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Treatment and Disposal of Irradiated Graphite and Other Carbonaceous Waste

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Executive summary

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Chapter contents

1 Introduction

Ignalina Nuclear Power Plant (INPP) is Lithuania's only nuclear power plant. Two RBMK-1500 type Soviet designed reactors (water-cooled graphite-moderated channel type reactors) are installed at INPP. These reactors are different from those operating in Russia.

2 The legislative and regulatory framework

The Law on Nuclear Energy[1] establishes the basis for the management of nuclear energy, the principles of state regulation of nuclear safety and radiation protection in the sphere of nuclear energy, basic conditions for licensing in the sphere of nuclear energy, basic conditions for transportation and storage of nuclear and radioactive materials used in the sphere of nuclear energy.

According this law the functions of safety and control of nuclear facilities are performed by the State Nuclear Safety Inspectorate of the Republic of Lithuania (VATESI) in collaboration with the Ministry of Health, the Ministry of the Environment, the Ministry of Transport and Communications and the other governmental institutions. VATESI together with the Ministry of the Environment approve technical regulations of the design and construction of nuclear facilities and maintenance of their structures. VATESI also approve standards and rules of operation of nuclear facilities, standards and rules of storage of radioactive materials used in nuclear energy and disposal of their waste; control the compliance with the requirements stipulated in licences, safety regulations and standards; issue licences to legal and natural entities for the design, construction, operation, safety appraisal of nuclear facilities and their systems, and other work related to safe operation of nuclear facilities.

The Law on Nuclear Energy provide competence to The Ministry of Health to approve regulatory acts and rules on the health of the personnel of nuclear facilities and the residents of the monitored zones of the facility and control compliance thereof.

The Ministry of the Environment after co-ordination with the Ministry of Health, establishes radiation protection standards and monitor compliance with them; co-ordinate in the manner prescribed by law assessment of the impact on the environment[2].

VATESI established special safety requirements for decommissioning of INPP and the individual stages of the decommissioning[3].

3 Policy objectives of decommissioning

The Lithuanian Government has approved the immediate dismantling concept for the decommissioning of the first power unit of INPP[4].

In 2002 Lithuanian Government approved also radioactive waste management strategy[5]. The tasks of the strategy includes reorganization of radioactive waste management at the INPP by implementing a new system of classification of radioactive waste in accordance with the IAEA recommendations and international practise, making preparations for the management of radioactive waste that will be generated as a result of decommissioning of the INPP, by installing the necessary radioactive waste management facilities in the Power Plant, construction of new repositories for radioactive waste.

It is planned to modernize, during the period from 2002 to 2009, the management and storage of solid short-lived and long-lived radioactive waste of the Ignalina Nuclear Power Plant with the view to:...

1. implementing a new system of classification of radioactive waste;
2. constructing a landfill repository for the disposal of very low level radioactive waste;
3. retrieving the short-lived waste accumulated in solid radioactive waste storage facilities, and characterizing, processing and transferring it back to the storage facilities;
4. retrieving, characterizing and processing the long-lived waste accumulated in solid radioactive waste storage facilities, installing adequate interim storage facilities for long-lived radioactive waste, and storing the long-lived radioactive waste in storage facilities without final immobilization until the final disposal methods are decided.
5. conducting analysis and preparing projects aimed at developing methodologies for calculation of conditional clearance levels and the most suitable methods of management of substances with contamination exceeding unconditional clearance levels[5].

It is planned to conduct, by 2005, the necessary investigations and draft recommendations on the construction of a near-surface repository for low and intermediate level short-lived radioactive waste[5].

For implementing the radioactive waste management strategy it is planned to put the Solid Waste Management and Storage Facilities (SWSF) into operation by 2010. The design lifetime of SWSF will be 50 years.

According the INPP Final Decommissioning Plan[6] graphite waste will be stored in the non-shielded containers placed in the Interim Storage of SWSF for long-lived waste, regardless of its radionuclide composition. The waste in the containers will be stored without grouting. Design life of the containers is 50 years.

The Lithuanian waste management agency (RATA) interim waste acceptance criteria[7] show that the INPP graphite waste does not meet the criteria for near-surface disposal due to the C-14 inventory (criterion for intrusion scenario is satisfied, but for long term migration from the repository site is largely exceeded). It is supposed to dispose of graphite waste after further treatment/conditioning in a repository for long lived waste in cavities at an intermediate depth or in deep geological repository.

4 Compliance with international guidelines and regulations

Lithuanian legislation follows closely international recommendations and practise.

5 Decommissioning of nuclear reactors - current situation

5.1 Ownership

The owner of all nuclear facilities in Lithuania, including the INPP, is the Lithuanian State.

5.2 Reactors shut down dates

In accordance with National Energy Strategy[8] adopted by the Lithuanian Parliament the first unit of INPP was shut down on December 31, 2004. The shut down of the second unit is scheduled for the end of 2009.

5.3 Projected decommissioning dates[6]

It is planned that in-line decontamination of the Main Circulation Circuit (MCC) and Purification and Cooling System (PCS), the Refuelling Machine, the Control and Protection System (CPS) and reflector cooling channels can start after the complete de-fuelling and the removal of the control rods and in-core instrumentation of Unit 1 reactor, together with the decontamination waste conditioning, on January 2009 and are scheduled over a 6 month period for MCC + PCS and a 4 month period for other decontamination operations. The Unit1 reactor complete de-fuelling can be finished by the end of 2008. Removal of the channels in the Unit1 reactor is scheduled for 2015, removal of the graphite and dismantling of the activated internal structures is planned to start in 2017, dismantling of the biological shield is scheduled to the end of 2019. Overall decommissioning planning is shown in Figure 1.

5.4 Geographical location of INPP and plan of reactor unit[9]

The INPP is located in the north-eastern part of Lithuania close to the borders of Belarus and Latvia as it is shown in Figure 2. The plant is built on the southern shores of lake Drūkšiai, 39 km from town Ignalina (about 6 000 inhabitants). The nearest cities to the plant are Visaginas (at six km from the plant, with about 28 000 inhabitants, residence of the INNP personnel), Daugavpils (at 30 km away from the plant, with about 120 000 inhabitants, belongs to Latvia) and Vilnius (at 130 km away, with about 545 000 inhabitants).

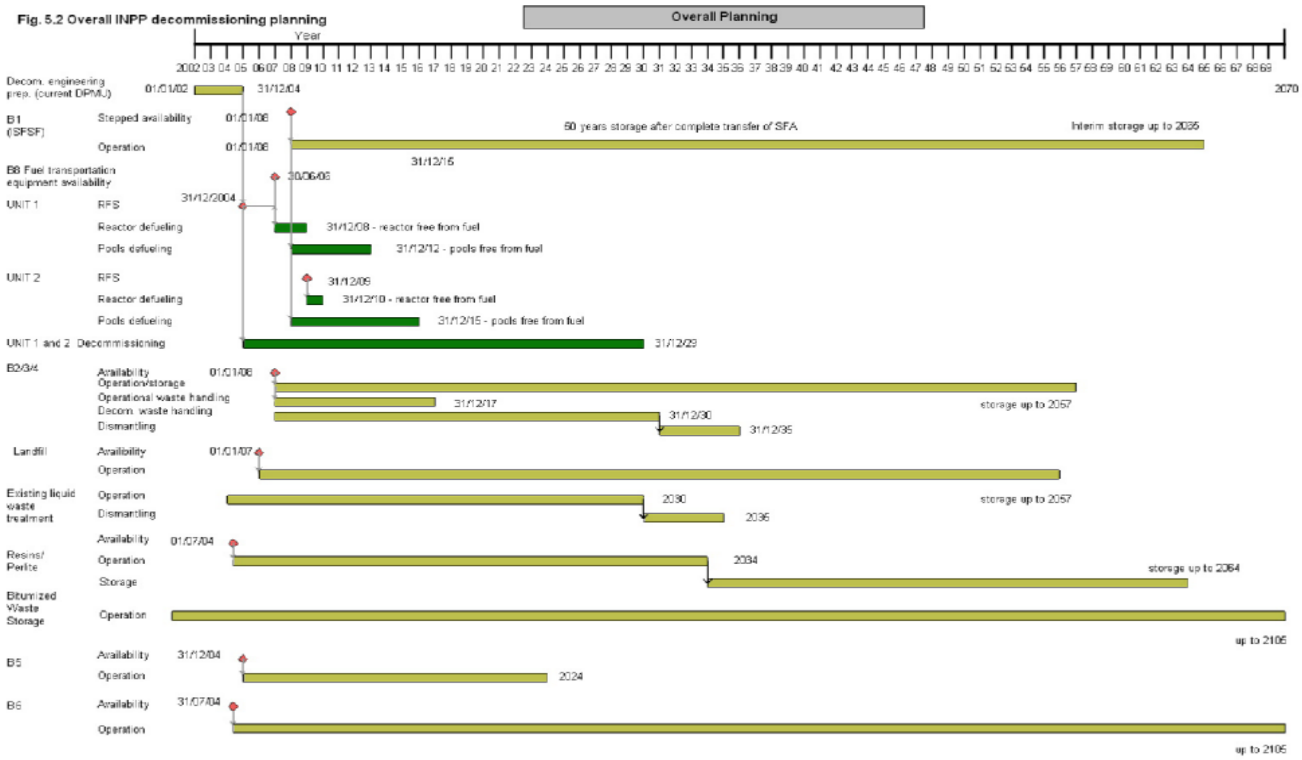


Figure 1 : Overall decommissioning planning of INPP

The site of the nuclear power plant covers an area of about 75 ha. The buildings take up about 22 ha. The general INPP panorama is shown in Figure 3.

