For the most part this Section describes the mechanical aspects of plant features located in the core region or its immediate vicinity. This encompasses the description of the fuel channels, the core block itself, its surrounding structures and shields. Section 4.3 describes the various control and instrumentation channels, the control rod drives and the fuel handling system, Section 4.4 presents the core block draining system. Section 4.5 departs from mechanical aspects and outlines the major operational procedures which directly involve the reactor core.

4.1 DESIGN BASIS

The RBMK-1500 is fueled by a graphite-moderated, water-cooled reactor core having a thermal power generation capacity of 4800 MW. It is designed to provide saturated steam at a pressure of 7.0 MPa. The fuel is low enrichment UO_2 which is loaded into the core in the form of zirconium clad, 13.6 mm diameter fuel rods. Initial enrichment was 2%, since 1997 reload fuel is 2.4%. Fuel clusters are made up of 18 such rods and each is positioned in an individual vertical fuel channel. There are 1661 vertical fuel channels having an active fuel length of 7 m. Design fuel burnup is 21.6 MWdays/kg though presently this can be lower because of safety-imposed restrictions related to minimizing of the steam reactivity coefficient. The real fuel burnup is about 12-16 MWdays/kg for loading of fuel with 2% enrichment, and not less 21 MWdays/kg for loading fuel with 2.4 % enrichment. The fuel clusters are cooled by water which enters at the bottom at a subcooling of 30 ^{o}C and exits the channels at an average steam volume fraction of about 76%. Nominal coolant flow rate at design power is 10000 kg/s.

4.2 DESCRIPTION OF SYSTEM

The position of the reactor core and its main components in a RBMK-1500 plant is shown in the schematic cross-section through the main reactor building provided in Fig. 4.1.

The core of the reactor is housed in a 25 m deep, 21x21 m cross-section concrete vault. The core volume is dominated by a large cylindrical graphite stack (1), an isometric drawing of this structure is shown in Fig. 4.2. The graphite stack is constructed of closely packed graphite blocks stacked into columns and provided with an axial opening. Most of the openings contain fuel channels. A number of them also serve other purposes (e.g. instrumentation, reactivity regulation). Therefore, adapting the nomenclature of the designer, these will be referred to as "special channels".

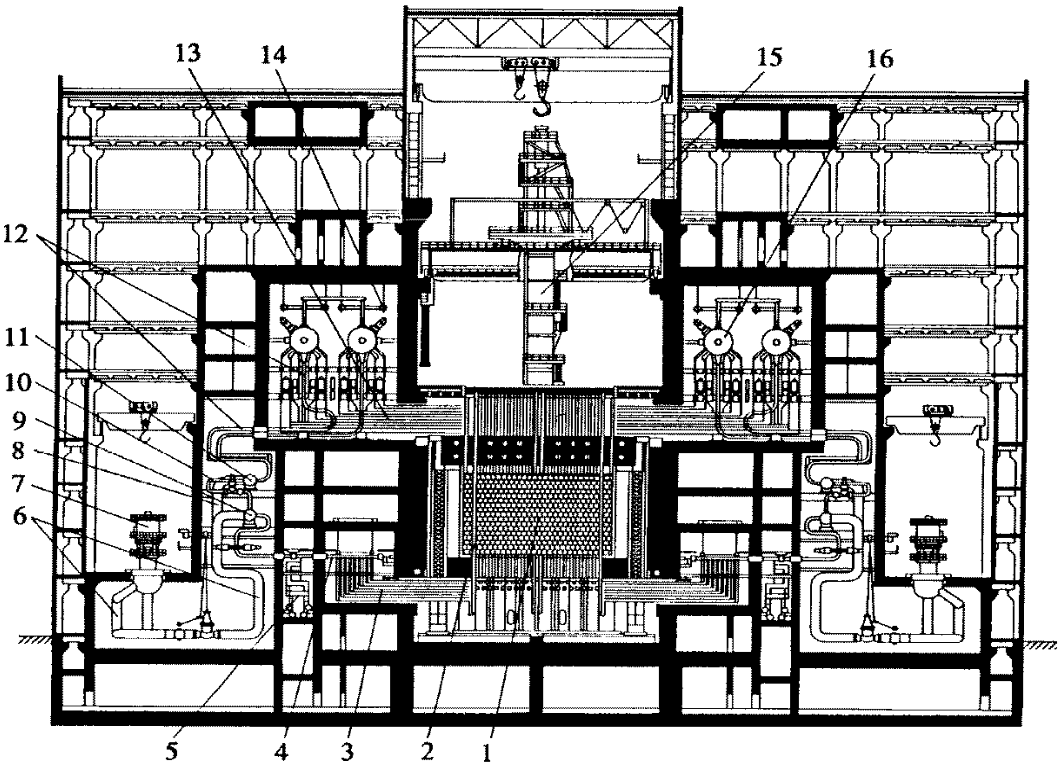

Fig. 4.1 General view of the reactor
1 - graphite stack, 2 - fuel channel feeder pipes, 3 - water pipes, 4 - distribution header, 5 - emergency core cooling pipes, 6 - pressure pipes, 7 - main circulation pump, 8 -suction pipes, 9 - pressure header, 10 - bypass pipes, 11 - suction header, 12 - downcomers, 13 - steam and water pipes, 14 - steam pipes, 15 - refueling machine, 16 - separator drum

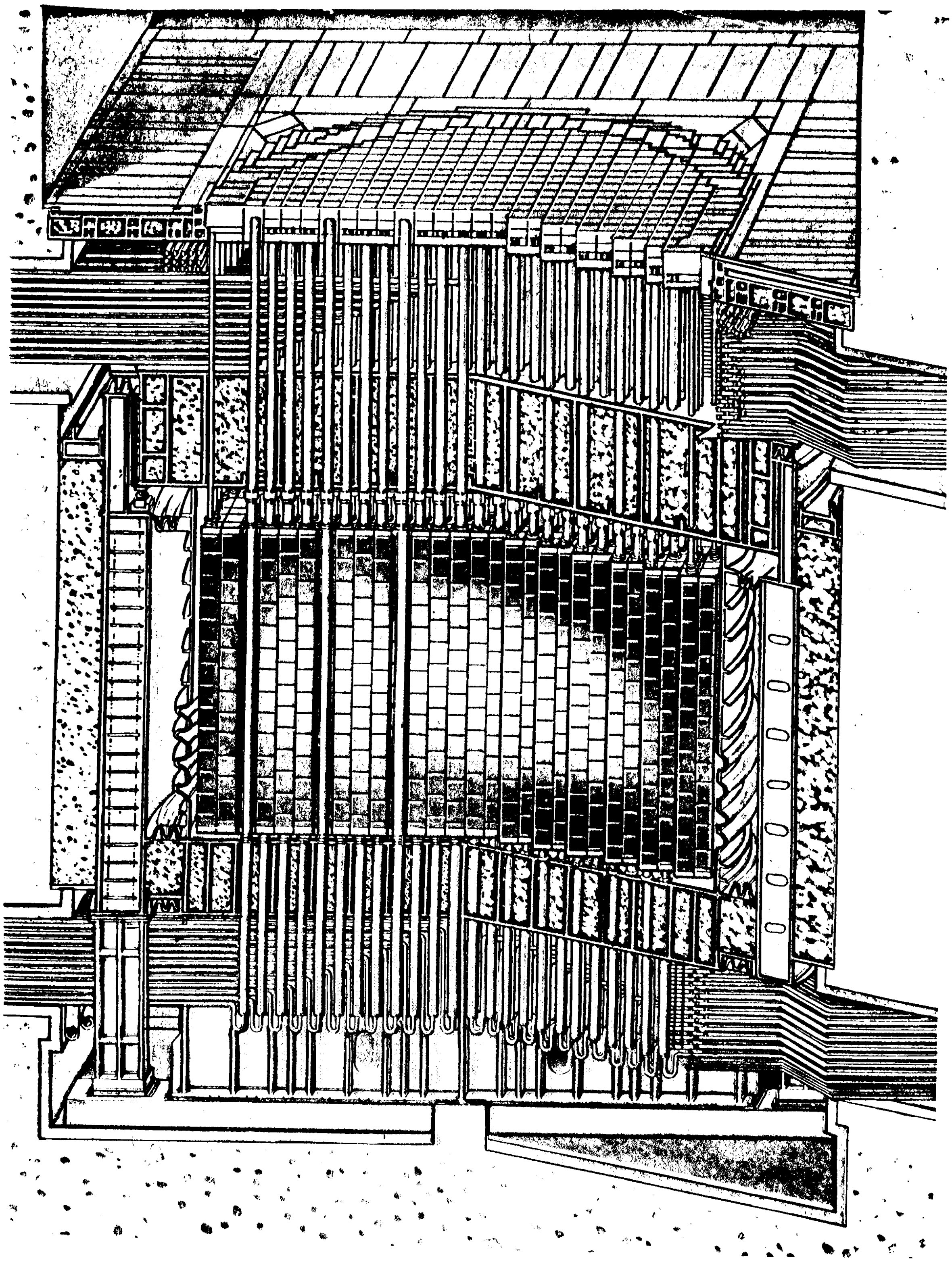

Fig. 4.2 General view of the graphite stack and the water-steam piping

The graphite stack is located in a hermetically sealed cavity consisting of cylindrical walls and top and bottom metal plates. The entire reactor cavity is filled with a helium (about 40 % by mass) and nitrogen mixture which prevents graphite oxidation and improves heat transfer from the graphite to the fuel channels. In order to prevent loss of helium, the space surrounding the cylindrical graphite stack is filled with nitrogen at a pressure of about 0.29 - 0.98 kPa greater than that of the helium-nitrogen mixture [62]. In the radial direction as well as above and below the reactor it is surrounded by the primary biological shield structures.

The coolant channels penetrating the reactor core are divided into two essentially independent cooling loops: one containing 830, the other 831 vertical channels with fuel assemblies. Each loop is provided with four main circulation pumps, one of which is kept in reserve during normal operation. The circulation of the coolant in each of the reactor cooling loops can be traced with the help of Fig. 4.1. Water from the main pump pressure header (9) is distributed first to 20 group distribution headers (4) from there to the feeder pipes (3), these then lead to the individual fuel channels. The water rises past the fuel assemblies, attains its saturation temperature, partly vaporizes (average steam quality is 23 %) and, in the form of a steam-water mixture, flows through the header pipes (13) to the separator drums (16). Here the two-phase mixture is separated, and the steam continues to the turbines. The condensate passes through deaerators, returns to the separator drums where it mixes with the unvaporized water. From there the condensate flows via standpipes to the pump suction header (11), and then to the main circulation pumps (7), which return it to the fuel channels.

As noted in previously, one of the important characteristics of RBMK reactors is their online refueling capability. Refueling at full reactor power is accomplished by means of the fueling machine (15). Under normal operation and nominal reactor power, it is feasible to change up to two fuel assemblies per day (24-hours). The maximum capacity of this machine is 5 fuel assemblies per day.

The reactor is provided with instrumentation systems monitoring the following parameter groups:

- axial and radial core flux distribution,
- fuel channel integrity,
- fuel cladding integrity in each fuel channel,
- coolant flow for each channel,
- metal structure and graphite temperature.

These systems provide integral information regarding the operation of the entire reactor and information regarding specified reactor core segments and individual fuel channels. Because of the very large size of the core and the resulting weak neutronic coupling of distant core segments, reactor operation requires a detailed spatial resolution of the main operational parameters.

4.2.1 The Graphite Stack

An isometric view of the graphite stack is presented in Fig. 4.2. The graphite stack of the RBMK-1500 reactors serves several functions. The primary one is neutron moderation and reflection, but it also provides structural integrity and in the event of a temporary cooling malfunction, a relatively large heat capacity.

The graphite blocks are assembled within the inner cavity of the reactor on a supporting metal structure. The stack can be visualized as a vertical cylinder, made up of 2488 graphite columns, constructed from various types of graphite blocks. Fig. 4.3 illustrates how these blocks fit together in the lower and upper regions of the stack. The blocks are rectangular parallelepipeds, with a base of 0.25 x 0.25 m, and heights of 0.2, 0.3, 0.5 and 0.6 m of which the 0.6 m blocks are most common. The short blocks are used only in the top and bottom end reflectors, as required to provide a staggered fit to neighboring columns. The total mass of graphite is about 1700 tons. The material must meet stringent purity requirements and has a density of 1650 kg/m^3.

The outer edge of the graphite stack is covered by a metal liner. The four rows of columns at the outer edge make up the radial reflector, and a 0.5 m thick layer at the top and bottom make up the end reflectors. The blocks possess a 0.114 m diameter bore opening through the vertical axis. This provides a total of 2044 channels which are used for placing fuel clusters, reactivity regulating control rods and several types of instruments into the core. In the remaining 444 columns located within the radial reflector the central holes are filled by graphite rods, increasing the density and neutron reflecting effectiveness of this part of the graphite stack. As shown in Fig. 4.3, the graphite columns rest on a steel support plate (5) which, in turn, is supported by a steel bushing (4). The bushing is welded to the top plate of the bottom biological shield. At the top of the stack, the columns are fastened and centered with respect to the guide pipes (9) welded into the top biological shield, by means of shield plates (7) and junction sleeves (8).

