	-	I,3	I,3
^{137}Cs	-	0,I9	0,9
^{140}Ba	I,I	0,5	I,I
^{140}La	0,6	I,7	I,7
^{141}Ce	I,I	I,6	2,3
^{144}Ce	I,0	I,5	3,4

4.10

Table 4.10   Relative content of radionuclides in the air above the Chernobyl nuclear power plant δ_i^ρ , % *)

Nuclides	26.04.86	29.04.86	02.05.86	03.05.86	04.05.86	05.05.86	Rel. content, δ_i of radionuclides in fuel on 26 April 1986
^{95}Zr	4,4	6,3	9,3	0,6	7,0	20	3,6
^{95}Nb	0,6	0,8	9,0	I,3	8,2	I8	3,8
^{99}Mo	3,7	2,6	2,0	4,4	2,8	3,7	3,9
^{103}Ru	2,I	3,0	4,I	7,2	6,9	I4	3,9
^{106}Ru	0,8	I,2	I,I	3,I	I,3	9,6	2,I
^{131}J	5,6	6,4	5,7	25	8,2	I9	2,3
$^{132}Te + {}^{132}J$	40	3I	I7	45	I5	8,6	6,4
^{134}Cs	0,4	0,6	0,6	I,6	0,6	–	0,6
^{136}Cs	0,3	0,4	0,5	0,9	–	–	0,I
^{137}Cs	–	–	I,4	3,7	I,3	2,2	0,4
^{140}Ba	3,2	4,I	8,0	3,3	I3	I2	3,8
^{140}La	II	4,7	I5	2,3	I9	I7	4,0
^{141}Ce	I,4	I,9	7,6	0,9	6,4	I5	3,6
^{144}Ce	I,6	2,4	6,I	–	5,I	II	3,4
^{147}Nd	I,4	I,7	2,5	–	2,I	5,4	I,4
^{239}Np	23	3,0	II	0,6	2,8	6,8	56,7
$\sum_i A_i$	$3,6 \cdot 10^{-7}$	$3,2 \cdot 10^{-7}$	$5 \cdot 10^{-8}$	$7 \cdot 10^{-8}$	$I \cdot 10^{-6}$	$7 \cdot 10^{-9}$	

*) $\delta_i^\rho = (A_i / \sum_i A_i) \cdot 100\%$, where A_i is the activity of the i-th radionuclide; the data are rounded off

Table 4.11 Values of Ω */, characterizing the emission of
non-volatile fission products relative to ^{131}I,
taking ^{95}Zr and ^{141}Cr as examples, for the
period 26 April to 13 May 1986

Date	^{95}Zr	^{141}Cr
26.04 **)	11	32
29.04	2,0	8,0
02.05	1,2	18,3
03.05	105	85,3
04.05	3,8	5,2
05.05	1,8	3,1
08.05	26	51
11.05	23	37
13.05	13	22

*)
$$\Omega_i = \frac{[A(^{131}J)/A(i)]}{[A(^{131}J)/A(i)]} \qquad \frac{\text{in air}}{\text{in fuel}}$$

$i = {}^{95}Zr ; {}^{141}Ce ;$

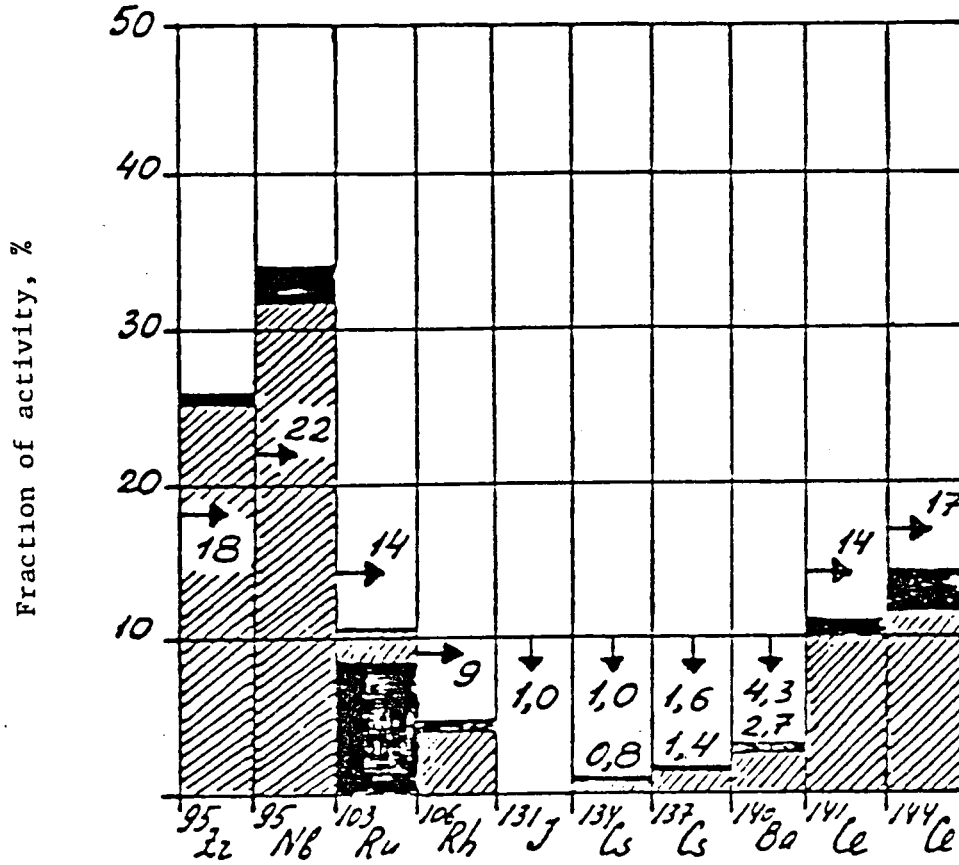A - activity of the radionuclide

**)   Initial discharge

Fig. 4.2. Fraction of radionuclide activity in the initial sample (▬▬) and the deposit (▨▨)
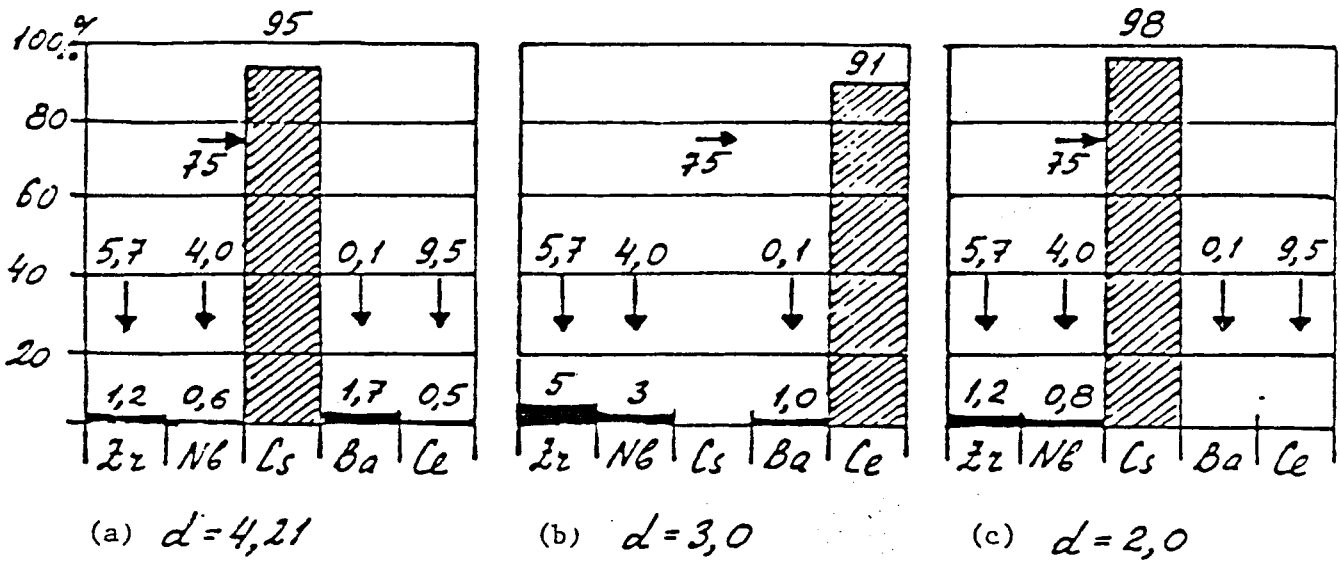
Fig. 4.3 Fraction of radionuclides in "hot" particles, fractionated in clerici solutions with densities of 4.2; 3.0; 2.0 g/cm^3 from samples of sand and dust (No. 16-LPD)