The INPP possesses two similar units of RBMK-1500 reactors, as shown in the Figure 4. 2004).

Figure 2 : The location of INPP

Each unit consists of five construction buildings; namely, buildings designated as A, B, V, G and D. There are also two separate reactor buildings A1 and A2 adjacent to a common building D1 and D2. The building of a common turbine hall (blocks G1 and G2) are adjacent to the blocks D1, D2. The main buildings of the plant are situated about 400-500 m from the banks of lake Drūkšiai.

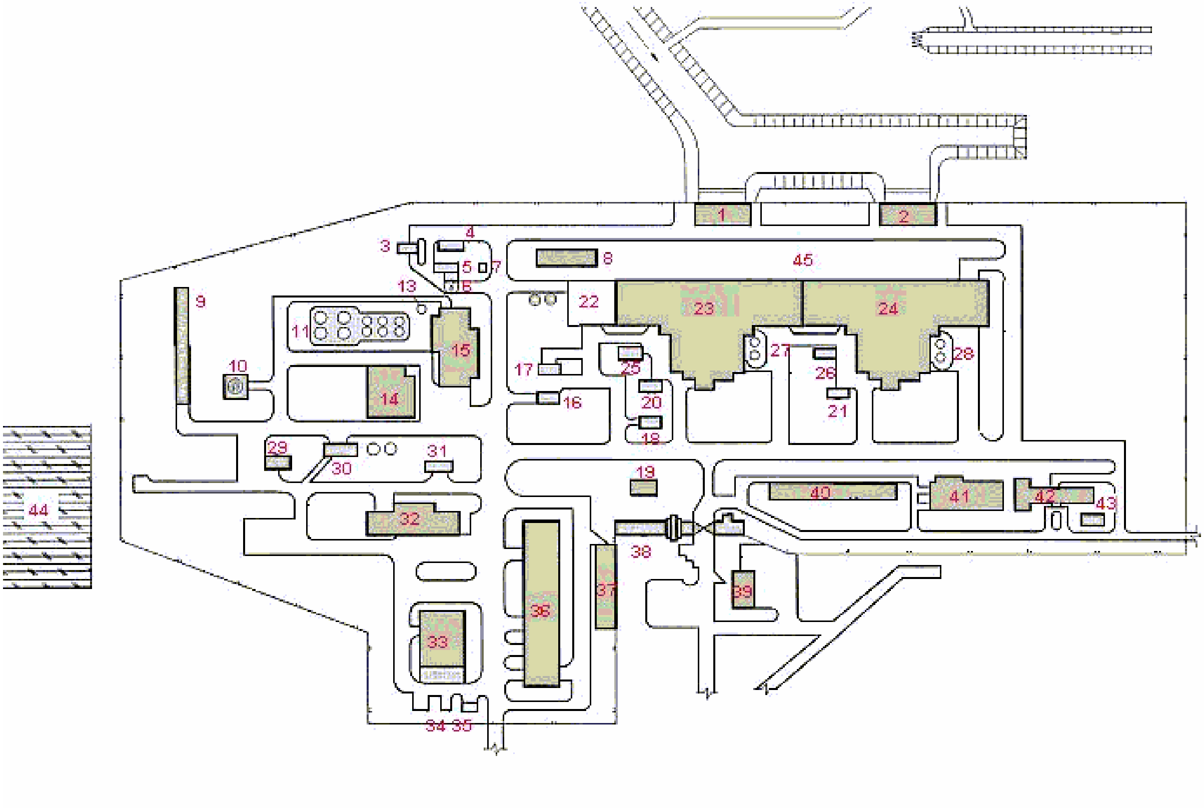


Figure 3: The general INPP panorama

1,2 - service water pump stations , 3 - acetylene bottle depot, 4 - oil depot, 5 - oil system equipment room, 6 - transformers equipment tower, 7 - pump station for waste and liquid sewerage discharge, 8 - hydrogen and nitrogen receiving facility, 9 - low-level radwaste storage facility, 10 - intermediate- and high-level waste storage, 11 - operational shower-water reservoir, 12 - drainage water tank, 13 - venting stack of the radwaste reprocessing building 150, 14 - bitumen storage, 15 - liquid waste storage, 16 - chemical water treatment building, 17 - primary grade water tanks, 18,19 – recreational facilities, 20,21 – gas purification systems, 22 - heat power station, 23,24 – building plant units 1 and 2, respectively, 25,26 – pressurized tank (accumulator) of the ECCS, 27,28 – purified demineralized water tanks, 29 - car-washing facility, 30 - bitumen depot, 31 - special laundry, 32 - chemical reagent depot, 33 - equipment storehouse, 34, 35- maintenance of fire extinguishers, 36 - repair building, 37,38 – administrative buildings, 39 – cafeteria, 40 - diesel-generator building, 41 - compressor and refrigeration station, 42 - nitrogen and oxygen manufacture building, 43 - liquid nitrogen reservoir, 44 - open distributive system.

The INPP possesses two similar units of RBMK-1500 reactors, as shown in the Figure 4. 2004).

Each unit consists of five construction buildings; namely, buildings designated as A, B, V, G and D. There are also two separate reactor buildings A1 and A2 adjacent to a common building D1 and D2. The building of a common turbine hall (blocks G1 and G2) are adjacent to the blocks D1, D2. The main buildings of the plant are situated about 400-500 m from the banks of lake Drūkšiai.

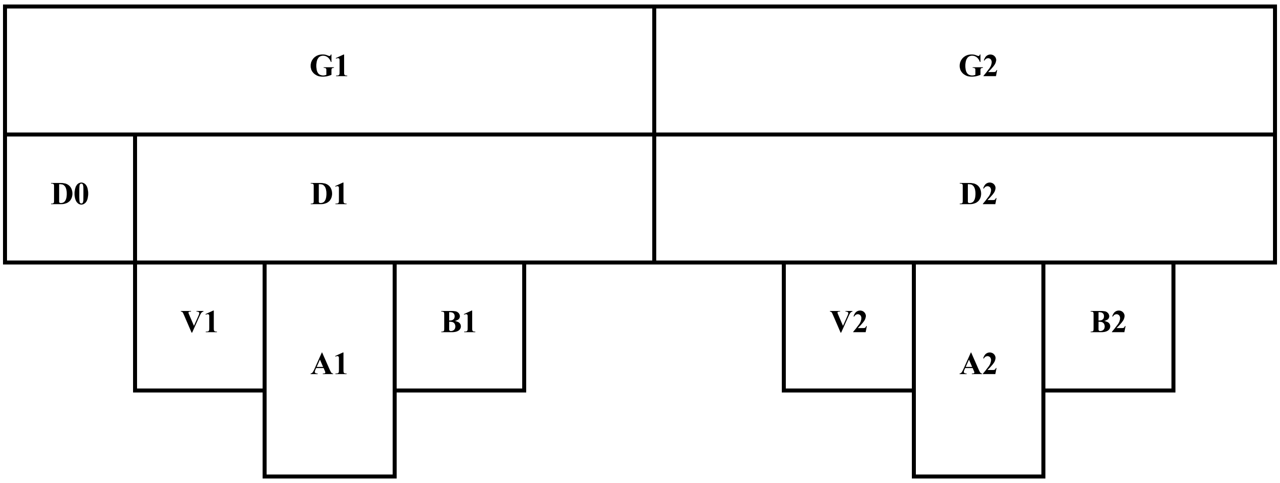
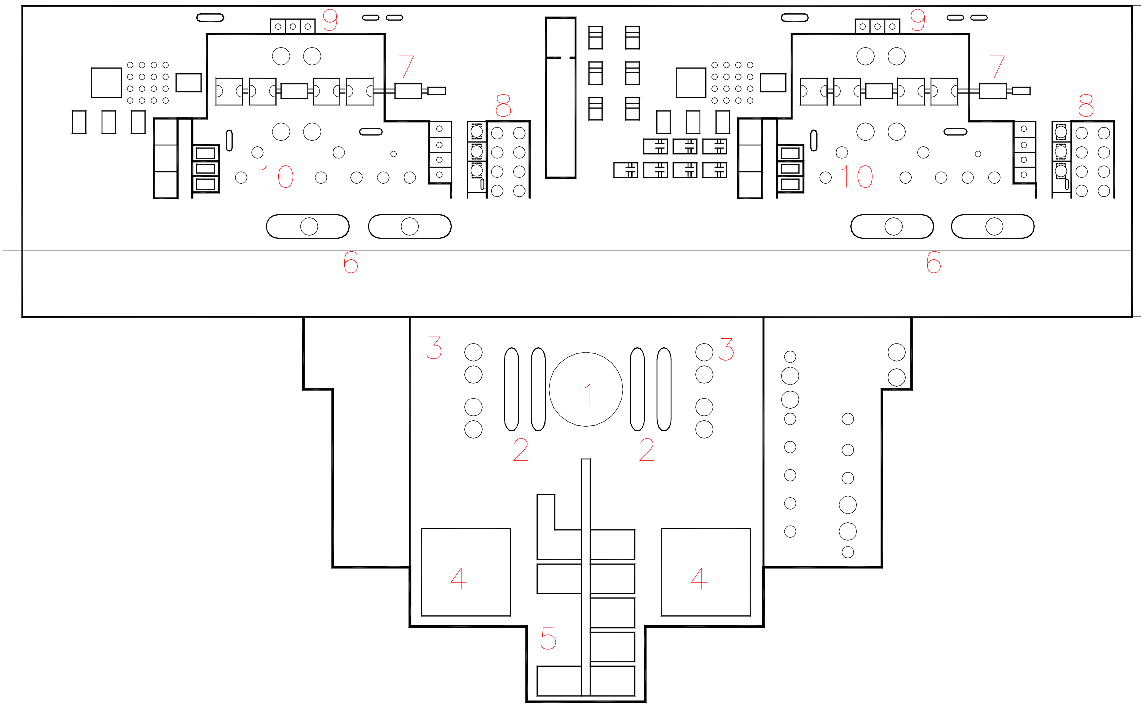


Figure 4: General arrangements of INPP units

A1, A2 - reactor buildings; B1, B2 - demineralized water treatment facilities of the MCC; V1, V2 - reactor gas circuitand special venting system; G1,G2 - turbine generators with auxiliary systems, feed facilities and heat supply facilities, D1, D2 - control, electrical and deaerator rooms; D0 - heat pipe service and fire fighting facilities.