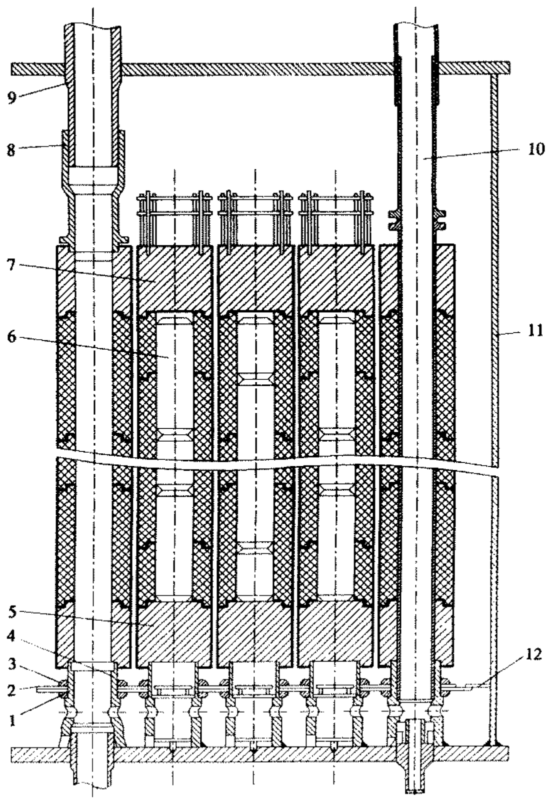

Fig. 4.3 Segment of the graphite stack
1 - top ring, 2 - diaphragm, 3 - bottom ring, 4 - bushing, 5 - steel support plates, 6 - graphite rods, 7 - shield plates, 8 - standpipe, 9 - guide pipe, 10 - reinforcing tube (reflector cooling channel), 11 - outer steel shell, 12 - ring plate

The shield and support plates have a similar purpose: namely, they consist of steel and, in addition to their fundamental function of joining the intermediate elements of the graphite stack, also ensure thermal insulation of the top and bottom metal structures, and in part serve as biological shielding. A diaphragm, indicated as (2) in Fig. 4.3 is fastened to the support bushings by means of a special rings (1), (3). Its primary purpose is to channel the helium-nitrogen flow coming through the bottom biological shield into the spaces between the channels and the graphite blocks. Secondly, it is intended to reduce the radioactive heat transfer between the support plates and the top plate of the bottom biological shield. The diaphragm is a 5 mm thick stainless steel sheet. The radial span between the diaphragm and the inside of the stack shell (11) is covered by a ring (12).

Radial creep of the graphite stack is restrained by 156 hollow reinforcing bars (10). These bars are positioned in the peripheral columns of the radial reflector. At the bottom, the reinforcing bars are welded to the support plate, while at the top they fit loosely into the guide tubes welded to the bottom plate of the top biological shield. This connection at the top allows freedom for thermal expansion. Since the reinforcing bars are hollow, they also serve as reflector cooling channels. Cooling water to these channels is supplied from above. The reinforcing bars are made from stainless steel tubes, with outside diameters of 0.110 m and wall thickness of 5 mm.

The corners of the rectangular cross-sections of the graphite columns in the stack are hollow and incorporate 17 vertical 45 mm diameter instrumentation channels used for measuring the temperatures of the graphite stack itself as well as the support and the shielding plates. Thirteen of these channels are positioned within the boundaries of the core, while four are in the radial reflector. Within each channel the temperature is measured at 5 vertical positions.

The graphite stack, including its hermetically sealed cavity, is called the sealed reactor space. This space is filled with a circulating helium-nitrogen mixture at a pressure of 0.49 - 1.96 kPa. During normal operation, the gas is supplied by means of 0.3 m inside diameter tubes, and removed through the fuel channel integrity monitoring system. Four drainage tubes (inside diameter of 0.15 m) are provided in order to guard against accidental releases.

When the reactor is in operation, all the components listed above are subjected to conditions of high temperature and intense neutron/gamma radiation. For example, the temperature of the support structures in the top part of the bottom biological shield reaches 350°C. The temperature of the bottom support plates reaches 440°C, while the maximum calculated graphite temperature is 750°C.

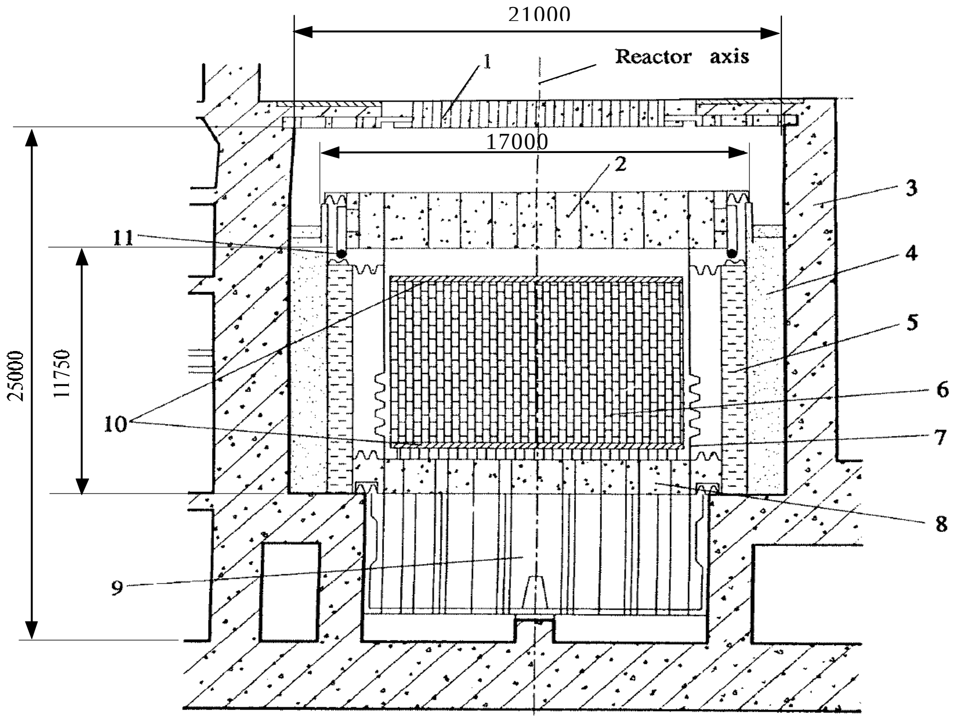

Fig. 4.4 Cross-section of the reactor vault
1 - top cover, removable floor of the central hall, 2 - top metal structure filled with serpentinite, 3 - concrete vault, 4 - sand cylinder, 5 - annular water tank, 6 - graphite stack, 7 - reactor vessel, 8 - bottom metal structure, 9 - reactor support plates, 10 - steel blocks, 11 - roller supports

4.2.2 Reactor Metal Structures

Fig. 4.4 provides a schematic overview of the principal metal components surrounding and supporting the reactor core. They consist of welded metal structures which transmit the weight of the reactor core and its components to the concrete foundations, and ensure the leaktightness of the inner reactor cavity. These structures also contribute to biological shielding.

The graphite stack is surrounded by a water-filled biological shield tank, where the water is contained in an annular metal tank (5). It has an outside diameter of 19 m, an inside diameter of 16.6 m, the plate wall thickness is 30 mm. Internally this reservoir is divided into 16 water-filled sealed vertical sections. Water is supplied to these reservoirs from the bottom, and is removed from the top. This shield component also contains the startup and operating range ion chamber channels, and instrumentation piping for thermocouples assigned to monitor shield water temperature. The space between the wall of the concrete vault and the shield tank (4) is filled with sand.

The most complicated heavy components are the top (2) and bottom (8) metal structures. The top cover is a 17.65m diameter cylinder, 3 m high, an isometric representation of which is shown in Fig. 4.5. The top and bottom of this cylindrical structure is made from a 40mm thick steel plate. Along the outside periphery these plates are hermetically welded and internally they are joined together by means of rigid vertical plates. Axial holes through this structure are positioned to match the openings in the graphite stack. Tubes are welded into these holes, to serve as guides for the fuel channels and other components of the control and instrumentation system. The inside cavities of this metal structure are filled with serpentinite (a mineral containing bound crystalline water). The quality of the welds must be adequate to meet helium leak-tightness requirements. The entire metal structure rests on 16 rollers, which in turn rest on the top of the reinforced structure of the radial biological shield tank (see Fig. 4.4). This structural component supports the weight of the loaded fuel and control channels, that of the floor segment extending to the central refueling hall, and the weight of the water pipes.

The construction of bottom metal structure (8) is very similar to top metal structure. The diameter of this structure is 14.5 m, its height - 2 m. This structure supports the weight of the graphite stack and the feeder pipes supplying coolant water to the fuel channels. The number and distribution of the openings is the same as those of the top biological shield. The leak-tightness of the structure is tested with an air-helium mixture at a pressure of about 0.125 MPa. The remaining internal spaces of the structure are filled with serpentinite and are pressurized with nitrogen.

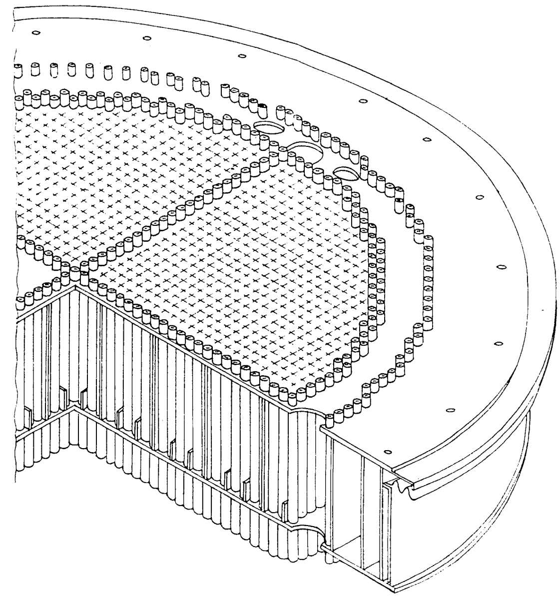

Fig. 4.5 Top metal structures

The bottom metal core support (9) shown in Fig.4.4 supports the weight of the entire graphite stack, the bottom biological shield, and the coolant water feeder pipes. The design of this support structure is rather simple: it consists of two heavy plates, which intersect at right angles along the center-line of the reactor and are in turn reinforced by 5.0 m high fins. These plates are welded to the bottom of the biological shield plate (8).

The cylindrical shell (7) of the reactor core (Fig 4.4) is constructed from a 16 mm thick plate, it has an outside diameter of 14.52 m and a height of 9.75 m. To compensate for axial thermal expansion, the shell is provided with a bellows compensator. The shell, together with the top and bottom metal structures, forms the sealed reactor core compartment.

The topmost structure, located above the coolant channel banks which pass through the core vertically and exit horizontally, is the upper shield cover. This structure is shown as item (1) in Fig. 4.4 and can also be identified readily in the isometric drawing of Fig. 4.2. The cover serves several purposes: it is a component of the biological shield, provides thermal insulation and controls the access to the fuel channels. The top surface of this cover is the floor of the refueling hall, its central part consists of individual plugs which can be removed for accessing the fuel channels and the special purpose channels. A schematic cross-section of this structure is shown in Fig. 4.6. It shows the block segments which bear against the tops of the vertical extensions (guide pipes) of the fuel channel tubes. The blocks are made of iron-barium-serpentinite concrete having a density of 4000 kg/m^3. They are constructed of two parts: the top segment is removable to provide accessibility to the upper

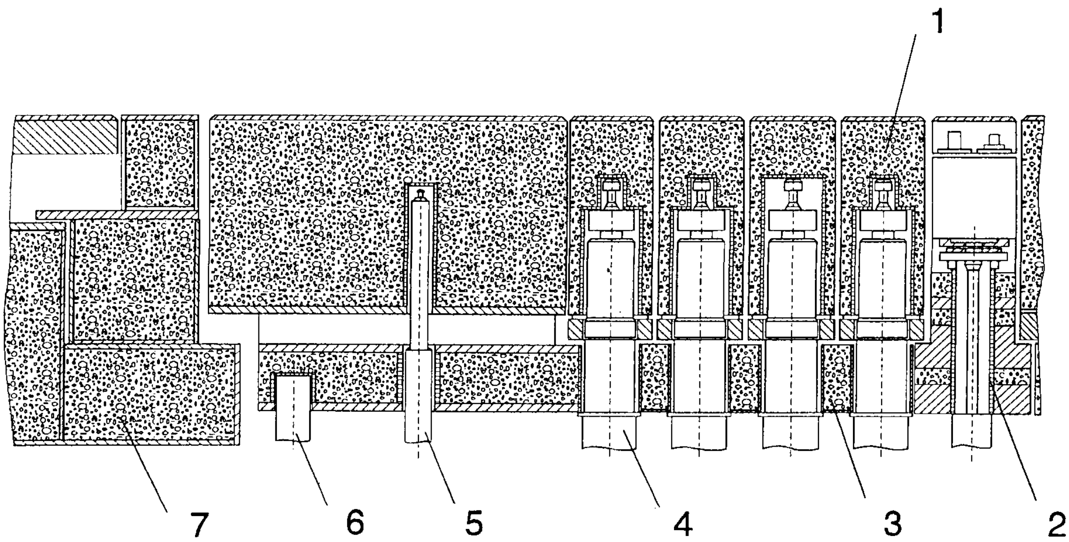

Fig. 4.6 Segment of the top cover
1 - removable blocks, 2 - top cover of the control rod channel, 3 - bottom block, 4 - top cover of the fuel channel, 5 - top cover of the temperature instrumentation channel, 6 - top cover of the reflector cooling channel, 7 - peripheral part of the cover

segment of the channel during refueling, the bottom layer segments are larger - one of these blocks covers three channels. All of the blocks are supported by the guide pipes of the fuel channels and the reflector cooling channels. The top and bottom block are staggered so that the gaps between blocks are covered, and the amount of direct radiation is reduced. The peripheral sections of the top shield cover consist of 0.70 m high metal containers, filled with a mixture of cast iron fragments (86 %) and serpentinite.

