DESIGN SCHEMES OF BLANKET FOR ACTINOIDS TRANSMUTATION

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1. Introduction

The actinoids such as alfa, beta, neutron source with billion year half - life determine the danger of radio - active wastes (RAW) for hundreds of thousands years. The nuclear transmutation processes (fission and other reaction) may be used for decreasing of danger, masses and radio activity of actinoids. The uranium and plutonium isotopes bred in irradiated fuel should be used as fissile material into fast breeder reactors, as well as Np,Am,Cm,Cf, if the problems of manufacturing of high-active fuel assembles will be solved. Otherwise at insufficient fast reactor share the additional specialized installations for actinoid transmutation maY be In need of - the fast and thermal fission reactors with spectrum shift , blankets of charged particle accelerator or fusion plasma driven machines.

The concept is considered with lead target of proton linac surrounded by subcritical blanket for transmutation of Np,Am,Cm and other nuclei.

Cca 60-75% of Np,Am,Cm mass for PWR, VVER-1000 irradiated fuel is Np-237 (cooling time 1.5-3 yrs). So in this work we paid main attention to this isotope. The rather high thermal neutron flux level is due to its transfer /1,7/.

The actinoid salts dissolved in heavy water are considered

/1,5,7/. Neutron source is molten lead target of 1GeV - 0,3A proton linac with vertical top beam input. Neutron generation rate equals $6*6*10^{19}$ 1/s.

The machine consists of:

1) proton linac;
2) molten lead target;
3) double-loop system of target cooling (first loop with lead, second one - water).
4) blanket with actinoids (possible - some FP like Tc,I,Cs,Sr) salt in the heavy water solution.
5) two (three) loop blanket cooling system:
first loop - salt in the heavy water solution,
the second one (when necessary) - heavy water,
the third one - light water.
6) the reloading and purification system (gas release etc).

On this stage we considered only blanket problems (without target) - homogeneous and heterogeneous design schemes, neutronics and thermal analysis, integral parameters.

This report is the first preliminary view on the concept.

2. Physical and Engineering Requirements to blanket

The preliminary studies for ideal blanket models showed that high neutron flux level - above $5*10^{15}$ $1/cm^2*s$ - is preferable for Np transmutation. The probability of it's fission (in actinoid mixture) becomes higher, the breeding of heavy isotopes - lesser. There is for essential fission rate (above 50%) short-lived nucl ide ^{238}Np ($T_{1/2}$ = Z.Id). The Np content in D_2O 4-20 g/liter is preferable, as well as D_2O then H_2O . Maximum power density (with flux level $5*10^{15}$ $1/cm^2*s$) may be above 100 W/cc . So one of the main problem for designing is to make the blanket cooling scheme.

From economical point of view, there is better to have one blanket unit (less mass of D_2O, structural materials), low extra pressure level. But these and other requirements are rather contradictional and sometimes incompatible in one unit.

3. Choice of Blanket Scheme

Homogeneous versions with low positive pressure.

The positive pressure level for all schemes isn't higher than 0.5 MPa. The cooling is performed by earring out of actinoids salt solution to external loop /2/.

For natural convection and heat conduction using preference the variant (Fig.4) was studied with closed lead target and skull on inboard its surface. The target and blanket are united to one unit .

The inherent essential lack of this simplest scheme is limited target power - 3.5 MW instead of 300 MW required.

Some improvement for molten lead temperature may be achieved by adding to preceding variant the forced lead circulation (Fig. 5). There is the lead layer on inner surface of titanium shell cooled by heat removing by heavy water solution on the external surface. The central part of target has the circulating molten lead. Integral heat removal is the same, so power level - 3.5 MW. Desire to improve the burn-up rate as well as to ensure the replacement of details resulted in scheme (Fig.6)with separate bodies of target (2) and heavy water tank (3). Proton beam has the casing joint in a vertical plane (l).

The lead jets allow to spread the proton - lead interadion zone.

There is helium gas between heavy-water tank and target vessel to ensure the necessary target-heavy-water gradient of temperature. The heat-exchangers, pipelines, operational equipment, pumps are placed to pressure-tight space within concrete mass of shield.

Replacement operations are possible but it Is necessary using the special and remove fixtures. The upper target power level may be cca 135 MW.

The variant of Fig.7. - the units are placed within air-tight stainless steel chambers (12) of concrete shield (13). The salt tank (2) - (~3600 dia) is placed at the center of chamber. The central channel (1000 mm dia, 5000 mm height) forms the porous lead target (1) by lead jets of header (5). Target vessel may be replaced if necessary for fluence or emergency reasons. Tank (2) by moving installation (9) maY be replaced to room (10) for the operations of disconnection and connection of piping to circular and thermal systems by manipulators and remote joints.

Hot lead jets (1) are collected in capacity tank (2) and pumped (11) through heat-exchanger (6) back to collector (5).

Pressurized Blanket

Both homogeneous and heterogeneous (channel-type) concepts are considered. In homogeneous systems the TA and FP solutions are used in two separate volumes. In heterogeneous systems the heavy water, separated from salts, is placed to special ampules.

The homogeneous blanket scheme is shown on Fig.8.

The high-pressure tank (2.0-5.0MPa) with central part for target has two concentric parts (inboard and outboard), separated hermetically.- Fig.9, .10.

Outboard section is filled by heavy water with salt solution of TA and (or) FP. Inboard section is filled by heavy water with Np salt solution and its irradiation products. Each section has it's own tight cover and inlet and outlet pipes of first loop. The same pipes in the bottom. Power density of inner section is up to 200 W/cc. The concentric deflectors (2-4 mm thick) are used (SS,Al,Zr alloys) for distribution of salt flows . It is necessary to have the pumping rate 3-5 m/s for inboard section salt. The power density of outboard salt is 10-100 times lower, transmutation rate lower too. The wall between sections (Zr or SS) is intended for salt flow separation and doesn't carry pressure - up to 4 mm thickness.

Dimensions:

central target channel (dia) - 1.0 m,

- inboard section (in.dia) - 2.4 m,

outboard section (ext.dia) - 4.4-m,

- height - 5.5-6 m.

Problems:

to support high pressure of mixture in large-volume sections;

to manufacture the thick (25-30 mm) Zr-alloy sheets;

to manufacture the steel-zirconium reducer for high pressure and large dimensions.

Heterogeneous blanket

The principal schemes are shown on Fig.10 and 11, vertical and horizontal views - on Fig.12.

The main units:

- tank with central hollow for target and with ~ 60 channels;
  ampules inserted into channels;
- 24 outboard sections with FP salt solution heavy water

Dimensions:

central hollow (dia) - 1.0 m

external section dia - 2.2 m

external ampule dia - 3.0 m

- tank height - 5.5-6 m.
- moderator - heavy water.

Pressure - 0.1-0.3 MPa (sections), 20 MPa (ampule).

Channel wall temperature - 300-350 ^{o}C.

Channel must be cooled or thermo-insulated.

Ampule consists of channel for circulating of mixture (Circuit 1) and jacket (Circuit 2) with either heavy water or inert gas as isolator.

Heterogeneous blanket features:

- possibilities to have different mixtures and pressure in ampules;
- ampules can be removed without removing of heavy water out of tank;
- steel-zirconium reducer up to 150 mm dia are manufactured;
- heavy water without pressure.

Materials

Stainless steels (12x18H10T type) and zirconium alloys (like 110,125 with 1% and 2.5% Nb) may be recommended.

They have appropriate mechanical and welding features, high radiation resistance in fluence up to 10^{23}-10^{24} $1/cm^2$ and corrosion resistance.

4. Thermo-Hydraulic Blanket Parameters.

Three - circuit scheme of blanket cooling was considered. The first loop - actinoid salt and FP solution in heavy water - has power density like in fuel element of power reactor, the second (intermediate) one - with heavy water, the third one - for heat utilization - with light water.

The problem is using of large quantity of low - parameter heat without boiling and evaporation of solution. With (90-120)^{o}C, 0.6 MPA of the 3rd circuit water it is possible use of heat for being heat - supply: with (180-240)^{0}C, (1.5-3 .0)MPa - for industrial heat, electricity production .

So two sets of boundary conditions (2nd Circuit) were used - (70-140)^{0}C -regime I, (220-250)^{0}C - regime 2. Maximum salt rate up to 4 m/s, temperature reserve up to boiling - 15^{0}C. The solution thermal features were taken as heavy water ones.

The conventional NPP heat exchange equipment were used (casing - tube type with counter current flow scheme).

Channel-type blanket.

Ampule type blanket has it's own independent circulate circuit including ampule, heat - exchanger, pump and piping. Two main parameters were taken into account -

absolute pressure value (15 MPa maximum);

– 2nd loop heavy - water temperature.