Both units have the following common facilities: low level waste storage, an open distribution system, nitrogen and oxygen manufacturing facility, diesel generator building and other auxiliary systems. A separate water-pump service station is also built for each unit, serving the needs of uninterrupted supply of water.

Figure 5 shows the top view of the main buildings of the INPP. Cross sections A-A and B-B through the building are displayed in the Figure 6 and Figure 7, respectively.



1 – reactor, 2 – drum–separator, 3 – main circulation pumps, 4 – accident localization system, 5 – spent fuel compartment, 6 – deaerators, 7 – turbine generators, 8 – condensate cleaning filters, 9 – first stage condensate pumps, 10 – separator – reheater

Figure 5 : Plan of one unit of the INPP

Building A contains an RBMK-1500 reactor with a Main Forced Circulation Circuit (MCC), and the following main auxiliary systems of the reactor: Emergency Core Cooling System (ECCS), Accident Localization System (ALS) and Control and Protection System (CPS). The hall above the reactor is a large open workspace housing the refuelling machine. The spent fuel storage pool is situated in an adjacent hall, but separated from the reactor hall. The reactor compartment consists of a rectilinear structure, the horizontal cross-section of which is 90 m x 90 m and a height of about 53 m. Building B houses the primary coolant purification system and the demineralised water treatment facilities. The reactor gas circuit and the special venting system are located in building V.

The building area for the special water treatment has dimensions of 66 m x 36 m, and the building for the gas circuit of the reactor measures 66 m x 25 m. Both of these buildings have a height of about 31 m. Building D houses the main control room, the electrical instrumentation and deaerator rooms. This common building for both units has an area of 600 m x 25.5 m and a height of about 44 m.

5.5 Reactor construction and characteristics[9]

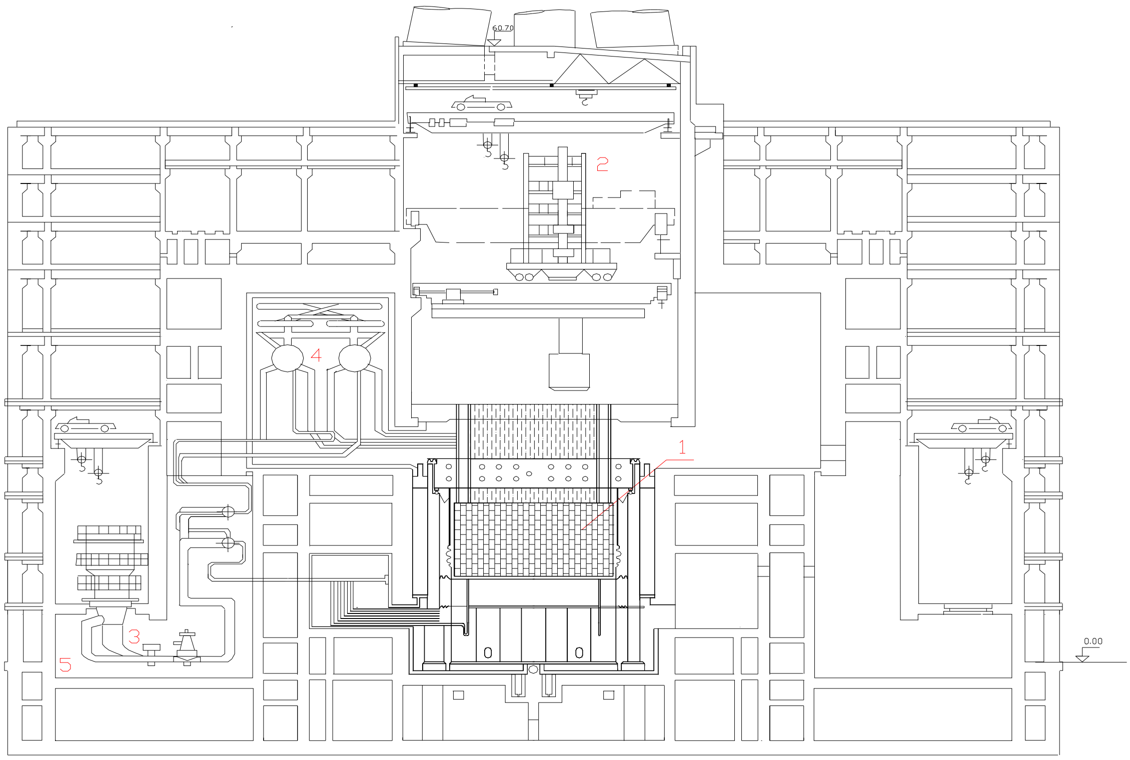
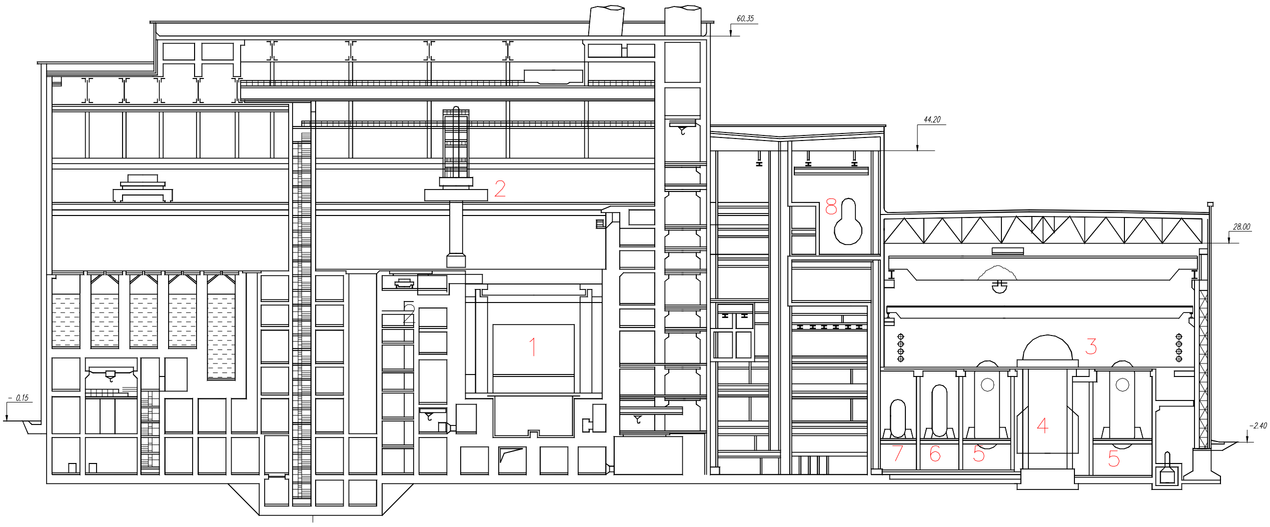


Figure 6: Cross-section A-A of one unit of the INPP

1 – reactor, 2 – refueling machine, 3 – main circulation pump, 4 – drum– separator, 5 – MCP pipelines

The INPP reactors belong to the category of "boiling water" channel-type reactors, a simplified thermal diagram of which is provided in Figure 8.



1 — reactor, 2 — refueling machine, 3 — turbine, 4 — condenser, 5 — separator — reheater, 6 — evaporator, 7 — boiler, 8— deaerator

Figure 7: Cross-section B-B of one unit of the INPP

The reactor cooling water, as it passes through the core, is subjected to boiling and is partially evaporated. The steam water mixture then continues to the drum-separators (3), the elevation of which is greater than that of the reactor. Here the water settles, while the steam proceeds to the turbines (4). The remaining steam beyond the turbines is condensed in the condenser (6), and the condensate is returned via the dearator (8) by the feedwater pump (9) to the water of the same drum-separator. The coolant is returned by the main circulation pumps (10) to the core, where part of it is again converted to steam.

This fundamental heat cycle is identical to the Boiling Water Reactor (BWR) cycle extensively used throughout the world, and is analogous to the cycle of thermal generating stations. However, compared to BWRs used in Western power plants, the Ignalina NPP and other plants with the RBMK type reactors have a number of unique features.