Air is continuously drawn from the refueling hall down through the gaps of the cover plates, and out into the ventilation system. This provides cooling for the cover and impedes the transport of radioactive material from the steam-water pipes to the refueling hall.

The gaps between the top and bottom plates and the blocks are used for positioning the wiring for the control system servomotors, the flux distribution instrumentation, and the temperature-monitoring instrumentation (thermocouples). All of the reactor metal structures, which are in a gas and steam environment, are covered by an anti-corrosive material.

4.2.3 Biological Shielding

All of the structures surrounding the core region contribute to some extent to biological shielding. The principal structural components have been described in the previous Section, they are complemented where required by additional material. The principal structures serving the shielding function include - the graphite reflectors, the internal spaces of the metal structures, the gap between the concrete vault and the outer surface of the core support metal structures. With respect to the center of the core, the biological shields can be divided into three parts: top shield (in the direction of the refueling hall), bottom shield (in the direction of the lower coolant channel banks), and radial shielding.

Biological shielding in the direction of the refueling hall encompasses the 0.5 m thick upper graphite reflector, 0.25 m high steel shielding blocks, the upper metal structure which is filled with a mixture of serpentinite chips and gallium (weight ratio of 3:2), and the top shield cover. The density of the fill material is 1700 kg/m^3, its height is 2.8 m, and the thickness of the steel foundation plates of the structure is 40 mm.

A number of special design features are incorporated into these structures in order to reduce direct streaming of radiation along the gas-filled channels (temperature, neutron flux instrumentation and ion chamber channels) and the fuel channels which in the upper region of the core are filled with a steam-water mixture. The fuel channels are capped with special steel-graphite plugs (Fig. 4.7) which incorporate spiral passages for the flow of the two-phase coolant. The ring-shaped gaps between the channels and the guide tubes are covered with shielding sleeves (Fig. 4.8). Graphite followers are employed in the control channels to reduce direct neutron and gamma streaming into the spaces underneath the reactor. Whenever possible, the gas and coolant pipes which penetrate the shielding structures are bent so that direct streaming is reduced.

The radial shield (Fig. 4.4) consists of the radial graphite reflector (average thickness 0.88 m), the shell of the core, the annular water-filled steel tank, sand filling between the tank and the walls of the reactor vault, and the 2 m thick concrete walls of the vault. The walls of the vault are made from ordinary construction concrete with a density of 2200 kg/m^3.

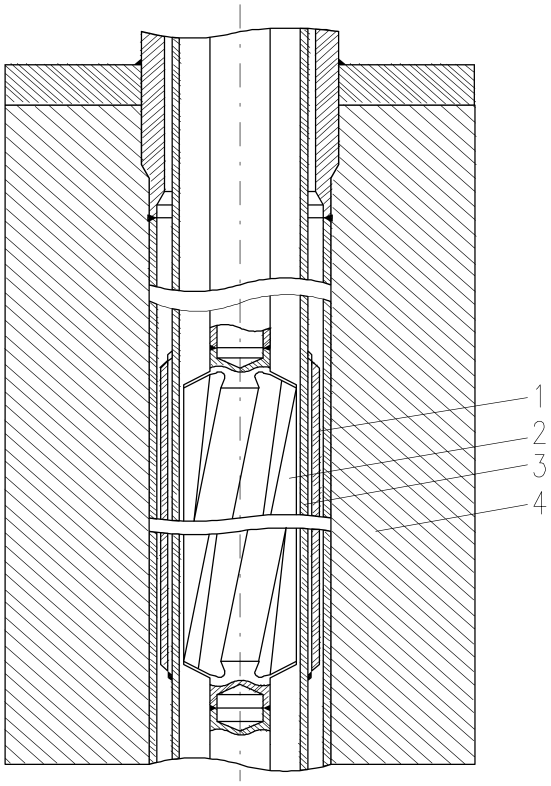

Fig. 4.7 Fuel channel shielding plug
1 - steel sleeve, 2 - steel helical plug, 3 - channel pressure tube, 4. serpentinite filling

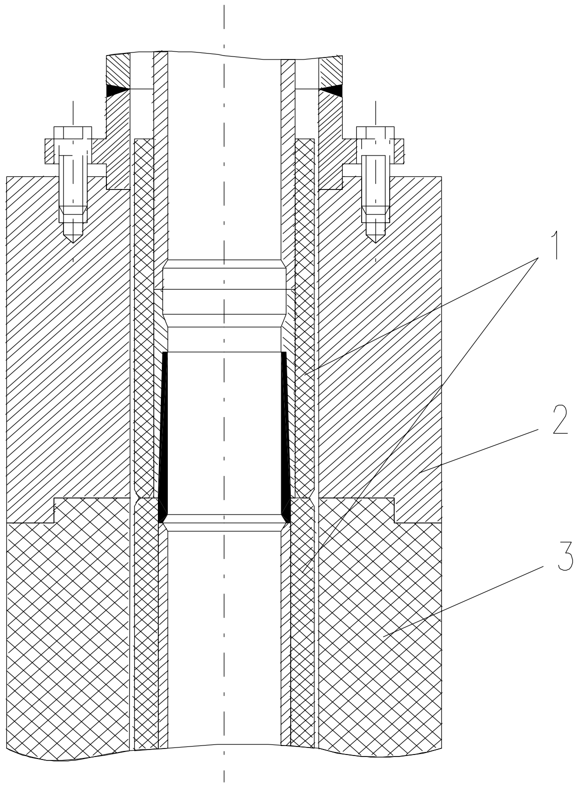

Fig. 4.8 Shielding sleeves in the top reflector
1 - graphite sleeves, 2 - steel shielding block, 3 - graphite reflector

A summary of the compositions and dimensions of the components used for biological shielding is presented in Table 4.1 [35].

During reactor operation the biological shielding limits the radiation dose rate in the refueling hall and in the areas adjacent to the reactor to levels not exceeding 2.8 10^{-5} Sv/h. During refueling operations the gamma dose in selected locations close to the refueling machine can range up to 1.0 10^{-3} Sv/h.

It is reported that the tests of the biological shielding effectiveness, conducted in the first unit of the Ignalina NPP with the RBMK-1500 reactor operating at nominal power, confirmed that the radiation field in the reactor service areas meets health standard requirements. For example, the average equivalent dose rate in the central refueling hall was found to be (11 - 18) x 10^{-6} Sv/h, while in the access chamber to the coolant flow control valves it did not exceed 4 Sv/h, with the reactor operating at thermal power 3850 MW. These tests were performed by the Moscow Research and Development Institute of Power Engineering (RDIPE - Russian abbreviation of NIKIET) [38].

The walls of the compartments of the main coolant circuit equipment are made from ordinary concrete (density of 2200 kg/m^3). Measurements of the effectiveness of biological shielding were performed on the second unit of Ignalina NPP in December, 1992. The measured dose rates are shown in column 3 of Table 4.2, and the calculated dose rates - in column 2 [3].

Table 4.1 Composition and dimensions (in meters) of principal biological shield components [35]

Material	Shielding Direction		
	Top	Bottom	Radial
Graphite (reflector)	0.5	0.5	0.88
Steel (shielding plates and metal structures)	0.29	0.24	0.045
Serpentinite filling (1700 kg/m^3)	2.8	1.8	-
Water (annular tank)	-	-	1.140
Steel (metal structure)	0.04	0.04	0.03
Sand (1300 kg/m^3)	-	-	1.3
Heavy concrete (4000 kg/m^3)	0.89	-	-
Construction concrete (2200 kg/m^3)	-	-	2.0

Table 4.2 Biological shielding parameters of the office premises which are adjacent to the operating equipment

Source - equipment	Thickness of concrete shielding, m	Calculated* dose rate, mR/h	Measured** dose rate, mR/h
Water-steam separators:			
side walls and bottom covering	1.4	1.4	2.5
end walls	1.0	-	0.9
top covering	0.9	-	0.26
Pipes between separators and main circulation pumps	0.9	1.4	1.2
Main circulation pump premises:			
wall adjacent to suction header	0.9	0.4	0.6
top covering	0.8	-	0.9
walls between compartments	0.6	-	1.6
Lower water pipes	0.5	0.7	3.0
Pipes from separator to turbine	0.7	1.4	0.4
Low pressure re-heaters	0.6	1.4	0.6
Deaerators	0.24	0.8	0.15

* Data compiled from [3]
** Measurements taken at the Ignalina NPP, December 1992

By the project, the compartments, which are part of the accident localization system of the Ignalina NPP unit 2, were reinforced with 5 mm thick stainless steel liners on the floors and 4 mm thick liners on the walls.

During nuclear fission 95 % of the generated energy is released in the fuel element and an additional 5 % is released in the graphite during neutron moderation and gamma absorption. A helium-nitrogen mixture circulates around the fuel channels and between the graphite blocks. This gas retards the oxidation process, and the humidity and temperature readings of the gas are monitored to indicate leaks of the fuel channels.

Under normal reactor operating conditions the biological shielding makes it possible to perform certain repair and maintenance tasks. This applies to piping, which serves the various channels and is located below the bottom and above the top biological shields. The non-service compartments are accessible only during the reactor shutdown. The list of these compartments is given in Table 4.3 [36].

Table 4.3 List of non-service compartments [36]

Compartment	Description
125	Compartment below reactor
208/1-2	ECCS compartments
210	Reactor vault
215	Connecting corridor between ACS tower
408/1-2	Corridors
409/1-2	Compartments of downcomers, pressure and suction headers
506/1-2	Separator drum and ACS tower compartment

4.2.4 Fuel Assembly and Fuel Channel

One of the principal distinguishing characteristics of the RBMK-type reactor is that each core fuel assembly is housed in an individual pressure tube. As was noted previously, the RBMK-1500 core contains 1661 fueled channels separated from its nearest neighbors by the walls of the pressure tubes and graphite blocks. Each pressure tube has considerable autonomy. For example, the coolant flow rate to the tube is controlled online by an individual isolation and control valve. This valve make it possible to de-couple it from the primary cooling system while the reactor is operation. This makes it possible to change fuel clusters online and also has a significant impact on the potential consequences of loss-of-coolant accidents.

4.2.4.1 Fuel Assembly

The nuclear fuel used in the Ignalina NPP is slightly enriched uranium (2% initially, converted to 2.4%) in the form of uranium dioxide. This is a chemically-stable and heat-resistant ceramic material. It is prepared in powdered form, pressed into small, 11.5 mm diameter and 15 mm long pellets and sintered in the presence of a binder. The pellet shape is adapted to an intensive, high-temperature operating mode. For example, the pellets have hemispherical indentations, in order to reduce the fuel column's thermal expansion and thermo-mechanical interaction with the cladding. The 2 mm diameter hole through the axis of the pellet reduces the temperature at the center of the pellet, and helps release the gases formed during operation.

The pellets are placed into a tube with an outside diameter of 1.3 cm, a wall thickness of 0.9 mm and an active length of 3.6 m. Tube material is an alloy of zirconium with one percent niobium. This alloy has good anti-corrosive properties and a low neutron absorption coefficient. The initial clearance between the UO_2 pellets and the wall of the tube varies from about 0.22 to 0.38mm.

The tubes are pressurized with helium at 0.5 MPa and sealed. In the radial direction the fuel clad is augmented by retaining rings which help to withstand the pressure of the fuel channel and improve the heat transfer from the pellet to the zirconium tube. In the axial direction, the fuel pellets are held in place by a spring.

The design of the RBMK reactor fuel described so far differs little from fuel elements manufactured for standard BWR-type reactors. For example, a typical BWR fuel tube in the United States is also manufactured from a zirconium-niobium alloy, has a similar wall thickness and an outside diameter ranging from 12 to 13.5 mm. The uranium enrichment is also similar: namely, 2 % to 2.4% in the case of Ignalina NPP, 2.2% to 3% in the case of the BWR. More significant design differences are present in the manner in which the fuel elements are mounted into a structurally integral fuel assembly (or fuel cluster). The shape of the assembly is determined by the geometric characteristics of the core fuel channel. In the case of a BWR this results in a square-shaped (usually 8x8) fuel cluster which fits into the square core spaces between the control rod blades. For an RBMK reactor, the fuel assembly must fit into a circular channel having an inside diameter of 80 mm and an active core height of 7 m. In order to achieve the required height, two fuel elements must be joined end-to-end. The radial special restriction determines the arrangement and the number of the fuel rods which can fit into a fuel assembly.

