Working Document
for the Post-Accident Review Meeting

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 2,7

DRAFT

August 1986

ANNEX 2

2. DESIGN OF THE REACTOR PLANT

The reactor plant is designed to produce dry saturated steam at a pressure of 70 kgf/cm^2 ($\simeq$ 7 MPa). It consists of the reactor proper with its monitoring, control and protection systems, and the piping and equipment of the multiple forced circulation loop (primary coolant circuit).

2.1. Reactor

The RMBK power reactor is a heterogeneous thermal neutron channel-type (pressure tube) reactor, in which graphite is used as the moderator, while the coolant is light water and a steam-water mixture circulating through vertical channels passing through the core.

The reactor core (1) takes the shape of a vertical cylinder with an equivalent diameter of 11.8 m and height of 7 m (see Fig. 2.1). It is surrounded by lateral and end graphite reflectors 1 and 0.5 m thick, respectively. The core is composed of fuel channels with the fuel assemblies inside them, a graphite moderator, channels with neutron absorber rods (control rods) and the sensors of the monitoring system. Some of the channels in the core are made of a zirconium alloy. The graphite stack consists of blocks assembled into columns with axial cylindrical openings into which the fuel channels are inserted. The fuel channels are located in 1661[*] cells in a square lattice with a 250 mm pitch. The channels of the control and protection system (CPS) number 211 and are arranged in the same way as the fuel channels in the central openings of the graphite stack columns (the arrangement of the channels is shown in Fig. 2.1a).

The grapite stack is located in a leaktight cavity (reactor space) formed by the cylindrical cowling (2) and the plates of the upper (4) and lower (3) metal structures. To prevent oxidation of the graphite and to improve heat transfer from the graphite to the fuel channels the reactor space is filled with a helium-nitrogen mixture with a volumetric composition of 85-90% He and 15-10% N_2. To prevent the possibility of helium leaking from the reactor space the inside cavities of the metal structures and the space around the cowling are filled with nitrogen at a pressure 50-100 mm H_2O (~ 0.5-1.0 kPa) greater than the pressure in the reactor space.

---

[*] The reactors of the first construction stages of the Leningrad, Kursk and Chernobyl' nuclear power stations contain 1693 fuel assemblies and 179 CPS channels.

The fuel channels are housed in tube ducts welded to the metal structures (5). The upper and lower metal structures and the water-filled annular tank (6) around the cowling serve as biological shielding for the rooms surrounding the reactor. The coolant (water) is fed in from below to each fuel channel through separate pipes. As it rises and flushes the fuel elements, the water heats up and partially evaporates; the steam-water mixture is led off from the top of the channels likewise through separate piping.

Nuclear fuel is reloaded without a reduction in reactor power by means of the refuelling machine.

Under steady-state operating conditions the intensity of the refuelling when the reactor is operating at nominal power is 1-2 assemblies per day.

The reactor is equipped with a control and protection system (CPS) and with monitoring systems which transmit information on the state of the core and the operation of various components, as well as sending the necessary signals to the CPS and the emergency signalling system.

Main characteristics of the reactor

Coolant flow through the reactor, t/h	37.6×10^3
Steam pressure in the separator, kgf/cm^2	70
Pressure in the group pressure headers, kgf/cm^2	82.7
Mean steam content at the reactor outlet, %	14.5
Coolant temperature, ^{o}C	
Inlet temperature	270
Outlet temperature	284
Maximum channel power, with allowance for 10% power distortion, kW	3000
Coolant flow rate in maximum power channel, t/h	28
Maximum steam content at channel outlet, %	20.1
Minimum critical power margin	1.25
Core height, mm	7000

Core diameter, mm	11 800
Fuel lattice pitch mm	250 x 250
Number of fuel channels	1661

2.1.1. Design of the fuel assembly and fuel element

The fuel assembly of the RMBK 1000 reactor consists of the following main parts (Fig. 2.2):

- Two fuel sub-assemblies (1);
- Supporting rod (2);
- Guiding tail and nose pieces (3 and 4);
- Nuts (5).

The fuel assembly is 1015 mm long.

Each sub-assembly consists of 18 fuel elements, a casing and 18 pressure rings.

The fuel element (2.2a) consists of the cladding (6), fuel column (7), holding spring (8), plug (9) and end piece (10).

The material of the cladding and end pieces is a zirconium alloy with 1% niobium (alloy 110). The spring is made of Ts2M zirconium alloy.
The outer diameter of the cladding is 13.6 mm and the minimal thickness 0.825 mm.

As the fuel use is made of sintered uranium dioxide pellets. The pellets are 11.5 mm in diameter and 15 mm high; to reduce the heat expansion of the fuel column the pellets are concave at the end. The mean mass of fuel in a fuel element is 3600 g, the minimum density of the pellets is 10.4 g/cm^3, and the diametric gap between the fuel and the cladding is 0.18-0.38 mm.

The fuel elements are made leaktight by resistance butt welding of the nose piece on to one end of the cladding tube and of plug on to the other.

The initial medium under the cladding is helium at a pressure of ~ 1 kg/cm^2 (0.1 MPa). The fuel column in the element is held in place by the spring with a constrictive force of about 15 kg.

The casing consists of a central tube 15 mm in diameter with a wall thickness of 1.25 mm, an annular grid (11) and 10 spacer grids (12). The central tube and end grid are made of a zirconium alloy with 2.5% niobium (alloy-125), while the spacer grids are made of stainless steel.

By means of two flairings the central tube is joined to the end grid in such a way that there is no possibility of an axial air gap at the join, and twisting of the grid with respect to the tube is also prevented. To keep the sub-assemblies in position and prevent them twisting with respect to one another, the casing tubes are fitted with special grooves. The spacer grids are fixed to the central tube at intervals of 360 mm. Each grid is secured by insertion of the projecting end of the central sleeve into two grooves on the tube in such a way that it can move along the tube if there is a small azimuthal air gap.

The spacer grid is assembled from individual shaped cells (12 cells in the peripheral row and 6 in the inside row), the central sleeve and an encircling rim. The parts of the grid are joined together by resistance spot welding. The openings for the fuel elements in the grid are 13.3 mm in diameter. On the rim of the grid there are projections making it easier to load the assembly into the channel. The diameter across the rim projections is ~ 78.8 mm.