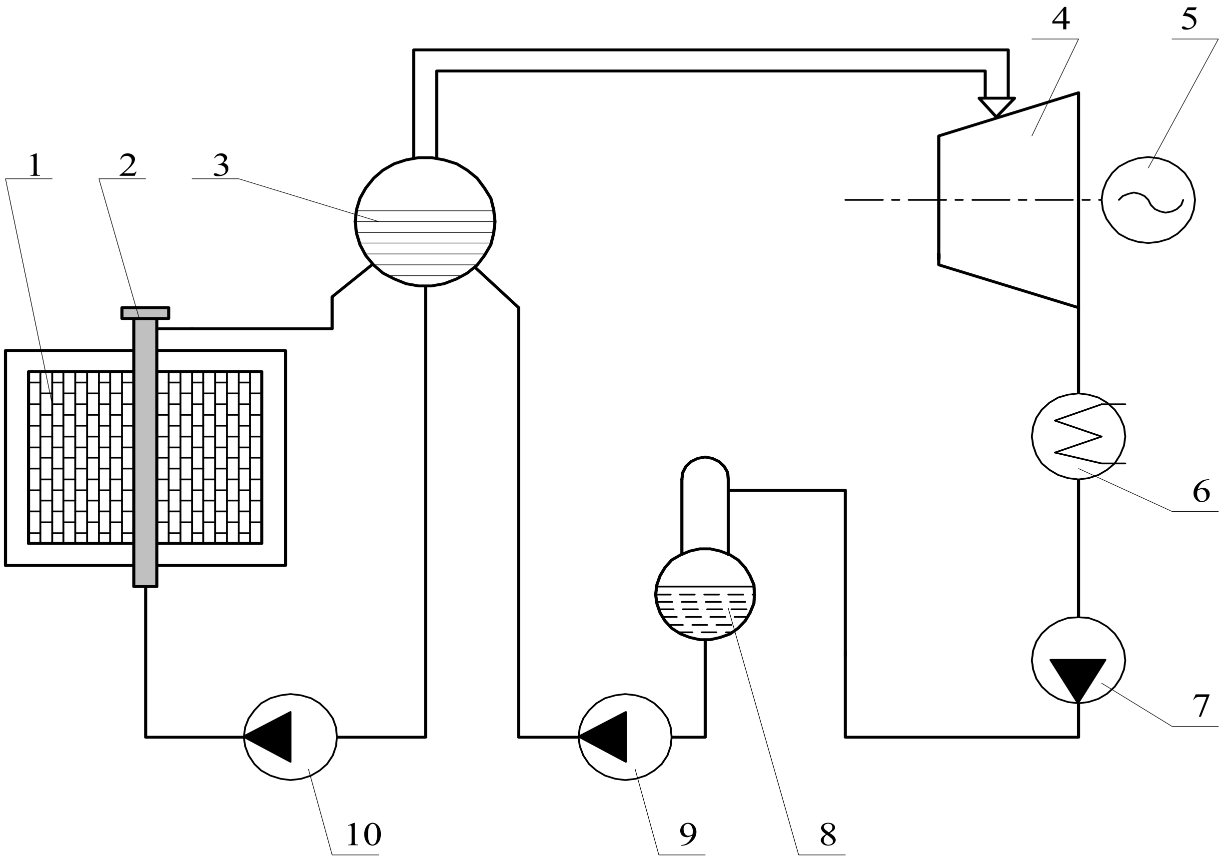


Figure 8: Simplified heat cycle diagram

1- reactor, 2-fuel channel, 3- drum-separator, 4- turbine, 5- generator, 6- condenser, 7- condensate pump, 8- deaerator, 9- feedwater pump, 10- main circulation pump.

Main parameters of RBMK-1500 reactor are presented in Table 1 for a reactor with the power capacity of 4800 MW.

5.5.1 Reactor vessel

The vessel of the reactor (Figure 9) is enclosed within the reinforced concrete vault (3) measured 21500×21500×25000 mm. and incorporates the following main metal structures:

- main support metal structure (9) (Structure S);
- bottom metal plate (8) with bellows compensators [bellows corrugated expansion joints] (Structure OR);
- reactor shell (7) with bellows compensators (Structure KZh);
- top metal plate (2) with bellows compensators (Structure E);

- annular metal structures (5) (Structure L);
- roller supports (11).

Metal structures of the reactor shell (7) together with the bottom and top plates (8 and 2 respectively), make up a leak-tight reactor cavity (6) enclosing the graphite stack.

Table 1 : Main parameters of RBMK-1500 reactor

Coolant	water (steam-water mixture)
Heat cycle configuration	single circuit
Power, MW:	
Thermal (design)	4800
Thermal (actual)	4200
Electrical (design)	1500
Core dimensions, m:	
Height	7
Diameter	11.8
Thickness of reactor graphite reflector, m:	
End	0.5
Side	0.88
Lattice pitch, m	0.25 x 0.25
Number of channels:	
Fuel	1661
Control and protection system	235
Reflector-cooling	156
Fuel	uranium dioxide
Initial fuel enrichment (designed*) for ^{235}U, %	2.0
Nuclear fuel burnup, MWday/kg	21.6
Temperatures, ^{o}C:	
Maximum temperature at center of fuel pellet	2100
Maximum graphite stack temperature	750
Maximum fuel channel temperature	350
Coolant temperature at fuel channel inlet	260...266
Coolant temperature at fuel channel outlet	284
Feedwater temperature	177...190
Excessive pressure, Mpa:	
Steam pressure at drum separators	6.38...6.87
Pressure in MCP pressure header	8.6
Coolant flow rate through reactor at normal power, m^3/s	10,83-13,33
Steam produced in reactor at normal power, kg/s	2056...2125
Void fraction at reactor outlet, %	23...29
Maximum fuel channel parameters:	
Fuel channel power, kW	4250
Coolant flow rate through fuel channel, m^3/s	0,011
bbVoid fraction at fuel channel outlet, %	36.1
Number of main circulation pumps	8
Capacity of main circulation pumps, m^3/s	1.805 – 2.22

*later a new fuel with enrichment of 2.4%, 2.6%, 2.8%, for ^{235}U was used

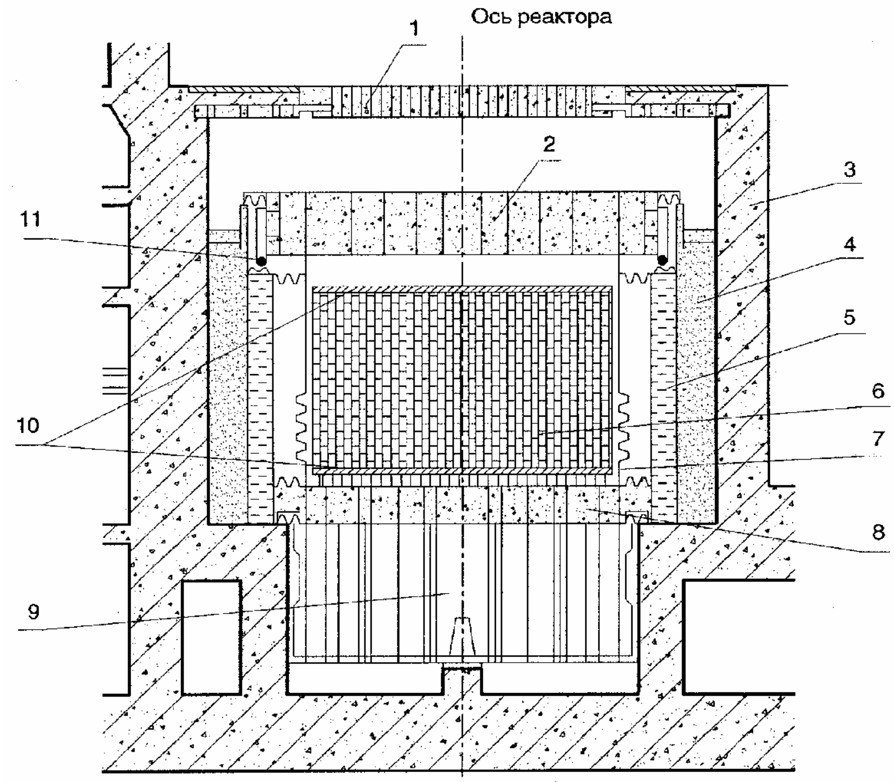


Figure 9 : Longitudinal section of the reactor vessel, layout of the constituent components

1-top cover; 2-top metal structure (Structure E); 3-concrete vault; 4-sand filling; 5-annular metal structure (Structure L); 6-Reactor cavity; 7-reactor shell (Structure KZh); 8-bottom metal structure (Structure OR); 9-main support metal structure (Structure S); 10-steel shield blocks; 11-roller supports

5.5.2 The main support metal structure

The main support metal structure (Structure S) (Figure [9]) (9) consists of two steel 10XH1M 5 meter high plates which intersect at right angles along the reactor centre-line and are in turn reinforced by vertical fins. It is fixed on a heat resistant concrete bedplate thus transmitting to the latter the weight of the bottom plate (Figure [9]) (8) the entire graphite stack (Figure [9]) (6) and the coolant feeder pipes.

5.5.3 Bottom plate

The bottom plate (structure OR) (Figure 9, Pos.8) is designed as a 14.5 m diameter and 2 m high cylinder consisting of a cylindrical shell, upper and lower lattices, radial and axial strengthening ribs. The ribs are welded both to lattices and the shell.

The inside cavity of the bottom plate is made leak-tight by welding the lattices to the shell...

The following components are welded into the bore holes located in the upper and lower lattices (Figure [10]):

- bottom guide tubes segments of the fuel channels (FC), CPS channels and reflector cooling channels;
- test bottom guide tubes;
- thermocouple sleeves;
- inlet and outlet helium feeder pipes and outlet pipes to remove gas mixture from the inner reactor cavity;
- drain pipes of the metal structure upper lattice, and inlet and outlet pipes for nitrogen in the metal structure.

The upper and lower lattices are made from 40 mm thick 10XH1M steel.

The inside cavities of the bottom plate are filled with serpentinite, a mineral containing bound crystalline water.

5.5.4 Reactor shell

The reactor shell (Structure KZh) (Figure [9]) (7) is designed as a welded cylinder comprised of 9.75 m high shells having an inner diameter of 14.5 m. The shells are made of 16 mm thick 10XH1M steel sheets and reinforced with annular fins. To compensate for axial thermal expansion, the shell is provided with expansion bends.