The set of parameters for regimes 1,2 is shown on Table 4.1.

It is possible for the 3d loop to realize steam - turbine cycle for electricity production with efficiency ~ 25%. The industrial pumps (4K-18 centrifugal one stage type for instance with inlet tube 100 mm dia) may be used.

The blanket has the separate loop for heavy water cooling.

Homogeneous blanket

Blanket (scheme on Fig.8.) consists of tank divided on two parts (zones) -

zone of high radiative intensivity with high TA salt density (1000 MWt);

-zone of TA and FP (300 MWt).

The heat removing is possible only with extreme pressure. It is strong technical problem for it's realizing for large - dimensional system (inner dia "4.5 m). If pressure limit is 5.0 MPa the Regime 2 would be impossible for 2nd Loop.

So only Regime I was considered. Because of high level of power density and it's essential space uniformity it is necessary to divide blanket zone into some axial subzones.

The increase of wall temperature Δt_{ad} because of interior salt heat sourse, was a function of salt flow (laminar or turbulent regime), gap dimension and power density level. So it is necessary to have 11 subzones for Zone I and 5 subzones for Zone 2 ; $\Delta t_{ad} \sim 10°$ C.

Zirconium is appropriate material for both temperature level (~ 400^{o}C) and neutron balance. -

Contours: salt solution is get to lower part of tank to Zone 2, then pumped through 11 ring subzones upstairs to piping, after heat - exchange equipment - to pumps and to lower part of tank again.

There is the same contour of Zone 2 .

The Ist Loop parameters are listed in Table 4.2. (Zone I) and 4.3. (Zone 2). Pumps of PWR VVER-1000 may be used. All these estimates are preliminary ones. The optimization and detalization are necessary. For example, the coil-type heat exchanger may be more compact.

5. Neutron-physical parameters

The idealized models: cylinder tank of 5 m height and 4 m dia with Np-salt in the heavy water solution. Lead target (1m dia, 5 m height) is separated from blanket part by 5 mm stainless steel wall. It was supposed neutrons are generated within central zone 3m*1m (dia) uniformly. With Np content 4 g/1 power density is about 200 W/cc, integral blanket power - 3200 M'W(t).

The power limit for this type of blanket - 135 MW only. It means: decreasing of neutron flux ten times;

probability of Np fission - 0.3 (instead of 0.4);

multiplication factor K_{eff} - 0.65-7 g/1 (instead of 0.8 - 4g/l) ;

10 blankets instead of 1;

maximum power density about 20 W/cc.

Neutron flux near first wall (between target and blanket) is (0.5-1)10^{15} $cm^{-2}s^{-1}$ with fast neutron (E>0.1 Mev)- 15-20% . It is caused by inelastic scattering in lead and scattering in heavy water.

For removing of 100-200 W/cc it is necessary to increase the pressure up to 2.- 5. MPa. Target vessel and inner wall have 7-10 g/cm^2 of stainless steel, plus steel deflectors,plus equilibrium actinoid contents - K_{eff} decreased to 0.5- 0.6 as well as fission and transmutation rates are minimized too.

It is supposed to use zirconium alloy instead of steel, to increase actinoid's content up to 6 g/1, K_{eff} - to 0.65 and as the result - fission power - 1300 MW with maximum power density 200 W/CC .

Heterogeneous variant -

Blanket consists of two raws of 60 ampules with actinoid salt and heavy water between them. The sections with FP solution are placed on the blanket periphery. The 1st and 2nd row power density differs not more than 5%. 200 W/cc power density (K_{ef} - 0.32, blanket fission power - 324 MW) corresponds to 3 g/l of neptunium with actinoids. 40 ampules of the 3rd row will arise power to 540 MW (4.5 g/l, 200 W/cc). Fast neutron flux (E > 0.1 MeV) - (l. 0-1.5)10^{15} $1/cm^2*s$ - first wall ; (1-4) 10^{14} $1/cm^2s$ - ampule and deflector walls.

6. Heavy water radiolysis

The problems of water radiolysis is very important for water-cooled reactors. The main part of fission energy in form of strongly ionization is absorbed by water. The large output of molecular products results from water radiolysis. Recombination rates are negligible. Data for light water are used /6.1/.

For pH ~ 2 output of FP /6.2/:

$g(H)=0$ $g(OH)=0$ $g(H_2)=1.83-2.0$ mol/100eV

$g(H_2O_2)=0.91-1.0$ mol/100eV

For heavy water $g(-D_2O)=3.66-4.1$ mol/100eV. So we have two main problems:

1) The large amounts of hydrogen and oxygen are produced. Because of explosion hazard the recombination process must be realised, especially with heavy water.

2) inspite of high enough decomposition rate for hydrogen peroxide with high temperature, it is possible excessing of volubility product for uranium peroxide and fuel precipitation.

3) At the case of nitrate salt fission fragments can result to nitrate (NO_3^-) reduction into nitrogen (N_2).

The most spreading state for actinoids is of three valence. The actinoid nitrates have the highest level of volubility

$Am(NO_3)*xH_2O$,

$Np(NO_3)*xH_2O$,

$Cm(NO_3)*xH_2O$.

4-20 g/l heavy metals content is more than small. We haven't yet data for mention salts and heavy water. The known analog - $UO_2(NO_3)$ has volubility up to 283 g/l. The experiments are needed in future. The production rate maY be very high, for 200 W/cc:

- $9.3*10^{-4}$ l/cc*s (NTP) of hydrogen;

0.7 mg/cc*s of peroxide.

For blanket 135 -1300 MW correspond Up to 6050 l (H_2)/s (NTP).

There were attempts to use catalizators for recombination (oRNL), two-valence copper,for instance /6.3,6.4/.

$$- d(H2)/dt = K [Cu^{++}][H_2]$$

$$K = 9*10^{13} \exp(-24500/RT) \ l/mol\text{-}hour$$

The steady-state gas pressure as result of radiolysis:

$$p(H2) = \frac{40.3 \, G(H2) \, M}{K[Cu^{++}]\alpha(T)}$$

M,MW/l - absorbed power,

α – Genry constant /6.5/.

The estimation of copper amount were done for the HRE-2 reactor /6.6,6.7/, it's using - /6.8/.

To avoid the fuel precipitation it is necessary to have low enough level of peroxide concentration. For example, at 100^0C limit level of power density is 0.09 kW/l /6.1/. Taking into account FP and corrosion products as catalizators it is possible /6.10/ to estimate permissible power density.

For improvement of neutron balance the using of N-15 isotope may be considered. There is reduction processes like

$$2DNO_3 \rightarrow D_2O + N_2 + 5/2 \ O_2.$$

The oxygen besides explosive danger results in corrosion rate rise.

Titanium and aluminium alloys may be recommended as structural materials, as well as if would decrease pH to 2 and temperature to 200^0C - stainless steel and zirconium alloys.

Table 4.1.

Thermal and hydraulic parameters of ampule channel

Parameter	Regime I	Regime 2
Allowed power density for salt solution, W/cc	200.0	100.0
Loop thermal power, MW	5.4	2.75
Salt solution rate, kg/s	25.5	25.5
Salt temperature, °C:		
- ampule inlet	281	303
ampule outlet	319	322
- heat-exchanger input	323	324
- heat-exchanger output	277'	301
Pressure losses, MPa:		
ampule	0.0054	0 .0054
- heat exchanger	0.0733	0.0845
- loop (sum)	0.093	0.104
Pumping power (η-0.75), kW	3.1	3.5
Heat - exchanger:		
- inner diameter, mm	210.0	210.0
- length, m	5.4	6.4
outer tube dia, mm	20.0	20.0
wall thickness, mm	2.5	2.5
- tube number	36	36
2 loop: Heavy water rate, kg/s	26.7	25.9
Temperature, °C:		
- input	92	22
output	140	250

Table 4.2.

Thermal and hydraulic parameters of inner blanket zone (Zone 1)

Parameter	pressure, MPa			
	2.0	3.0	4*0	5.0
Thermal power,MW	1004.0	1004.0	1004.0	1004.0
Salt solution rate, t/s	15	15	15	15
Salt velocity,m/s	4.0	4.0	4.0	4.0
Salt temperature,°C				
- tank inlet	163	184	200	213
- tank outlet	I79	200	216	230
- heat-exchanger input	180	201	2I7	231
- heat-exchanger output	162	183	199	212
Pressure losses,MPa:				
- tank	0.003	0.003	0.003	0.003
- heat-exchanger	0.4	0.29	0.24	0.2I
- loop (sum)	0.41	0.3	0.25	0.22
Pumping power,kw	5000	5850	4850	4254
Heat-exchanger:				
-number	4	4	4	4
-inner diameter,mm	2550.0	2550.0	2550.0	2550.0
-length,m	36.4	26.3	2I.6	I8.8
-out tube diameter,m	20.0	20.0	20.0	20.0
-wall thickness,mm	2.5	2.5	2.5	2.5
-tube number	54I8	54I8	5418	5418
2 loop: Heavy water rate,kg/s	I723.0	17'23.0	1723.0	1723.0
Temperature,°C				
- input	I40.0	I40.0	I40.0	I40.0
output	82.I	87.I	89.5	90.8

Table 4.3.