The cells are made of tubing with a wall thickness of 0.35 mm; the central sleeve is made of tubing with a wall thickness of 0.5 mm, and the rim from tubing with a 0.3 mm in wall thickness.

The fuel elements are secured to the end grid by means of pressure rings made of stainless steel. The securing system cannot be taken apart, since the pressure rings deform when the fuel elements are secured.

The design of both fuel sub-assemblies is identical.

When the fuel-assembly is being put together, the nose piece, the two sub-assemblies, and the tail piece, which is fixed with a nut, are mounted on the central rod. The nut is prevented from unscrewing by means of a pin.

Two types of fuel-assembly are inserted in the reactor: a working assembly and an assembly for use as a monitor for the power density (over the core radius) which is different from the working assembly in terms of the design of the tie rod. The latter is hollow and consists of a tube with a 12 mm outside diameter and wall thickness of 2.75 mm, and a plug, both made of zirconium alloy (alloy-125), a steel-zirconium transition piece and an extension tube made of stainless steel.

2.1.2. Fuel channel (Fig. 2.3)

The fuel channel is intended to house the fuel assemblies with the nuclear fuel and to control the flow of coolant. The casing of the channel is a welded structure consisting of a middle and end part. The middle (2) is made of zirconium alloy (Zr + 2.5% Nb) and composed of a tube 88 mm in outside diameter with a wall thickness of 4 mm, an upper (1) and lower (5) end piece made of corrosion-resistant tubing (steel 08 Cr18Ni10Ti). The middle part is joined to the ends by means of special steel-zirconium transition pieces (3, 4).

The transition joints - corrosion-resistant steel-zirconium alloy - are manufactured by means of vacuum diffusion welding (Fig. 2.3(a)).

The transition joints are designed to produce programmed configurations and stresses in the area of the joint that guarantee strength and reliability under operating conditions. The inside part of the transition is made of zirconium alloy, while the outside part around it is made of corrosion-resistant steel. During the diffusion welding a thin layer of mutually diffusing products forms on the contact surface of the parts being joined together. The quality of the diffusion welding is checked by ultrasonic flaw detection and metallographic devices. As part of the fuel channel the transition pieces are also tested for helium leaktightness and hydraulic pressure.

The channel tubes are joined to the zirconium parts of the transition pieces by electron-beam welding. To improve the corrosion properties of the welded joints they undergo additional strengthening and heat treatment.

The steel parts of the transition pieces are welded to the top and bottom parts of the fuel channel by argon welding. A metallic coating of aluminium is applied to the outer surfaces of the steel parts in the channel to protect them against corrosion.

To improve heat flow from the graphite block to the channel, slotted graphite rings 20 mm high are fitted onto the middle of it and positioned very closely together along the channel so that every other ring is directly in contact, by means of its lateral surface, either with the pipe (7) or with the inside surface of the block (6), as well as being in contact at their ends.

The minimum gaps between the channel and ring - 1.3 mm - and ring and block - 1.5 mm - are designed to prevent wedging of the channel in the stack through radiation-induced thermal shrinkage when the reactor is in operation.

The channel body is housed in the reactor in tube ducts (3, 4) welded to the top and bottom metal structures (Fig. 2.4). It is attached immovably to the upper duct by means of a thrust collar and filament seam made by argon arc welding (1). The lower part of the body is welded to the metal structure duct, being joined to it through the bellows compensating unit (2); this makes it possible to compensate for any difference in thermal expansion of the channels and metal structures, as well as ensuring reliable leaktightness of the reactor space. The channel body is designed to operate safely for 30 years, but whenever necessary a defective channel body can be taken out of the reactor and replaced by a new one with the reactor shutdown.

The fuel assembly with its fuel elements (5) is mounted inside the channel on a suspension (6), which keeps it in the core and enables the refuelling machine to replace a spent fuel assembly without stopping the reactor.

The suspension is fitted with a closing plug (7), which is mounted in the housing of the upper duct. This plug hermetically seals the inside of the duct by means of a ball-type shutter fitted with a sealing washer. The unsealing operations during refuelling are carried out by the refuelling machine using remote control.

2.1.3. Control channels (Fig. 2.4)

These channels are intended to contain the control system rods, vertical power density monitors and ionization chambers. The middle of the channel (3) is made of a zirconium alloy (Zr + 2.5% Nb) and constitutes a tube 88 mm in diameter and with a wall thickness of 3 mm. The upper (1) and lower (4) end parts are made of corrosion-resistant piping (steel 08 Cr18Ni10Ti). The middle part is joined to the end tubes by means of steel-zirconium transition pieces similar to those used for the fuel channels. The channels are secured immovably to the upper tube duct by means of a thrust collar and a filament seam, and to the lower duct via the bellows compensating unit. The CPS channels in the upper part have heads (5) designed for the attachment of actuators and for supplying cooling water to the channel. Graphite sleeves (6) are placed over the channel and provide the requisite temperature conditions for the graphite column. At the bottom of the channel is a throttle device (2), which ensures that the channel is completely filled with water.

Placing of the control channels in the graphite columns independently of the fuel channels guarantees their preservation and, consequently, the efficiency of the control elements contained in them in the event of possible accidents due to rupture of the fuel channels.

2.1.4. Metal structures of the reactor (Fig. 2.1)

The lateral biological shielding tank (6) takes the form of a cylindrical reservoir with an annular section 19 m in outside diameter and 16.6 m in inside diameter: it is made of low-alloy steel sheeting of the pearlite class (10 CrSiNiCu) 30 mm thick. Inside the tank is divided into 16 vertical leaktight compartments filled with water, the heat from which is removed by the cooling system. The top metal structure (4) is a cylinder 17 m in diameter and 3 m high. The upper and lower plates of the cylinder are made of steel (10 CrNilMo) 40 mm thick welded to the lateral shell by means of leaktight welds, and welded to each other by means of vertical strengthening fins. The holes in the top and bottom plates are for the welded-in tube ducts (5) holding the fuel and control channels. The space between the tubes is filled with serpentinite (a mineral containing bound water of cystallization). The metal structures are mounted on 16 roller-type supports attached to the projection of the annular part of the lateral biological shielding and bear the weight of the loaded channels, the floor of the central hall and the piping of the upper steam-water and water communication lines.