Content of caesium radionuclides (^{134}Cs and ^{139}Cs together) in (a) 5.0 x 10^{-9} g/g; (c) 1.4 x 10^{-9} g/g
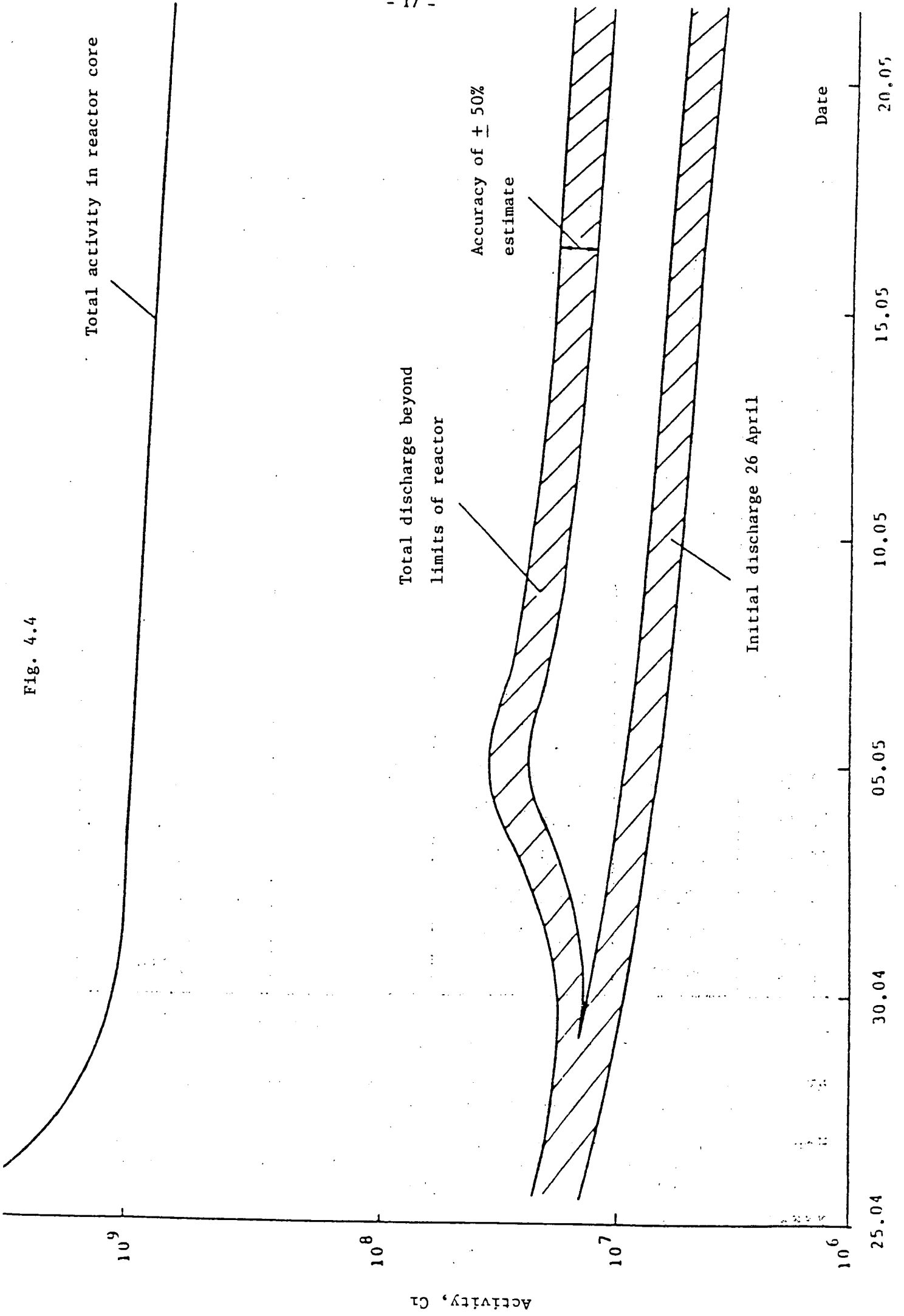
Fig. 4.4

Table 4.12 Results of measurements of power of discharge from the reactor and of an estimated amount in a cloud, on the basis of an analysis of air samples

Date of sampling	Time of sampling	Specific activity of air, Ci/L	Power of discharge, Ci/d	Estimate of amount in cloud, Ci/km^3
09.05	18.30	$54 \cdot 10^{-10}$	12600	
11.05	13.15	$38 \cdot 10^{-10}$	8700	
13.05	13.15	$2 \cdot 10^{-10}$	420[x]	
16.05	13.15	$8 \cdot 10^{-10}$	1680[xx]	
19.05	13.15	$0,05 \cdot 10^{-10}$	50	
22.05	09.30	$0,05 \cdot 10^{-10}$	50	
23.05	09.30	$0,02 \cdot 10^{-10}$	20	
24.05	09.30.	$1 \cdot 10^{-10}$		100
25.05	09.30	$3 \cdot 10^{-10}$		300
26.05	09.30	$0,2 \cdot 10^{-10}$		20
27.05	09.30	$0,2 \cdot 10^{-10}$		20
28.05	09.30	$0,2 \cdot 10^{-10}$		20
29.05	09.30	$0,1 \cdot 10^{-10}$		10
30.05	13.00	$2 \cdot 10^{-10}$		200[xx]
01.06	09.30	$0,2 \cdot 10^{-10}$		20
02.06	17.00	$0,25 \cdot 10^{-10}$		25
03.06	14.30	$0,12 \cdot 10^{-10}$		12
04.06	09.30	$0,08 \cdot 10^{-10}$		8
05.06	09.30	$0,12 \cdot 10^{-10}$		12
06.06	09.30			100[xxxx]

[x] The sampling was made outside tne loop, which led to a reduction in tne concentration of nuclides.

[xx] The data were verified against the results of measurements of the Institute of Experimental Metrology

[xxx] The sampling was made in daytime. This accounted for an increase in the concentration of nuclides due to an elevated dust condition due to work on the area of the power station.

[xxxx] After a rainfall.

Table 4.13 Daily discharge, q , of radioactive substances into the atmosphere from the damaged unit (not including noble gases)*

Date	Time after accident, days	q MCi **)
26.04	$0^{1)}$	12
27.04	1	4,0
28.04	2	3,4
29.04	3	2,6
30.04	4	2,0
01.05	5	2,0
02.05	6	4,0
03.05	7	5,0
04.05	8	7,0
05.05	9	8,0
06.05	10	0,1
09,05	14	$\simeq 0,01$
23.05	28	$20 \cdot 10^{-6}$

1) Initial discharge

The value given is with allowance for decay on 6 May 1986.

At the time of discharge, the activity was 20-22 MCi.

The composition of the discharge is shown in Table 4.14.

*) The error in the release evaluation is ± 50%. Contributing to it are the dosimetric equipment error, the error in measuring the isotopic composition of air and soil samples and the error in averaging fallout over a large area.

**) The values of q are adjusted to 6 May 1986 with allowance for radioactive decay (the release on 26 April 1986 amounted to about 20 MCi at this moment in time). For the composition of the release, see Table 4.14.

Table 4.14   Radionuclide composition of discharge from the damaged unit of Chernobyl' nuclear power plant[*/]

Nuclide [***)]	Activity of discharge, MCi		Fraction of activity discharge from reactor on 6 May 1986, %
	26.04.86	06.05.86[**)]	
^{133}Xe	5	45	Possibly up to 100
85	0,15	-	-"-
85	-	0,5	-"-
^{131}I	4,5	7,3	20
132	4	1,3	15
134	0,15	0,5	10
137	0,3	1	13
99	0,45	3	2,3
95	0,45	3,8	3,2
103	0,6	3,2	2,9
106	0,2	1,6	2,9
140	0,5	4,3	5,6
141	0,4	2,8	2,3
144	0,45	2,4	2,8
89	0,25	2,2	4,0
90	0,015	0,22	4,0
239	2,7	1,2	3,2
238	$0,1.10^{-3}$	$0,8.10^{-3}$	3%
239	$0,1.10^{-3}$	$0,7.10^{-3}$	-"-
240	$0,2.10^{-3}$	1.10^{-3}	-"-
241	0,02	0,14	-"-
242	$0,3.10^{-6}$	2.10^{-6}	-"-
242	3.10^{-3}	$2,1.10^{-2}$	-"-

[*)]   Error of estimate: $\pm$ 50%, explanation in Footnotes to Table 4.13

[**)]   Total discharge up to 6 May 1986

[***)]   The data presented relate to the activity of the main radionuclides measured on radiometric analyses

5. ATMOSPHERIC TRANSPORT AND RADIOACTIVE CONTAMINATION OF THE ATMOSPHERE AND OF THE GROUND

5.1. Formation of the basic contamination source - the cloud and the gas stream - as a result of the accident at the Chernobyl Atomic Power Station.

