2.2 RF DEMO Ceramic Helium Cooled Blanket, Coolant and Energy Transformation Systems

V.Kovalenko[a,*], A.Borisov[b], V.Demidov[c], V.Kapyshev[c], A.Leshukov[a], V.Poliksha[a], A.Popov[a], G.Shatalov[b], Yu.Strebkov[a]

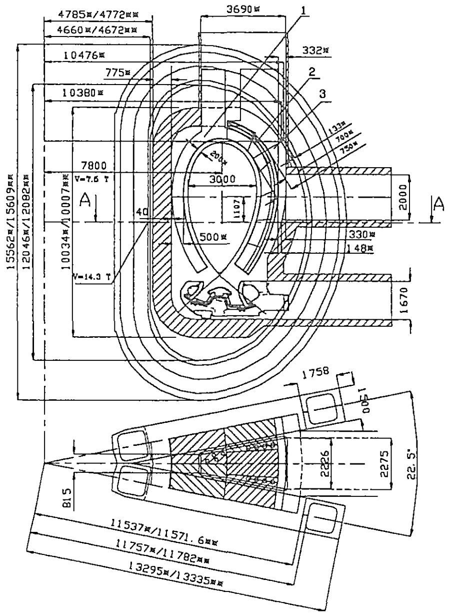
[a]Federal State Unitary Enterprise “Dollezhal Research and Development Institute of Power Engineering”, PO Box 788, Moscow 101000, Russian Federation
[b]Russian Research Center ”Kurchatov Institute”, Kurchatov Square 1, 123182 Moscow, Russian Federation
[c]Federal State Unitary Enterprise “A.A.Bochvar All-Russia Research Institute of Inorganic Materials”, P.O. Box 369, Moscow 123060, Russian Federation
*Corresponding author.Tel.: +7-95-2689243; fax: +7-95-9752019.
E-mail address: koval@entek.ru

Abstract

RF DEMO-S reactor is a prototype of commercial fusion reactors for further generation. A blanket is the main element unit of the reactor design. The segment structure is the basis of the ceramic blanket. The segments mounting/dismounting operations are carried out through the vacuum vessel vertical port. The inboard/outboard blanket segment is the modules welded design, which are welded by back plate. The module contains the back plate, the first wall, lateral walls and breeding zone. The 9CrMoVNb steel is used as structural material. The module internal space formed by the first wall, lateral walls and back plate is used for breeding zone arrangement. The breeding zone design based upon the poloidal BIT (Breeder Inside Tube) concept. The beryllium is used as multiplier material and the lithium orthosilicate is used as breeder material. The helium at 0.1 MPa is used as purge gas. The cooling is provided by helium at 10 MPa. The coolant supply/return to the blanket modules are carrying out on the two independent circuits. The performed investigations of possible transformation schemes of DEMO-S blanket heat power into the electricity allowed to make a conclusion about the preferable using of traditional steam-turbine facility in the secondary circuit.

1. Introduction

DEMO-S reactor is a prototype of the commercial fusion reactors for further generation. DEMO-S reactor is intended to use the operation experience with thermonuclear plasma. This plasma should have the parameters that are correspond to the operation conditions of industrial power fusion reactors. The reactor contains the following systems: electromagnetic system including the toroidal and poloidal field coils with electrical power supply and cooling systems; fusion energy utilization system including blanket, first wall with cooling systems and heat power conversion systems and also the divertor with cooling system; current driving system; remote handling system; tritium recovery and extraction system; vacuum pumping and cleaning system and other systems for reactor repair and operation.



1 - inboard blanket segment; 2 - outboard blanket segment, 3 - vacuum vessel.
*- operation temperature, **- room temperature