Thermal and hydraulic parameters of outer blanket zone (Zone 2)

Parameter	Pressure, MPa			
	2.0	3.0	4.0	5.0
Thermal power,MW	297.0	297.0	297.0	297.0
Salt solution rate,kg/s	5428	5428	5428	5428
Salt velocity,m/s	0.4	0*4	0.4	0.4
Salt temperature,°C				
- tank inlet	147	168	183	197
- tank outlet	160	181	196	210
- heat-exchanger input	160	181	196	210
- heat-exchanger output	147	167	193	I97
Pressure losses,MPa :				
- tank	0.0001	0.0001	0.0001	0.0001
- heat-exchanger	0.0014	0.0007	0.0005	0 .0004
- loop (sum)	0.0014	0 .0007	0 . 0005	0.0004
Pumping power,kW	10.1	4*7	3.6	3.0
Heat-exchanger:				
-number	2.0	2.0	2.0	2.0
- inner diameter,mm	68I0.0	68I0.0	68I0.0	68I0.0
- length,m	8.4	3.46	2.38	I.88
outer tube diameter,mm	26.0	26.0	20.0	20.0
wall thickness,mm	2.5	2.5	2.5	2.5
- tube number	38646	38646	38646	38646
2 loop: Heavy water rate,kg/s	7307.0	7307.0	7303.0	7307 .0
Temperature,°C				
input	140.0	140.0	140.0	140.0
output	134.5	134.8	134.9	134.9

Parameters of Blanket variants

Parameter	Type		
	Low-pressure homegeneous	Pressurized	
		homogeneous	channel
Linac:			
proton energy, Gev	I	I	1
beam current, A	0,3	0,3	0,3
Blanket numbers	IO "	1	1
Blanket power, MW(t)	1350	1300	324-540
Transmutation rate, kg/y	532	511	I27-2I2
Blanket:			
Fission power, MW	135	1300	324-540
Transmutation rate,kg/y	53,2	511	127-212
Type	two sectioned tank	two sectioned tank	Channel-type
Dimensions,m:			
height	5	5,5-6	5,5-6
diameter	3,6	4,4	3
Loop number	2	3	3
1 loop: pressure,MPa	0,5	2,0-5,0	15
Heat-exchanger number		4	60-100
Heat-exchanger dimensions,m:			
length		36,2-I8,8	5,4
diameter		2,55	0,21
Heat using	Heat-Supply	Heat-supply	Steam-turbine cycle
Amount of heavy water(1 Loop),t	140	320	80-85
Actinoid mass (1 Loop),t	0,98	1,8	0,025-0,05

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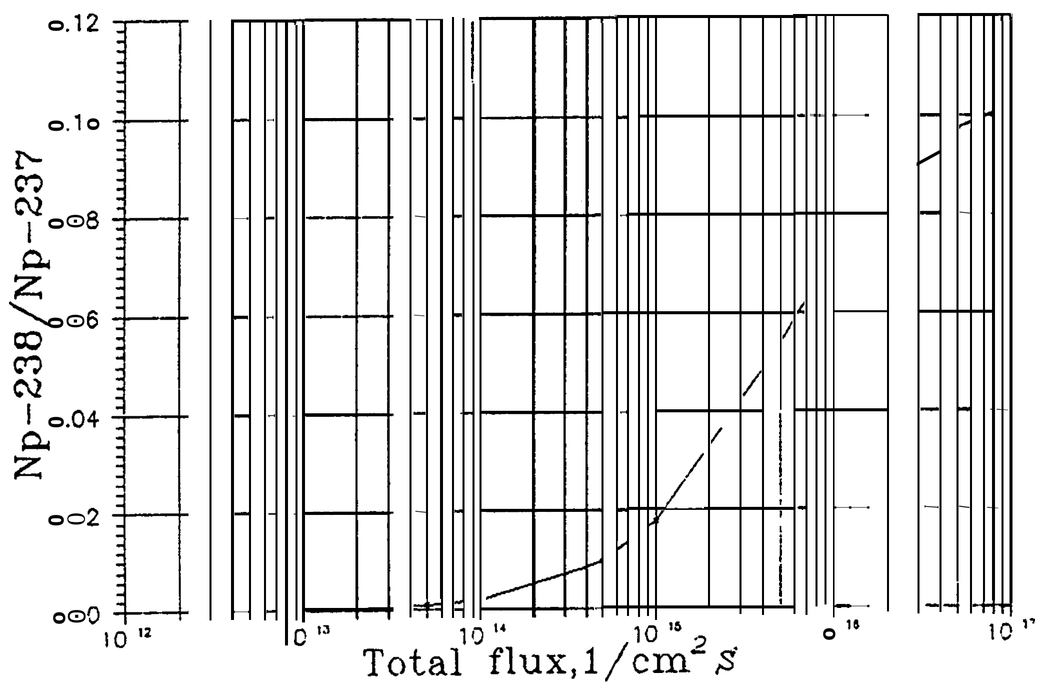