A schematic representation of the principal features of a fuel assembly is shown in Fig. 4.9. The assembly contains 18 fuel elements arranged within two concentric rings in a central carrier rod. The carrier rod is a 15 mm diameter tube with a 1.25 mm wall thickness and is made of a zirconium (2.5 % Nb) alloy. The complete fuel assembly is made up of two segments which are joined by means of a sleeve (7) at the central plane. Thus, along the axis of the core there is a region in which fission does not take place. This generates a flattening of the fast neutron flux and a dip of the thermal neutron flux at this location and influences the neutron kinetic characteristics of the core.

The lower segment of the fuel assembly is provided with an end grid and ten spacing grids. The central tube and the end spacer are also made from the zirconium (2.5% niobium) alloy. The remaining spacers are made from stainless steel and are rigidly fixed (welded) to the central tube and are positioned 360 mm apart. The top segment has 10 spacing grids placed 360 mm apart, and in addition, at every 120 mm this segment is provided with specifically designed spacers which act as turbulence enhancers to improve the heat transfer characteristics. The fuel tubes are mounted so that axial expansion of the upper or lower segments takes place in the direction towards the center of the core.

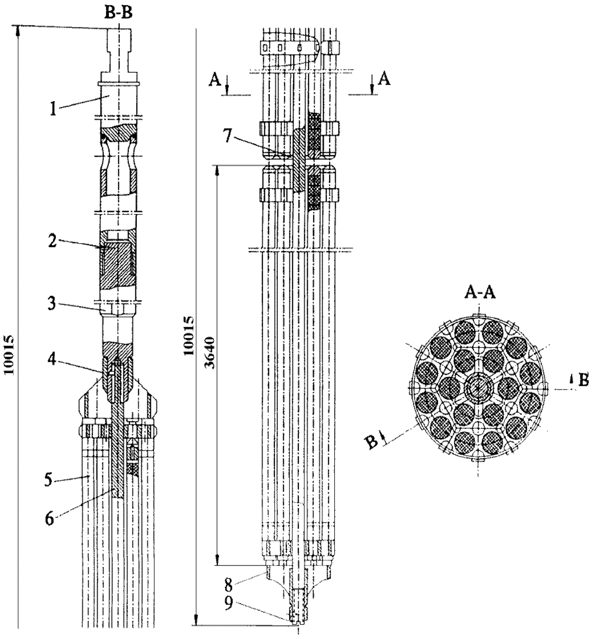

Fig. 4.9 Fuel assembly
1 - suspension bracket, 2 - top plug, 3 - adapter, 4 - connecting rod, 5 - fuel element, 6 - carrier rod, 7 - end sleeve, 8 - end cap, 9 - retaining nut

For ease of manipulation, the fuel assembly is provided with appropriate fittings at both ends. The principal technical parameters of the fuel assemblies are summarized in Table 4.4 [2,35].

The fuel assemblies described in this Section can be of two types: regular fuel assemblies and instrumented fuel assemblies which contain a neutron flux detector. In an instrumented fuel assembly the detector is contained within a tube which replaces the main carrier rod. This tube has an outside diameter of 15 mm and a wall thickness of 2.75 mm.

4.2.4.2 Fuel Channel

The top, center, and bottom segments of a typical reactor fuel channel are shown schematically in Fig. 4.10. The main component of the channel is the coolant-carrying tube constructed from separate end and center segments. The center segment (9) is an 88 mm outside diameter (4 mm thick wall) tube, made from a zirconium-niobium alloy (Zr + 2.5 % Nb). The top (3) and bottom (11) segments are made from a stainless steel tube. The choice of zirconium-niobium for the center part was made because of the relatively low thermal neutron absorption cross-section (σ = (0.2 - 0.3) $\cdot$ 10^{-29} m^2) of the material and its adequate mechanical and anti-corrosive properties at high temperatures (up to 350 ^oC). The center and end pieces are joined by special intermediate couplings, made from a steel-zirconium alloy.

Table 4.4 Fuel assembly parameters [2,35,36]

Fuel pellet	
Fuel	Uranium dioxide
Fuel enrichment in ^{235}U, %	2 & 2.4
Edge pellet enrichment, %	0.4
Fuel pellet density, kg/m^3	10400
Fuel pellet diameter, mm	11.5
Fuel pellet length, mm	15
Pellet central orifice diameter, mm	2
Maximum temperature at the center of the fuel pellet, ^0C	2100
Fuel element	
Fuel element cladding material	Zr+1 % Nb
Outside diameter of fuel element, mm	13.6
Length of fuel element, m	3.64
Active length of fuel element (height of fuel pallet column in cold state), m	3.4
Cladding wall thickness, mm	0.825
Clearance between fuel pellet and tube, mm	0.22-0.38
Mass of fuel within fuel element, kg	3.5
Helium pressure in the cladding, MPa	0.5
Maximum permissible temperature of fuel element, ^0C	700
Average linear thermal flux, W/cm	218
Maximum linear thermal flux, W/cm	485
Fuel assembly	
Number of segments per fuel assembly	2
Number of fuel elements per segment	18
Total length of fuel assembly, m	10.015
Active length of fuel assembly, m	6.862
Fuel assembly diameter (in the core), mm	79
Mass of fuel assembly without bracket, kg	185
Total mass of fuel assembly with the bracket, kg	280
Total steel mass of fuel assembly, kg	2.34
Total mass of zirconium alloy within assembly, kg	40
Mass of uranium within fuel pellet, kg	111.2
Mass of uranium within edge fuel pellet, kg	1.016
Maximum permissible power of fuel channel, MW	4.25
Authorized fuel assembly capacity, MWdays/assembly	2500
Authorized lifetime of fuel assembly, year	6

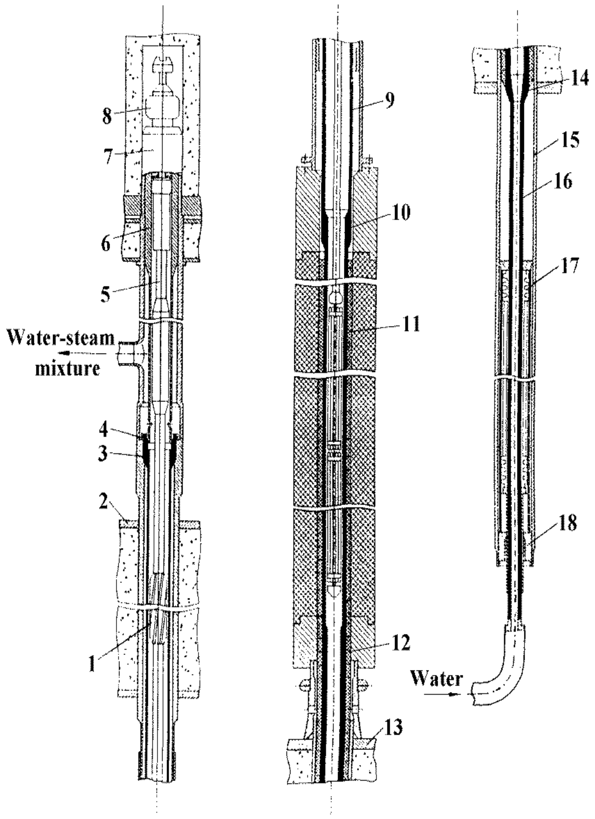

Fig. 4.10 Fuel channel
1 - steel biological shield plug, 2,10 - top and bottom metal structures, respectively, 3 - top part of the fuel channel, 4 - welding-support ledge, 5 - fuel assembly support bracket, 6 - encasement cylinder, 7 - seal plug, 8 - graphite cylinder, 9 - central part of the channel, 11 - bottom part of the channel, 12 - thermal expansion bellows compensator, 13 - stuffing box

The fuel channel tubes are set into the circular passages which consist of the aligned central openings of the graphite blocks and the stainless steel guide tubes of the top and bottom core plate structures described in Subsection 4.2.2. The channel tubes are welded to the top (2) and bottom (10) metal-structure plates to maintain the core region hermetically sealed. The tube is welded to a support ledge (4) at the top, and at the bottom to the guide tube of the metal structure (11). A bellows (12) is used to compensate for the differences in thermal expansion between the reactor metal core plates and the fuel channel. In case of failure of the bellows, additional sealing is provided by a pressure seal (13). The design life of the channel tube is about 20-25 years. If necessary, the channel tube can be replaced by removing the top and bottom welds.

As noted in Subsection 4.2.1, the fuel coolant tubes also provide cooling for the energy deposited in the graphite moderator of the core region. In order to improve heat transfer from the graphite stack, the central segment of the fuel channel is surrounded by the 20 mm high split graphite rings (8). These rings are arranged next to one another in such a manner that one is in contact with the channel, and the other with the graphite stack block. The minimum clearance between the fuel channel and the graphite ring is 1.15 mm, and between ring and graphite stack 1.385 mm (Fig. 4.11). These clearances prevent compression of the fuel channel tube due to radiation and/or thermal expansion of the graphite stack. Due to graphite shrinkage and the expansion of the pressure tube, the thickness of this gap is gradually reduced during plant operation. This phenomenon has a potential impact on plant operability and is therefore discussed in more detail in Subsection 4.2.4.3.

The fuel assembly is suspended in the center of the channel by means of a bracket (5, Fig. 4.10). The bracket is provided with a seal plug (7), which hermetically seals the fuel channel tube after the fuel assembly is installed. Since all work related to sealing, unsealing and fuel changing is complished by remote control via the refueling machine, the seal plug must have an appropriately simple design which is shown in Fig 4.12. The main parts of this plug are the bolt (4) and ring (9). When the bolt (4) is fully loosened, the fuel assembly, which is supported by the bracket (13) together with the seal plug, is lowered into the fuel channel tube by the refueling machine. The ball bearings (8) then drop into the groves of the expansion bushing (10), and are confined by the outside diameter of the retaining ring (9). The bolt (4) is then tightened with a special key of the refueling machine to seal the channel. As the bolt tightens, the expansion bushing pushes the bearing balls into a ring-shaped groove in the body of the plug. As the bolt moves further, the now enclosed bearings are tightened within the groove thus preventing upward motion of the bracket, and the compression bushing (11) compresses the sealing gasket (12).

The seal plugs described in the previous paragraphs pertain to the plugs used in unit 1 of the Ignalina NPP. The seal plugs used in unit 2 have a somewhat different construction. They have a spiral shape and the hanger of the fuel assembly is fixed not by bearing balls, but by special retaining nuts.

Fuel channels described in this Section may also contain supplementary absorbers. They may also be devoid of structural elements and just filled with cooling water.

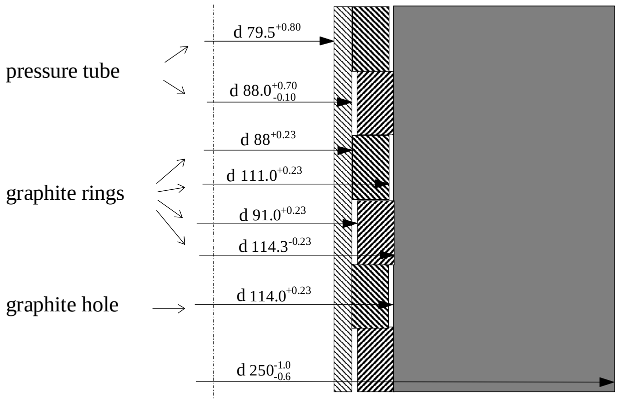

Fig. 4.11 Graphite and zirconium interaction zone

4.2.4.3 Pressure Tube - Graphite Gap

The interaction of fast neutrons can lead to dimensional changes in various materials. For example, in graphite moderated reactors, initial accumulation of the fast neutron dose produces a gradual shrinkage of the graphite blocks. For the RBMK reactors this results in a decrease of the bore diameter through which the fuel channel passes. For the pressure tube made of a Zr + 2.5 % Nb alloy, the effect is opposite, due to thermal and irradiation effects the tube diameter increases. As a result, the gap between the pressure tube and the graphite, which has a nominal thickness of 1.5 mm (Fig. 4.11) is gradually diminished leading to an eventual closure of the gap. The measured and the

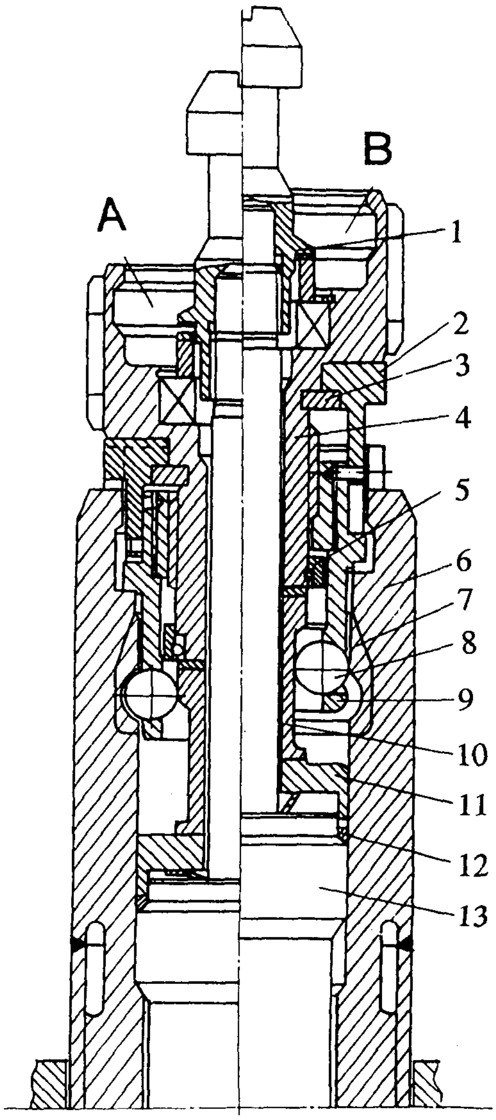

Fig. 4.12 Fuel channel seal plug (for unit 1)
1- support handle, 2- flange, 3- retaining ring, 4- bolt, 5- support ring, 6- plug encasement tube, 7- brazing, 8- bearing ball, 9- retainer ring, 10- expansion bushing, 11- compression bushing, 12- sealing gasket, 13- support bracket of fuel assembly.
A - operating position (channel sealed),
B - position of the plug before sealing the channel

projected rate of gap closure for unit 1 of the Ignalina NPP as a function of the integral power per channel is shown in Fig. 4.13. For the high power channels in the Ignalina NPP this translates to a net operating time before the first gaps close of about 16 years.