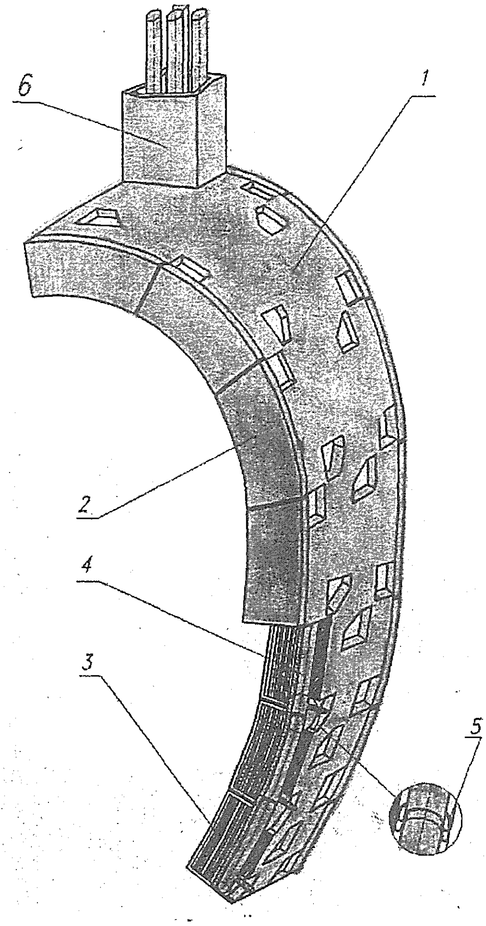
Fig. 1. DEMO-S reactor layout

The general layout of DEMO-S reactor adopted at the present design stage and the main dimensions are shown on fig. 1. The values of major and minor plasma radius are adopted in accordance with the results of DEMO-S plasma characteristics analysis with account of the following restrictions: the maximum magnetic field of toroidal coils is 14 – 14.5 T; the reactor fusion power is lower than 3 GW and correspondingly the electrical power is lower than ~ 1.5 GW; the average neutron load on blanket first wall is lower than ~ 2.5 MW/m^2, this value is determined by the operability of the adopted ceramic blanket design.

The blanket segments are mounted/dismounted through the vacuum vessel vertical port. The main dimensions of toroidal field coils, vacuum vessel and divertor region are extrapolated on the ITER reactor parameters. The thickness of plasma scrape-off layer is adopted to be 20 cm and will be refined after the detailed calculation of magnets configuration.

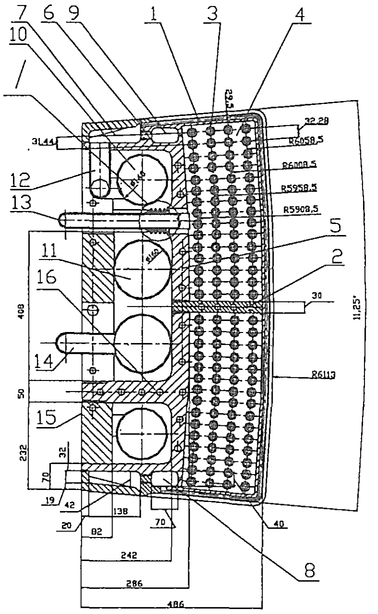
2. Design scheme of DEMO-S ceramic blanket

The segment structure is the basis of the DEMO-S reactor ceramic blanket (Fig. 2). The segments mounting/dismounting operations are carried out through the vacuum vessel vertical port. The inboard blanket total thickness (including the mounting and technological clearances) is 520 mm and the radial thickness of outboard blanket is 750 mm. The vacuum



1 - back plate; 2 - first wall; 3 - breeding zone; 4 - coolant collector; 5 - compensatory; 6 - tailer.

Fig. 2 Toroidal cross-section of inboard blanket segment



1-first wall; 2-stiffness rib; 3-breeding element; 4-multiplier; 5-back plate; 6-partitions of first wall collectors; 7-first wall inlet collector; 8,9-first wall outlet collector; 10-segment coolant supply collector; 11-segment coolant return collector; 12-supply branch-pipe for module coolant; 13,14-return branch-pipes for module coolant; 15-back plate; 16-back plate cooling channel.

Fig. 3. Toroidal cross-section of inboard blanket segment

vessel is the vacuum boundary of plasma chamber formed by the blanket first wall.

The vacuum vessel tightening is carried out by the tongue welds between the cover and branch-pipe of vacuum vessel vertical port. The tongue welds are performed also between the vacuum vessel cover and blanket segments flanges. The welds places of blanket segments flanges and cover are provided by bellows in order to compensate the thermal expansions.

It is proposed to use the circumferential bands (by the analogue with cask design fastened by rings) for joining the blanket segments. Segments attachment concept suggests the possibility to compensate the thermal expansions through the radial and vertical displacements providing, the displacements in toroidal direction are not allowed.

It is proposed to use the suspension on the inclined plates or the spherical support pillars for the attachment of lower circumferential bands on the vacuum vessel.

The inboard/outboard blanket segment is a tight welded design. The inboard/outboard blanket segment contains the welded back plate, first wall module and breeding zone. Back plate is a load-bearing structure and the first wall modules are welded to back plate. The structural material of blanket segment elements is ferrite martensite steel (9CrMoVNb).

The internal space formed by the first wall module and back plate is used for breeding zone arrangement (Fig. 3). The breeding zone design based upon the poloidal BIT concept (Breeder Inside Tube).

The coolant pipelines are located in the back plate cavities. The pipelines dimensions are the following: 140 mm in diameter (for inboard blanket), 180 mm in diameter (for outboard blanket). The compensatory are located in the weld places of pipelines sections. These compensatory are intended to compensate the difference of pipelines and back plate thermal expansions.

The module is the main blanket design element having the back plate as the carrying element. The blanket module contains the first wall and breeding zone.

The first wall has a complicated shape plate with toroidal coolant channels. The first wall has a beryllium protective coating. The first wall has stiffness ribs (one rib for the inboard blanket and two ribs for outboard one) for the required strength during all types of the operation conditions. The first wall has the two inlet and two outlet collectors. The first wall outlet collectors are connected with the breeding zone inlet collectors.