Fig.1. Np-237 content versus flux level

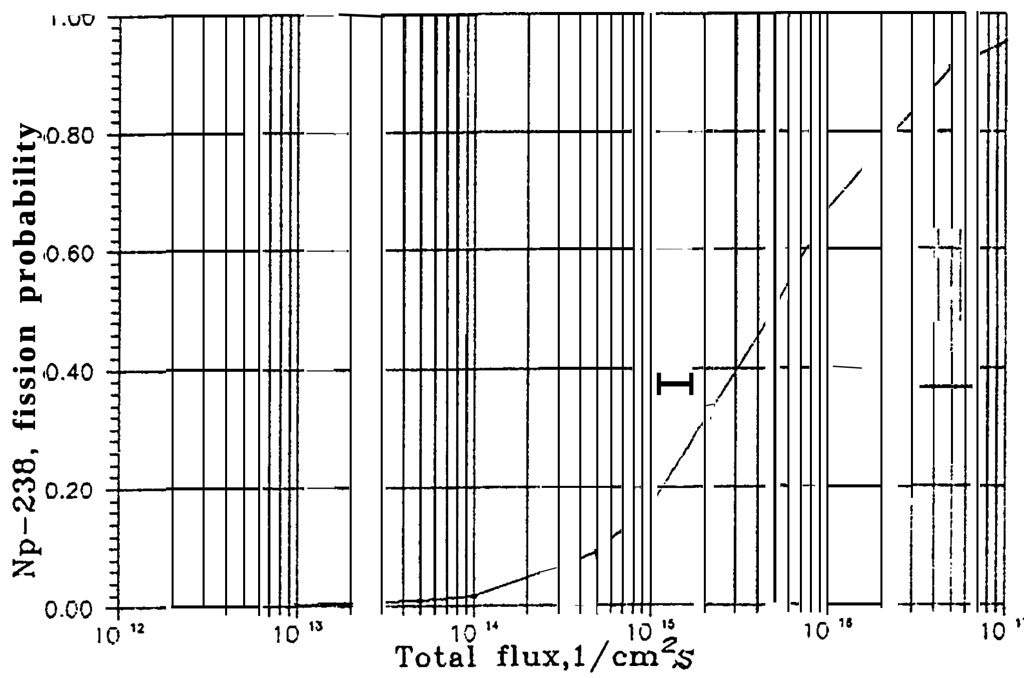


Fig.2. Np-237 fission probability versus flux level

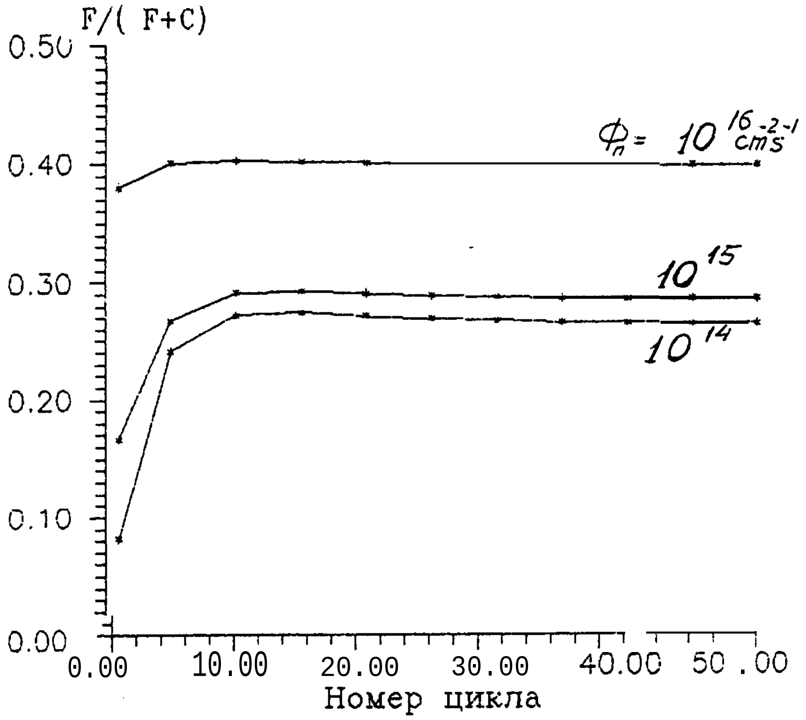


Fig. 3. Np-237 fission/absorption rate ratio for cycle regime

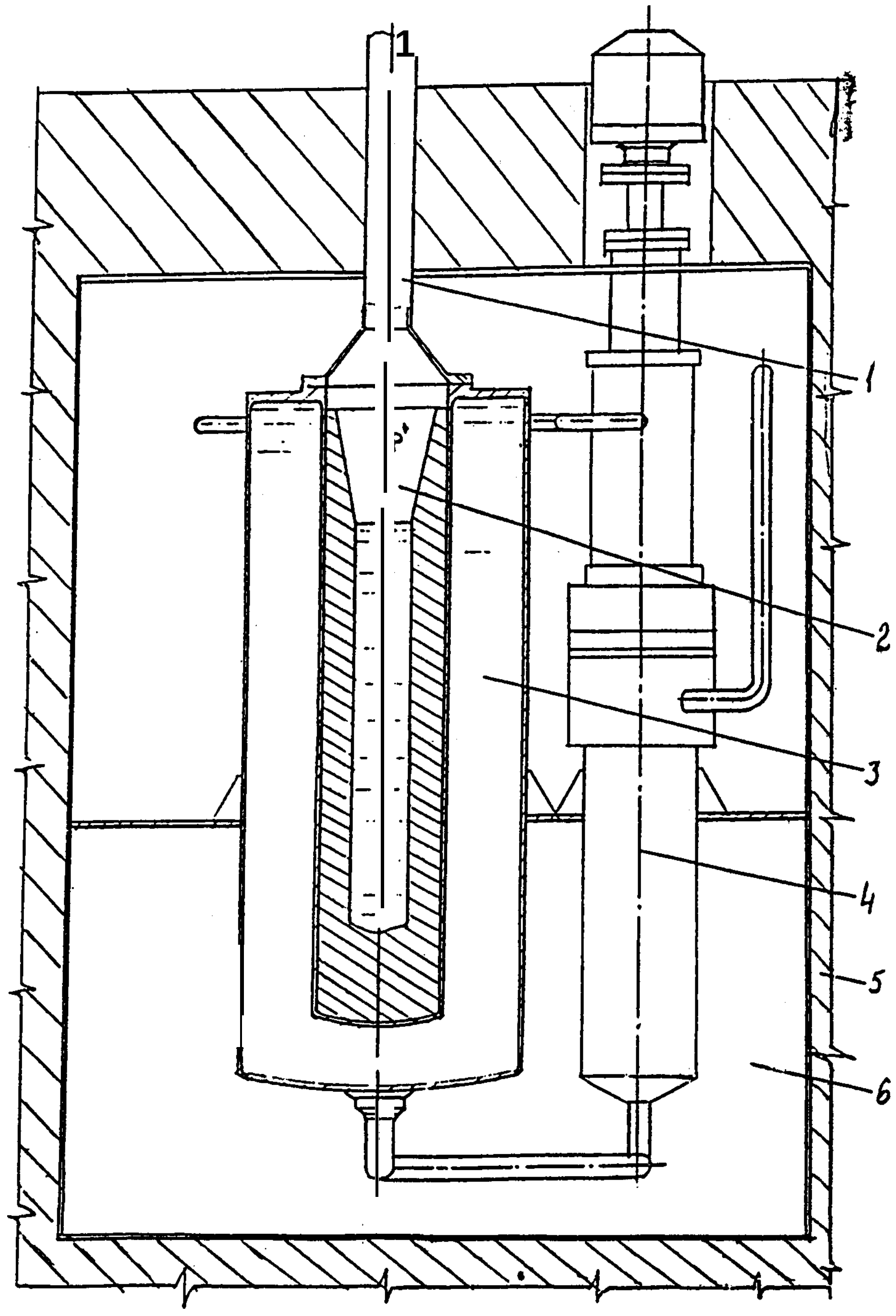


Fig.4. Homogeneous blanket scheme.

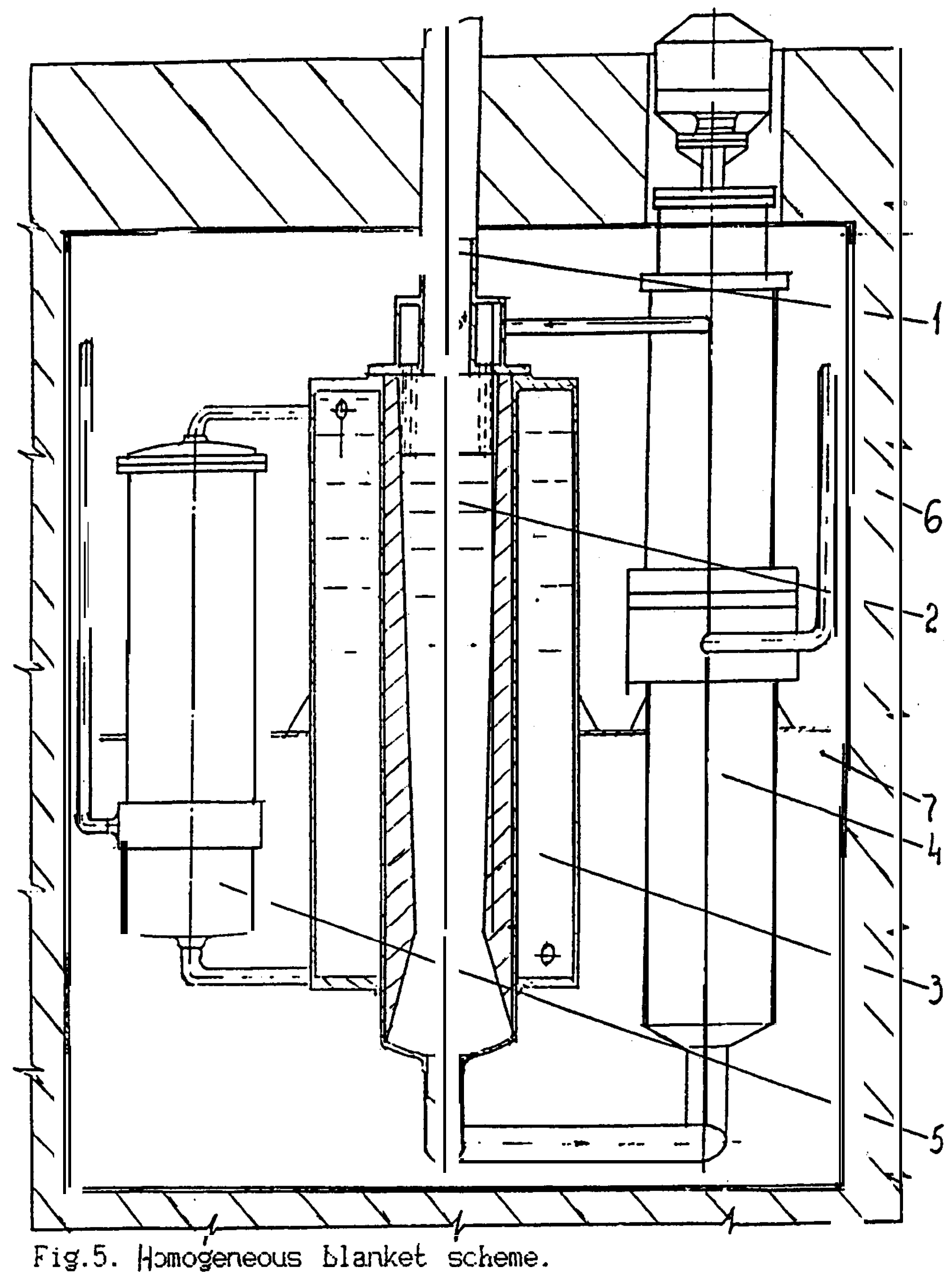


Fig.5. Homogeneous blanket scheme.