5.5.5 Top plate

The top plate (Structure E) (Figure [9]) (2) is both a top reactor biological shield and support metal structure for the fuel channels, suspensions of the startup and operating ionizing chambers, top removable cover and reactor top pipework.

The top plate is made in the form of a cylinder having a diameter of 17 m and a height of 3 m. The upper and lower lattices of the cylinder are made from 40 mm thick 10XH1M steel and seal-welded to the shell. The lattices connect to each other with axial reinforcing fins.

The inside cavity of the top plate is made leak-tight by welding the lattices to the shell and subsequent helium testing of the welds.

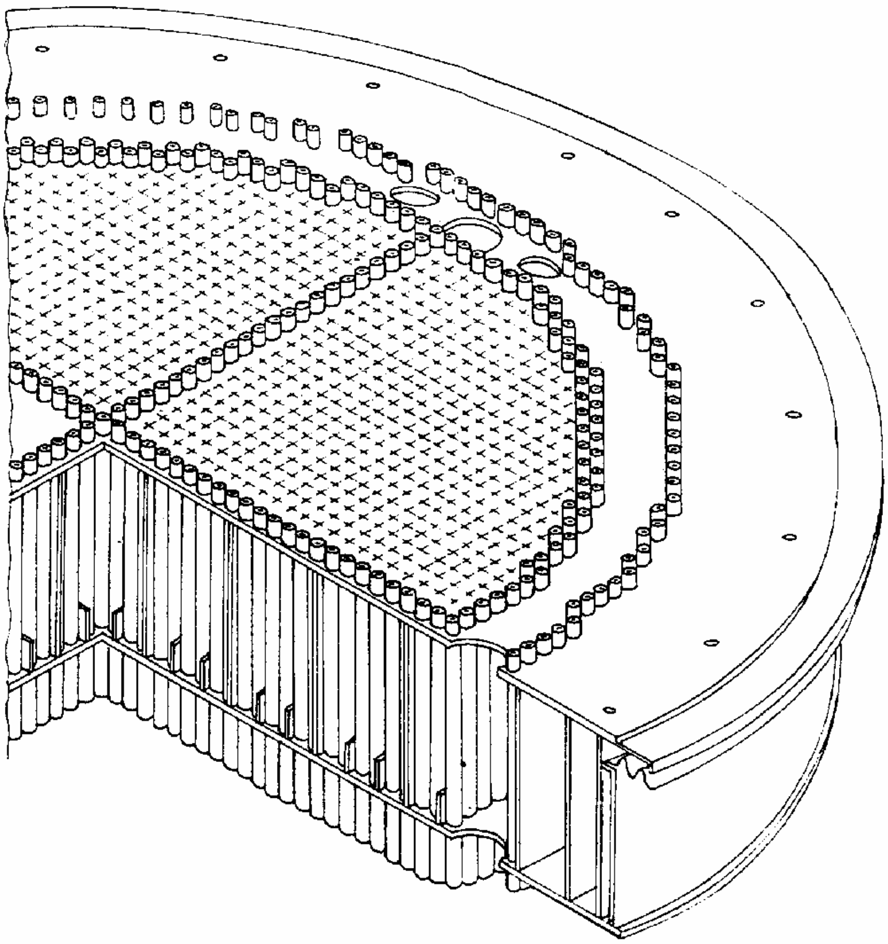


Figure 10: The bottom plate of the reactor vessel (Structure OR)

The following components are welded into the top plate:

- top guide tube segments of the fuel channels, CPS channels and reflector cooling channels;
- TV camera channels;
- test top guide tubes;
- working ionization chambers and start-up ionization chamber guide tubes;
- thermocouple sleeves;
- outlet pipes to remove steam-gas mixture from the inner reactor cavity;

- inlet and outlet helium feeder pipes.

The inner cavities of the top plates are filled with serpentinite the top plate rests on the 16 roller supports mounted on the projection of the annular biological shield tank (Figure [9]). The top plate takes the forces induced by the weight of the loaded channels, reactor hall removable top cover, top steam-water pipes and CPS water pipes.

The top and bottom plates are filled with a serpentinite mixture which contains by weight 90% of hydride magnesium silicates, the rest is taken up by oxides of ferrum, aluminum and calcium. Shielding efficiency of this mixture depends on the presence of the chemically bound water and stability of the mixture at the temperature of 450°C.

Crushed stones and pebbles with a size fraction of 20-40 mm are used to stuff the compartments in the top and bottom plates where the t test guide tubes are welded and the drain pipes are housed.

5.5.6 Annular metal structures

The annular metal structures consist of a small (Structure M) and big (Structure L) radial annular tanks. The tanks are made of hollow annular cylinders which are separated into 16 sealed compartments. These compartments are filled with water. The small tank rests on the metal structures of the big tank.

The tanks have an outer diameter of 19000 mm whilst the inner diameters are 17800 mm for small and 16600 mm for the big one respectively. The small tank is 3200 mm high. The height of the big tank is 11050 mm.

The top plate rests on the annular metal structures (Figure [9]), namely, the big tank consisting of an inside and outside shells are covered with horizontal end sheets. The distance between the shells is 1200 mm. Blank and perforated stiffening partitions positioned at a circular pitch angle of 7°30′ and at a ratio of 1 to 2 ensure structural strength of the tank. The blank ones partition the tank into 16 sealed compartments. The partitions are provided with man holes that have to be seal-closed during reactor operation.

16 roller supports are mounted on the top end sheet above the partition joints. These places are reinforced with stiffeners. The radial ionization chamber sleeves are welded into the tank top sheet.

The radial shield tank houses the following items:

- 16 water inlet pipes;
- 24 drain pipes for the radial ionization chamber shells;
- 16 thermocouple guide tubes.

The big and small tanks are communicating vessels. Cooling water comes in at the bottom of the big tank and out at the top of the small one. Drainage is available for the small tank both at the top and the bottom.

The space between the tanks is filled with sand (Figure [9], Pos.4).
Metal structures of both annular tanks are made of steel.

5.5.7 Graphite stack

The graphite stack of the reactor serves the function of neutrons moderator and reflector…
The graphite stack is a vertically-positioned cylinder made up of 2488 individual graphite columns and enclosed in the metal reactor shell. (Figure [11]10)

The graphite columns rest on steel support plates Ass.18 (Figure [11]) (3), which in turn, are supported by the bushings (Figure [11]) (2), mounted on the top lattice of the bottom plate (Structure OR) of the reactor vessel.

Steel shield plates Ass.07 (Figure [11]) (6) rest on upon the graphite columns. They serve both as top biological shield and thermal shield for the lower lattice of the reactor vessel top plate (Structure E). The graphite columns are constructed from separate graphite blocks.
The four rows of columns at the outer edge act as a radial reflector whilst the 0.5 m thick top and bottom graphite layers form serve as end reflectors.

The graphite blocks (Ass.05) are rectangular parallelepipeds with a base of 250 × 250 mm and height of 200, 300, 500 and 600 mm. (Figure [12]). The main are those of 600 mm height. The short ones are found only in the end reflectors and provide axial mutual slip of the blocks' joints of the adjacent columns.

Conical male-female joints provide centering of blocks in the columns (Figure [12]), while centering of the graphite columns with the guide tubes welded into the lower lattice of the top reactor metal structure is achieved with the help of shield plates and junction sleeves.

The blocks have 114 mm diameter bore openings designed to house the guide tubes for fuel and special channels in all 2052 columns... The openings in 436 radial reflector columns that do not have reflector cooling channels are filled with continuous graphite rods.

Radial shift of the graphite stack is restrained by 156 reinforcing bars. These bars are placed in 114 mm diameter holes in the peripheral columns of the radial reflector.