The consequences of gap closure have not been thoroughly analyzed. However, it is in general agreed that operation after the gaps are closed may cause one or more of the following:

- accelerated graphite brick cracking,
- appearance of additional uncontrolled loads causing a possible loss of fuel channel integrity,
- impaired sensitivity of the fuel channel integrity monitoring system,
- difficulty or impossibility of replacing fuel channels using standard pressure tube extraction techniques,
- possible bending of fuel channels during power operation.

In order to preempt the listed problems the RBMK designers recommend the replacement of pressure tubes before a large fraction of the gas gaps have closed. This has been carried out in Leningrad units 1 and 2. It should be noted that after re-tubing a renewed gap closure is not expected to occur [96].

For the Ignalina NPP the gap-closure issue has received considerable attention. It was considered in some detail in the SAR [62] and was the subject of a 1997 workshop conducted at Encinitas, California [97]. An important on-going contribution to the resolution of this issue is the expanded measurement program initiated at the Ignalina NPP in 1997.

Two types of measurements are made. In one series of measurements ultra-sound techniques are employed to measure the dimensions of the metal pressure tube. The instrument used is developed by ABB TRC AB, Sweden [98]. It is designed for fast measurement of

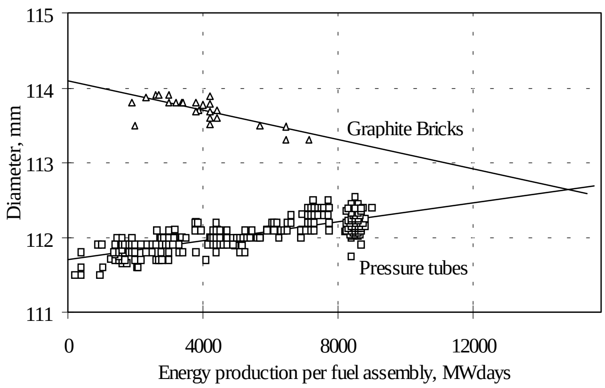

Fig. 4.13 Change of hole diameter in graphite bricks and equivalent diameter of pressure tubes (pressure tube channel & graphite rings) during operation of Ignalina NPP unit 1 [62]

inner diameter and wall thickness, and is capable of inspecting 30 fuel channels per day. The measurement of the inside bore diameter of the graphite is more laborious. It requires the removal of the metal tube and an insertion of specially calibrated instruments. Both sets of measurements are performed during regularly scheduled maintenance shutdowns. The proposed measurement program is outlined in Table 4.5. As the table shows, it is expected that by 2001 a total of 1200 pressure tubes will have been measured. This constitutes the entire population of high to medium power channels present in the core. The number of projected measurement of graphite bore diameters is smaller, and should reach a statistically significant total of 130 measurements by 2001. These field measurements will make it possible to achieve a considerably more accurate depiction of the true state of the graphite-pressure tube gap in unit 1 of the Ignalina NPP.

4.3 REACTIVITY CONTROL SYSTEM

The RBMK-1500 reactivity control systems reflect the general complexity of this reactor type. For example, to meet the various neutron flux and fission power control needs, seven different types of control rods are used. They differ in their structure, insertion speed, insertion direction or the control mode (automatic or manual). The individual rod types and their control systems are described in Section 6. This Section 4.3 deals with several complementary control-related aspects:

- Subsection 4.3.1 describes the control rod and instrumentation cooling system,
- Subsection 4.3.2 describes the fuel handling system,
- Subsection 4.3.3 gives the characteristics of the servomotors.

In order to identify the mentioned control rod types reference should be made to the tables and graphs presented in Subsection 6.4.3.2.

Table 4.5 Fuel channel inspection program for unit 1 of the Ignalina NPP

	Year	No. of fuel channels for which the diameter of the pressure tube is measured	No. of fuel channels for which inside diameter of the graphite bore hole is measured
1	1997	150	-
2	1998	150	20
3	1999	300	30
4	2000	300	30
5	2001	300	50

4.3.1 Special Purpose Channels

Of the 2052 channels which penetrate the reactor graphite stack, 1661 of them are purposed for fuel loading, and the remainder, including additional channels in the radial reflector, are termed "special purpose channels" and contain control rods or various types of instrumentation. A list of the number of various channel types and their purpose is presented in Table 4.6 [35]. The channels with control rods, the channels carrying vertical traverse flux distribution instruments and the fission chamber channels are all identical. A schematic of their structure and the guide tubes is shown in Fig. 4.14. The upper segment of the guide tube incorporates a compensator bellows (2) to accommodate the significant thermal expansion of the channels due to the large temperature difference between the top biological shield and the cold guide tubes. The lower section of the channel guide tube, unlike that in the fuel channel, also contains a thermal expansion compensator (6). The top and bottom sections are made of stainless steel, while the middle section is of a zirconium - niobium alloy.

The channels with control rods (Fig. 4.14) are provided with a metal cover (4) which is employed for mounting the control rod drive mechanisms (5) and for providing access to cooling water. The lower ends of the ionization chamber and flux detector channels are sealed by metal caps. The ionization chamber channel caps are made of stainless steel, and also serves in supporting the ionization chambers. The caps of the other channels are made of an aluminum alloy. At the bottom of this type of a channel is a throttling device (7), which provides some resistance to water flow, and helps to ensure reliable filling of the channel.

Table 4.6 The channels and their number [35]

Type of channel	Number of channels
Channels inside graphite columns	
Fuel channels	1661
Channels with control rods	211
Channels with in-core sensor of axial power density monitoring	20
Channels with fission chambers	4
Total number of the reactor Control and Protection System (CPS) channels	235
Radial reflector cooling channels	156
Total number of channels inside graphite columns	2052
Channels at the intersections of graphite columns	
Graphite temperature instrumentation channels in the core	13
Graphite temperature instrumentation channels in the radial reflector	4
Gas sampling channel	1
Total number of channels at the intersections of graphite columns	18
Channels in radial biological shielding	
Ionization chamber channels:	
for normal reactor operation	20
for reactor start-up	4
Total number of channels in radial biological shielding	24

The CPS channels are cooled by an independent water circuit provided with its own pumps and heat exchangers. The cooling water is supplied to the channels from above, and flows over the exterior and interior casings of the absorber rods. In this process, the water is heated from 40 ^{o}C to a temperature of 70 ^{o}C. During reactor operation, regardless of the position of the control rod, the inside of the channel is filled with water. When the absorber rod is withdrawn from the core, and if no special provisions are taken, its volume would be replaced by water. Because water is a moderately strong neutron absorber, most control rods have not only a boron carbide absorber, but also a graphite follower which displaces water and improves the reactor's neutron balance.

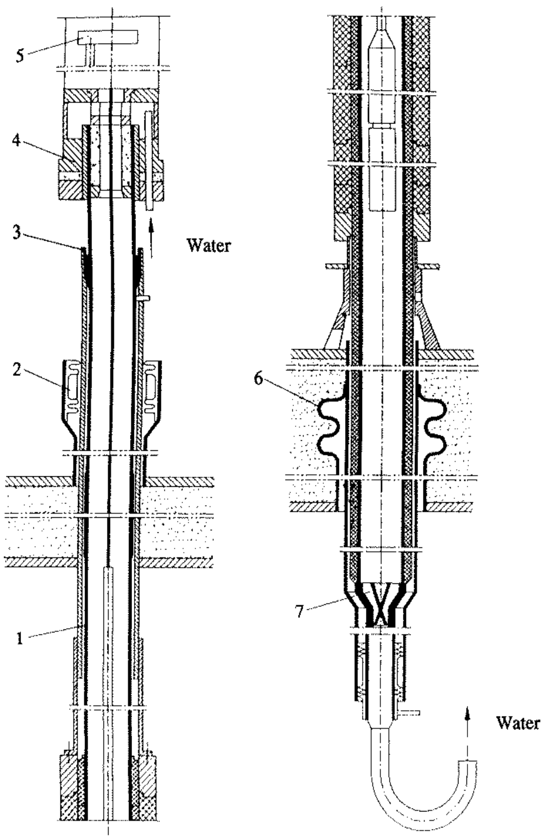

Fig. 4.14 Reactor-control and protection system channel
1 - channel opening, 2 - thermal-expansion bellows compensator, 3 - welding-support ledge, 4 - channel cover, 5 - operating mechanism, 6 - bottom bellows compensator, 7 - throttling device

The above described channels are always filled with either control rod or a graphite control rod follower and cooled with water. Post-Chernobyl modifications included the addition of 24 fast acting scram-type rods. To achieve higher insertion speeds this rod type must drop into a gas-filled channel without having to displace water. As described in Section 6, this led to a different rod design and required also some changes in the top and bottom fittings of the special purpose coolant channels. These channels are cooled by a lowing film of water and internally supplied nitrogen. Therefore, the top cover includes both access to the liquid and the gas coolants and a distributor which creates the falling liquid film. The bottom cap is provided with a liquid collector.

Cooling channels also provide cooling to the radial reflector (4) of the graphite stack shown in Fig. 4.15. These channels also cool the radial reflector reinforcing tube (5), and reduce the heat flow toward the shell of the graphite stack and its compensator. The channel is made of stainless steel. The cooling water is supplied to this channel from above through a central tube, it flows down to the bottom biological shield, then rises again to the top in the annular space between the two tubes, and finally leaves the channel.

Radial reflector cooling channels, CPS channels and fuel channels are inside the central part of the graphite columns, the openings of which are 114 mm diameter. Total number of channels inside the graphite columns is 2052.

The corners of the rectangular cross-sections of the graphite columns in the stack are hollow and incorporate 17 vertical 45 mm diameter instrumentation channels used for measuring the support and the shielding plates. Thirteen of these channels are positioned within the boundaries of the core, while four are in the reflector. Within each channel the temperature is measured at 5 vertical positions. One channel of the same type is placed in the core and is used for gas sampling. Consequently, there are 18 channels in the graphite stack of the reactor which are outside the graphite columns.

In the radial biological shielding of the reactor there are a total of 24 channels into which radial ionization chambers are positioned. Reactor startup channels are made of shell inside of which there is as suspension bracket and a convex lead shield (it mass is 1220 kg) which protects startup ionization chambers from the gamma radiation. The normal reactor operation ionization chamber channels are quite analogous to the channels mentioned above except that are no lead shields. This is because at normal reactor operation the measured neutron flux significantly exceeds the gamma radiation.

4.3.2 Fuel Handling System

One of the distinguishing features of the RBMK - type reactor is its on-line refueling capability. This complicated operation is accomplished by an especially

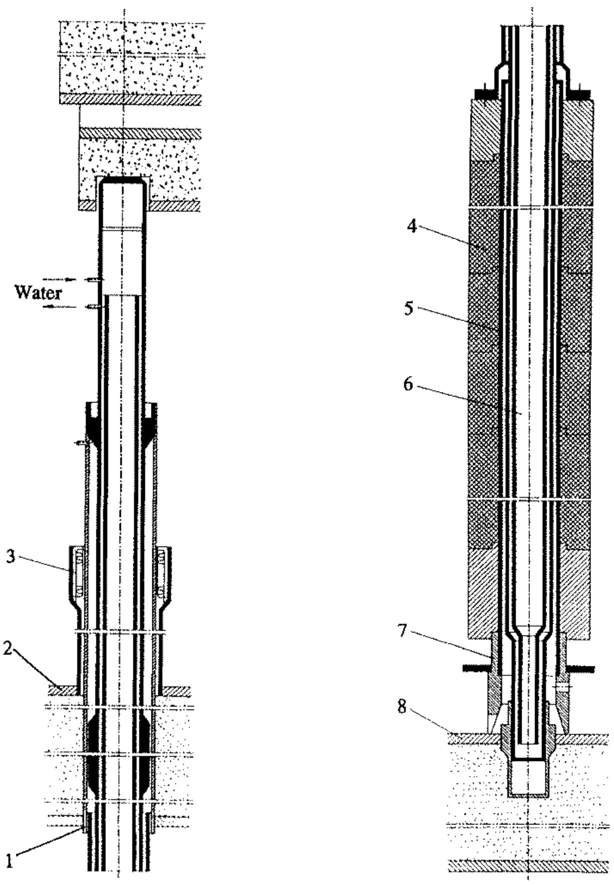

Fig. 4.15 Reflector - cooling channel
1 - external bushing, 2 - top biological shield, 3 - thermal - expansion bellows compensator, 4 - radial reflector, 5 - reinforcing tube, 6 - an annual double - wall tube arrangement for central flow in one direction to the end of the tube, then reversing to annual flow in opposite direction, 7 - support sleeve, 8 - bottom biological shield.

designed fuel loading and unloading machine. Besides changing fuel bundles without shutting down the reactor, the refueling machine can also be used to inspect a fuel channel by a special fuel-assembly-shaped calibration instrument, seal off a fuel channel with a standard or an emergency sealing plug, and to correct certain emergency conditions.