The inboard/outboard blanket breeding zone contains 4/7 rows of circular coolant channels (28 mm in exterior diameter and 14 mm in internal diameter, wall thickness is 1 mm). The internal space of circular channel is used for breeder location. A pebble-bed of lithium orthosilicate is used as breeder material. The breeder enrichment on ^{6}Li is increasing moves away from the first wall. The free space between first wall, back plate and external surfaces of coolant circular channels is used for multiplier location. A beryllium pebble-bed or porous beryllium is used as multiplier material. The rows of breeding zone coolant channels are connected in series.

The coolant supply/return to the blanket modules are carrying out on the two independent circuits. This allows to perform the coolant supply to the first wall cooling channels from the two independent collectors and to provide the coolant opposing flowing in the adjacent channels. This cooling scheme allows maintaining blanket integrity in LOCA conditions in a single circuit.

The possible sequence of the segment assembling process (inboard blanket) is shown on figure 4. The element numbers mean the priority of design elements joining.

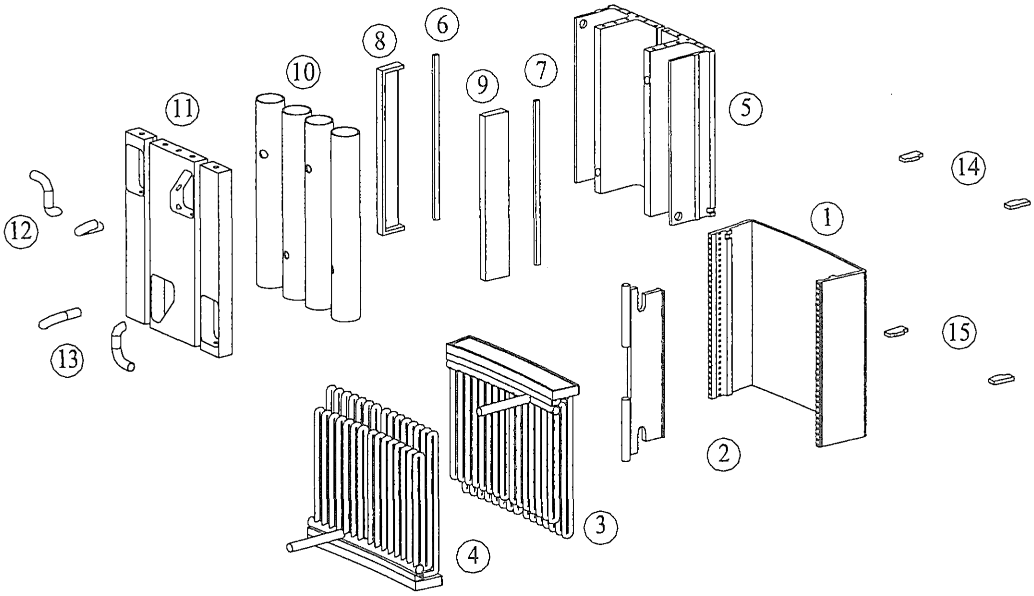


Fig. 4. Blanket segment assembling scheme

3. Neutronic calculation results for DEMO-S ceramic blanket

The neutronic calculation is performed for the case when the blanket has been assembled from modules (module characteristics are presented in table 1). Each module in the calculation model corresponds to the detailed description of design elements. The technological clearance between the modules is 20 mm. The reactor total thermal nuclear power is specified at 2.5 GW. The accuracy of the rear presented values for reaction rates, TBR and specific heats is higher than 1%.

Table1.

Parameters of DEMO blanket module

Row №	Cell dimension (cmxcm): radial x toroidal	Channels number	Gasket diameter(cm)		Ceramic breeder enrichment on ^{6}Li,%
			channel	breeder	
Outboard blanket					
1	5x3.154	36	2.8/0.1	1.4/0.1	40
2	5x3.154	36	2.8/0.1	1.4/0.1	40
3	5x3.154	36	2.8/0.1	1.4/0.1	50
4	5x3.154	36	2.8/0.1	1.4/0.1	50
5	7x3.5	36	2.8/0.1	1.8/0.1	50
6	7x3.5	36	2.8/0.1	1.8/0.1	90
7	5x3.5	36	2.8/0.1	1.8/0.1	90
Inboard blanket					
1	5x3.55	30	2.6/0.1	1.4/0.1	40
2	5x3.55	30	2.6/0.1	1.4/0.1	40
3	5x3.55	30	2.6/0.1	1.4/0.1	50
4	5x3.55	30	2.6/0.1	1.4/0.1	50
Ceramic- Li_4SiO_4 – pebble-bed with 38% porosity, beryllium - pebble-bed with 22% porosity.					