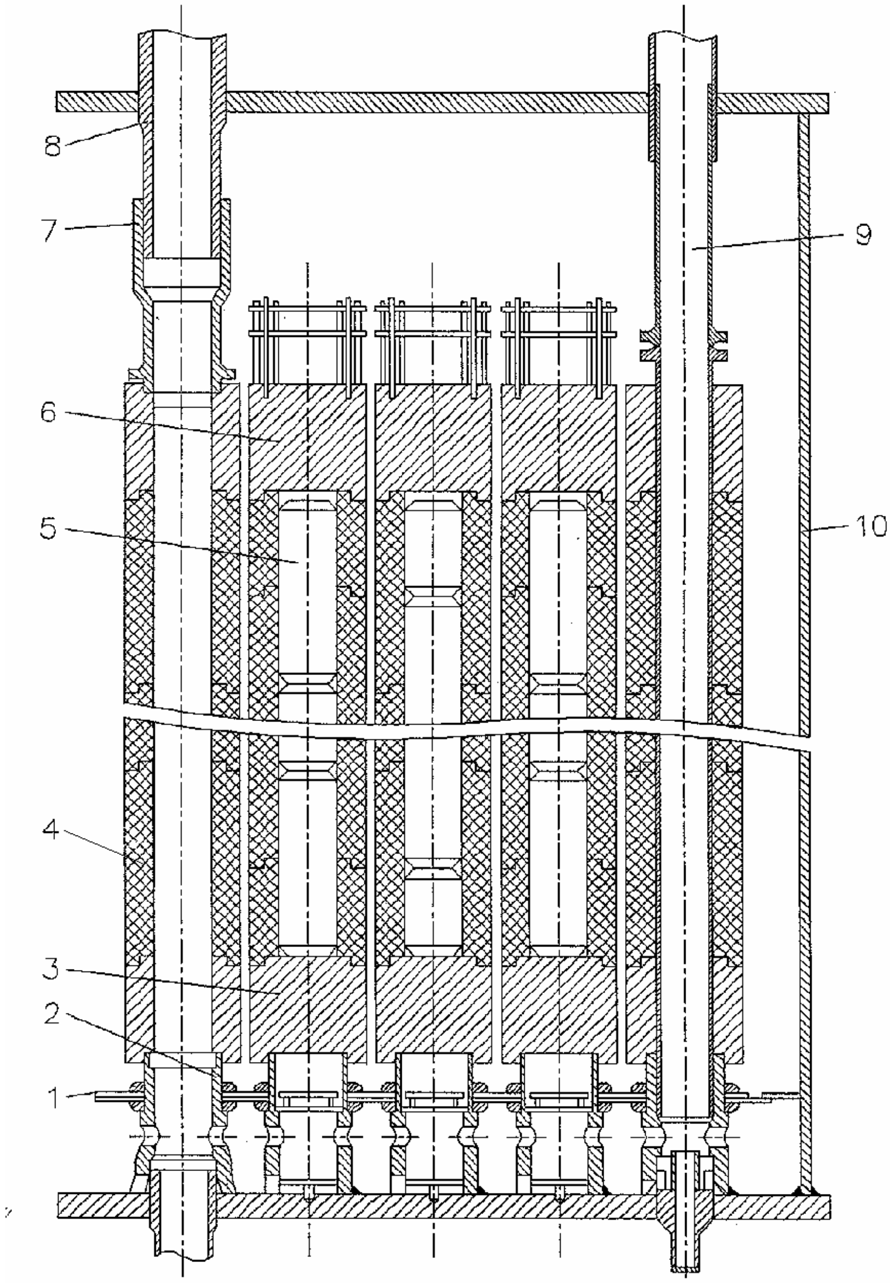


Figure 11: Segment of the graphite stack schematic (column for fuel and special channels, three reflector columns and one reflector cooling channel)

1-diaphragm; 2-support bushing; 3-bottom shield steel block; 4-graphite block; 5-graphite rod; 6-top shield steel block; 7-FC top guide tube; 8-channel guide tube; 9-reflector cooling channel; 10-reactor shell

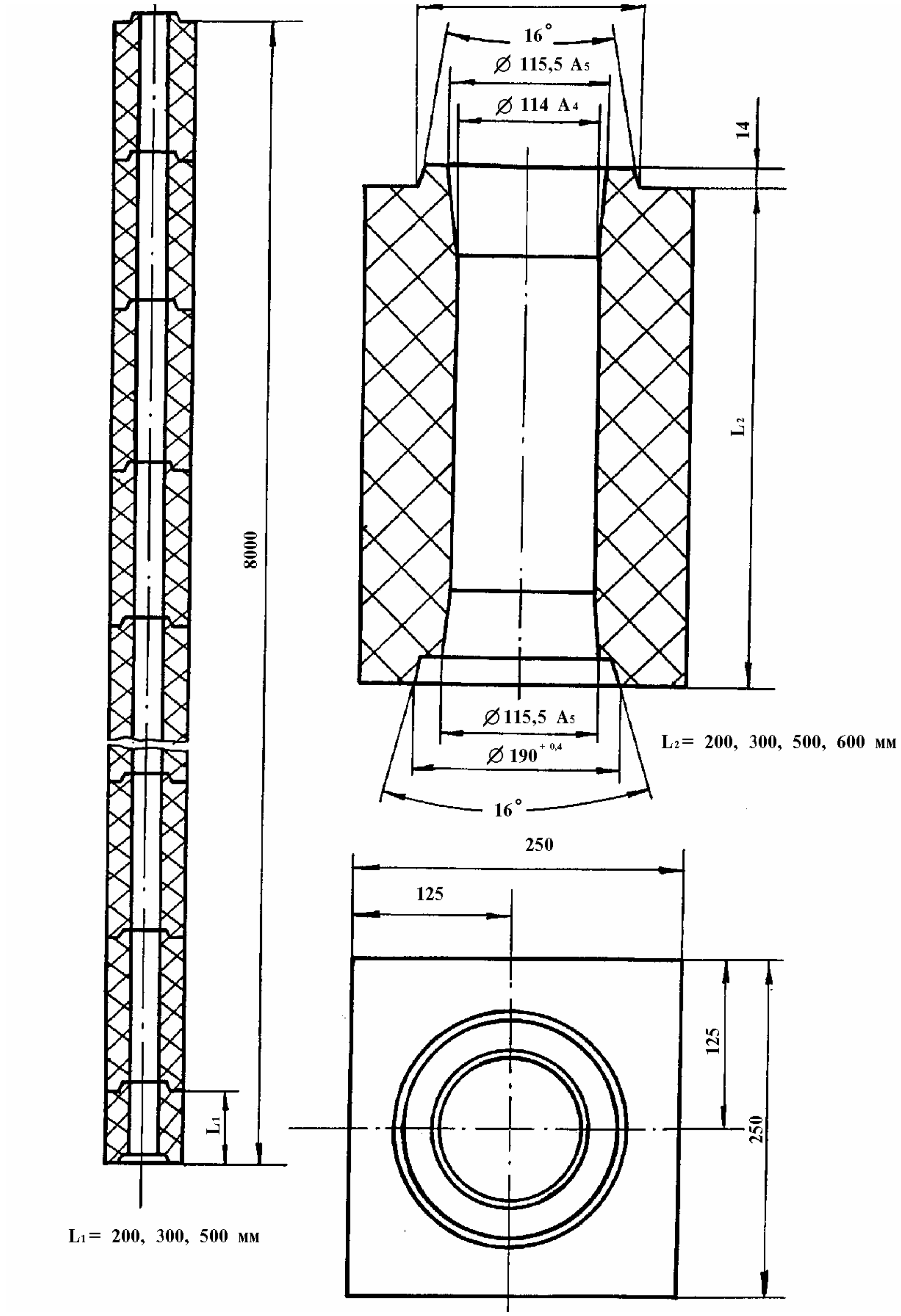


Figure 12: Graphite stack components

Seventeen 45 mm diameter vertical bore openings house temperature channels. The temperature channels are located at the joints of the graphite columns in the stack 13 of these channels are located inside the core and 4 in the radial reflector.

The main parameters of graphite stack are summarized in Table 2.

Table 2 The main parameters of graphite stack

Number of graphite columns	2488
Number of layers in a stack	14
Primary graphite blocks overall dimensions (mm)	250 × 250 × 600
Secondary graphite blocks overall dimensions (mm)	250 × 250 × 500 250 × 250 × 300 250 × 250 × 200
Diameter of the opening in the graphite block (mm)	114 + 0,23
Number of cells to house technological and special channels	2052
Number of radial reflector cells housing continuous graphite rods	436
Number of cells to house reinforcing bars in the radial reflector	156
Number of temperature channels	17 (of which 13 in the AZ and 4 in radial reflector)
Diameter of the temperature channel aperture (mm)	45

5.6 Graphite waste[6]

The INPP graphite waste consists of shattered graphite sleeves originating from spent fuel channels and CPS channels, of graphite bricks and sleeves resulting from the decommissioning.

Following estimated quantities of graphite waste are to be dealt with are presented in Table [3]

Table 3 : Amount of graphite waste

Graphite	tons	m³
Operational waste	55	46
Decommissioning waste: graphite bricks and sleeves for 2 units	3788	2945
Total	**3843**	**2991**

On the basis of container internal dimensions of 2.8 m x 1.45 m and a height of 1.01 m, it is assumed that an average of 2.625 m³ of graphite bricks could be placed inside one container (estimation basis: bricks of 0.25 m x 0.25 m x 0.6 m only are considered, 50 being placed vertically on the bottom of the container and 20 being placed horizontally on top of the first layer). About 1140 containers would be required to pack the graphite waste. The external volume of these containers to be interim stored on the INPP site would represent some 7054 m³.

The corresponding costs are estimated in Table 4:

Table 4: Graphite waste management costs

Costs	**MEUR**
Containers	1.54
Interim Storage	3.53
Total	**5.07**

6 Graphite characteristics

6.1 Origin of virgin graphite and manufacturer of graphite components

Graphite bricks (grade GR-208) of the stack and graphite sleeves (grade GRP-280) for RBMK-1500 reactor have been produced by Russian manufacturer Chelyabinsk Electrode Plant from petroleum coke.

6.2 Chemical and physical properties of graphite

Graphite articles (blocks and rods) meet the following requirements:

- Graphite ultimate resistance at 20 ± 10 °C, no less than, MPa:
  to compression - 30;
  to strain - 5;
  to bending - 6.
- Average graphite density (g/cm^3) – 1.695.
- Physical assessment index, millibarns, not more than:
  blocks - 3.68;
  rods - 3.77.
- Specific electrical resistance, not more than, Om • mm^2/m - 14
- Ash content, not more than, % – 0.04

The results of impurity analyses of the RBMK-1500 graphite sleeve specimen by gamma spectroscopy based on activation by neutrons and by glow discharge mass spectroscopy (data underlined), including some data from literature, are represented in Table 5.

6.3 Radioactivity of irradiated graphite

Activity of irradiated graphite in the RBMK-1500 reactor as a function of cooling time is shown on the Figure 13.

6.4 Radionuclide inventory in irradiated graphite

Assessment of contamination levels of critical nuclides (H-3, C-14, Ni-59 , Ni-63) at reactors final shutdown (RFS) times as well as total inventory of both Units are presented in Tables 6.