As a result of the accident, a significant quantity of the radionuclides which had accumulated in the reactor during operation escaped beyond the confines of the power station.

The cloud which formed at the time of the accident produced a radioactive trail on the ground in a westerly and a northerly direction depending on the meteorological conditions governing the transport of the air masses. Subsequently, for a considerable time, a stream of gaseous, volatile and aerosol products continued to flow from the accident zone. The most intense stream was observed during the first 2-3 days after the accident in the northerly direction, where the radiation levels reached 1000 mR/hour on 27 April and 500 mR/hour on 28 April at a distance of 5-10 km from the reactor site (at an altitude of 200 m). According to aircraft monitoring data, the height of the stream on 27 April exceeded 1200 m in the north-westerly direction at about 30 km from the reactor site, and the radiation levels at that height were about 1 mR/hour. During the following days, the height of the stream did not exceed 200-400 m.

Portions of the contaminated air masses (the cloud and portions of the stream of radioactive products) spread for considerable distances over the territory of the USSR depending on the wind direction.

Gamma-spectrum analyses of air samples revealed fission products which had accumulated in the reactor (Zr^{95}, Nb^{95}, Mo^{99}, Ce^{141}, Ce^{144}, I^{131}, Te^{132}, I^{132}, Ru^{103}, Ru^{106}, Ba^{140}, La^{140}, Cs^{137}, Nd^{147}) and also isotopes resulting from induced activity: Np^{239}, Cs^{134}.

A characteristic feature of the radioactive products escaping to the atmosphere is that they were enriched in iodine and caesium radionuclides. Table 5.1 gives calculated fractionation (enrichment) coefficients of various radionuclides relative to zirconium-95 based on analyses of atmospheric aerosol samples collected in the immediate vicinity of the reactor (the "close-in zone") during the early days after the accident.

5.2. <u>Meteorological conditions affecting the dispersion of radioactive products from the Chernobyl Atomic Power Station</u>

On 26 April 1986, the area around the Station was in a low-gradient pressure field with a slight wind varying in direction. At an altitude of 700-800 m to 1.5 km, the area around the Station was at the south-west periphery of a high-pressure zone with the air masses in this layer moving north-westwards at a speed of 5-10 m/sec. This was confirmed by measurements of radiation levels and radioactive fallout along the air particle dispersion trajectory at an altitude of 0.7-1.5 km (see Figs 5.1-5.3).

The further dispersion in the 0.7-1.5 km layer of air particles leaving the area around the Station on 26 April was in a north-westerly direction, subsequently turning to north.

On 26 April, the long-distance transport of the air masses in the ground layer was in the westerly and north-westerly directions, the air particle dispersion trajectory reaching areas on the frontier with Poland on 26 and 27 April; this was confirmed by radioactivity fallout measurements. On the following days, from 27 to 29 April, aircraft monitoring data indicated transport of radioactive products in the ground layer of air at a height of 200 m in a northerly and a north-westerly direction from the Station.

The meteorological conditions from 26 to 29 April which governed the dispersion of air masses in the area around the Station virtually determined the basic zone of close-in radioactive fallout to the north-west and the north-east of the Station. This was confirmed by aircraft measurements - made during the following days - of radiation level distributions on the ground in the close-in zone.

Subsequently, there was an insignificant escape of radioactive products from the area around the Station, with their transport in a southerly direction until 7-8 May, causing radioactive fallout in that direction.

5.3. <u>Radioactive contamination in the area around the Station and assessment of the total quantity of radioactive products deposited as fallout in the close-in zone</u>

As a result of the meteorological conditions governing the dispersion of radioactive products in the atmosphere and their precipitation on the underlying surface during the period 26-30 April, a zone of close-in radioactive fallout was formed. Since 29 April, there have been regular airborne gamma surveys of the distribution of radioation levels on the ground. Fig. 5.4 shows the distribution of radiation levels on the ground on 29 May.

From data on the gamma dose rate distribution on the ground at different times it was possible to estimate the total quantity of the radioactive products precipitated in the close-in zone of the radioactive trail.

Table 5.2 gives results obtained by integrating over the areas bounded by the various dose rate isolines (in (R/hour) x m^2) and also the total amount of radioactive products in the close-in zone of the radioactive trail (from the Station boundary out to a distance of 80 km) expressed in MeV/sec and in Curies.

During the period from 10 to 30 days after the accident, the following radionuclides were identified in the close-in zone of the fallout trail: Mo^{99}, Zr^{95}, Nb^{95}, Ce^{141}, Ce^{144}, I^{131}, Te^{132}, I^{132}, Ru^{103}, Ru^{106}, $Ba^{140}+La^{140}$, Cs^{134}, Cs^{137}, Sr^{89}, Sr^{90} and Y^{91}. Plutonium isotopes were found on the ground surface.

On the basis of data on ground contamination densities in different zones of the trail, the amounts of individual radionuclides deposited as fallout in the close-in zone of the trail were estimated by comparing with the dose rate at "D"+15 (see Table 5.3).

5.4. Radioactive contamination of the atmosphere and the ground in the USSR

During the period 26 April - 5 May there was formed a zone of radioactive fallout within and beyond the territory of the USSR as a function of the meteorological transport conditions. The amount of radioactive products deposited in the European part of the USSR was about 1.2 x 10^8 (R/hour) x m^2 or 4.0 x 10^{17} MeV/sec. Thus, the total fallout in the close-in and far-out zones was about 7.0 x 10^{17} MeV/sec by 5 May 1986 - about 3% of the total energy production of the radioactive products in the reactor at that time.

Depending on the meteorological transport conditions, the radioactive products entered the ground layer of the atmosphere at different times for different observation points.

Table 5.4 shows the change in the concentrations of some radionuclides at a permanent observation point belonging to the State hydrometeorological network (Varyshevka, about 140 km south-east of the Station).

Figures 5.5 and 5.6 gives results of determinations of various radionuclides in the ground air layer at the Berezinsky National Park carried out at a complex background monitoring station located 120 km to the north-east of Minsk.

The fallout of radioactive products from the atmosphere was monitored by a network of stations run by the State Committee for Hydrometrology using collection panels ("planchettes") which were exposed for periods of 24 hours.

Table 5.5 gives observation results for Kiev and Kaliningrad.

5.5. Radioactive contamination of rivers and reservoirs

Information about the radioactive contamination of rivers and reservoirs was obtained through the isotopic analysis of one-litre water samples taken from the surface water layer at regular intervals (of 1-3 days) at the mouth of the rivers Pripyat', Teterev, Irpen' and Desna and at the point of water extraction from the river Dnepr (Vyshgorod). Starting on 26 April, surface water samples were taken from all parts of the Kiev reservoir in a major sampling exercise using boats.

The investigations showed that the radioactive contamination of rivers and reservoirs was due initially to aerosol fallout onto the surface of water bodies and subsequently to runoff from contaminated catchment areas (during May there was almost no rainfall in this region). The initial results of determinations of radioactive substances in the water bodies investigated are given in Table 5.6.

Table 5.7 gives, for two water bodies, maximum concentrations found during the observation period (starting 1 May).

The highest iodine-131 concentrations in the Kiev reservoir near the point of water extraction from the river Dnepr were observed on 3 May. This reflected the fallout of radioactive aerosols onto the surface of the Kiev reservoir and the time taken to reach this point by contaminated water from the river Pripyat'.

During the period 13-20 May, the total beta activity of the water in the river Dnepr near the Kiev Hydro Station was in the range $(1-5) \times 10^{-9}$ Curie/litre.