The bottom metal structure (3), which is 14.5 m in diameter and 2 m high, is similar in design to the top structure. It is loaded by the graphite stack mounted on top of it together with the supporting units and lower water communications. The number and arrangement of the lower fuel and control channel ducts welded to the top and bottom of the lower metal structure are the same as in the upper structure. The cavity inside it is filled with serpentinite. The supporting metal structure on which the lower metal structure is mounted is composed of plates with reinforcing fins 5.3 m high which intersect at the centre of the reactor and are perpendicular to each other (7).

The cylindrical shroud (2) is a welded shell with an outside diameter of 14.52 m and height of 9.75 m made of steel sheeting (10 CrNilMo) 16 mm thick. To compensate for longitudinal heat expansion the shroud is fitted with a lens-type compensator. The shroud, together with the top and bottom metal structures, forms the closed reactor space.

The metal structure of the top covering (8) has an opening for the insertion of the fuel and other special channels. It is covered over by a removable floor (9) consisting of individual slabs. The floor acts as biological shielding for the central hall and, furthermore, serves as heat insulation for it. The floor consists of upper and lower slabs and blocks resting on the fuel and reflector channel ducts. The slabs and blocks are metal structures filled with iron-barium-serpentinite cement stone.

Air is extracted from the central hall through gaps in the floor and then passes to the ventilation shafts. The air cools the floor and prevents the possibility of radioactivity releases entering the hall from the room containing the steam-water communications.

2.1.5. Graphite stack (Fig. 2.1)

The graphite stack (1) is assembled on the lower metal structure inside the reactors space. It takes the form of a vertical cylinder made up of 2488 columns of graphite blocks with a density of 1.65 g/cm^3. The blocks are shaped like parallelepipeds with a 250 x 250 mm section and height of 600 mm. The mass of the stack is 1700 t. There are openings 114 mm in diameter along the axis of the blocks, forming ducts in the columns to hold the fuel channels and CPS channels. Each graphite column is mounted on a steel base plate (10), which in turn rests on a cup welded to the top plate of the lower metal structure. The graphite stack is made secure against movement in a radial direction by means of rods positioned in the peripheral columns of the lateral reflector. At the bottom the rod is welded to the supporting cup, while at the top it is joined immovably to the tube duct welded to the bottom plate of the upper metal structure. The hollow rod, made of corrosion resistant steel (08 Cr18Ni10Ti) piping, holds the channel for cooling the reflector blocks. The heat released in the stack is removed basically to the fuel channels and partially to the CPS channels. The presence of firm-contact rings on the channels and the helium-nitrogen mixture with which the channel-ring and ring-block gaps are filled keep the stack at a temperature not exceeding 700°C.

In the case of the graphite blocks the highest temperature zones are to be found on the block edges, while the lowest temperatures are found on the inner surface of the vertical openings into which the fuel and other channels are placed. The highest temperature is found in by the blocks located in the middle of the centre part of the core.

The greatest temperature differential - between the edge and inner surface of the opening - is to be found in the block with the fuel channel and amounts to ~ 150°C.

2.1.6. Biological shielding

The biological shielding of the fourth unit reactor of the Chernobyl' nuclear power station has been designed in accordance with the requirements in force in the USSR - "Radiation Safety Standards NRB-76" and "Health Regulations for Designing and Operating Nuclear Power Plants SP-AEhS-79".

The dose rate for external exposure in the central hall and serviced buildings adjoining the reactor vault do not exceed 2.8 x 10^{-2}mSv/h (2.8 mrem/h). During refuelling, at the time when the spent fuel assembly is removed and passed through the floor of the central hall, the gamma dose rate close to the refuelling machine briefly rises to 0.72 mSv/h. In the room containing the water communication lines below the reactor the shielding ensures that the neutron flux density drops to values at which there will be no appreciable activation of the piping and structures. It is only permitted to enter that room when the reactor has been shut down.

Shielding against radiation from the coolant in the piping and equipment of the main circuit makes it possible to carry out repair and adjustment operations while the reactor is in operation; for example, channel-by-channel adjustment of the coolant flow by means of multipurpose valves fitted in the group headers, repairs to the electric motors of the main circulation pumps, and so on. Radiation heat release is reduced to values at which the temperature of the supporting metal structures (top, bottom and tank) and the reactor shroud is not more than 300°C, which makes it possible to use low-alloy steel.

The fast neutron fluence with an energy of more than 0.1 MeV reaching the reactor shroud and sheeting of the metal structures close to the core has not exceeded 10^{20}n/cm^2 in 30 years of operation.

The shielding designed takes the following form (Fig. 2.1).

Mounted on each graphite column, between the end reflectors 500 mm thick and the upper and lower metal structures, are steel blocks (10) (the lower ones are 200 mm thick and the upper ones 250 mm) designed to reduce the fast neutron fluence onto the metal structures supporting the load, as well as to reduce the energy released in them.

The space between the tubes in the top and bottom metal structures is filled with serpentinite (3, 4), which makes it possible to reduce the length of the fuel channels and the overall dimensions of the building.

Above the steam-water communication lines is a protective covering (floor of the reactor hall), the central part of which - the slab flooring (9) - is made up of a set of blocks resting on the tops of the channel ducts. These blocks are made of iron-barium-serpentinite cement stone. The overall thickness of the covering is 890 mm. The upper flooring protects the central hall against radiation from the reactor and from the piping containing the radioactive coolant, and together with the refuelling machine container reduces the intensity of the radiation when unloading spent fuel assemblies. The peripheral part of the upper covering (8) constitutes metal cases 700 mm high filled with a mixture of pig iron shot (86% mass) and serpentinite.

In a radial direction the lateral reflector consists of four graphite blocks, with a mean thickness of 880 mm. The annular water tank (6) lying behind the reactor shroud reduces the radiation fluxes to the walls of the reactor vault (11), which are made of building concrete (density 2.2 t/m^3 and wall thickness 2000 mm). The space between the tank and the walls is filled with ordinary sand (12).

The thicknesses and composition of the materials of which the RBMK reactor shielding is made in the main directions away from the core are shown in Table 2.1.

Table 2.1. Thickness of shielding materials (in a direction away from the core centre) (mm).