Table 5: The results of impurity analyses of the RBMK graphite specimen[10]

Impurity	Concentration, ppm	Impurity	Concentration, Ppm	Impurity	Concentration, ppm
Li	0.004 – 0.05	Ni	0.39	La	0.15
Be	0.02	Cu	0.1	Ce	0.269
B	0.05	Zn	0.02	Pr	0.08
N	0.5 – 70	Ga	0.01	Nd	0.11
O	40 - 197.5	Ge	9.0	Sm	0.0213
Na	4.64; 5.0	As	0.011	Eu	0.0026
Mg	7.0; 0.5	Se	0.003	Tb	0.0027
Al	9.2; 1.0	Br	0.025	Dy	0.0032
Si	1.0	Rb	0.008	Ho	0.0094
P	0.5	Sr	0.96	Er	0.0053
S	5 – 52	Zr	1.0	Tm	0.0056
Cl	7.6	Mo	0.17	Yb	0.014
Ar	0.14	Ru	0.07	Lu	0.0015
K	1.9; 1.5	Ag	0.003	Hf	0.0058
Ca	51.9; 2.0	Cd	0.015	Ta	0.0019
Sc	0.05	In	0.003	W	0.047
Ti	17.4	Sn	0.15	Re	0.0019
V	17.4	Sb	0.004	Au	0.00022
Cr	0.6; 0.3	Te	0.014	Hg	0.00062
Mn	0.58; 0.2	I	0.04	Th	0.0079
Fe	18.7; 1.0	Cs	0.0016	U	0.016
Co	0.019	Ba	2.01		

6.5 Irradiation history

Irradiation history of the graphite from the Unit 1 can be recovered from the annual thermal power histogram shown on the Figure 14.

Graphite irradiation temperature: 500 – 690°C.

Table 6: Contamination levels (critical nuclides only) at RFS[6]:

Nuclide	Specific Activity (Bq/m^3)	Total inventory (2 units)
H-3	6.8×10^{13}	2.0×10^{17}
C-14	8.1×10^{10}	2.4×10^{14}
Ni-59	3.1×10^{7}	9.1×10^{10}
Ni-63	5.8×10^{9}	1.7×10^{13}

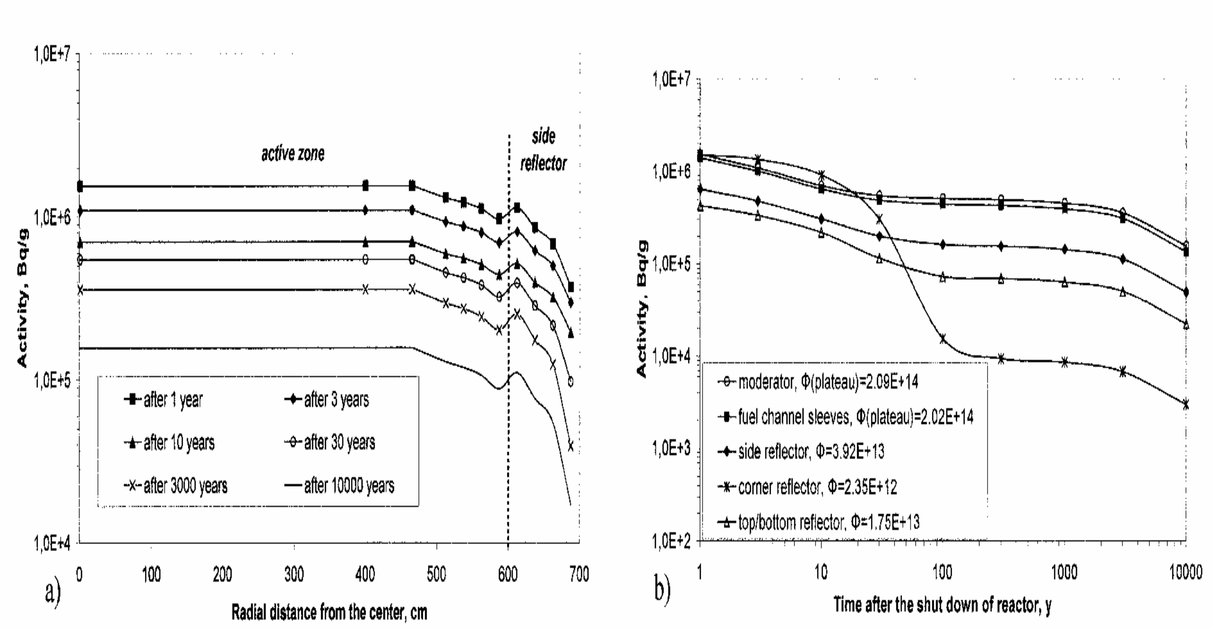


Figure 13: Activity in the RBMK-1500 reactor as a function of cooling time: a) radial distribution of activity in moderator; b) the activity in all graphite construction, the flux Φ is in n/(cm^2 s)

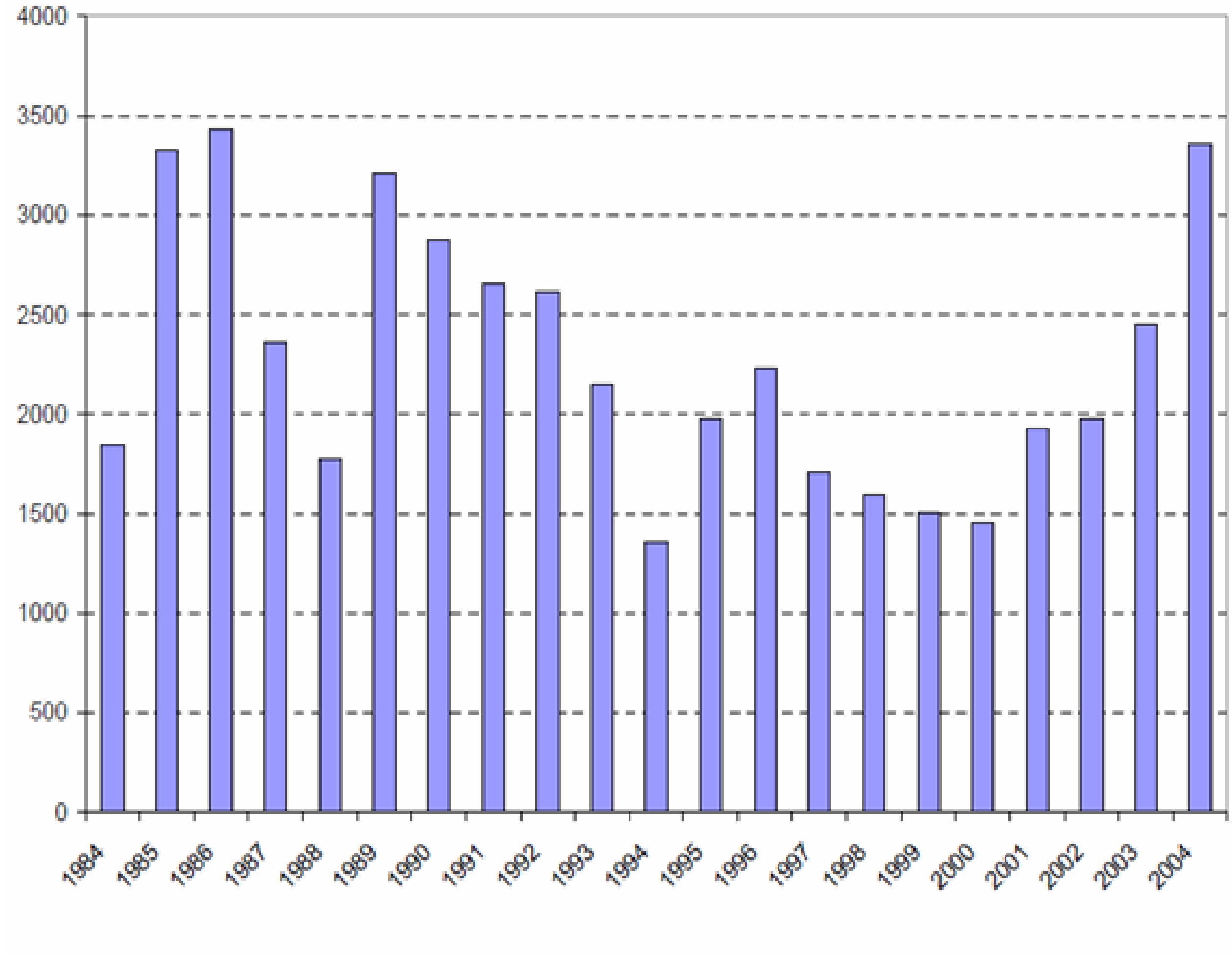


Figure 14b: Graphite stack components (on the ordinate axis thermal power of the reactor in MW is shown)[11]

In Table 7 Co-60 activity and contact dose rate evolution after the reactor final shutdown is provided.

Table 7: Co-60 activity and contact dose rate evolution after the RFS[6]:

	Time after RFS (years)				
	0	**5**	**10**	**20**	**50**
Co-60 (Bq/g)	8.1×10^{4}	4.2×10^{4}	2.2×10^{4}	5.8×10^{3}	1.1×10^{2}
Dose Rate, 10 cm (mSv/h)	2.4×10^{1}	1.4×10^{1}	7.5×10^{0}	2.1×10^{0}	3.9×10^{-2}

Calculated axial distribution of the activity in the RBMK-1500 reactor after 1, 30, 300 and 3000 years after the shut down of the reactor is shown in Figure 15.

The specific activities of radionuc;ides, which exceed their clearance levels in the given graphite structure as well as other radionuclides, which may be important from radiological point of view in moderator and in the corner reflector are shown in figure 16.