5.6. Plutonium contamination of the atmosphere and the ground

Plutonium contamination investigations were carried out with the help of a special vehicle which was in use in obtaining air, soil and grass samples over a ring-shaped expanse of territory outside the 30-km zone (May 1986).

As can be seen from Table 5.8, at all sampling points the concentration of plutonium in the air was below the maximum permissible level $(3 \times 10^{-17}$ Curie/litre for $Pu^{239})$.

Table 5.9 gives values for the density of the plutonium contamination of soil and grass at various points.

Table 5.1

Radionuclide	Ce^{144}	Ce^{141}	Ba^{140}	I^{131}	Ru^{103}	Ru^{106}	Cs^{137}
Fractionation coefficient	1.23	1.03	0.84	5.22	2.21	1.7	5.64

Table 5.2

Date	Integral (R/hour) x m^2	Amount of radioactive products in trail		Fraction of total energy production of radioactive products in reactor zone on that date (%)
		MeV/sec	Curie	
11/5/86	7.9×10^7	3.3×10^{17}	1.2×17^7	1.6

Table 5.3

Radionuclide	Zr^{95}	Ce^{141}	Ce^{144}	I^{131}	Te^{132}	Ru^{103}	Ru^{106}
Amount in trail (Curie)	1.8×10^5	1.7×10^6	1.3×10^6	1.3×10^6	2.5×10^6	1.5×10^6	5.7×10^5
Fraction of amount in reactor zone (%)	1.5	1.7	1.0	5.1	5.0	1.4	0.8

Radionuclide	Ba^{140}	Cs^{134}	Cs^{137}	Sr^{89}	Sr^{90}	Y^{91}	Total amount
Amount in trail (Curie)	9.1×10^5	1.3×10^5	2.8×10^5	6.2×10^5	8.5×10^4	$6,4 \times 10^5$	1.12×10^7
Fraction of amount in ractor zone (%)	1.4	0.6	1.9	1.2	0.85	0.85	1.4

Table 5.4

$(Curie/m^3)$

Sampling date (1986)	I^{131}	Zr^{95}	Ba^{140}	Cs^{137}
26-27/4	3.2×10^{-12}			
27-28/4	5.7×10^{-15}			
28-29/4	2.4×10^{-13}	2.7×10^{-14}	2.4×10^{-14}	5.4×10^{-14}
29-30/4	2.2×10^{-11}	1.6×10^{-12}	2.1×10^{-12}	8.4×10^{-12}
30/4-1/5	8.3×10^{-9}	2.2×10^{-9}	5.7×10^{-9}	2×10^{-9}
1-2/5	1.1×10^{-9}	1.9×10^{-10}	8.7×10^{-10}	5.5×10^{-10}
2-3/5	2.5×10^{-11}	4.1×10^{-11}	4.5×10^{-11}	1.1×10^{-11}
3-4/5	3.1×10^{-11}	1.1×10^{-11}	1.2×10^{-11}	5.1×10^{-12}
4-5/5	1.6×10^{-11}	9×10^{-12}	8.7×10^{-12}	1.4×10^{-12}

Table 5.5

Sampling date (1986)	Curie/km² x day Kiev				Curie/km² x day Kaliningrad			
	I^{131}	Ba^{140}	Zr^{95}	Cs^{137}	I^{131}	Ba^{140}	Zr^{95}	Cs^{137}
26-27/4	1.9×10^{-2}	1.9×10^{-3}	1.3×10^{-3}	1.1×10^{-3}	2.0×10^{-2}	3.8×10^{-3}	3.8×10^{-3}	2.3×10^{-3}
27-28/4	6.6×10^{-2}	6.4×10^{-3}	2.3×10^{-3}	7.8×10^{-3}	4.6	6.3×10^{-2}	2.7×10^{-2}	1.0×10^{-1}
28-29/4	2.5	7.1×10^{-1}	8.3×10^{-1}	9.6×10^{-2}	4.9	5.1×10^{-2}	3.8×10^{-2}	8.4×10^{-2}
29-30/4	10.3	3.2	6.0×10^{-1}	3.2×10^{-1}	10.5	1.3×10^{-2}	1.6×10^{-2}	1.2×10^{-2}
30/4-1/5	2.6	8.6×10^{-1}	5.7×10^{-1}	9.2×10^{-2}	2×10^{-1}	1.1×10^{-2}	4.3×10^{-3}	4.8×10^{-3}
1-2/5	3.3×10^{-1}	2.2×10^{-1}	2.5×10^{-1}	1.1×10^{-2}	1.6×10^{-1}	-	2×10^{-2}	3.2×10^{-3}
2-3/5	7.8×10^{-1}	1.0×10^{-1}	2.2×10^{-1}	2.3×10^{-2}	4×10^{-2}	1.3×10^{-2}	4.3×10^{-3}	9.2×10^{-4}
3-4/5					2.4×10^{-2}	7.3×10^{-3}	7.5×10^{-3}	1×10^{-3}
4-5/5					1.6×10^{-2}	3.8×10^{-3}	1.0×10^{-2}	7.3×10^{-4}

Table 5.6

Water body and sampling date	Radionuclides (10^{-9} Curie / m^3)					
	I^{131}	Ba^{140}	Zr^{95}	Sr^{89}	Y^{91}	H^3
Pripyat' river 1/5/86	80	25	18	5.6	1.6	0.6