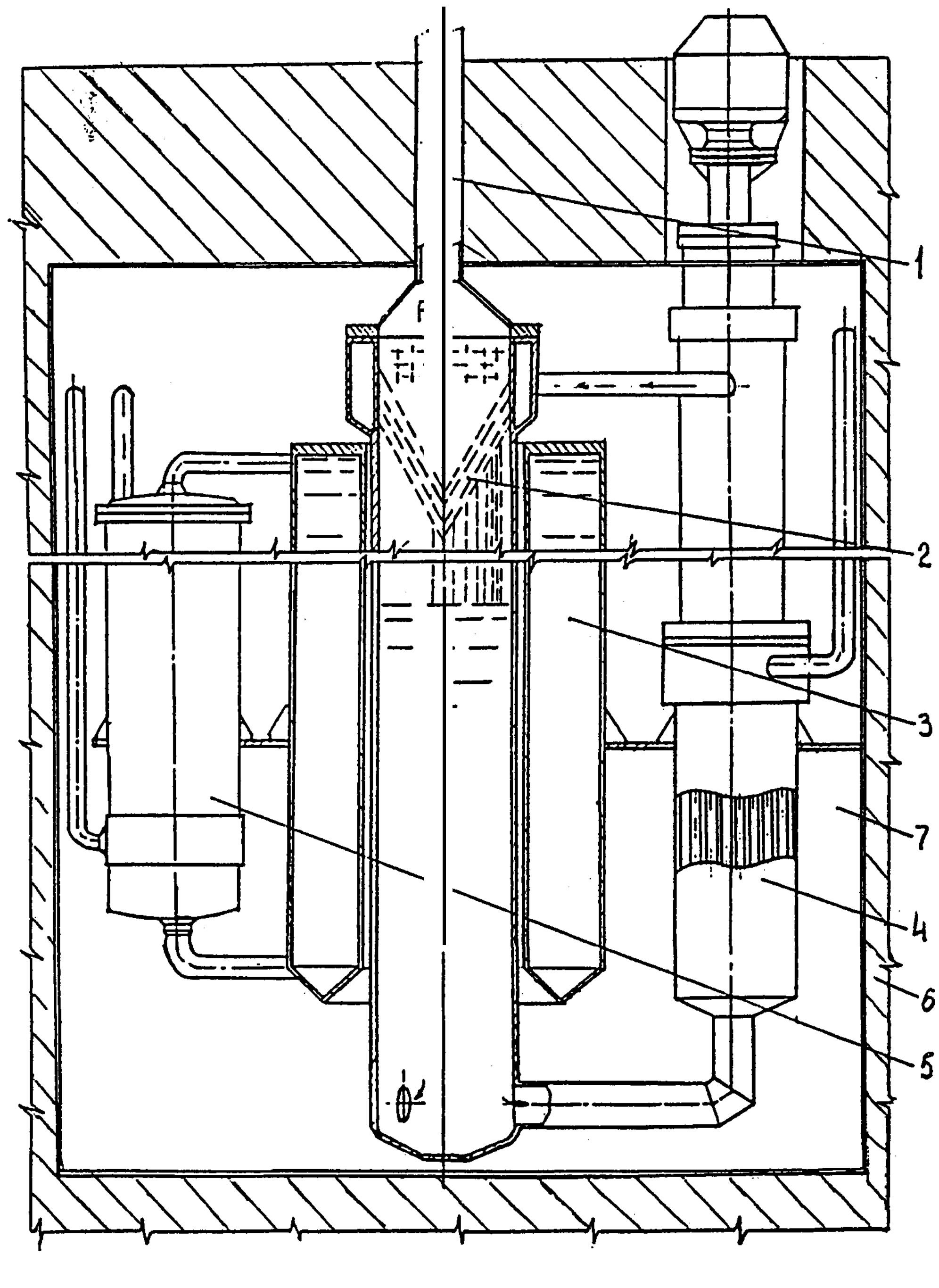


Fig.6. Homogeneous blanket scheme.

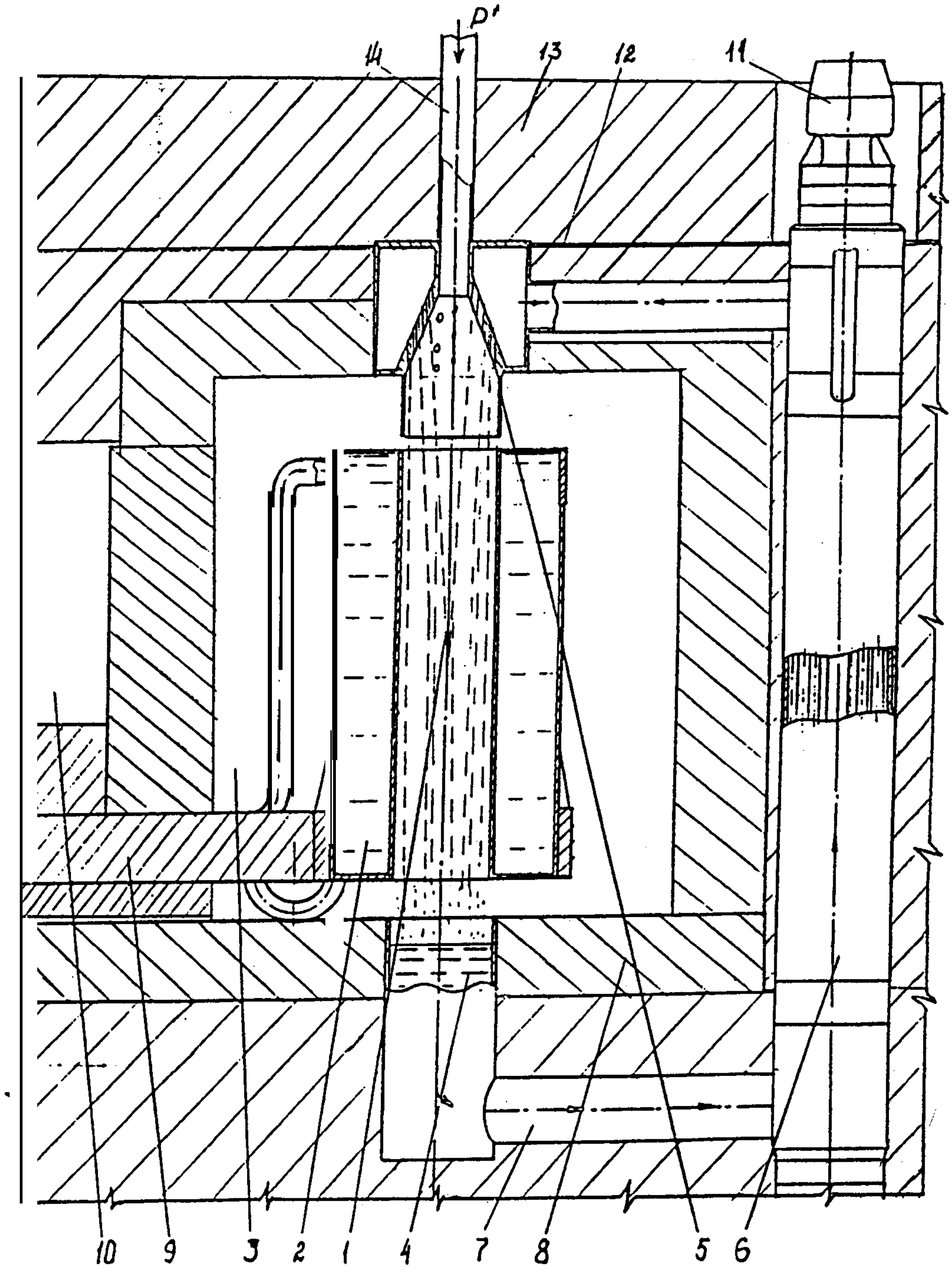


Fig.7 Homogeneous blanket scheme.