On line reloading operations at nominal power must ensure that the coolant flow to the fuel assembly being changed is not interrupted. The refueling machine is capable of changing up to five fuel assemblies per day when the reactor is in operation, and up to 20 when the reactor is shut down.

The principal components of the refueling machine (shown schematically in Fig. 4.16) are: the refueling machine transport mechanism (1), a container (3) which serves as a biological shield, two replaceable caskets (4) (one mounted in the machine, the other kept in the repair area), a metal frame (9), the positioning mechanisms (8), and control equipment.

The refueling machine is moved through the reactor hall by means of the transport mechanism. A bridge-type crane (2), consisting of 21 m long beams, moves on transverse tracks located in the upper section of the reactor hall with 39.6 m of travel distance. On the bridge, 11 m above the hall floor, a carriage (1) transports the refueling machine equipment along the other axis. The travel distance of the carriage is 12.5 m. The bridge and the carriage can be moved at two speeds, 9.75 and 1.2 m/min. The slow speed is used for final, accurate positioning. During this operating phase the bridge and the carriage move in 1 mm increments.

The container (3) in Fig. 4.16 is a steel cylinder, assembled from six sections. Its inside diameter is 0.77 m and the wall thickness is 0.5 m. The lower part of the container incorporates a movable biological shield (7) used to screen the gap which appears between the bottom of the container and the hall floor during refueling operations. The operator's booth and access platforms are located on the outside of the container, the inside provides space for the movable fuel casket (4).

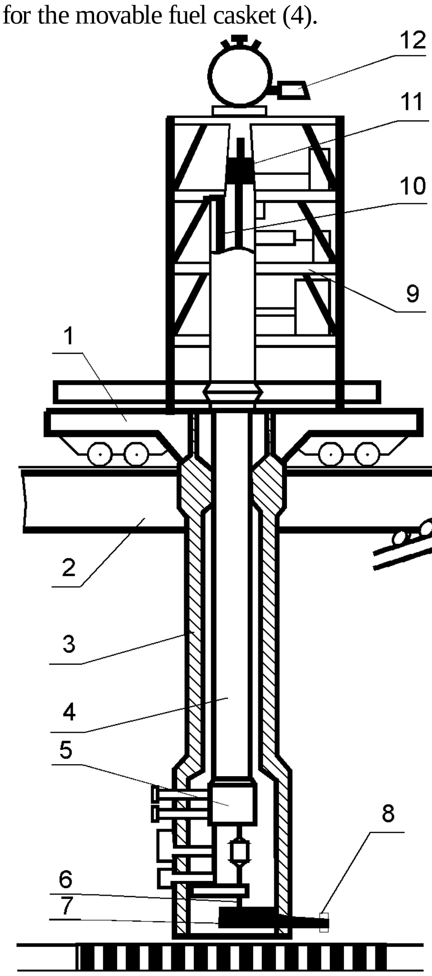

Fig. 4.16 Refueling machine
1 - carriage of refueling machine, 2 - refueling machine bridge, 3 - container, 4 - fuel casket, 5 - closing mechanism, 6 - standpipe, 7 - bottom movable biological shield, 8 - refueling machine positioning systems, 9 - metal frame, 10 - fuel assembly receptacle, 11 - grabber, 12 - grabber control mechanism

The fuel casket (4) is the principal component of the refueling machine. It consists of a cylindrical pressure vessel together with its internal operating mechanisms. These mechanisms can perform the following functions:

- hermetically connects the cavity of the casket to the top of the fuel channel,
- unseal and reseal the fuel channel,
- remove a spent fuel assembly,
- measure the inside dimensions of the fuel channel,
- load a fresh fuel assembly,
- install an emergency plug into a fuel channel.

The metal frame (9) above the carriage houses the equipment supplying the refueling machine with process water, feedwater, pressurized air, inspection and measurement instruments, and control-related equipment.

The mechanisms (12) for raising and lowering the fuel assembly are mounted on the top part of the casket shown in Fig. 4.16. The assemblies are lifted by means of a mechanical grabber mechanism shown in Fig. 4.17.

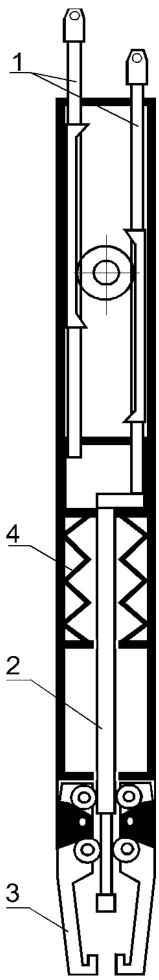

Fig. 4.17 Grabber
1 - movable racks, 2 - extender, 3 - jaws,
4 - shock absorber

This mechanism consists of a cylindrical body holding a pinion gear on opposite sides of which ride two movable racks (1) connected to the controlling mechanism. The top ends of the racks are welded to the chains used to lift the grabber. The bottom end of one of the racks is welded to an extender (2), which works the jaws (3) of the grabber. If both of the chains which control the grabber move in the same direction, the jaws stay closed and the fuel assembly is raised or lowered. If they move in opposite directions, a cam opens the jaws, and the fuel assembly is released. The high pressure segment of the casket contains only the grabber, the chains and their gears, all of the control mechanisms are external to the fuel casket.

The central part of the casket contains a three-section, 16.5 m long fuel assembly receptacle (10) shown in Fig. 4.16. Each section of the receptacle has four slots, which can store new fuel assemblies, the fuel channel gauge, and the emergency plug. One slot is left empty to receive the spent fuel assembly.

The bottom part of the fuel casket contains a closing mechanism (5) and a standpipe (6). The closing mechanism serves to lock and unlock the casket to the fuel channel. It also acts as a biological shield during removal of the spent fuel. This mechanism consists of two dampers, with parallel disks installed in series within one frame.

The standpipe is used in performing the connection to the fuel channel. When the refueling machine is positioned over the required fuel channel, the standpipe is lowered so that it encloses the top part of the fuel channel. The joint is sealed by means of an inflatable rubber gasket. A special key located inside the standpipe is used for activating the fuel channel seal plug when sealing or unsealing the channel.

Two methods are used for positioning the refueling machine so that it coincides with the fuel channel coordinates:

a) Positioning from the operator's room. In this case the operation is monitored by closed-circuit television.
b) Positioning from the machine booth on top of the fuel casket bridge. In this case optical instruments are employed.

In case steam escapes from the fuel channel, and it is impossible to use either the optical or the television system to position the machine accurately over the fuel channel, a contact positioning system is utilized.

4.3.3 Control Rod Drive Characteristics

The RBMK-1500 power plant employs several types of control rods. In terms of travel direction and response time they can be divided into three categories. The "standard" control rods are inserted from the top, and drop into a water-cooled channel, the fast-acting "scram" rods drop from the top into a gas filled channel, and finally, control rods used for vertical power shaping are inserted from the bottom of the core. Section 6 lists additional control rod classification categories, but these depend on function or control mode. These three types of control rods are powered by appropriate servodrives [1,5].

The isometric view of a servodrive used for the predominant (Type 1) control rod is presented in Fig. 4.18. The control rod is withdrawn from the core by means of a metal tape which is wound on a drum (4). The housing is constructed of an aluminum alloy. The drive is powered by a DC motor (type D500MF) and is provided with a direct electromagnetic clutch for braking. Magnitude of the load is indicated by a temperature sensor. The position of the control rod is indicated on a dial for manual inspection or a selsyn indicator (5) (type BM-404NA), which is connected to the rod via a reducer. It has top and bottom position switches and a delayed dynamic-braking switch. Positions of the rods are replicated on the main control panel and the completion of either insertion or extraction of the rod is indicated by a specific sound signal.

In the earlier RBMK-1000 reactor plants the control rods were suspended by steel cables, while in the advanced RBMK-1500 pants a steel tape is used, which has similar strength characteristics but a significantly longer life. The tapes are fastened via eccentric cams to the drums, and the rods are suspended at their ends via locks and dampers. The 40 mm wide, 20 mm thick, and 7.9 m long tapes are made from specific steel (type 12Ch18N9).

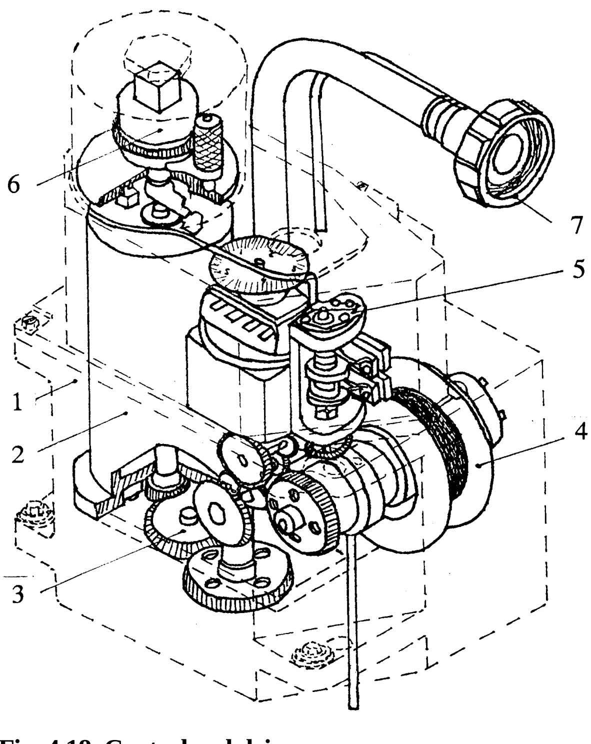

Fig. 4.18 Control rod drive
1 - housing shell, 2 - DC motor, 3 - gear-train reducer, 4 - drum, 5 - selsyn indicator with switches, 6 - manual mechanism, 7 - electrical connection

In the neutral position the induction coil of a servodrive and the anchor of its motor are disconnected, while the DC clutch is turned on. Consequently the brakes of the motor-rotor are activated. As soon as the logic control circuit issues an order for the removal of a rod, the induction coil of the motor is activated and the clutch is disconnected. Voltage is supplied to the anchor in about 0.2 s, the motor starts to extract the rod and continues until the limit microswitch turns off the power supply from the motor to the clutch. Each rod can be inserted either manually or automatically. In manual operation the gravitational fall of the rod is damped. Simultaneously as the rod is released, voltage is supplied to the induction coil, this operation is referred to as dynamic breaking. In this mode the electric motor serves as a generator. In case of an automatic scram the rod is in free fall for 5 s, the induction coil is reactivated in 5 s and dynamic braking is established to cushion the final segment of rod travel. If the electric current supply to the CPS rods fails, the rods are automatically released to fall into the reactor core.

The shortened absorber rods (Type 2) are drawn upwards into the core from the bottom. This requires the modification of three specific features of the servodrives. Firstly, the direct electromagnetic clutches are replaced by clutches acting in the inverse direction, secondly, an inverse calibration is provided on the dial located on the selsyn beam, and third, the length of the suspension tapes is increased to 8.035 m.

Dynamic breaking is provided during removal of the rods in the downward direction. In case of electric current failure, the clutches lock and the rods are maintained in their positions.

The fast-acting scram rods (Type 3) drop into a gas-filled, water-film-cooled channel. This design feature requires several specific design modifications. Thus, the servodrive mechanism is provided with a valve which admits the gas coolant and includes a float-operated lever which closes the entrance in the event if the channel should become flooded by coolant water. Because the drop height into an RBMK reactor core is about 8 m, a completely free drop could generate excessive speeds and lead to damage. To mitigate this situation the drive is equipped with a tachometric generator which provides breaking when the rod achieves excessive speeds. To allow higher speeds the gear train of the drive is modified so that the inertial resistance is reduced.

Most of the Type 1 rods are directly controlled by the operator and used to flatten the radial power distribution. Some are controlled by Local Automatic Control (LAC) or Local Emergency Protection (LEP) zone signals, i.e. they are controlled by the Power Density Distribution Monitoring System (PDDMS). Four other Type 1 rods are controlled by the lateral ion chambers of the automatic control system. Four Type 2 rods (shortened absorber rods) are also part of the automatic control system, controlled by the lateral ionization chambers. The rods can be divided into seven groups according to their function. The breakdown is provided in Table 4.7 [37].