Table 5.7

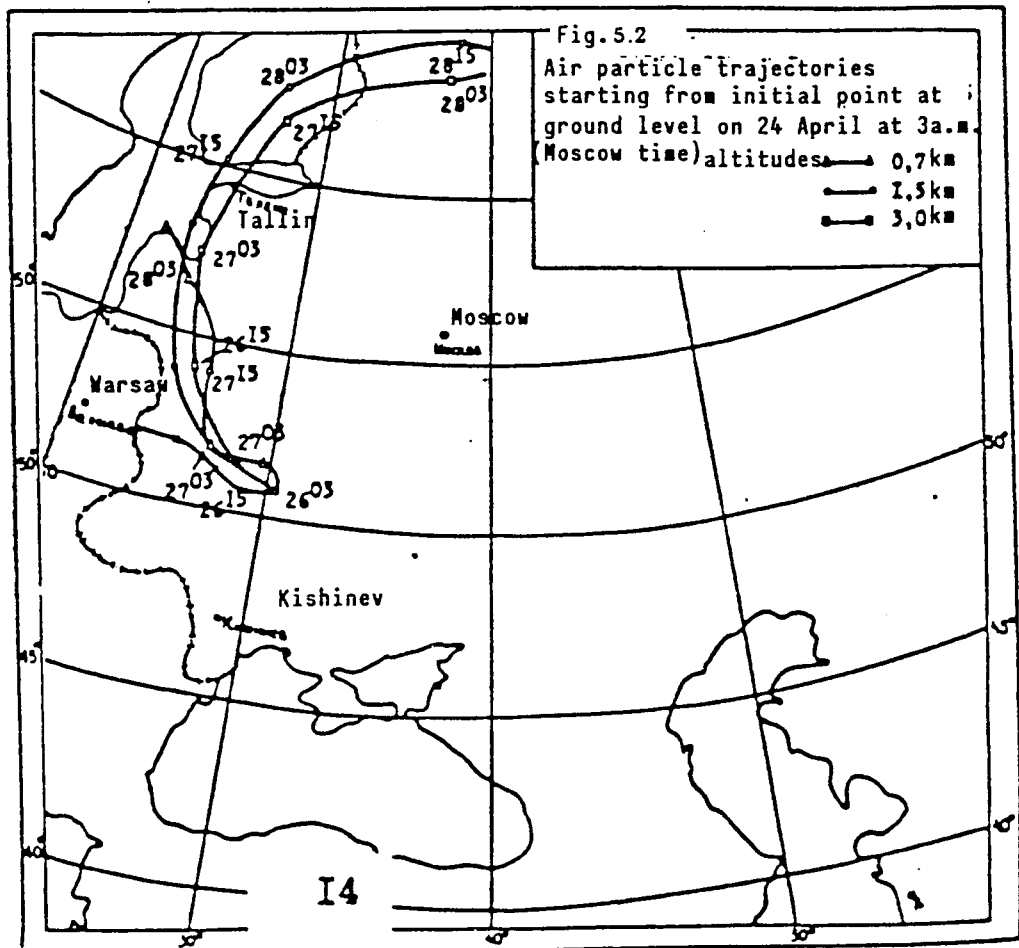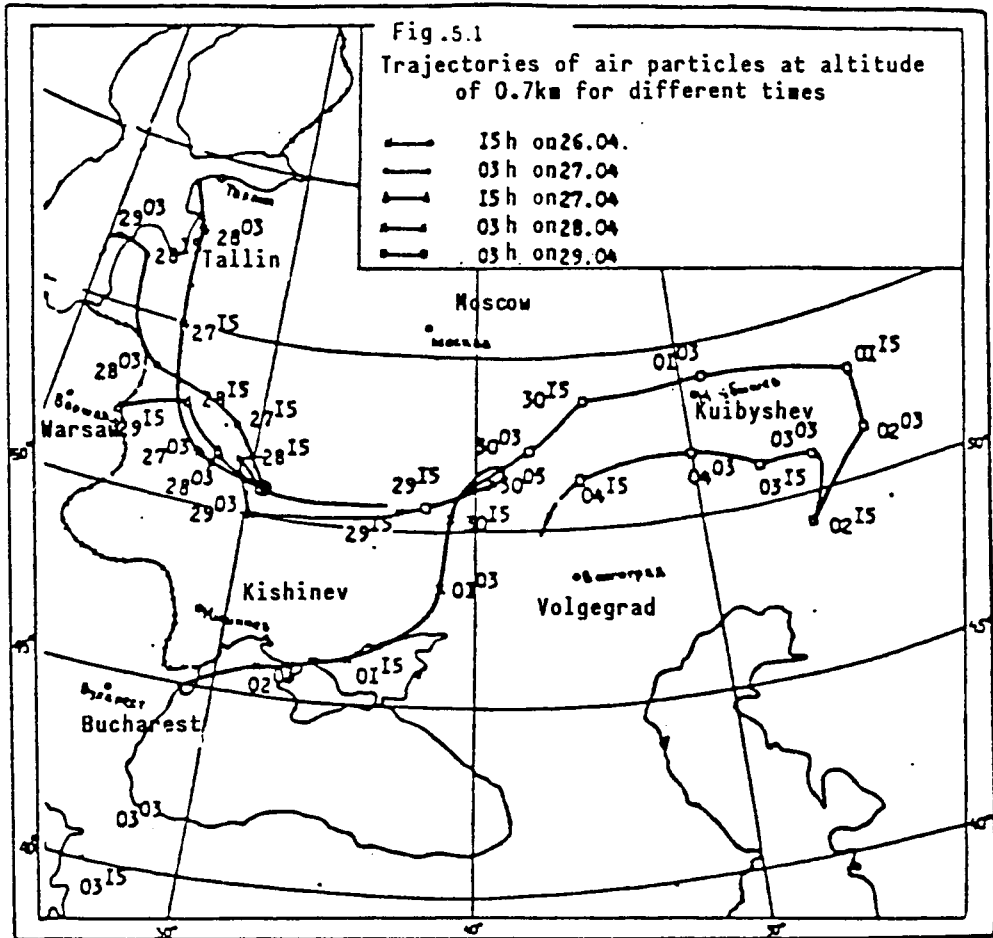| Water body	Date of observation of maximum concentration	Concentration, 10^{-9} Curie/litre		
		iodine-131	barium-140	zirconium-95
Pripyat' river	2 May	120	60	42
Kiev reservoir	3 May	28	17	20

Table 5.8

Concentration of all plutonium isotopes (C) in air (Curie/m^3) at h = 1.5 m

Sampling date	Distance from source	C,Curie/m^3
19/5/86	100 km to SSE	0.48×10^{-14}
20/5/86	72 km to ENE	0.35×10^{-14}
20/5/86	105 km to NNE	0.75×10^{-15}
21/5/86	48 km to NNE	0.65×10^{-14}
21/5/86	60 km to NNE	0.39×10^{-14}
22/5/86	55 km to W	0.21×10^{-14}
22/5/86	45 km to WSW	0.85×10^{-14}
22/5/86	35 km to WSW	0.17×10^{-14}
22/5/86	45 km to SW	0.70×10^{-15}

Table 5.9

Density of surface contamination of surface layer and
of grass by all plutonium isotopes

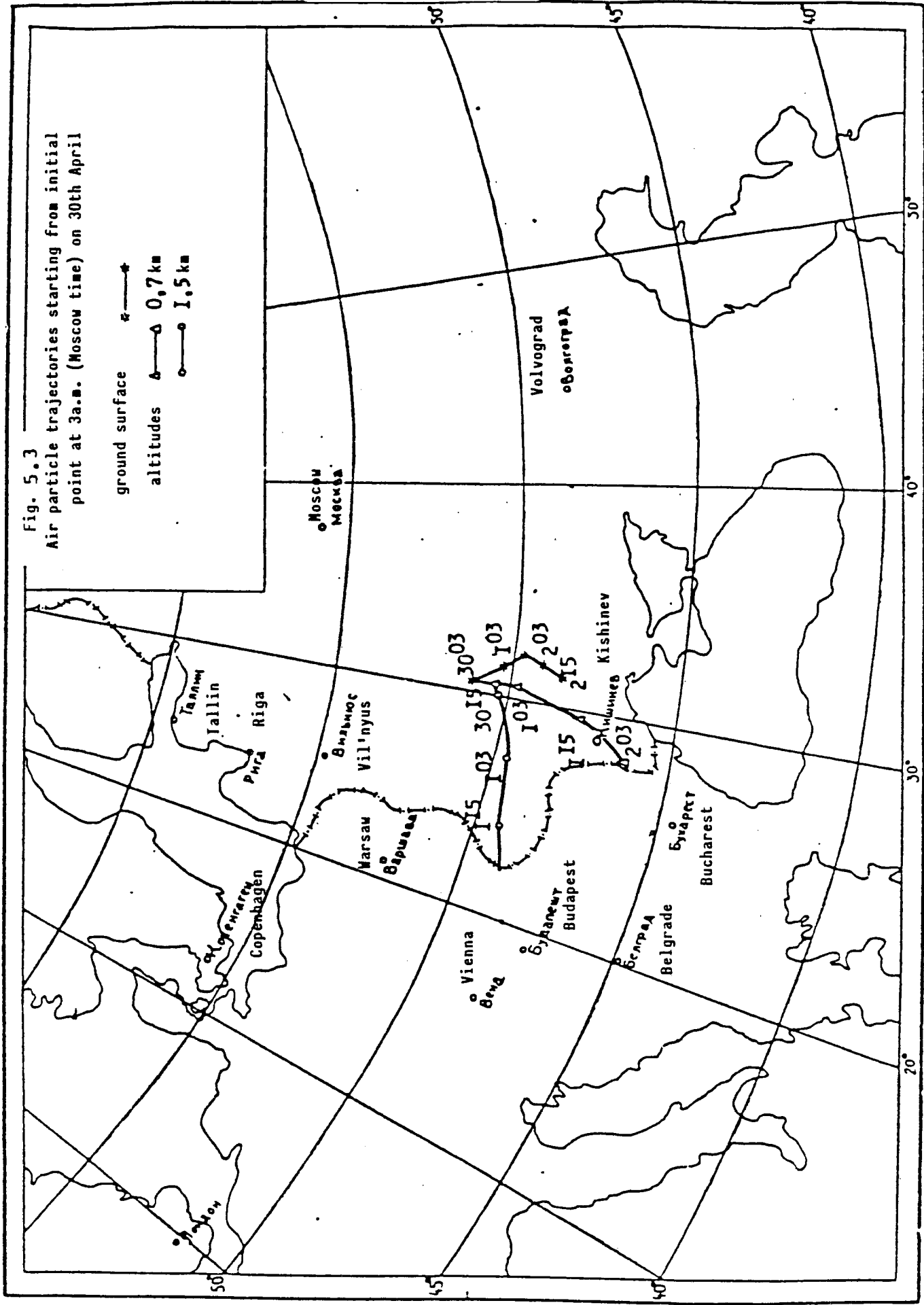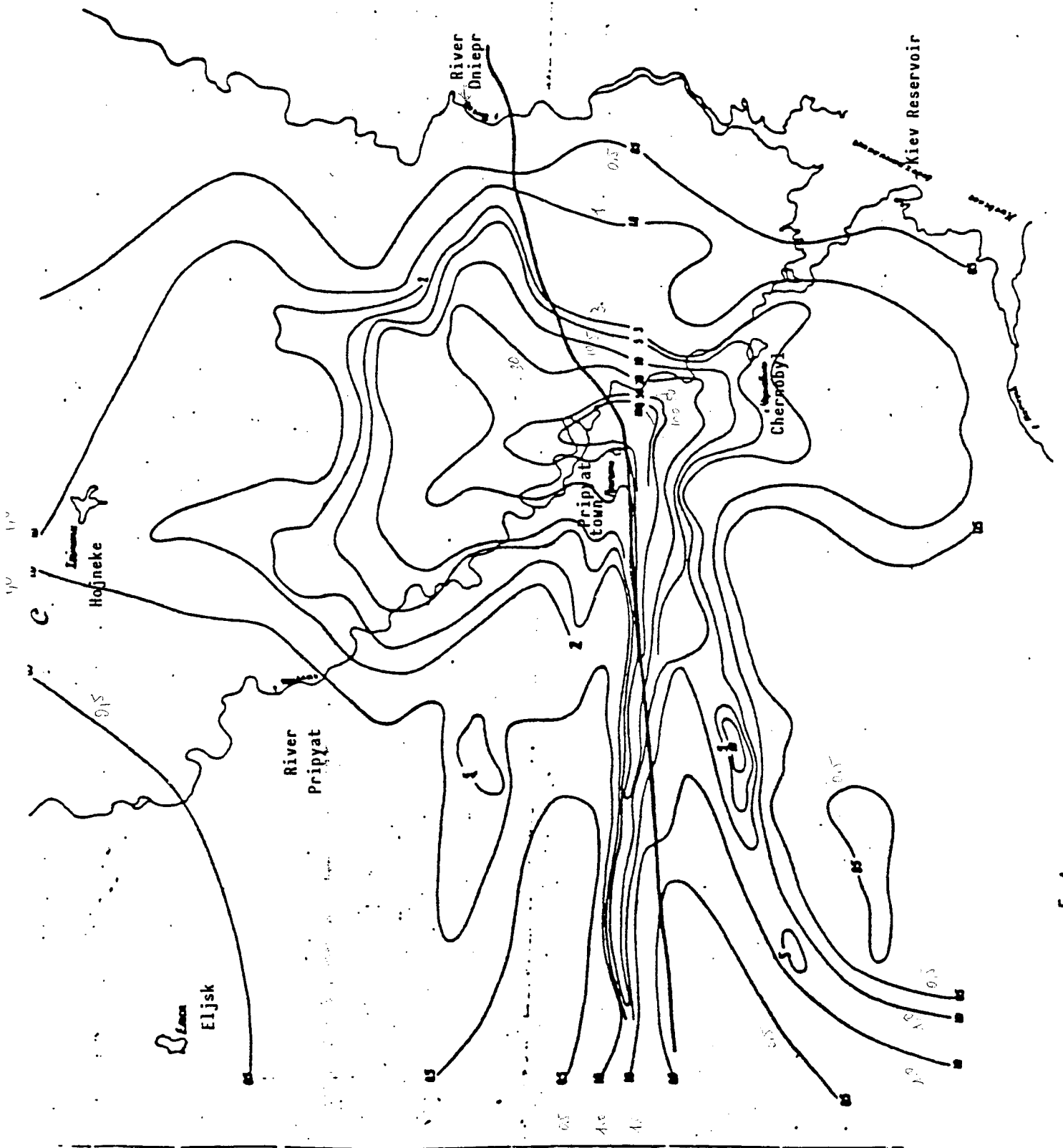| Sampling date	Distance from source	σgrass	σsurf. layer
		(C u r i e / m^2)	
20/5/86	105 km to NNE	1.3×10^{-10}	3.6×10^{-10}
21/5/86	48 km to NNE	2.3×10^{-9}	5.1×10^{-9}
22/5/86	55 km to W	1.6×10^{-9}	3.3×10^{-9}