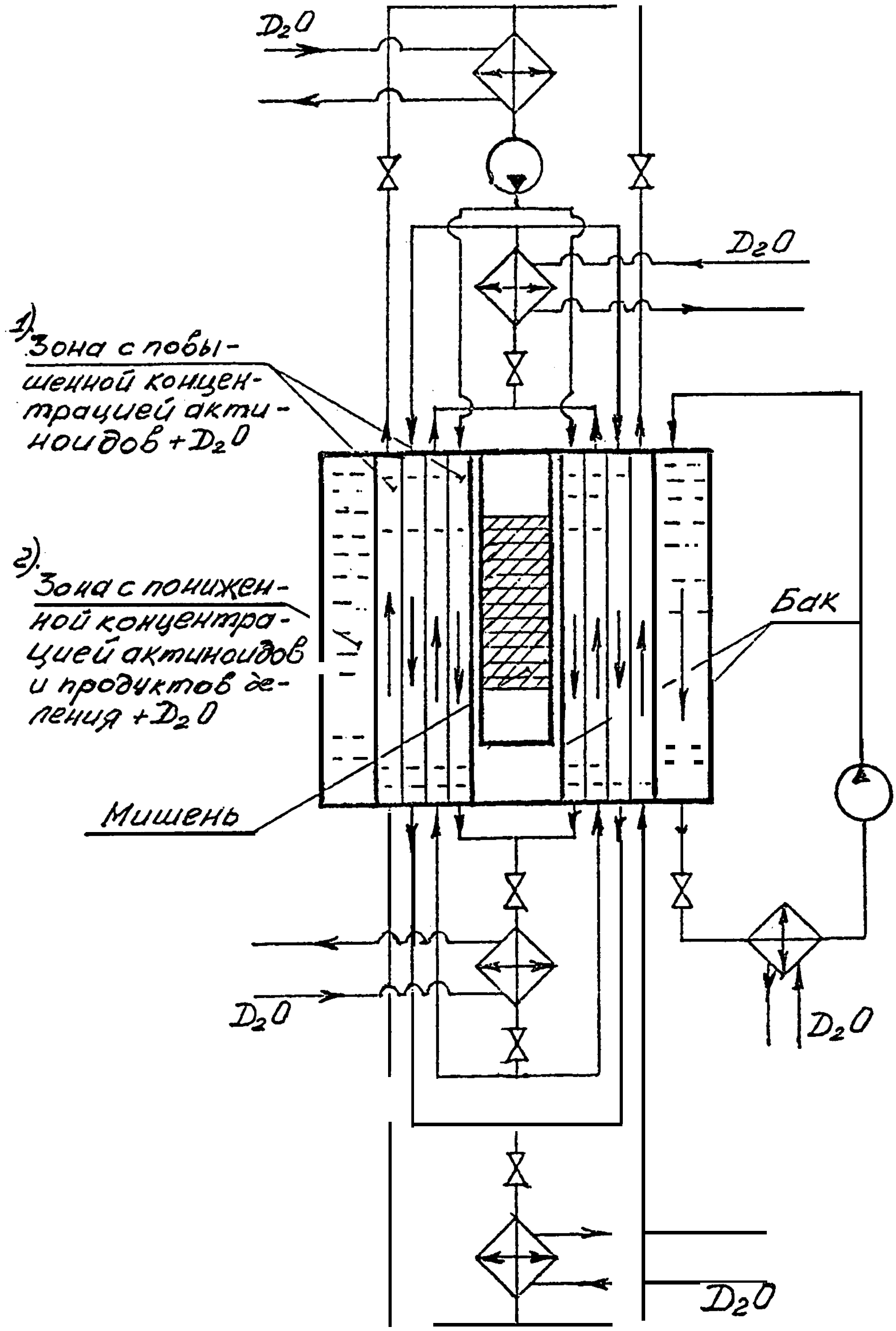


Fig.8 Homogeneous blanket scheme.

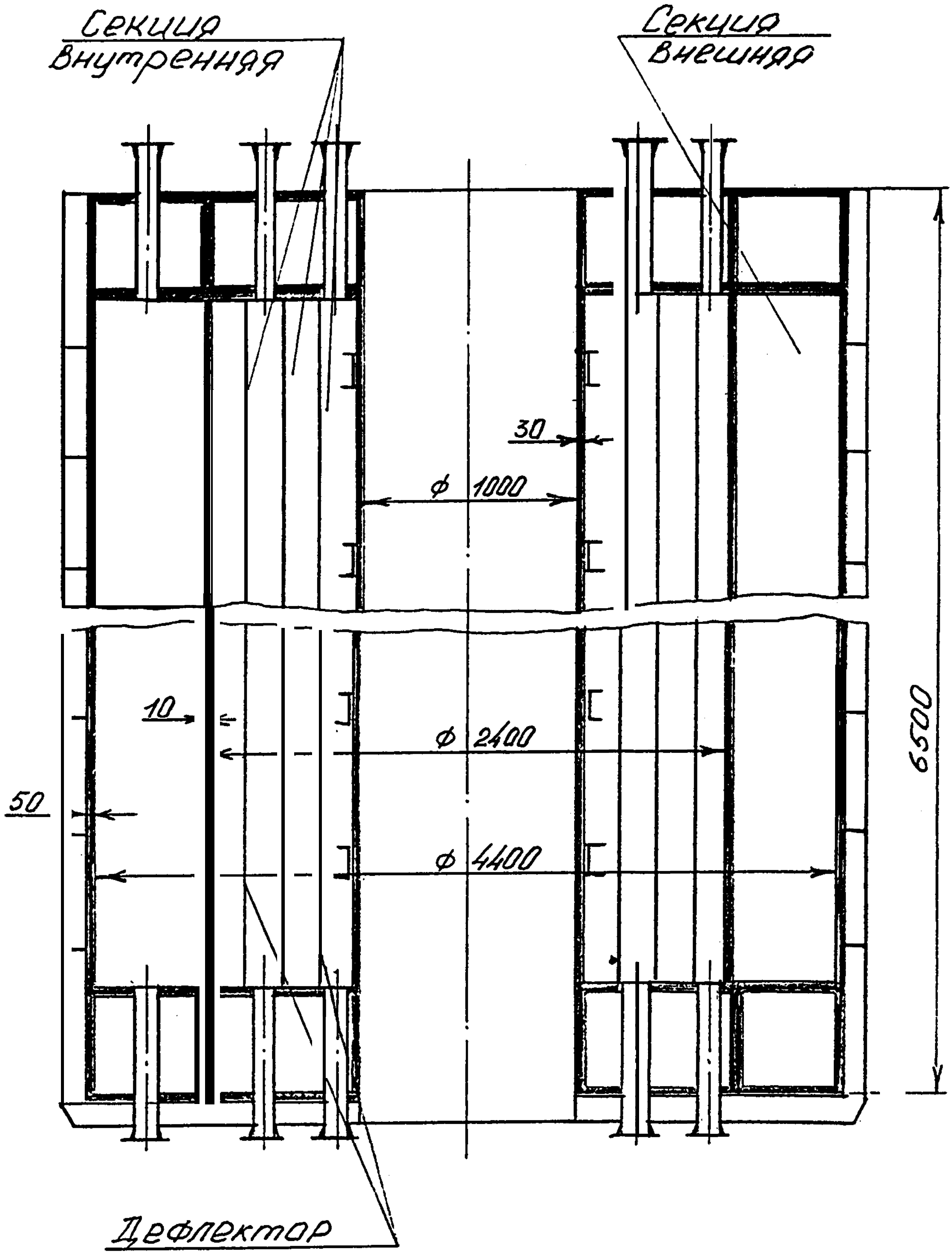


Fig. 9. Homogeneous blanket scheme.