Material	Direction		
	Upward	downward	radial
Graphite (reflector) (mm)	500	500	880
Steel (protective plates and sheeting of the metal structure) (mm)	290	240	45
Serpentinite filling (1.7 t/m^3)(mm)	2800	1800	-
Water (annular tank)(mm)	-	-	1140
Steel (metal structures)(mm)	40	40	30
Sand (1.3 t/m^3)(mm)	-	-	1130
Heavy concrete (4.0 t/m^3)(mm)	890	-	-
Building concrete (2.2 t/m^3)(mm)	-	-	2000

A reduction in the intensity of radiation streaming through the gas-filled channels (for temperature sensors, neutron flux detectors and ionization chambers) or channels with less effective shielding (steam-water mixture in fuel channels) is attained by inserting shielding plugs made of steel or graphite (Fig. 2.5). The annular gaps between the channels and the guide tubes are closed by means of shielding sleeves (Fig. 2.6).

The gas piping which passes through the shielding structures is made with bends (No. 13 in Fig. 2.1).

To prevent neutron streaming and gamma radiation, as well as to reduce the activation of the structures in the area below the reactor, the displacers in the CPS channels are filled with graphite (Figs 2.17 and 2.30).

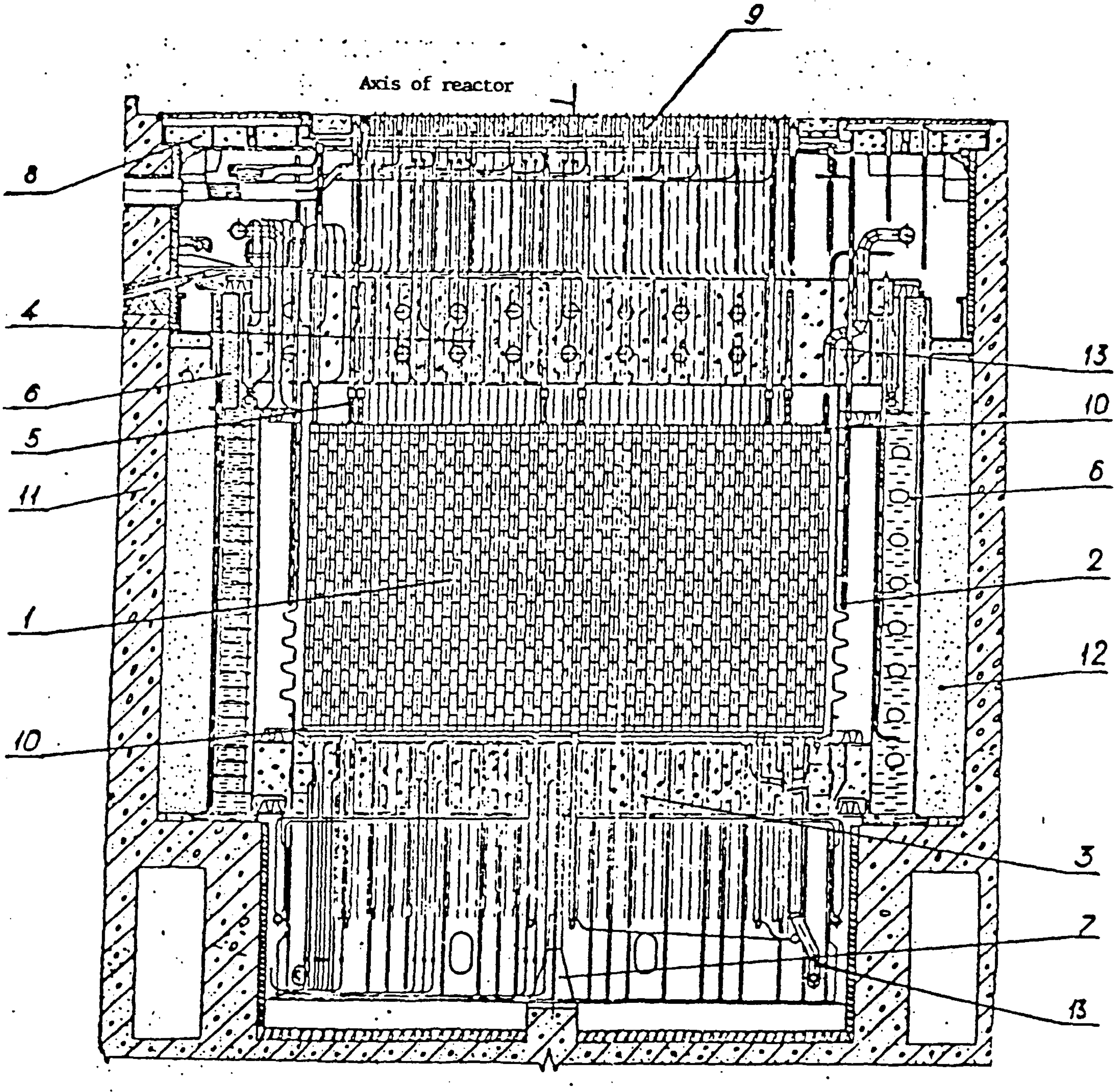


Fig. 2.1

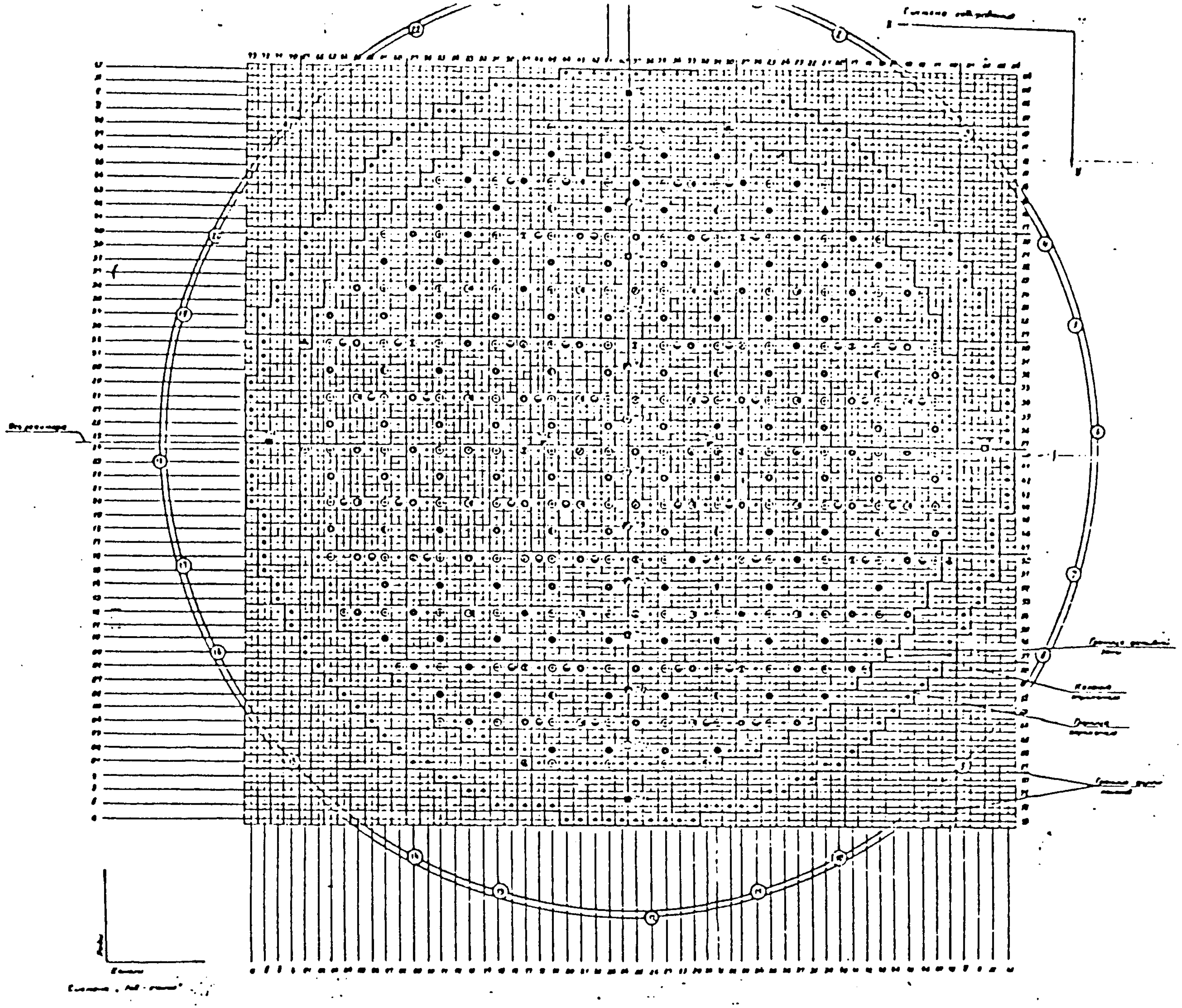


Fig. 2.Ia

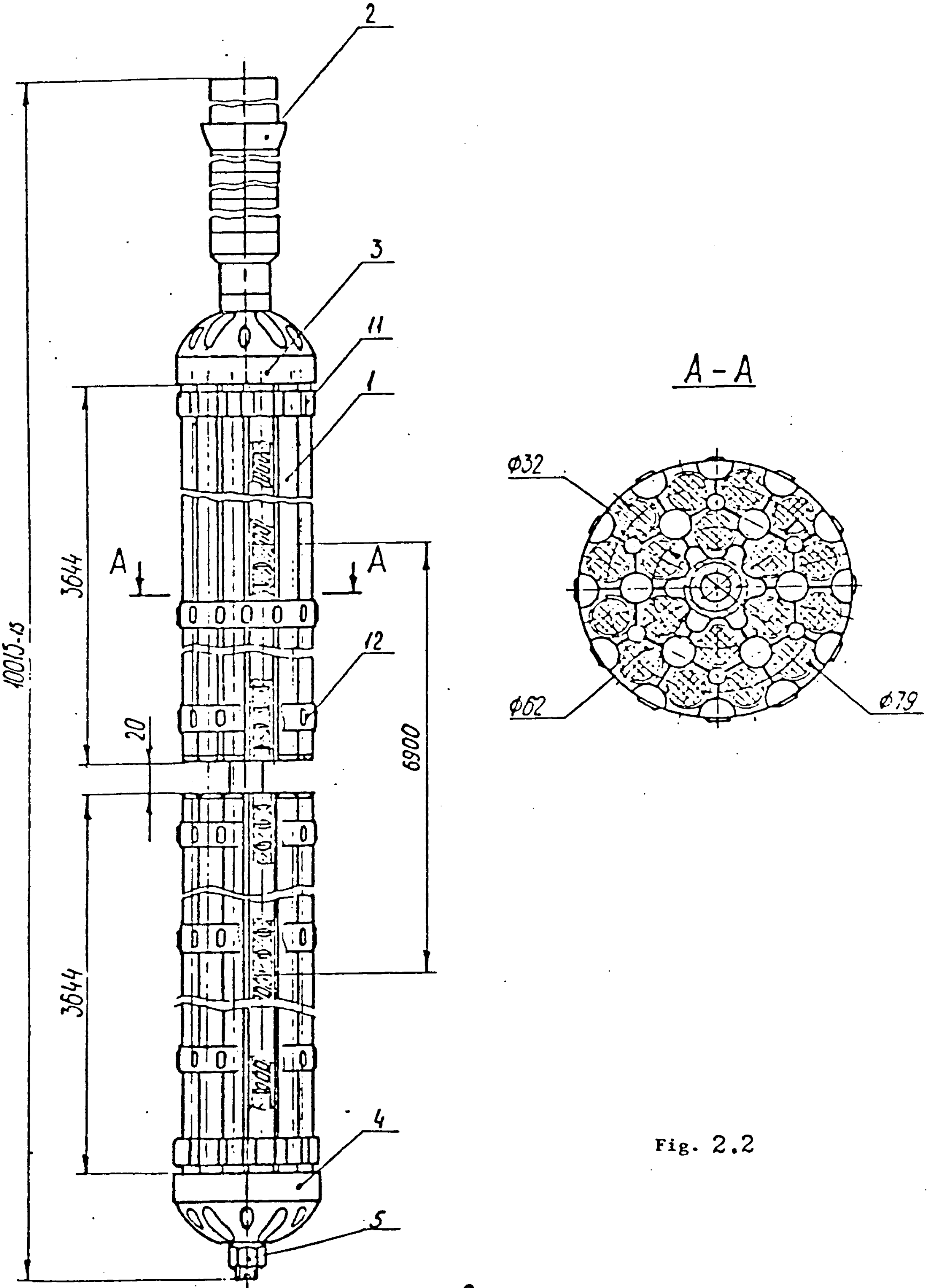


Fig. 2.2

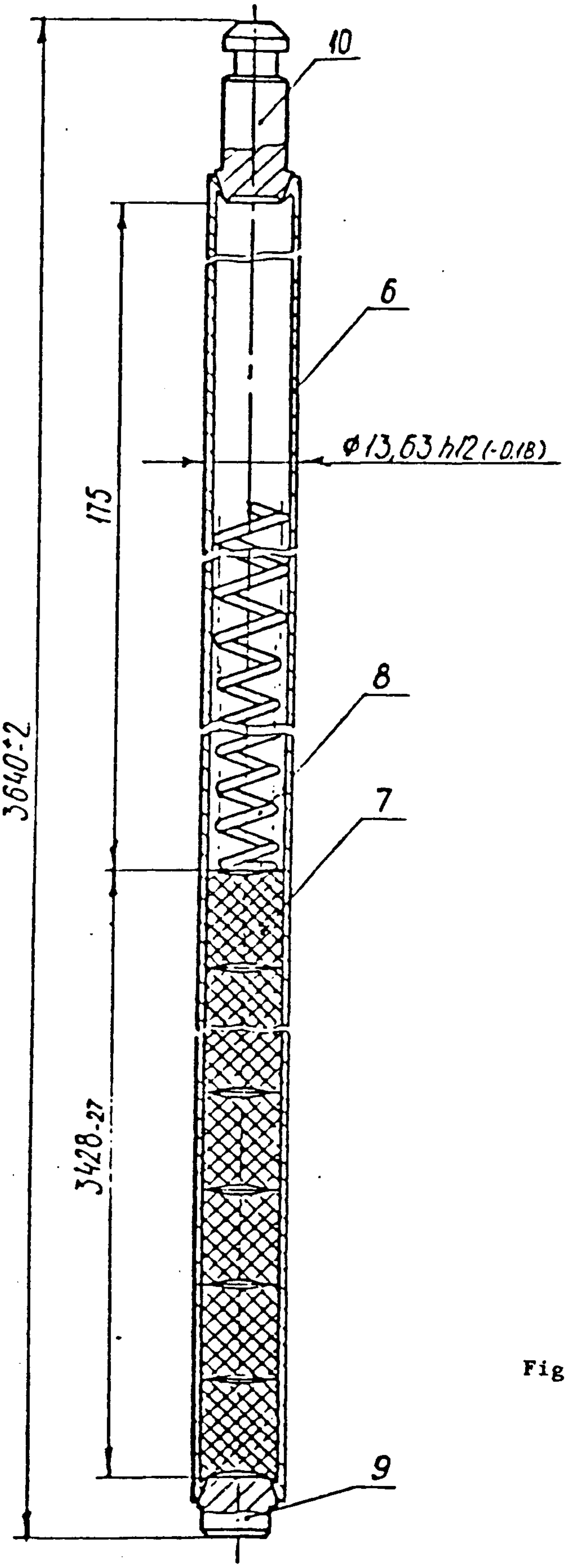
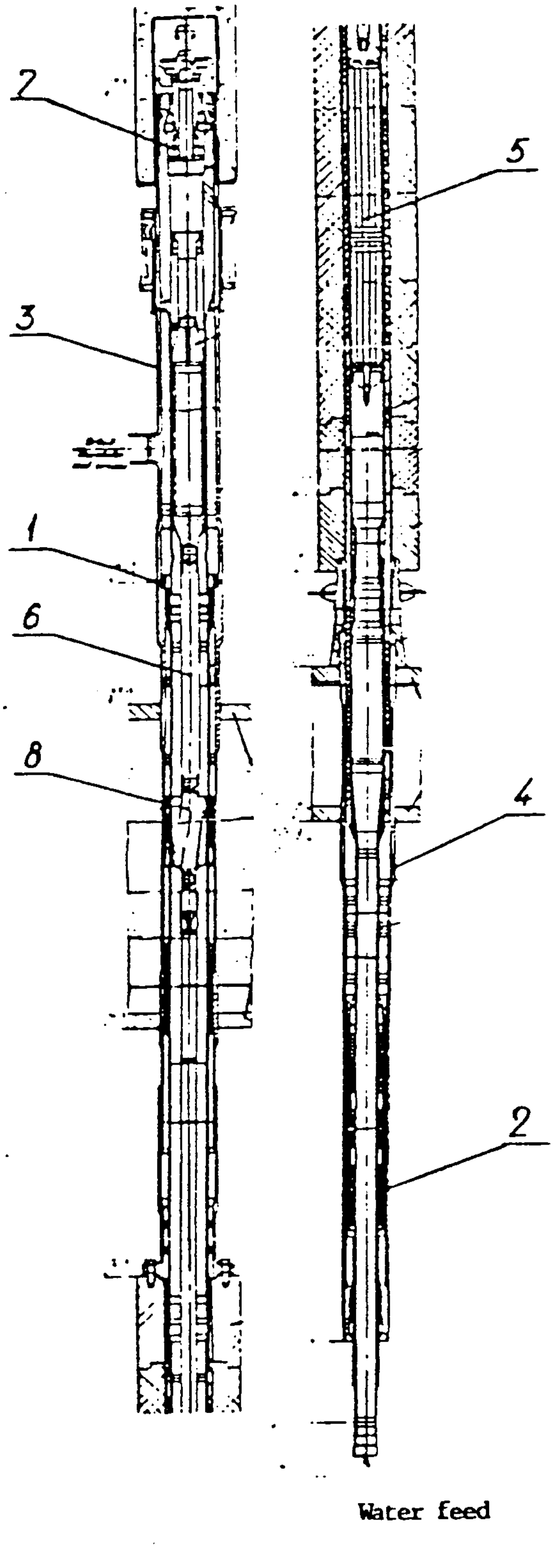