Fig.5.1
Trajectories of air particles at altitude
of 0.7km for different times

15h on26.04.
03h on27.04
15h on27.04
03h on28.04
03h on29.04

Tallin

Moscow

Warsaw

Kuibyshev

Kishinev

Volgegrad

Bucharest

Fig.5.2
Air particle trajectories
starting from initial point at
ground level on 24 April at 3a.m.
(Moscow time) altitudes 0,7km
1,5km
3,0km

Tallin

Warsaw

Moscow

Kishinev

14

Fig. 5.3
Air particle trajectories starting from initial
point at 3a.m. (Moscow time) on 30th April

ground surface
altitudes   0,7 km
             1,5 km

River
Dniepr

Kiev Reservoir

Chernobyl

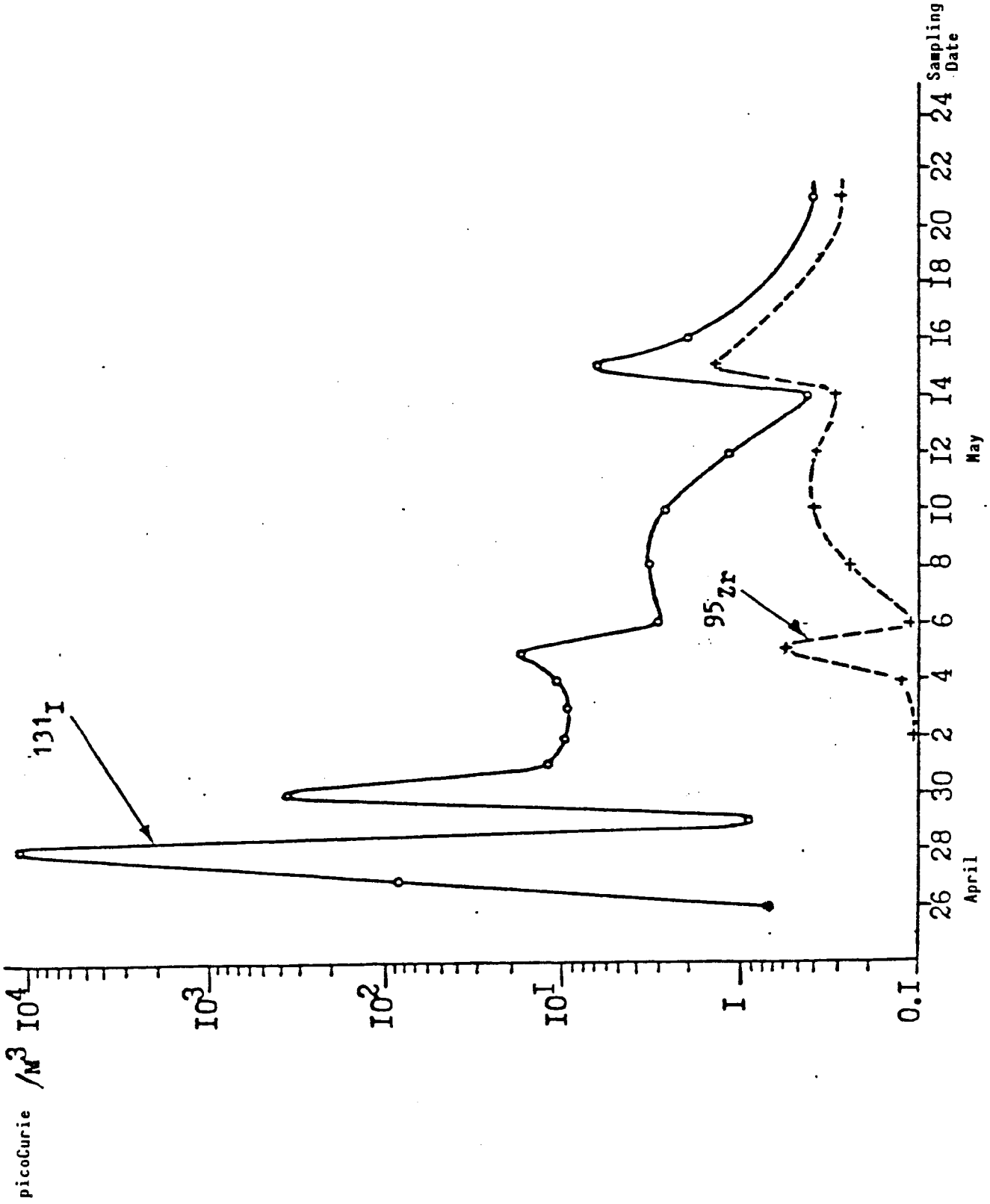Pripyat
town

Hojneke

River
Pripyat

Eljsk

5.4.