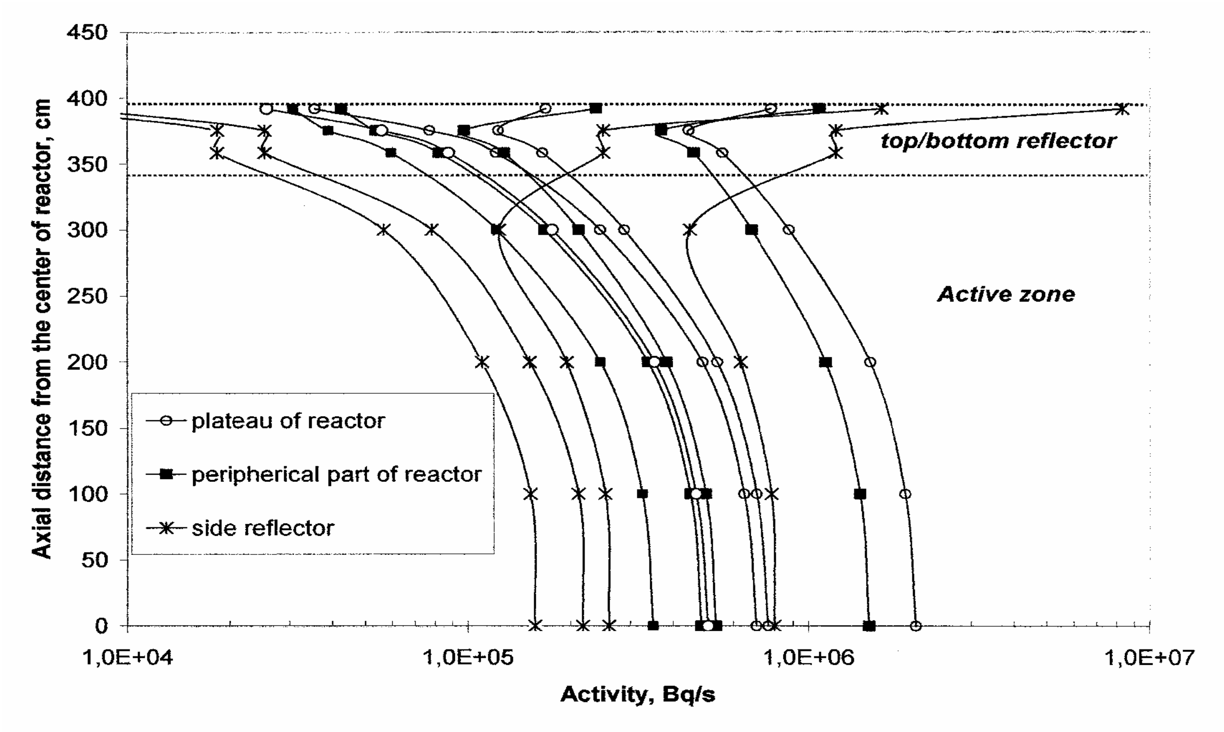


Figure 15: Axial distribution of the activity in the RBMK-1500 reactor after 1, 30, 300 and 3000 years (from left to the right) after the shut down of the reactor[10].

In the right part of the figure the clearance levels[12] for individual radionuclides are presented. Although C-14 and tritium constitute major activity in all the irradiated graphite constructions, respectively $7.03 \cdot 10^{14}$ Bq and $3.83 \cdot 10^{14}$ Bq, and are crucial to the long-term waste management, the role of other radionuclides such as Fe-55 and Co-60, etc. have to be duly evaluated, especially for dismantling and on-site waste management purposes. The presence of transuranium elements in the quantities shown in the figure may not cause particular risk to waste handling. However, their average activity in the moderator is about 230 Bq/g, which is rather close to the 370 Bq/g limit recommended by IAEA for acceptance of waste packages and is likely to be exceeded because of eventual uncertainties due to the initial impurity of U and irradiation parameters.[10]

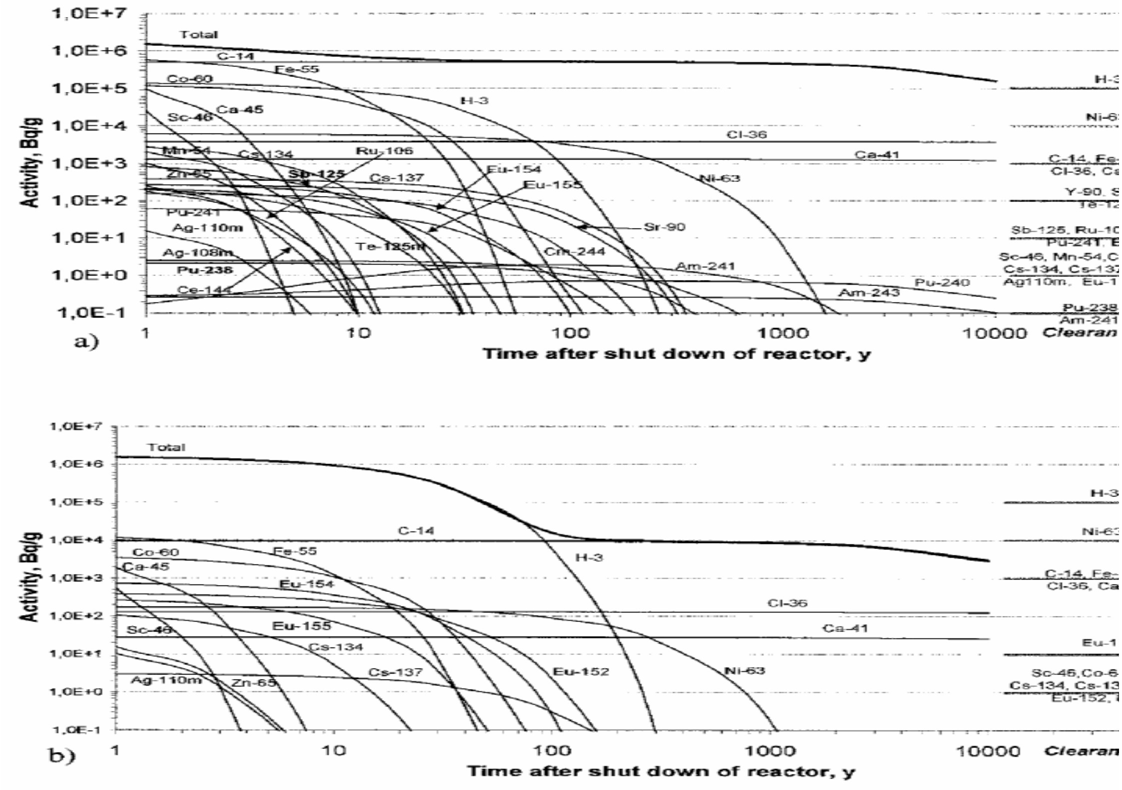


Figure 16: Specific activities of radionuclides as a function of cooling time: a) in moderator and b) in the corner reflector as a function of time[10]

The degree of uncertainty of calculated total activity as a function of cooling time due to uncertainty of concentration of impurities of key-elements in moderator can be assessed from Figure 17.

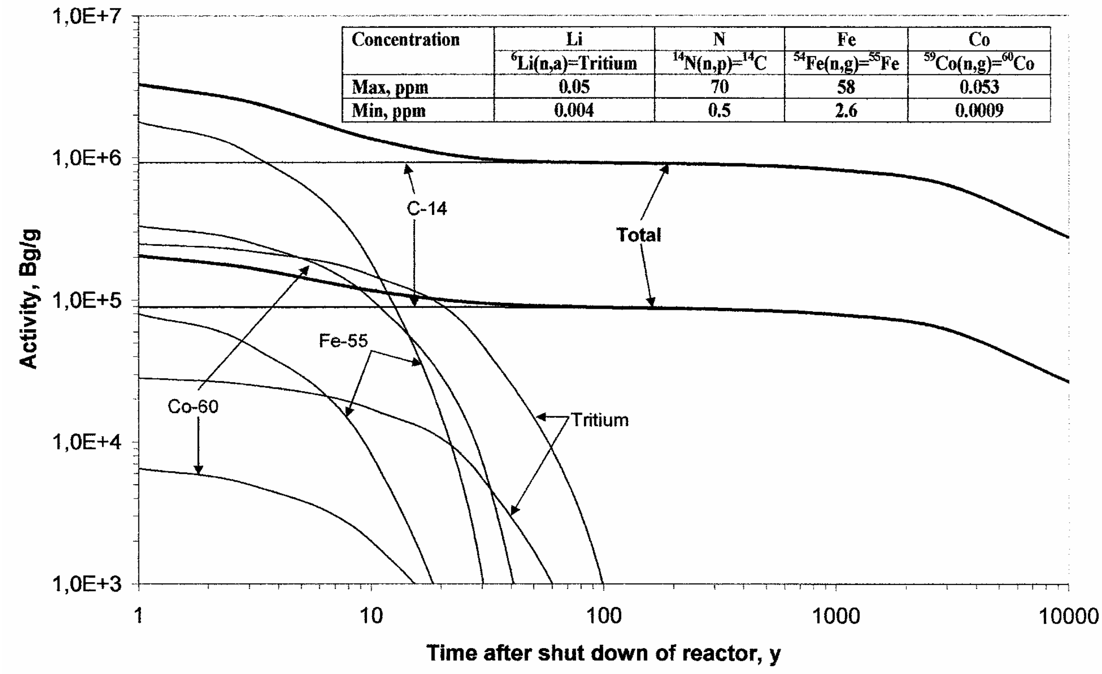


Figure 17: Calculated total activity in moderator in the case of maximal and minimal concentration of impurities of key elements as a function of cooling time[10]

7 References

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