Table 4.7 Reactivity control system rods [37]

Rods	Number	Time to fully insert rod (automatic shutdown), s	Rod insertion speed shutdown automatic, m/s	Rod insertion speed shutdown manual, m/s
Type 1 rods				
1 - Manual Control Rods (MCR)	107	12-14	0.4±0.1	0.4±0.1
2 - Local Automatic Control Rods (LACR)	12	12-14	0.2±0.05	0.2±0.05
3 - Local Scram Rods (LSR)	24	12-14	0.4±0.1	0.4±0.1
4 - Automatic Control Rods (ACR)	4	12-14	0.2±0.05	0.2±0.05
Total type 1 rods:	147			
Type 2 rods				
5 - Shortened Automatic Control Rods (SACR)	4	12-14	0.4±0.1	0.4±0.1
6 - Shortened Absorbers Rods (SAR)	36	12-14	0.4±0.1	0.4±0.1
Total type 2 rods:	40			
Type 3 rods				
7 - Fast - Acting Scram rods (FASR)	24	2.0-2.5* 5.0-7.0**	- -	- 1.15±0.2**
Total number of control rods	211			

* Fast-acting scram
** AZ-1 scram

4.4 REACTOR DRAINING SYSTEM

Excess coolant inventory in the various circuits which serve to cool the core and the surroundings structures is controlled by the Reactor Draining System. The draining system is designed to perform the following functions:

- draining and monitoring of coolant leaks in the reactor cavity from damaged fuel channels, control rod channels and radial reflector cooling channels,
- draining of condensate from the reactor cavity auxiliary pipelines (upper and lower steam-gas release circuit,
- centralized permanent monitoring and recording of total water leak rates into the reactor cavity,
- draining of condensate from gas cavities of reactor metal structures adjacent to the biological shielding-annular water tanks (upper and lower interbellow cavities and reactor interface cavity) and from peripheral ionization chamber.

The reactor draining system consists of three following components:

1. Components draining the reactor cavity,
2. Components draining the regions around the metal structures,
3. Components draining the peripheral ionization chambers.

4.4.1 The Reactor Cavity Draining System

A block diagram of the reactor draining system is shown in Fig. 4.19.

The upper plate of bottom metal structure (6) is a bottom boundary of the reactor cavity (4), where moisture is accumulated in case of leaking control rod channels, radial reflector cooling channels and fuel channels during reactor operation. The 150 mm diameter pipes are welded into each of the bottom metal structure quadrants. Outside the reactor the pipelines merge in pairs into a pipeline, which is welded downstream into an 8 m - high hydrolock (11). The merged pipelines from both reactor halves are equipped with valves (14) for visual drainage monitoring.

The four 50 mm diameter draining pipelines of the upper steam-gas release circuit (1) merging into the 150 mm diameter pipeline of drainage removal from the bottom metal structures into the 8 - meter hydrolock (11). There is a measuring tank (13) with water level indicator in the 8 m hydrolock outlet piping, which allows to monitor the leak rate of water drained from the bottom metal structure and upper steam-gas release circuit pipelines. From the 8 m hydrolock water is further directed to a "dirty" demineralized water tank (17).

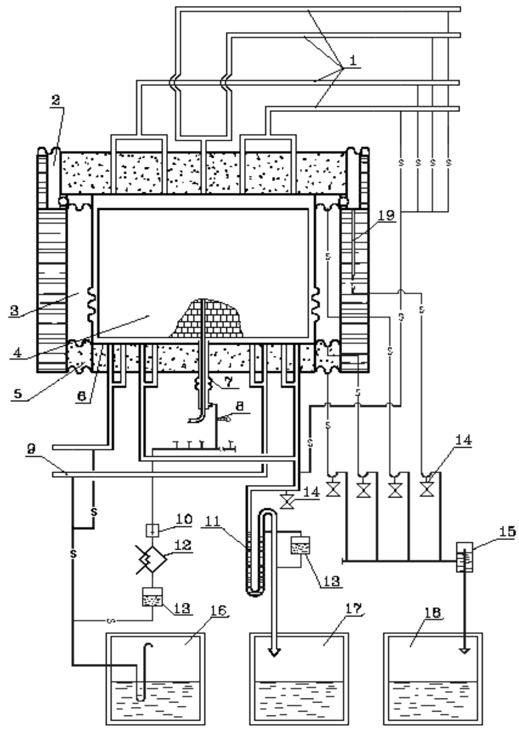

Fig. 4.19 Block diagram of the reactor draining system

1 - upper steam-gas release circuit pipelines, 2 - upper interbellow cavity, 3 - reactor interface cavity, 4 - reactor gas cavity, 5 - upper interbellow cavity, 6 - bottom metal structure, 7 - control rod channel bellow, 8 - temperature detector, 9 - upper steam-gas release circuit pipelines, 10 - drainage visual indicators, 11 - 8-meter hydrolock, 12 - heat exchanger, 13 - drainage measuring tank, 14 - valves for visual drainage monitoring, 15 - tank-hydrolock, 16 - draining tank, 17 - "dirty" demineralized water tank, 18 - floor drain water reception tank 19 - peripheral ionization chambers

The control rod channel bellow (7) draining pipelines are located at the lower housing of a control rod channel. The upper part of the housing shows up above the upper plate of bottom metal structure (6). Moisture may appear in control rod channel bellows from the reactor cavity by condensing on colder walls of a control rod channel and flowing downwards. Condensate from every bellow is drained through 10mm diameter pipelines into a 50mm diameter header. Each of the reactor quadrants has a header of its own. Nitrogen or a nitrogen - helium mixture from the reactor gas circuit is pumped through all the draining pipelines. Each control rod channel bellow draining pipeline is equipped with a temperature detector (8), which indicates the appearance of leaks. The signals go to MCR at drainage temperature drop to 160°C. Leaks from each of the reactor quadrant draining headers are drained through drainage visual indicators (10) into a heat exchanger (12) and after cooling are collected in a control rod channel bellow drainage measuring tank (13). In the tank moisture is separated from gas (nitrogen or a nitrogen - helium mixture), the gas being returned into the reactor gas circuit, and the condensate being drained via a hydrolock into the draining tank (16).

The draining pipelines of the lower steam-gas release circuit (9) consist of two outlet 50mm diameter pipes merging into a discharge pipeline of the control rod channel bellow drainage measuring tank into the draining tank (16).

The total value of leakage at the bottom of the reactor is measured by registering of the leakage into the both measuring tanks (13) Bottom metal structure (6), upper steam-gas release circuit pipelines (1) and control rod channel bellow (7) drainage measuring tanks (13) have level meters and motor-driven discharge valves. The system operates in an automatic mode. Signals from level indicators are processed in a summator and self-recorded in terms of cumulative the reactor cavity water leak rate.

An enunciator sends a warning signal in the Gas Circuit Control Room when the leak rate increases to 7 l/h, an emergency alarm is sent to MCR (Main Control Room) when the leak increases to 10 kg/h. Upon receipt of the alarm, standard plant operating procedures require the operator to terminate reactor power by activating the AZ-1 signal. No signals are transferred to the Control Protection System.

4.4.2 Metal Structures and Peripheral Ionization Chambers Draining System

By design some metal structures gas cavities (upper (2) and lower (5) interbellow cavities and reactor interface cavity (3)) have an interface with biological shielding - annular water tanks. The metal structures draining system is designed to monitor status of biological shielding - annular water tanks and drain potential leaks and condensate from these metal structures gas cavity. The leaks are drained through a special 40 mm diameter pipeline from all lowest points of the gas cavity compensating bellows. Each draining pipeline has a valve (14) for visual monitoring of condensate presence. Leak number control was not envisaged by the design. In order to avoid connection between reactor metal structures gas cavities and the atmosphere, the draining pipelines are welded into a tank-hydrolock (15). The content of the tank-hydrolock is drained into a floor drain water reception tank (18).

The peripheral ionization chambers (19) are located in the reactor biological shielding - annular water tanks. A special draining system is provided to monitor the leak-tightness of ionization chambers casings and timely drain potential leaks and condensate. Separate drainage pipes (40 mm diameter) from each chamber are connected to tank-hydrolock (15). The each pipeline from ionization chambers casing is equipped with valves (14) for visual drainage monitoring.

4.5 OPERATIONAL PROCEDURES

During a scheduled shutdown the reactor must be allowed to cool completely. This implies that the critical state of the reactor is reached with temperatures below 80 ^oC in the MCC and 100 ^oC in the graphite stack, respectively.

This Section presents a brief description of the procedures employed during the standard power plant operations as startup, shutdown and refueling [36]. Note that the descriptions must refer repeatedly to various plant systems which for the RBMK reactors can have different connotations than those for the more familiar PWR or BWR plant types.

4.5.1. Startup

Reactor startup proceeds in two main steps. During step one reactor power is increased until the minimum controllable power level is established, in step two it is taken to full power. The minimum controllable power level is reached when the full power instrumentation train is able to register and control the neutron flux levels, it constitutes about 0.3 % of the nominal thermal power and never exceeds 240 MW or 5 % of the design thermal power.

Step 1:

⇒ Preparing for startup after a planned maintenance shutdown.
⇒ Reaching the minimum controlled power.

A) Before starting the reactor, the following operations must be performed:

- the seals of the MCC must be tested,
- control instrumentation must be checked and made ready for operation. Special attention must be paid to the flow-rate meters of the fuel channel coolant,
- heating the MCC,
- separator drums must be filled to a liquid height from 1000 to 1400 mm from the bottom. The fill-water, must meet the following criteria:

a) Water pH at 25^{o}C	5.5-7.2
b) Relative electric conductivity at 25^{o}C, μS/cm	≤ 1.5
c) Calcium hardness, μg(equiv.)/kg	≤ 3*
d) Bulk iron concentration, μg/kg	≤ 20
e) Bulk chloride ion concentration, μg/kg	≤ 10
f) Bulk mineral oil concentration, μg/kg	≤ 100

* water hardness of one μg/kg is equivalent to that hardness, which would be present in one kg of water with 20.04 μg of Ca ions or with 12.16 μg of Mg ions.

- the reactor nitrogen blowers must be in operation,
- emergency controls of the MCC must be checked,
- fuel channel flow-rate meters must be activated and their readings recorded.

B) At least two main coolant pumps (MCP) must be turned on, their flow rates must reach 1.805 to 1.944 m^3/s (6500-7000 m^3/h) with throttle-control on each pump.
C) The purification system of the cooling water must be turned on, its flow rate adjusted to meet the requirements of the water purity criteria.

D) The no-access areas must be cleared of personnel. Ignitable materials must be isolated.

E) The following parameter limits must never be exceeded:

- water temperature heating rate in the MCC 10 $^oC/h$,
- temperature difference between the top and bottom metal walls of the separator drum 40 ^oC,
- temperature difference between the top metal wall of the separator drum and the supply water 150 ^oC,
- temperature differences between the top metal plate of the reactor and the fuel channel 50 ^oC in the central sections, and 120 ^oC in the periphery.

F) Excess water must be discharged into the clean-water storage tanks.

G) Before heating the main circulation loop above 100^{o}C, the following operations must be performed:

- all safety valves checked,
- the accident confinement system (ACS) set in operation,
- the necessary amount of water stored and its supply piping checked,
- deaerators filled with water at least 1 m from the bottom,
- the diesel electric power generator set in "ready" mode,
- electric power supply circuits of 6 kV and 0.4 kV checked.,
- water quality must meet the following criteria:

	MCC	CPS
a) The pH value at 25^{o}C	5.5-8.5	4.5-6.2
b) Relative electric conduction at 25^{o}C, µS/cm	≤ 2	-
c) Calcium hardness, µg(equiv.)/kg	≤ 50	-
d) Bulk silicium acid concentration, µg/kg	≤ 2000	-
e) Bulk iron concentration, µg/kg	≤ 500	≤ 100
f) Bulk cooper concentration, µg/kg	≤ 50	-
g) Bulk chloride ion concentration, µg/kg	< 100	≤ 50
h) Bulk mineral oil concentration, µg/kg	≤ 200	≤ 100
i) Bulk aluminum concentration, µg/kg	-	≤ 100

- water in the ACS compartments must conform as follows:

a) level in the hot condenser chamber pools	2.5 m
b) level in the condenser basins	1.05 m
c) level in the water storage chambers	2.8 m

d) There must be no water in the water-exhaust pipes.

H) Before initiation of control rod withdrawal, the following operations must be performed:

- the power supply system of the CPS must be checked,
- neutron flux instrumentation verified,
- emergency blocks and the emergency protection system AZ-1 prepared for operation,
- servo-drives of control rods checked by raising them manually,
- at least two MCPs in each pumping station turned on,
- coolant flow rate of at least $2.77 \cdot 10^3$ m^3/s (10 m^3/h) maintained in the fuel channels,
- fuel channel control valve operation checked,
- the PDDMS set in operation,
- the adequacy of the reactor nitrogen pressurization system verified,
- proper sealing of the fuel channels ensured,
- the ACS and CPS set in "ready" mode,
- the ECCS set in "ready" mode.

I) A representative of the Lithuanian Regulatory Body (VATESI) must be present, when the reactor is brought up to the minimum controlled power level.

J) The procedure for reaching the minimum controlled power is as follows:

- CPS rods are lifted, beginning with the LEP rods and proceeding to the automatic control and manual control rods,
- the startup procedure must be stopped if any discrepancy in the instrumentation readings is noted,
- up to four rods may be lifted simultaneously at 60 s intervals before criticality is achieved,
- if in 10 minutes time after the withdrawal of control rods is initiated the reactor does not achieve criticality, the reactor is shut down by re-inserting the control rods,
- the automated control system is initiated after a power level of about 30 MW(th) is reached,
- the power level of the reactor must not exceed 240 MW(th) during the warm-up of its main circulation circuit.