Table 2 contain the following neutronic parameters of reactor outboard and inboard blankets: poloidal distribution of neutronic load on the reactor first wall; module area; heat power of each module and it's elements - first wall including beryllium layer, lateral first wall, stiffness ribs (partitions), lower and upper headers, materials of row cell (beryllium and ceramic pebble –bed and steel gasket), back wall. The total power generation is presented for module and blanket section. Maximum neutron load is in the area of module N°11 (outboard blanket) and module N°4 (inboard one). These are 3.80 MW/m^2 and 2.83 MW/m^2 respectively.

Table 2.

Heat power generation (kW) in the module design elements for DEMO outboard/inboard blanket

Module No	8/1	9/2	10/3	11/4	12/5	13/6	14/7
P,*MW/m^2	2.97/1.79	3.24/2.46	3.41/2.73	3.80/2.83	3.79/2.71	3.12/2.41	2.39/2.74
S,** m^2	0.983/1.25	1.05/1.19	1.13/1.23	1.10/1.19	1.06/1.19	1.06/1.32	0.9/1.44
First wall	720/673	801/730	940/793	866/742	838/793	772/828	588/893
Lateral wall	122/72	121/87	131/98	133/95	129/98	109/93	93/96
Partitions	190/60	185/72	199/87	210/81	203/79	177/76	144/81
Headers	226/169	253/177	283/191	299/185	292/185	263/193	215/218
1-row	554/588	613/681	687/707	722/696	696/690	593/719	492/880
2-row	458/456	492/534	546/577	579/566	560/560	472/583	381/733
3-row	400/390	425/453	471/494	495/488	475/471	403/499	313/621
4-row	339/346	357/422	393/462	414/473	387/442	323/456	247/615
5-row	380/-	400/-	441/-	465/-	440/-	374/-	279/-
6-row	302/-	322/-	349/-	359/-	344/-	290/-	214/-
7-row	169/-	176/-	182/-	208/-	199/-	160/-	124/-
Back wall	290/593	339/684	363/786	373/776	341/766	289/810	215/964
Total in module	4150 3347	4488 3841	4986 4195	5123 4102	4904 4085	4225 4257	3305 5101
Section 22.5^0	12450 6694	13452 7681	14958 8390	15369 8204	14712 8169	12675 8514	9915 10202

* neutron load on module first wall, ** - first wall area

The heat power of outboard blanket segment (includes 7 modules) is 32.4 MW, for inboard one – 30 MW and 1/16-th part of reactor (22.5^0) extracts 157 MW. The materials of divertor cassette generate the power of 8 MW. Taking into account that no less than 8 horizontal ports should be occupied by the plasma heating and diagnostic systems (this fact of course reduces the number of power modules in blanket) the total heat power of reactor blanket is be 2.508 GW. This value corresponds to the energy multiplication factor of 1.18.

The heat power distributes in module as follows: 17-20% - in the first wall, 9-12% - in the lateral wall, headers and stiffness ribs, 7-19% - in back wall and 53-63% in module lattice. The heat load on the back wall of inboard blanket is twice higher than for the outboard one because of the lower thickness in inboard blanket.

Table 3 contains the total value of tritium generation on all the channels of each row (on one source neutron on the sector rows). The TBR is 0.92 for 22.5^0-section. The total *n,2n* reactions number on beryllium and iron is 0.798. The assumption on the presence of 8 non-blanket ports decreases the TBR in DEMO reactor down to 0.87.

Table 3.

Tritium breeding ratio (TBR) in DEMO reactor (on one source neutron)

Row N°	Row thickness, cm	^{6}Li,%	Inboard blanket	Outboard blanket	In reactor
1	5.	40	0.084	0.108	0.192
2	5.	40	0.076	0.093	0.169
3	5.	50	0.076	0.093	0.169
4	5.	50	0.076	0.071	0.147
5	7.	50	-	0.099	0.099
6	8.	90	-	0.089	0.089
7	5.	90	-	0.055	0.055
Total on reactor			0.312	0.608	0.920
Relation to the surface area.			35.7%	58.0%	
Number of n,2n-reactions - 0.798					

4. Thermal hydraulic calculation results for circulation circuit of DEMO-S blanket module

The coolant circulation circuit of DEMO-S reactor contains 4 loops. Each loop removes the heat power from 12 outboard and 8 inboard blanket segments that are connected in parallel to the supply and return collectors. Each segments contains its own supply and return collectors. The 7 modules with first wall and breeding zone are connected in parallel to these collectors. The inboard and outboard blanket modules have the different thickness of breeding zone (200 mm and 400 mm correspondingly). The helium (P=10 MPa, inlet temperature is 300°C) is used as coolant. The total helium mass flow rate through the breeding zone is 1800 kg/s.

Table 4 contains the evaluation results of coolant pressure drops in cooling system with the channels preliminary dimensions (the drops in steam-generator have not been taken into account). The total pressure drops in the circulation loop are 0.16 MPa at coolant outlet temperature of 519°C.

Table 4.