Fig. 2.2a

RBMK fuel channel



Water feed

Fig. 2.3

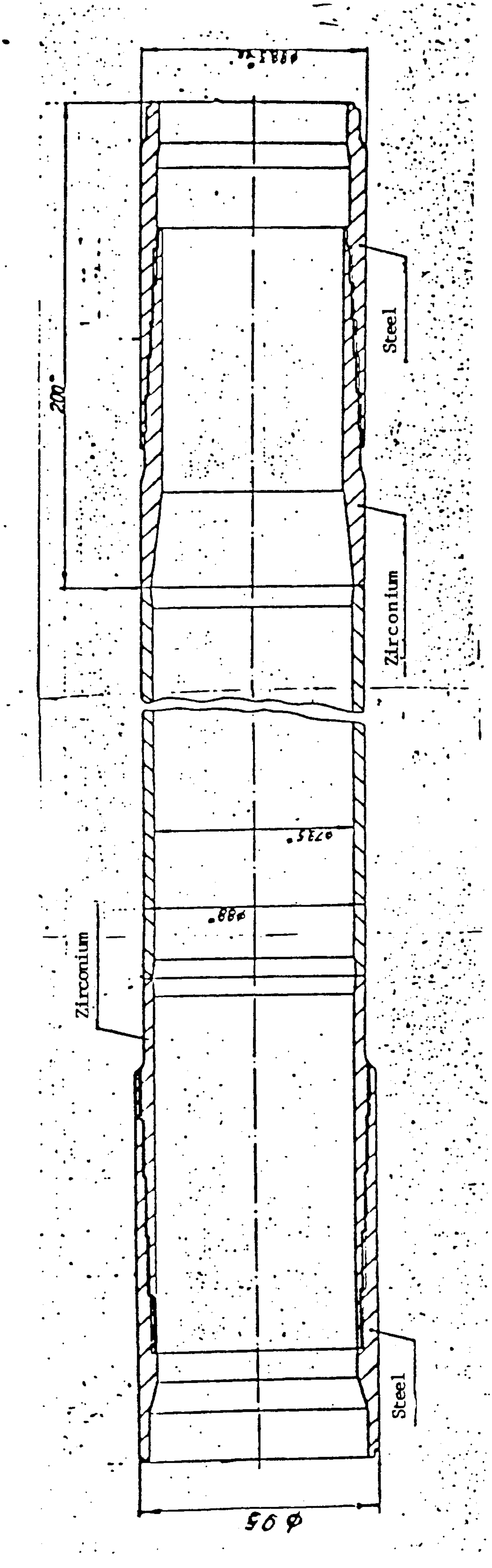


Fig. 2.3a

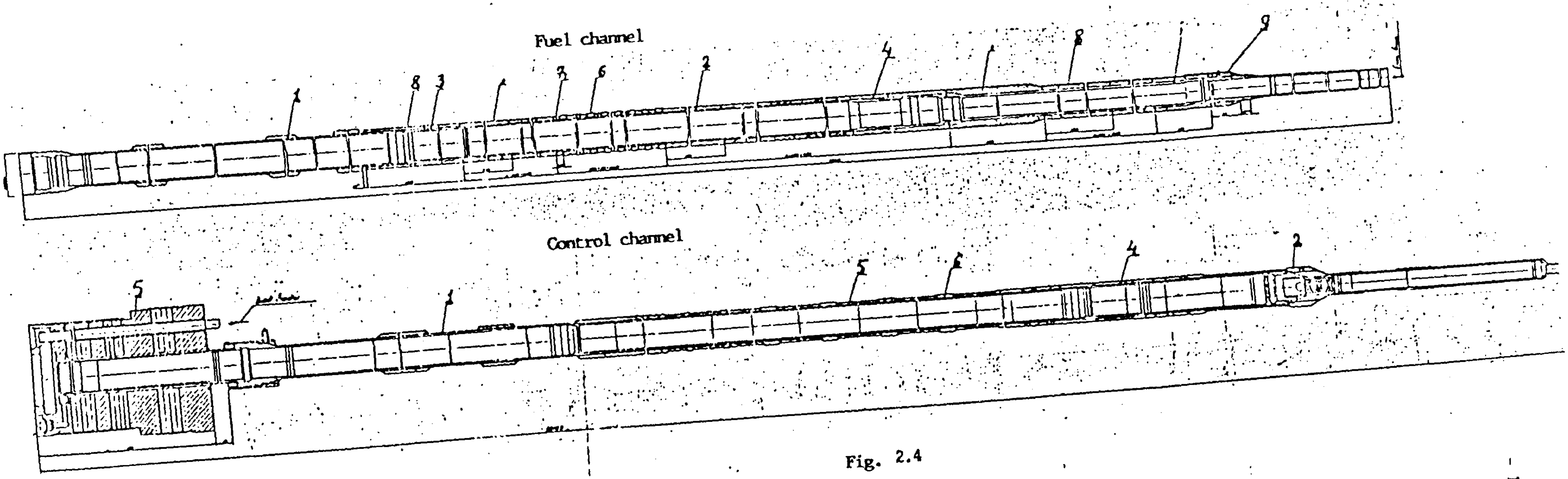


Fig. 2.4

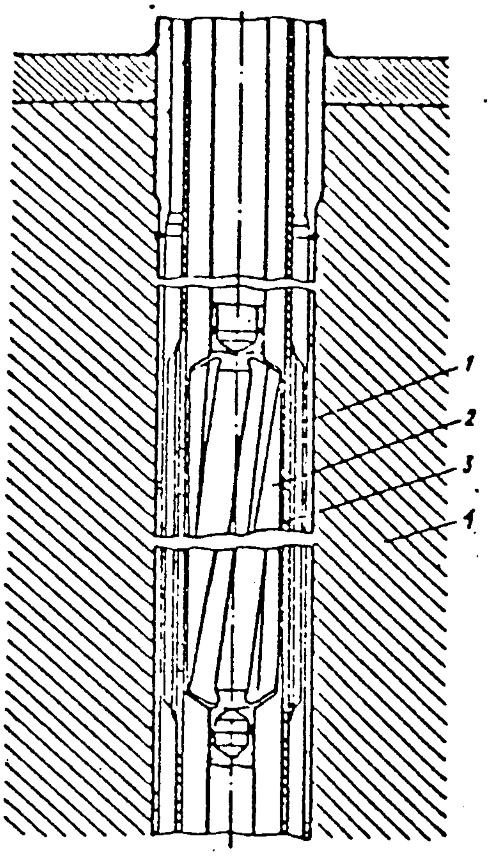


Fig. 2.5. Position of shielding plug in fuel channel: (1) steel sleeves; (2) helical steel plug; (3) channel tube; (4) serpentinite filling