K) Warm-up of the MCC:

- when the absolute pressure within the separator drum reaches 0.1962 to 0.392 MPa (overall 1-3 kgf/cm^2), the steam discharge valves and the deaerators must be initiated,
- when the separator drum absolute pressure reaches 0.3-0.7 MPa, hermetic seals of the fuel channels must be checked visually,
- water quality must now meet the following criteria:

	Feedwater	Condensed water after filtering
a) The pH value at 25^{o}C	5.5-7.8	6.5-7.5
b) Relative electric conduction at 25^{o}C, μS/cm	≤ 1.5	≤ 0.5
c) Calcium hardness, μg(equiv.)/kg	≤ 5	≤ 1
d) Bulk silicium acid concentration, μg/kg	≤ 100	≤ 50
e) Bulk iron concentration, μg/kg	≤ 50	≤ 20
f) Bulk copper concentration, μg/kg	≤ 5	≤ 5
g) Bulk chloride concentration, μg/kg	≤ 10	≤ 10
h) Bulk mineral oil concentration, μg/kg	≤ 200	-

Step 2:

⇒ Raising the reactor power above the minimal controlled power level.
⇒ Initiating reactor operation.

A) Before reactor power can be increased, the following operations must be performed:

- final adjustment of the fuel channel coolant flow-rate control made,
- operation of the gaseous coolant loop checked,
- operational water levels in the separator drum and in the deaerator attained,
- proper water levels in the ACS and in the water supply systems assured,
- measurement and recording of operational parameters verified,
- coolant channel flow rates checked and recorded.

B) Water quality parameters must be rechecked.

C) A representative of VATESI must be present, when the reactor is brought above minimum controlled power level.

D) The procedure for increasing reactor power is as follows:

- the increase is accomplished in several stages:

Parameter	Number of stage					
	1	2	3	4	5	6
a) Reactor power,						
MW(th)	240	1000	2600	3300	4200	4800
MW(e)	-	250	750	1000	1300	1500
%	-	17	50	67	87	100
b) Minimum time to reach the next stage, h	0.5	0.5	1.5	2.17	7.0	11.0
c) Minimum time spent at given power, h	-	2.0	2.0	3.0	1.0	-

E) After the operation at stage 2 is stabilized:

- increase the flow of the MCP by opening the throttling regulating valves,
- establish proper flow rate of the feedwater by MFWP:

Maximum flow rate of each MCP, m^3/s (m^3/h)	Supply rate of feedwater to each side of MCC, kg/s (t/h)	
	3 MCP in operation	2 MCP in operation
1.94 (7000)	below 180 (450)	below 125 (650)
2.5 (9000)	180 to 350 (450-900)	125 to 250 (650-1250)
2.78 (10000)	over 350 (900)	over 250 (1250)

F) After the operation at stage 3 is stabilized:

- start the third MCP in each pumping station (if only two are in operation),
- initiate helium-nitrogen cooling of the reactor.

G) The transition from stage 3 to stage 4 must occur in 50 MW(e) (150 MW(th)) steps, maintained for 10 min. The operation in each step should not be less then 20 min.

H) The transition from stage 4 to stage 5 must occur in 50 MW(e) (150 MW(th)) steps, maintained for 20 min. The operation in each step should be continued not less then 1 hour.

I) Further power increases must occur in 50 MW(e) (150 MW(th)) steps. Each power increase step is maintained for 30 min. The duration of operation in each steps should be not less 3 hour.

J) If an emergency signal is generated by an energy distribution detector, the procedure must be stopped, the failure must be analyzed and eliminated. If two emergency signals are generated, the power must be reduced until both signals cease. Only then can corrective procedures be initiated.

K) The turbogenerators can be started after the drum pressure reaches 7 MPa.

4.5.2 Shutdown

A) Normal shutdown of power units must adhere to the following procedures:

- the power is decreased while maintaining a constant pressure in the separator drum by reducing the reactor power and the load of one turbine at a time, this is followed by a similar reduction at the next turbine,
- while reactor power is reduced to 1000 MW(th), two or three MCPs are in operation in each pumping station and their flow rate is reduced to 1.8 m^3/s (6500 m^3/h) using throttling regulating valves,
- the turbine is fed from the auxiliary transformer,
- power is decreased continuously by pushing of AZ-1 button.

B) Normal cooling of the reactor and the MCP:

- reduce steam pressure in the separators by discharging steam via steam discharge valves (SDV-C), then with the aid of coolers and regenerators of the cooling system. If necessary, discharge through steam discharge valves which directs excess steam to the turbine condens (SDV-A) into the ACS condensing pools,
- after the chain reaction has ceased, at least two MCPs must be in operation in each pumping station,
- after the MCC has been cooled to 180 ^oC, at least one MCP must in operation in each loop,
- after the MCC has been cooled to 100 ^oC, the main circulation pumps may be stopped,
- observe the inertia in the MCP, to note any reverse flow or failure of a check valve to close,
- the Purification and Cooling System (PCS) must be in operation until the reactor is completely cool.

C) During normal cooldown of the reactor observe the following criteria:

- the minimum cooling rate is 10 ^oC/h,
- the temperature difference between the top and the bottom of the separator drums must not exceed 135^oC,
- the temperature difference between the metal of the upper sections of the separator drums and the water supply must not exceed 150 ^oC,
- the temperature difference between the metal wall of the reactor and the fuel channel must not exceed 50^oC in the central region and 120 ^oC in the periphery.

D) Emergency cooling of the reactor and the main circulation circuit, which is initiated under the following circumstances:

- a reactivity-related shutdown of the reactor,
- a failure in the MCC, in the main steam line or in the feedwater supply line,
- the failure of a fuel channel or of CPS,
- a fire in the control room.

Emergency cooling rates must not exceed 30 ^oC/h.
Steam pressure in separator drums is reduced by discharging part of the steam by SDV-C. When the water temperature decreases below 180 ^oC, the purification and cooling system is switched on.
E) The main circulation circuit must be cooled down to 70 or 80 ^oC and the graphite stack down to about 100 ^oC.

4.5.3 Refueling Operation

The following refueling machine service areas are located in the main refueling hall:

A) The refueling machine storage area.
B) A practice and a calibration area. This area is used for adjustment and testing of the refueling machine. Practice operations include: filling the fuel casket with condensate, refueling operations, loading of new fuel into the fuel casket, decontamination of the interior of the fuel casket, and replacement of the inflatable rubber gasket surrounding the standpipe.
C) The spent fuel reception area.
D) A repair area for replacement of damaged fuel caskets. A completely prepared reserve fuel casket is kept in this area.

The refueling machine operates in the following modes: checkouts and preparation, loading of new fuel, online refueling, and refueling of a shut down, cool reactor.

<u>Checkout and Preparation of the Refueling Machine</u>

When the power is turned on, the coolant tank is automatically filled with reactor feedwater. Subsequently the machine is moved to the practice stand area, where it loads the channel gauge and the channel plug into appropriate receptacles of the fuel casket. After this is accomplished the fuel casket is filled with water from the coolant tank. Then the dampers of the closing mechanism are shut, the condensate from the standpipe is drained, and the machine is disconnected from the loading socket.

<u>Loading of New Fuel</u>

The refueling machine, with the casket filled with feedwater at a temperature of 30 ^oC, is positioned over the practice socket, into which a new fuel assembly has previously been loaded. The machine is joined to the upper section of the socket by means of the standpipe, and the joint is sealed. The socket and the standpipe are filled with water. The dampers of the closing mechanism are opened, the new fuel assembly is pulled into the receptacle of the fuel casket and locked in. The dampers of the closing mechanism are shut, water is drained from the standpipe and the practice socket, and the refueling machine is disconnected from the socket and is moved to the reactor channel to be reloaded.

<u>Fuel Assembly Replacement</u>

The operator issues directions to prepare the fuel channel for refueling. The block covering the fuel channel is removed and if a flux detector cable is present, it is disconnected. This is accomplished manually in the refueling hall.

Two stages of the operations performed by the refueling machine are illustrated schematically in Fig. 4.20. After the refueling machine is positioned over the fuel channel, the standpipe control mechanism (1) lowers the standpipe (3), which encloses the upper portion of the fuel channel (10). The joint is sealed by the inflatable rubber gaskets (5), and the standpipe is filled with water from the tank. Subsequently, the closing mechanism dampers are opened, and the fuel casket is pressurized by the machine's feed pump until it matches the pressure in the fuel channel. The grabber (7) is then lowered, and clamps on to the handle of the fuel channel seal plug. The sealing mechanism (2), using a special key (4) to turn the fuel channel seal plug (9), unseals the channel. Water is pumped in small quantities from the casque to the fuel channel. The cold water prevents steam and hot water from entering the refueling machine from the fuel channel. The coolant water is being pumped during the time when the new fuel assembly is being loaded. The grabber is used to lift the spent fuel assembly to a height of 7.5 m into the cooling zone, where it is kept for about 10 minutes. Afterwards, the fuel assembly is pulled into the casque receptacle.

To ascertain that the coolant channel is free of obstructions, it is inspected by means of a movable gauge, and then the new fuel assembly is lowered into the reactor. The fuel channel is then resealed. The coolant feed pump is disconnected, and the pressure in the fuel casket falls to atmospheric levels. The closing mechanism dampers are closed, the standpipe space is connected to a special ventilation system, and the leak-tightness of the fuel channel seal is verified. Before disconnecting from the channel, pressurized air is forced into the standpipe to displace the cooling water back into the supply tank. After this operation, the standpipe seal is released, the refueling machine is disengaged from the fuel channel and moved towards the spent fuel reception area.

As the spent fuel reception unit is already prepared to receive the spent fuel assembly into the storage pool casing, the spent fuel is loaded into one of the reception unit's sockets. The machine with the spent fuel is moved to the water-filled casing, is connected to it, and the standpipe cavity is filled with water from the supply tank. The closing mechanism dampers are opened, and the spent fuel assembly is transferred from the fuel casket to the casing. The dampers are closed, the water from the standpipe is forced back into the tank, the machine is disengaged from the casing, and is then ready to perform the next fuel-changing cycle.

Refueling a Cool (Shut Down) Reactor

Two options are available: changing two fuel assemblies at once and replacing the removed spent fuel with new ones, or, removing four spent fuel assemblies and loading new ones without the use of the refueling machine.

In either case, the operations performed by the refueling machine are greatly simplified, since the water pressure in the reactor is reduced (down to 0.2-0.5 MPa). Using the first option, the fuel-assembly-changing cycle takes 350 minutes, so the refueling machine can change 8 fuel assemblies per day in this mode. If the refueling machine is used only to remove the spent fuel from the fuel channels, the transfer cycle takes 267 minutes. In this case, up to 20 fuel channels per day can be refueled.

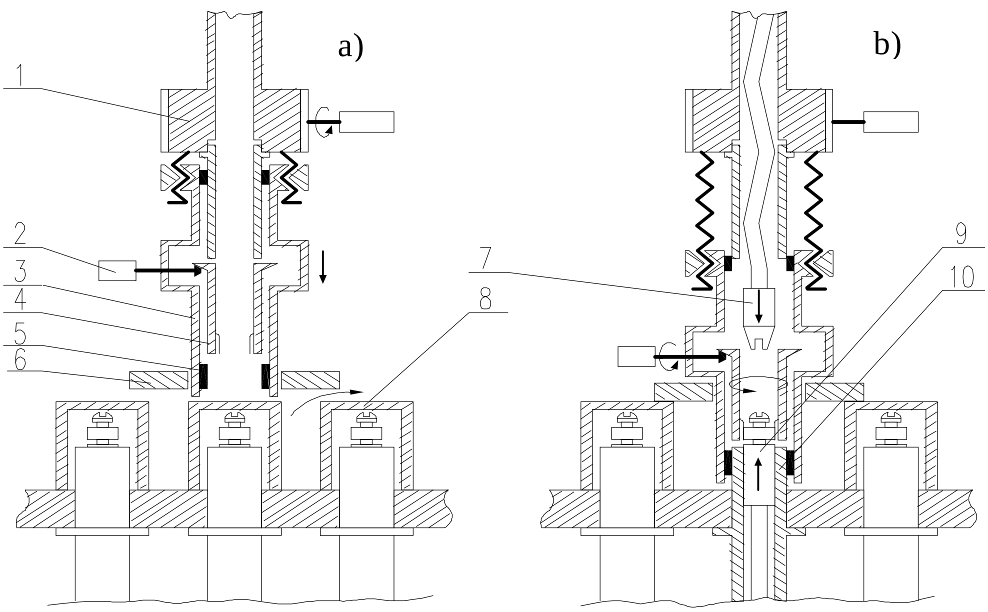

Fig. 4.20 Refueling machine operation

a) refueling machine positioning over the fuel channel, b) unsealing of the fuel channel

1 - standpipe control mechanism, 2 - special sealing key control mechanism, 3 - standpipe, 4 - special key, 5 - inflatable rubber sealing gaskets, 6 - bottom biological shield, 7 - grabber, 8 - enclosing clock, 9 - fuel channel seal plug, 10 - fuel channel body