Geometrical dimensions and pressure drops for coolant circulation channels

Circulation channel section		D, m	L, m	v, m/s	Δp, MPa
Steam-generator - supply collector		1.00	20	70.9	0.011
Supply collector-module	outboard blanket	0.18	25	64.7	0.030
	inboard blanket	0.14	25	66.2	0.039
Module	outboard blanket	-	-	-	0.0630
	inboard blanket	-	-	-	0.0392
Module-return collector	outboard blanket	0.18	25	94.6	0.043
	inboard blanket	0.14	25	101.2	0.060
Return collector - steam-generator		1.0	20	98.6	0.014

where D - internal diameter of pipeline section; L - section length; v - coolant velocity Δp - pressure drop.

Thermal hydraulic calculation results for DEMO-S inboard and outboard blankets are presented in tables 5-6. It is visible from calculation results that the temperatures on the first wall external surface (for outboard and inboard blankets correspondingly) are 528°C and 605°C, coolant heat-ups - 53°C and 84°C, pressure drops - 0.057 and 0.019 MPa.

Table 5.

First wall thermal hydraulic parameters

First wall	T_1, °C	T_2, °C	T_{FW}, °C	V, m/s	Δp, MPa
Outboard/inboard blanket	300/300	353/384	529/605	75/45	0.045/0.015

where: T_1 - coolant inlet temperature; T_2 - coolant outlet temperature; T_{FW} - temperature on first wall external surface; V - coolant outlet velocity; Δp - pressure drops.

Table 6.

Thermal hydraulic parameters of outboard/inboard blanket breeding zone

Row number	1	2	3	4	5	6	7
Q_k, KW	21/20	17/16	14/13	13/11	12/-	10/-	5/-
ΔT, °C	65/49	54/40	59/33	47/26	55/-	43/-	17/-
G, kg/s	0.05/0.08	0.05/0.08	0.05/0.8	0.05/0.08	0.05/-	0.05/-	0.05/-
T_1, °C	418/433	472/474	413/507	460/530	515/-	558/-	489/-
ΔP, atm	0.03/0.05	0.03/0.05	0.04/0.06	0.052/0.065	0.066/-	0.071/-	0.108/-
T_{zmax}, °C	998/1000	1017/1012	954/997	910/945	1002/-	981/-	785/-
T_{zcmax}, °C	1004/1006	1024/1018	960/1003	915/950	1005/-	984/-	786/-
$T_{bemaxpb}$, °C	650/655	640/630	537/619	553/617	687/-	681/-	509/-
T_{s1}, °C	488/491	540/530	493/560	525/577	559/-	597/-	510/-
T_{s2}, °C	493/497	524/517	454/537	490/555	552/-	582/-	493/-
V_1, m/s	23.4/31.2	25.5/33.3	26/35	26.5/36	27/-	29/-	35/-

Where: Q_k - element heat power; ΔT - coolant heat-up; G - coolant mass flow rate; T_1 - coolant outlet temperature; ΔP - pressure drops on hydraulic channel; T_{zmax} - maximum temperature of ceramic pebble-bed; T_{zcmax} - maximum temperature in the center of ceramic pebble-bed grain; $T_{bcmaxpb}$ - maximum temperature of beryllium pebble-bed; T_{s1} and T_{s2} - maximum temperatures of breeding element internal and external jackets; V_1 - maximum coolant temperature in hydraulic channel

It is visible from the calculation results that the breeding material maximum temperature is in the range of 700-1050°C. The maximum temperatures of beryllium pebble-bed in the outboard/inboard blanket are 680°C /655°C. The multiplier (beryllium pebble-bed) temperature in the contact points with metal structure is not higher than 600°C. The operation temperature of breeding elements steel jackets is not higher than the allowed temperature for the given steel grade (600°C). The outlet temperatures from outboard/inboard blanket module are 515°C /528°C, the helium outlet temperature from blanket is 520°C. The total coolant pressure drop in DEMO-S circulation circuit (without the steam-generator account) is 0.16 MPa, that is the acceptable value.

5. Evaluation results of temperature fields and thermal stresses in modules

The temperature fields in the equatorial cross-sections of outboard (fig. 5) and inboard (fig. 7) blanket modules have been calculated on the ANSYS program. These temperature fields have used for the thermal stresses evaluation in modules structure. The thermal stresses have been calculated on the assumption of planar stressed state. The thermal stresses fields for outboard and inboard blankets are presented on figs. 6 and 8.