Fig. 5-4

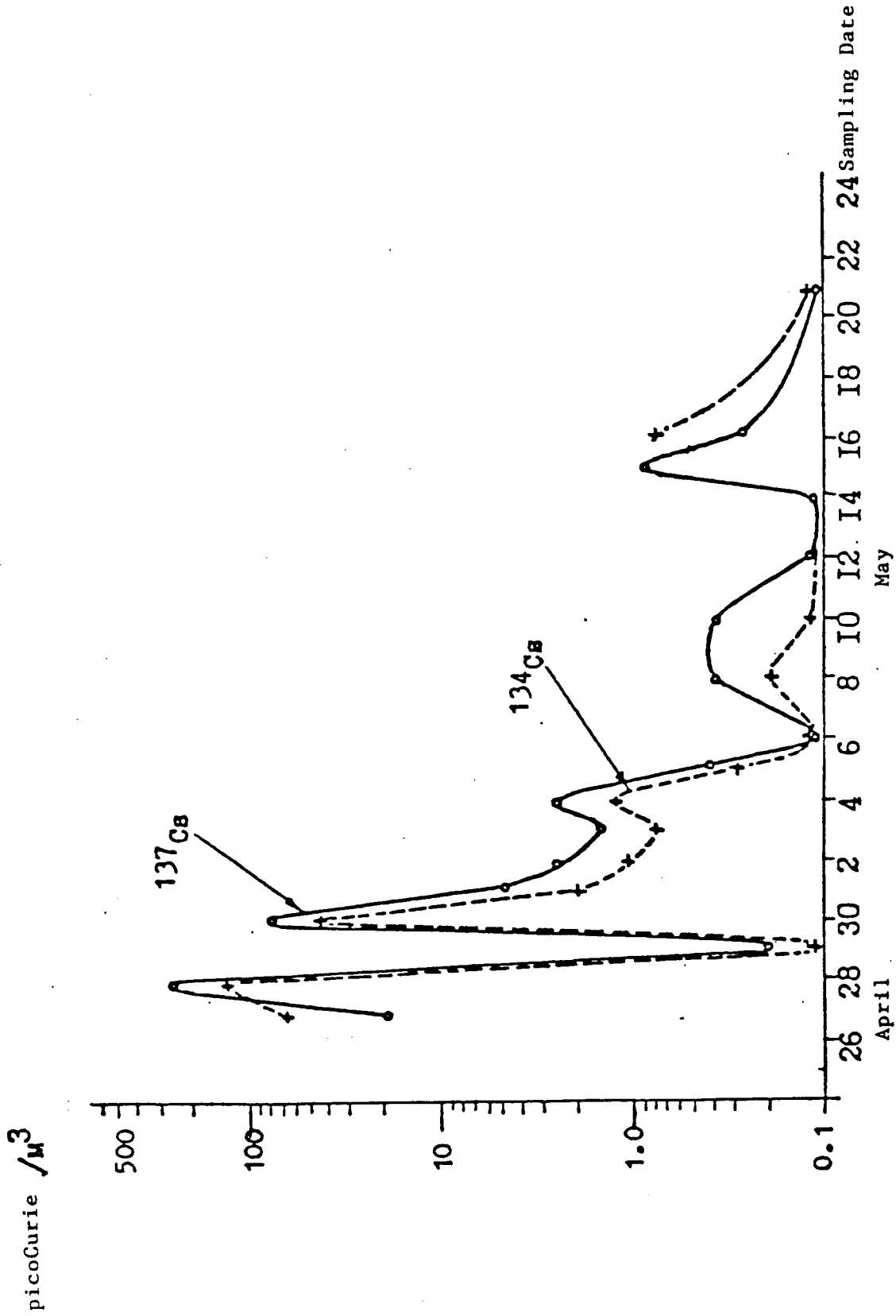Fig. 5.5. Specific activity (picoCurie/m^3) of ^{131}I and ^{95}Zr in atmospheric air at background monitoring station at Berezinsky National Park

Fig.5.6. Specific activity (picoCurie/m^3) of ^{137}Cs in atmospheric air at background monitoring station at Berezinsky National Park

EXPERT EVALUATION AND PREDICTION OF THE RADIOECOLOGICAL STATE
OF THE ENVIRONMENT IN THE AREA OF THE RADIATION PLUME
FROM THE CHERNOBYL' NUCLEAR POWER STATION
(AQUATIC ECOSYSTEMS)

6. EXPERT EVALUATION AND PREDICTION OF THE RADIOECOLOGICAL STATE OF THE ENVIRONMENT IN THE AREA OF THE RADIATION PLUME FROM THE CHERNOBYL' NUCLEAR POWER STATION (AQUATIC ECOSYSTEM)

For a number of reasons the hydrological environment plays a special role in the determination of the scales and possible consequences of radioactive contamination. As a result of washout, the radioactive substances in the drainage area flow into water reservoirs, where the radionuclides are redistributed and accumulate in components such as bottom sediments, aquatic plants and fish. This leads to additional exposure of both aquatic organisms and man, who is associated with the hydrosphere through the food chain.

From the very first days after the accident arrangements were made for monitoring the content of radionuclides in water and bottom sediments both within and outside the 30 km zone around the plant. Owing to the sedimentation processes, the major part of the radioactivity entering the hydrological environment migrated with comparative rapidity to the bottom sediments, which exhibit a radionuclide concentration higher than the activity of water by two to four orders of magnititude (Table 6.1). According to the experimental data obtained by the Institute of Nuclear Research of the Ukrainian Academy of Sciences, the Institute of Geochemistry and Analytical Chemistry of the USSR Academy of Sciences and the All-Union Research Institute for Nuclear Power Plants, the spatial distribution of radionuclides in the hydrological environment is substantially inhomogeneous. The maximum radionuclide concentration is observed directly in the cooling pond of the power plant, where the total activity of water and bottom sediments attain values of the order of $\sim 10^{-8}$ Ci/L and $\sim 10^{-3}$ Ci/kg, respectively. The concentration of artificial radionuclides in the Kiev reservoir and in the rivers falling into it is substantially lower (by a factor of 10^2–10^4).

In the time dynamics of radionuclides three characteristic stages can be distinguished. In the first stage (up to the end of May 1986) the magnitude of radioactive contamination was determined basically by the short-lived radionuclides, especially ^{131}I. In mid May the ^{131}I concentration in drinking water was $n.10^{-9}$ Ci/L, which was somewhat higher

than permissible concentration category B under NRB-76 (Radiation Safety Standards) (by a factor of 2-10 for the river Pripyat'). However, by the beginning of June the ^{131}I content in river water had already fallen by more than an order ($< n.10^{-10}$ Ci/L).

In the second stage, as ^{131}I decays the comparatively short-lived radionuclides such as ^{89}Sr, ^{95}Zr, ^{95}Nb, ^{141}Ce, ^{103}Ru, ^{140}Ba and ^{140}La make an appreciable contribution to the formation of artificial radioactivity. During 10-20 June the concentration of these radionuclides was $\sim 10^{-10}$ Ci/L and $10^{-7}-10^{-8}$ Ci/kg in the Kiev reservoir water and bottom sediments, respectively, and $\sim 10^{-9}$ Ci/L and $10^{-7}-10^{-5}$ Ci/kg in the water and bottom sediments of the river Pripyat'.

In the third stage, after the decay of ^{131}I and other relatively short-lived radionuclides, the main role in the formation of artificial radioactivity will be played by the long-lived radionuclides such as ^{137}Cs, ^{134}Cs and ^{90}Sr. During 10-20 June the ^{137}Cs concentration was $\sim 10^{-10}$ Ci/L and $\sim 10^{-9}$ Ci/kg in the water and bottom sediments, respectively, of the river Dnepr. In the cooling pond of the Chernobyl' power station and in the Pryipyat' the ^{137}Cs concentration was appreciably higher (by a factor of 10^4-10^2). The ^{90}Sr concentration in river water varied essentially within $10^{-11}-10^{-10}$ Ci/L. Considering their long half-life (about 30 years), further decreases in ^{137}Cs and ^{90}SR activity in water bodies will be fairly slow.

On the basis of experimental data on radionuclide distribution in the components of the aquatic ecosystem, calculated exposure dose estimates were made for aquatic organisms with allowance for the geometric characteristics of hydrobionts.