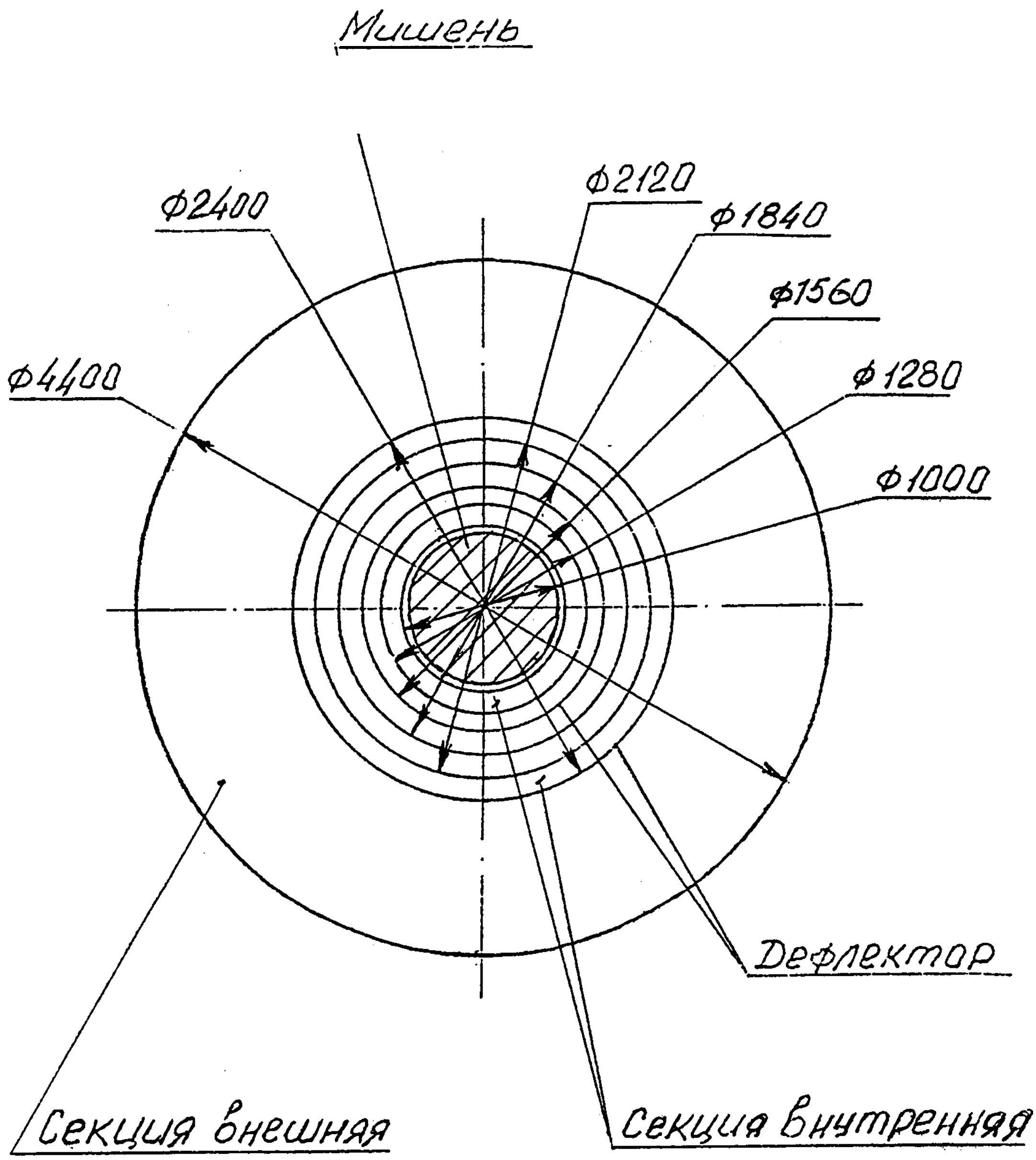


Fig. 10. Homogeneous bl anket scheme.

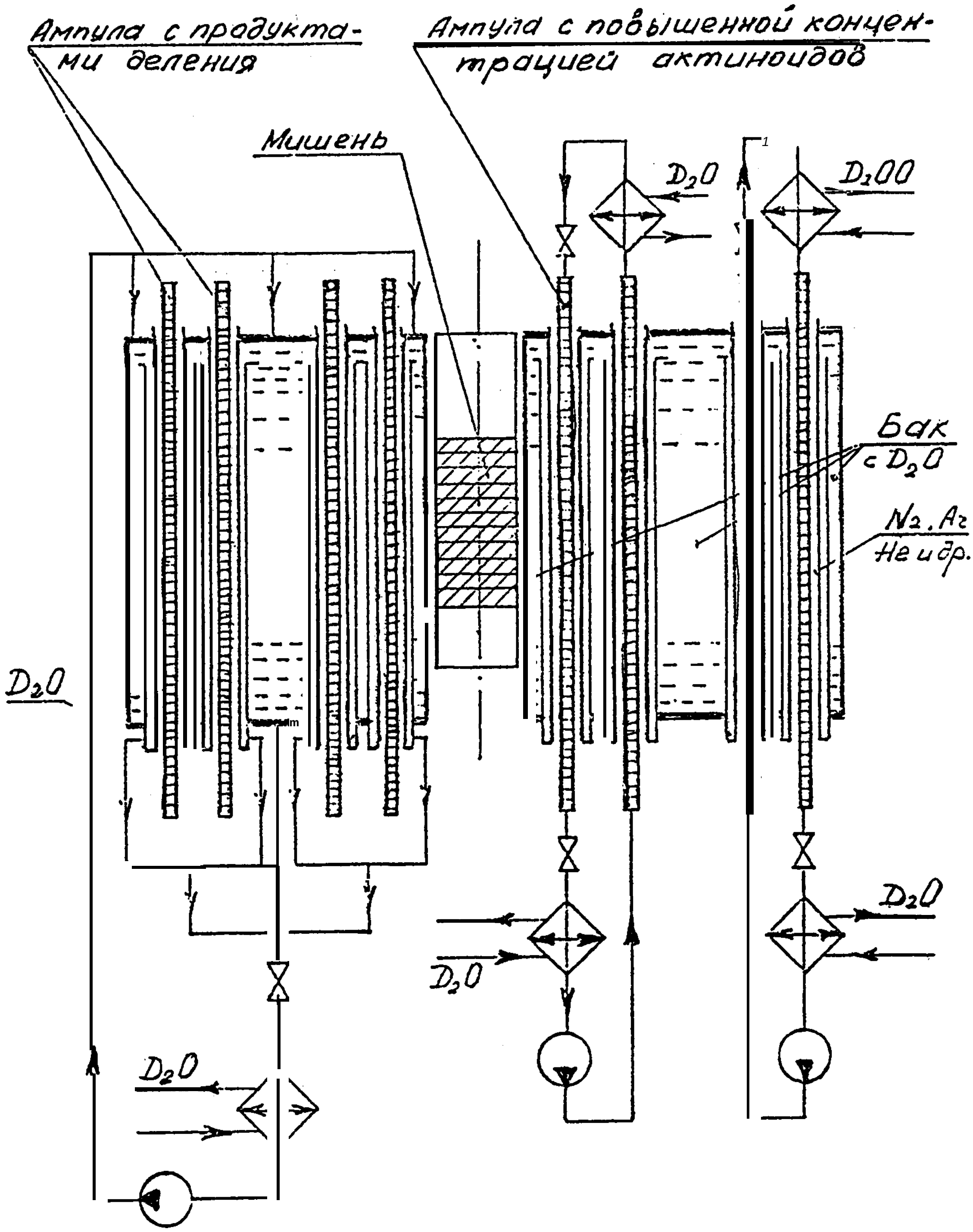


Fig.11. Heterogeneous (ampule-channel) blanket scheme.