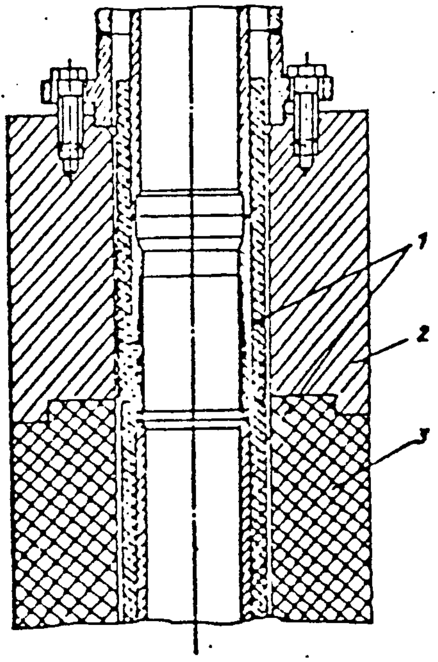


Fig. 2.6. Arrangement of shielding sleeves in upper reflector area: (1) graphite sleeves; (2) steel shielding block; (3) graphite reflector

2.2. Primary circuit (multiple forced circulation circuit)

(Fig. 2.6) [?]

The purpose of the primary circuit is to supply water to the process channels and to remove the steam-water mixture, which forms in them as a result of the heat taken up from the fuel assemblies, for subsequent separation of the steam. It consists of two loops, similar in their arrangement and equipment, which function in parallel and indendently; each removes heat from half of the reactor's fuel assemblies. A loop includes: 2 drum-type steam separators (int. diam. = 2600 mm), downpipes (325 x 16), 4 main circulation pumps, main circulation pump suction pipes (int. diam. = 752 mm) and fittings, main circulating pump pressure header (int. diam. = 900 mm), distributing headers (325 x 15 mm) with isolating and regulating valves, water lines (57 x 3.5 mm), process channels and steam lines (76 x 4 mm). (A diagram of the primary circuit fittings is shown in Fig. 2.7). [Missing from original.]

Water from the suction header (1) passes through four pipes to the main circulating pumps (2). Under normal operating conditions at normal power three of the four main circulating pumps are in operation, with one held in reserve. Water leaves the main circulating pumps at a temperature of 270°C at a pressure 82.7 kgf/cm^2 through pressure pipes, in each of which are installed in sequence a non-return valve, a gate valve and a throttle valve, and then flows into the main circulating pump pressure header (3), from where it passes through 22 lines into the distributing headers (4), which have non-return valves at their inlets, and then along individual water lines (5) into the process channel inlets (6). The flow rate through each process channel is determined by means of isolating and regulating valves in accordance with the flowmeter readings. As it passes through the process channels, the water surrounding the fuel elements is heated to saturation temperature, partially evaporates (14.5% on average) and the steam-water mixture at a temperature of 284.5°C and a pressure of 70 kgf/cm^2 (~7 MPa) flows through the individual steam lines (7) into the separators (8), where it is separated into steam and water. In order to keep the levels the same, the separators are interconnected with separate shunts for water and steam. Saturated steam passes through the steam collectors to the turbines. The water which has been separated out is mixed at the separator outlets with feed water, and flows through 12 downpipes (from each separator) into the suction header at a temperature of 270°C; this provides the cavitation margin required by the main circulating pumps.

The temperature of the water flowing into the suction header depends on the rate of steam production of the reactor unit. When this decreases, the temperature increases somewhat because of the changing ratio of water from the drum separators, at a temperature of 284°C, and feed water, at a temperature of 165°C. When the reactor is being powered down, the flow rate through the primary circuit is controlled using throttle-type control valves so that the temperature at the main circulation pump inlet maintains the necessary cavitation margin.

2.3. Special control channel cooling circuit

There is a special, independent cooling circuit for the side screen and the control channels, vertical power density monitors and the startup ionization chambers. The water circulates under gravity, i.e., because of the difference in level between the upper (storage) and lower (circulation) tanks. Cooling water at 40°C flows from the upper tank through a header along individual lines to the channel end-plugs, and continues downwards removing heat and warming up in turn to a temperature of 65°C. It then passes through a discharge header into heat exchangers, where it is cooled to 40°C, and collects in the lower tank, from which it is pumped back up into the upper tank. The mean flow rate through the control channels is 4 m^3/h and the overpressure at the channel end-plugs is 3.5 kgf/cm^2. The flow rate through each channel is controlled using isolating and regulating valves in accordance with the flow meter readings.

2.4. The gas circuit

Under normal operating conditions, a helium-nitrogen mixture flows at 200-400 nm^3/h [sic] at an overpressure on entering the reactor space of 50-200 mm head of water equivalent (0.5-2.0 kPa) through pipes which pass through the lower part of the metal structure, it is removed through the process channel failure monitoring system pipes and through special channels which remove the gas from the piping sectors of the upper part of the metal structure. The gas mixture then passes through a condenser, a three-stage scrubbing system, its flow rate is controlled by throttle and it returns to the reactor space. The gas is circulated by means of compressors.

The gas scrubbing system consists of a set of contact catalysers, scrubbing and dewatering units and cryogenic cooling system units. In the contact catalyser, hydrogenation with H_2 takes place at a temperature of ~160°C, with the formation of water vapour and combustion of CO to CO_2 and the release of heat. The reaction takes place in an oxygen atmosphere in the presence of a platinum catalyser. After passing through the contact catalyser, the gas passes through a refrigerator and dehumidifier and then on into the scrubbing and dewatering unit, which is equipped with zeolite and mechanical filters. Adsorption takes place and CO_2, H_3, C_2 and water vapour impurities are scrubbed from the helium-nitrogen gas, which then passes to the cryogenic cooling unit. Any impurities remaining in the gas are removed in this unit by dephlegmation at a temperature of -185°C.