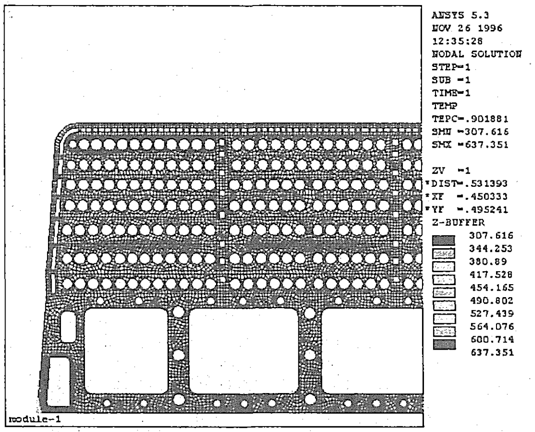


Fig. 5. Temperature field in the equatorial cross-section of outboard blanket segment

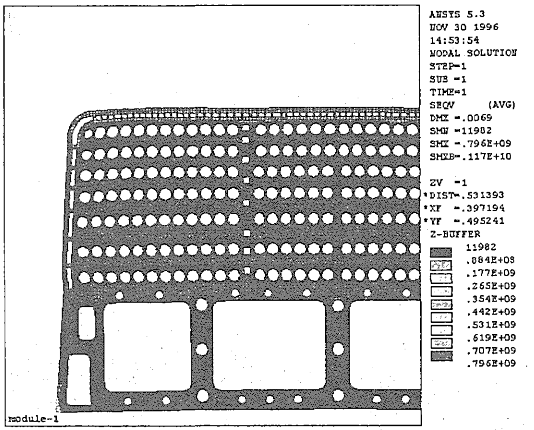


Fig. 6. Stresses distribution in the equatorial cross-section of outboard blanket segment

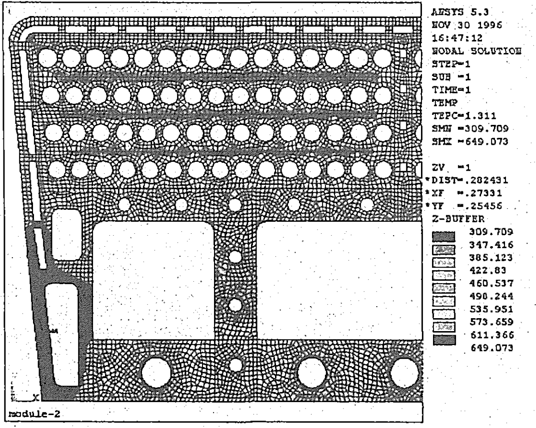


Fig. 7. Temperature field in the equatorial cross-section of inboard blanket segment

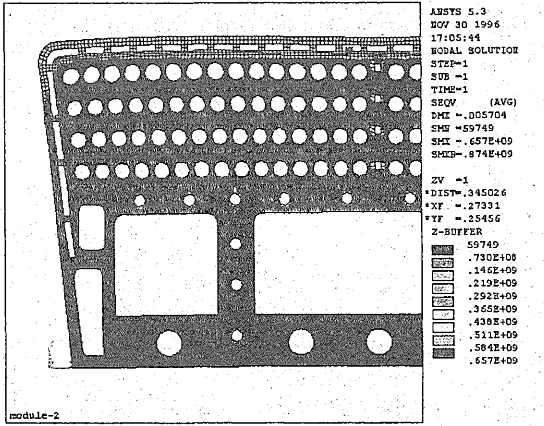


Fig. 8. Stresses distribution in the equatorial cross-section of inboard blanket segment

6. Power transformation system for helium-cooling DEMO-S blanket

The number of heat-removal loops for fusion reactor blanket is the defining item for power transformation scheme choice. The safety problem of reactor and station as a whole also have been taken into account. The possible schemes of power transformation are presented on fig. 9.