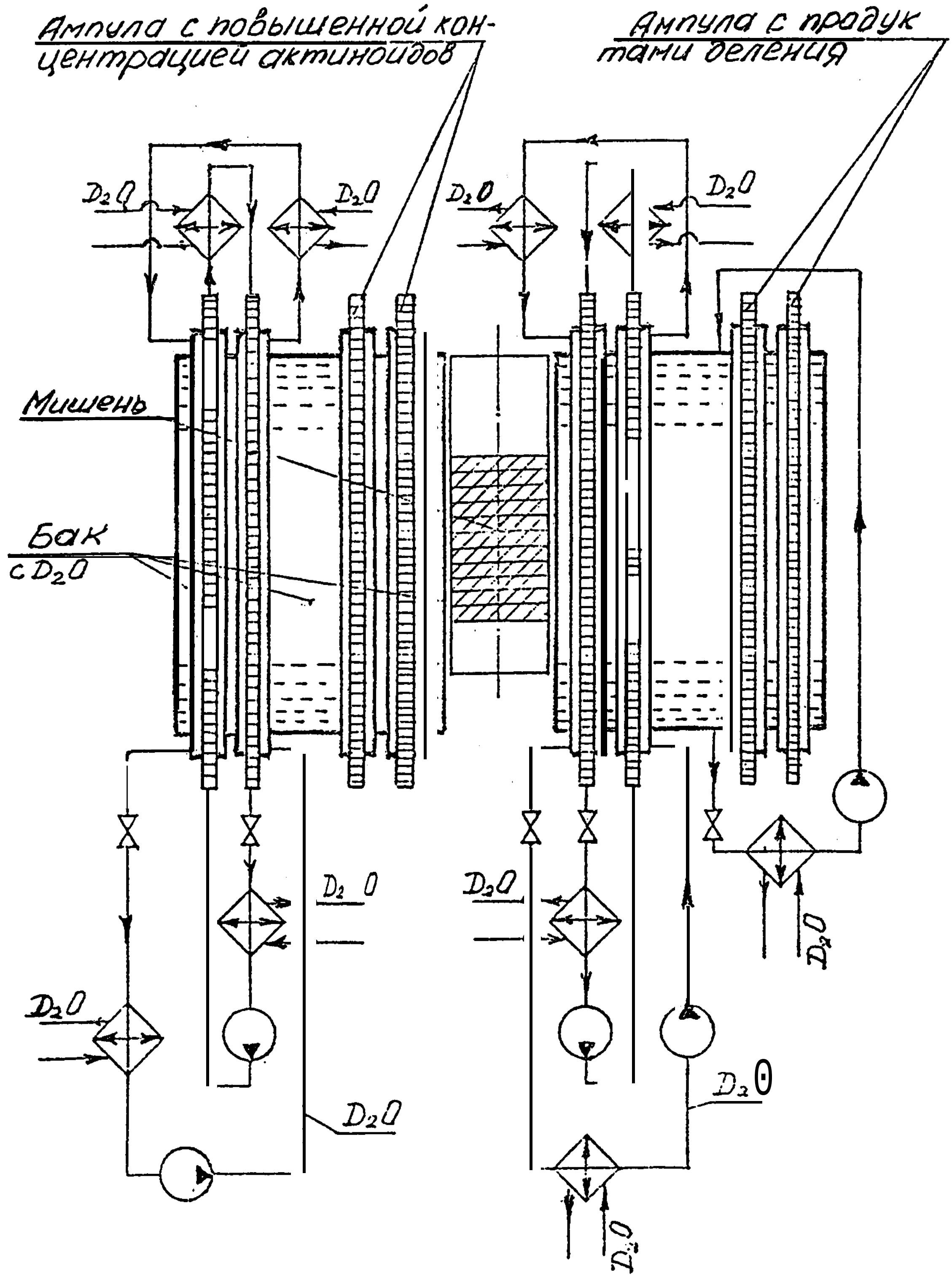
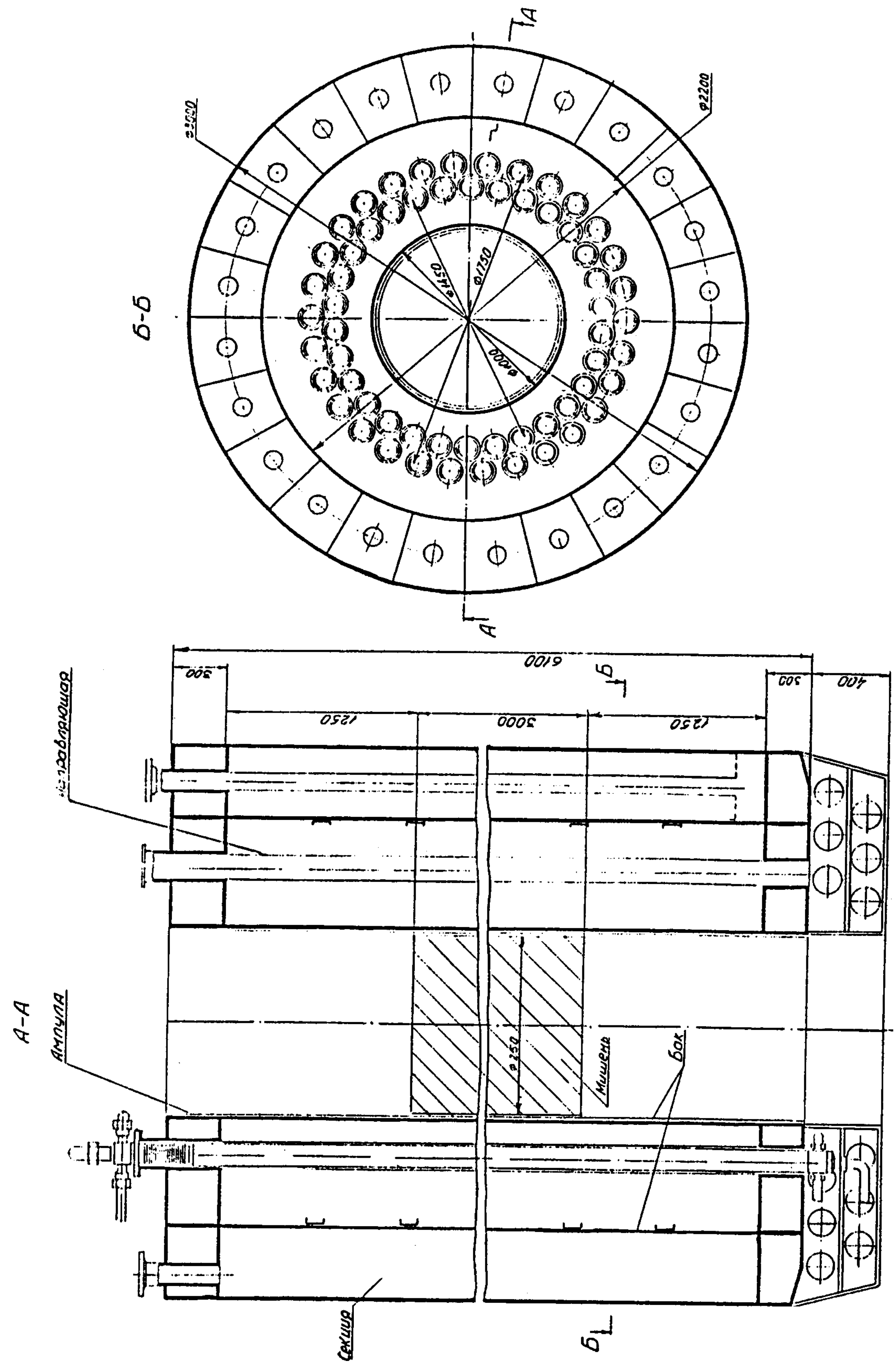


Fig. 12. Heterogeneous (ampule-channel) blanket scheme,

Fig. 13. Heterogeneous (ampule-channel) blanket scheme.



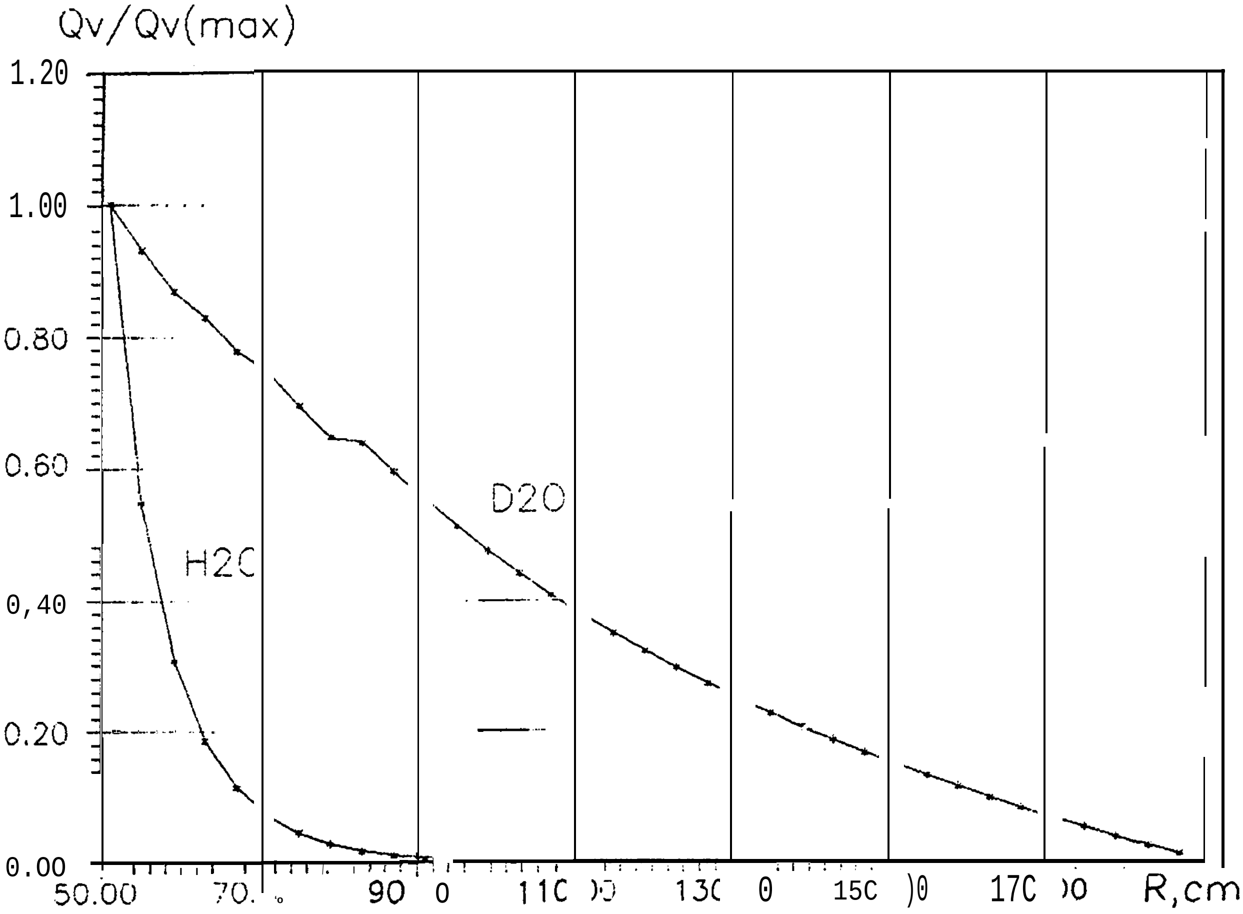


Fig. 14. Power density radial distribution for H2O-D2O blanket.