Exposure doses from gamma emitters were calculated with allowance for the buildup factor for scattered radiation. The following dose components were evaluated: external exposure from water, bottom sediments and organisms accumulating radionuclides; internal exposure from incorporated radionuclides. The results of calculations from the data for June 1986 and the predicted absorbed dose rates for June 1987 are given in Fig. 6.1 and Table 6.2.

Analysis of the calculated estimates of the additional exposure doses for hydrobionts indicate the following:

- The highest dose burdens are borne by hydrobionts directly populating the cooling pond. Near the bottom the level of external exposure is 4.3 rad/h on an average; the level of internal exposure for aquatic plants attains 10 rad/h. The highest dose burdens will be borne by the benthic organisms and also the roe and fries of phytophilous species of fish which breed and live in the

undergrowths of aquatic vegetation. In the case of these organisms, both the direct and indirect effects of prolonged radioactive exposure may be expected to appear.

- The exposure doses for organisms populating the rivers in the contaminated zone (the river Pripyat' and others) are substantially lower (by a factor of $\sim 10^2$) than for those living in the cooling pond.

- The dose burdens on hydrobionts inhabiting the Dnepr are close in the order of magnititude to the natural background, exceeding the latter in the case of individual hydrobionts by a factor of 5–10.

- Analysis of the contributions of radionuclides to the total exposure dose shows that the principal dose-contributing nuclides at present are the relatively short-lived elements: ^{95}Zr, ^{95}Nb, ^{141}Ce, ^{140}Ba, ^{140}La, ^{89}Sr, ^{103}Ru, etc., whose contribution to the total exposure dose for most components of the aquatic ecosystem exceeds 70–80%. The contribution of the long-lived ceasium isotopes (^{137}Cs and ^{134}Cs) to the total dose does not at present exceed 4–5%. This means that as the short-lived radionuclides decay the exposure dose for aquatic organisms will gradually fall and by the 1987 vegetative season we can already expect a decline in the dose burdens for most hydrobionts by an order of magnitude over virtually the whole contaminated area, including the cooling pond. Thereafter a relative stabilization of the additional dose burden on the aquatic organisms can be expected since by 1987 it will be determined mainly by long-lived radionuclides such as ^{137}Cs and ^{90}Sr.

In speaking about the possible biological effects of ionizing radiation it must be borne in mind that individual groups of living organisms exhibit very wide differences in their resistance to the action of radiation.

Of the hydrobionts the most vulnerable link in the chain is fishes and it is the economic species of these which form the final link in the accumulation of radionuclides in the food chain from the aquatic ecosystem to man. It is known that the exposure dose rate for freshwater fishes under natural conditions varies within 0.007–0.023 mrad/h.

Experimental studies on evaluation of the action of low doses in fish have shown that a dose rate below 0.4 mrad/h (4 rad/year) does not have adverse consequences for the vital activity of fish.

In the range up to 40 mrad/h (365 rad/year) various kinds of disturbances are observed in the functions of organs although on the whole the radioecological resistance is maintained at the population and organism levels. Further rise in the exposure threshold above 140 mrad.h (3.5 rad/day) may produce adverse effects at the population level and cause the disappearance of some of the most radiosensitive species.

As preliminary predictive evaluations show, the exposure doses for most aquatic organisms in the Kiev reservoir (0.1-1.0 mrad/h) do not exceed the range in which populations suffer radiation damage. In the river Pripyat' (buoy 204) the exposure doses for fish are about 50 mrad/h, i.e. there is a likelihood of the adverse action of exposure on the haematopoietic, immune and reproductive systems. Of these, the most significant will be the genetic effects - the advance action on the sex cells.

In the cooling pond of the Chernobyl' power station, there were the highest exposure doses - up to 5 rad/h in a number of locations - for hydrobionts and this will lead to an appreciable radiation effect on the aquatic ecosystem and in particular on the fish community.

The proposed evaluation of the radioecological state of the water bodies is preliminary and should subsequently be refined on the basis of the following data:

- The dynamics of movement of radionuclides from the drainage surface into water bodies, especially during the autumn rains and the spring flood;

- The time dynamics and spatial distribution of radionuclides in hydrobionts, especially in the economic species of fish;

- More accurate information on the species composition, character of migration, feeding spectra and ecophysiological parameters of aquatic organisms;

- Physicochemical forms of the existence of the radionuclides in the components of the aquatic ecosystem;

- Refinement of the basic hydrological parameters of pathways of transfer of radionuclides in the aquatic ecosystems (cooling pond - Pripyat' - Kiev reservoir - Dnepr).

From the scientific and practical standpoints, the following problems are of appreciable radioecological interest:

- Evaluation of the mechanisms of the possible radioecological effects in the case of prolonged (chronic) action of low exposure doses from artificial radionuclides;

- Evaluation of the mechanisms of the secondary ecological effects due to non-uniform action of the radiation factor on the ecological characteristics of species. Non-uniform weakening (or strengthening) of species upon radioactive contamination will lead to changes in the interaction between species and, as a result, to changes in the structure of the ecosystem. As examples of the secondary effects of radioactive contamination one may mention increase in the population of harmful organisms in the active silt and in the contaminated locations of ecosystems near water, changes in the self-cleaning capacities of water bodies and so on.

It will be necessary to organize and carry out long-term comprehensive radioecological studies both within and outside the 30 km zone in order to resolve the above-mentioned problems.

Table 6.I

Specific activity (Ci/kg) of bottom sediment samples in June 1986 (10 - 20 June 1986) (according to the data of the Institute of Nuclear Research, Ukranian Academy of Sciences), Institute of Geochemistry and Analytical Chemistry (USSR Academy of Sciences) and All-Union Research Institute for Nuclear Power Plants)

Sampling Location	Zr-95	Nb-95	Ce-141	Ce-144	Ba-140	La-140	Ru-103	Cs-134	Cs-137	I-131
Chernobyl' Power Station Cooling Pond		10^{-3}	$2\cdot10^{-3}$	$3\cdot10^{-4}$	10^{-4}	$2\cdot10^{-4}$	$6\cdot10^{-4}$	$4\cdot10^{-5}$	$7\cdot10^{-5}$	$1,0\cdot10^{-5}$
River Pripyat'	$8\cdot10^{-6}$	$1,1\cdot10^{-5}$	$2,7\cdot10^{-6}$	$4\cdot10^{-6}$	$5,4\cdot10^{-7}$	$1,3\cdot10^{-6}$	$1,6\cdot10^{-6}$	$2,7\cdot10^{-7}$	$4,7\cdot10^{-7}$	$9,4\cdot10^{-8}$
River Dnepr	$5,3\cdot10^{-8}$	$7,1\cdot10^{-8}$	$2,8\cdot10^{-8}$	$4,1\cdot10^{-8}$	$2,6\cdot10^{-8}$	$4,3\cdot10^{-8}$	$3,6\cdot10^{-8}$	$2,4\cdot10^{-9}$	$5,1\cdot10^{-9}$	$6,3\cdot10^{-9}$

Table 6.2

Calculated estimates and predictions of exposure doses for aquatic organisms (mrad/h) in the area of the radiation plume from the Chernobyl' nuclear power station (10-20 June 1986)

Water body	External exposure		Internal exposure		
	from water	from bottom sediments	aquatic plants	plakton	fish
Chernobyl' Power Station cooling pond	10 (2) ✸	4300 (300)	10000 (1000)	1000 (100)	500 (50)
River Pripyat' (buoy 204)	0,1 (0,009)	40 (3,3)	110 (15)	12 (2)	6 (0,8)
River Dnepr (Kiev, Inst. of Hydrobiology, Ukr. Academy of Sciences)	0,002 (0,0002)	0,3 (0,025)	1,0 (0,2)	0,1 (0,015)	0,04 (0,01)
Natural background	0,0001-0,006	0,002-0,02	0,08-0,2	0,002-0,016	0,003-0,005

✸   The figures in brackets are predictions for June 1987.

Fig. 6.I.

Calculated estimates and predictions of exposure doses for aquatic organisms in the region of the radiation plume from the Chernobyl' nuclear power station (10-20 June 1986)

Dnepr (Kiev, Inst. of Hydrobiol.)

Pripyat (buoy 204)

Chernobyl' power station cooling pond

I — External exposure from water
2 — External exposure for bottom sediments
3 — Internal exposure – against plants
4 — Internal exposure – plannton
5 — Internal exposure – fish

— 1986   — prediction for 1987

— natural background

- 8 -

9