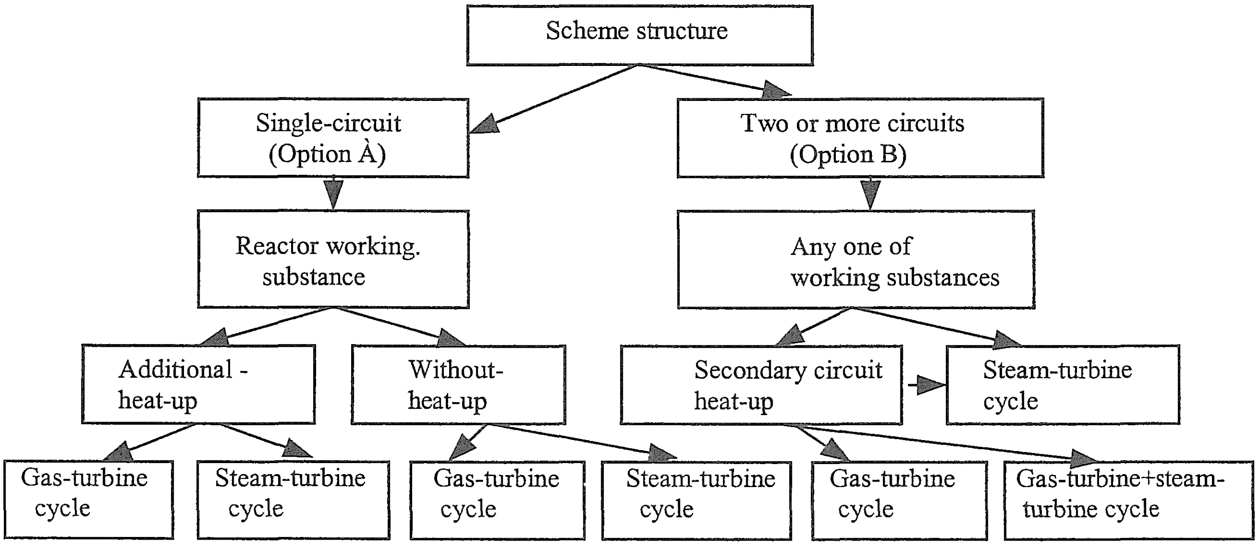


Fig. 9. The possible schemes of power transformation

The performed investigations of possible transformation schemes of DEMO-S blanket heat power into the electricity allowed to make a conclusion about the preferable using of traditional steam-turbine facility in the secondary circuit. This facility is performed on the moderate steam parameters that have been produced in the direct-stream steam-generator with helium adopted parameters in the reactor primary circuit. These parameters are defined by the possibility of the ensured cooling of all the design elements (including the first wall and breeding zone).

The initial data for the development of power transformation scheme for DEMO-S blanket are the following: the cooling is performing by helium at nominal pressure of 10 MPa and inlet/outlet temperatures of 300/500°C on the four identical loops (625 MW is removing by each loop). This scheme should provide the possibility of turbine facility operation on the nominal power level during 15-30 min. (the mode of technological pause in the plasma burning reaction). This scheme should also provide the preliminary warm-up possibility of the metalwork, pipelines and secondary circuit facility up to the nominal mode temperatures.

Taking into account the above mentioned information the K-800-130/3000 steam turbine has been proposed for DEMO blanket power transformation. The contact design of this turbine has been developed by Leningrad Metal Plant for the BN-800 reactor design.

The adopted solution about the steam turbine using has determined the structural scheme of blanket heat power transformation (fig. 10). This solution allows to reduce (in 4 times) the technological space as compared with the using of turbine apparatus for each separate helium loop.

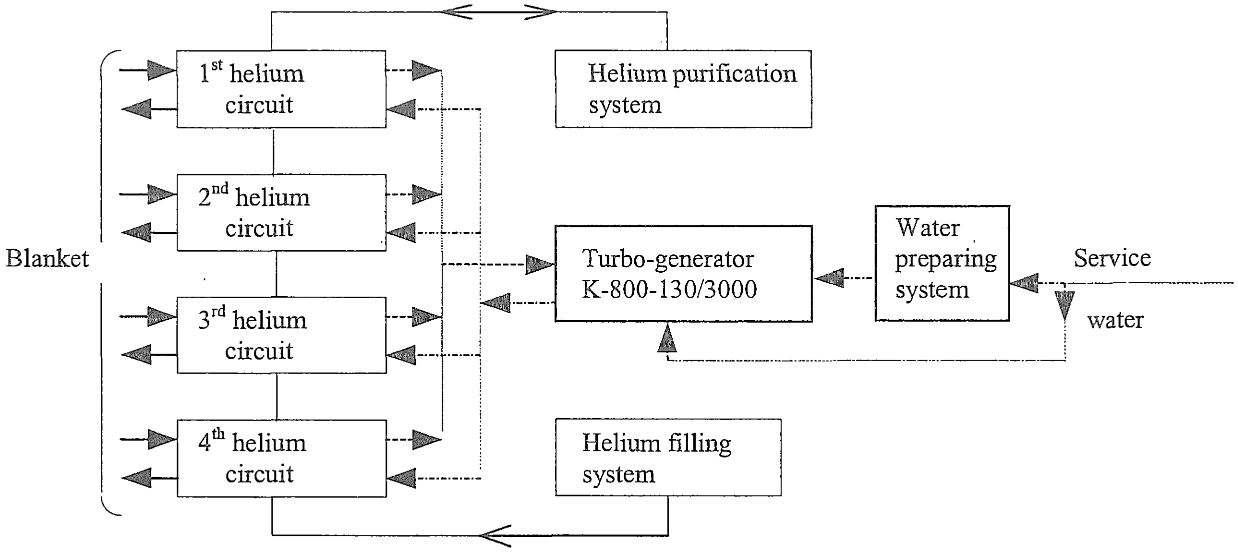
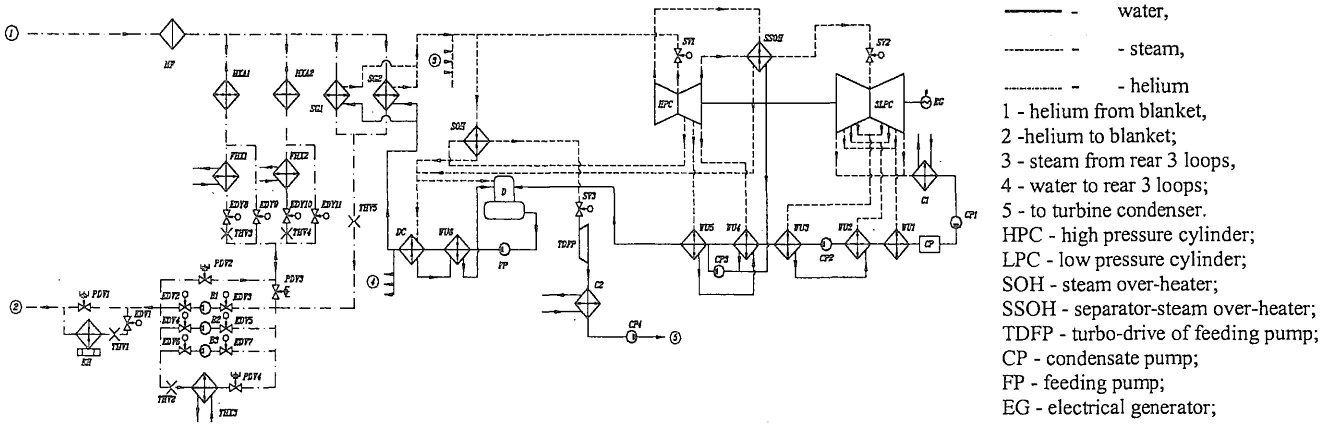


Fig. 10. Structural scheme of DEMO blanket heat power transformation

The principle technological scheme of DEMO blanket power transformation system with intermediate overheating by own live steam is presented on fig. 11. The blanket heat removal scheme includes four identical enclosed loops of the primary circuit (fig. 11 contains only one loop) and one secondary loop with steam-turbine cycle.



——— - water,

-------- - - steam,

-·-·-·- - - helium

1 - helium from blanket,

2 -helium to blanket;

3 - steam from rear 3 loops,

4 - water to rear 3 loops;

5 - to turbine condenser.

HPC - high pressure cylinder;

LPC - low pressure cylinder;

SOH - steam over-heater;

SSOH - separator-steam over-heater;

TDFP - turbo-drive of feeding pump;

CP - condensate pump;

FP - feeding pump;

EG - electrical generator;

C - condenser; CP - condensate purification; WU - warm-up facility; DC - drainage cooler; D - deaerator; SV - stop valve; SG - steam generator; HXA - heat exchanger-accumulator; FHX - finish heat exchanger; B - blower; MF - mechanical filter; EH - electrical heater; THV - throttle valve; EDV - electrical drive valve; PDV - pneumatic drive valve.

Fig. 11. Principle scheme of helium circuit with intermediate steam overheating

Each primary loop contains the equipment for heat transformation and transportation (HXA1 and HXA2 heat exchangers-accumulators with FHX1, FHX2 corresponding finishing heat exchangers and two parallel modules of direct-flow team generators SG1 and SG2), coolant circulating facility (B1-B3 blowers), EH electrical heater, MF mechanical filter, FHX3 heat exchanger, connecting pipelines. The secondary circuit loop contains the K-800-130 turbine flow part with intermediate separator-steam over-heater (SSOH). The turbine flow part loaded on the electrical generator (EG), condenser (C1), regenerative system of feeding water heat-up that contains the warm-up facilities (WU1-WU6), deaerator (D) and condensate pumps (CP1-CP3). The turbine facility contains the steam over-heater (SOH) that is necessary for feeding pump (FP) turbo-drive (TD), condenser (C2) and condensate pump (CP4). This scheme provides the three operation modes: 1) preliminary warm-up of blanket, equipment and pipelines up to the temperature of 300°C; 2) nominal operation mode of DEMO-S reactor during the plasma burning; 3) the turbine facility operation during the pause.

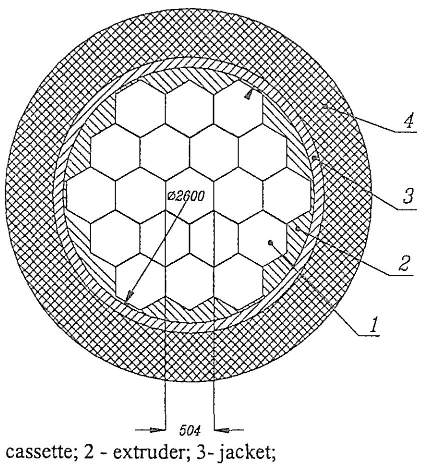
The main characteristics of K-800-130/3000 steam-turbine facility are presented in table 7. Table 8 contains the evaluative calculation results of scheme thermal technical parameters. The calculations have been performed without the account of heat drops to the environment. The calculations objective is to determine the nominal characteristics of main equipment.

Table 7.
The main characteristics of K-800-130/3000 steam-turbine facility

Fresh steam mass flow rate, t/h	3171,2
Fresh steam pressure, kgf/cm^2	130,0
Fresh steam temperature, °C	485
Steam pressure after intermediate over-heating, kgf/cm^2	4,24
Steam temperature after intermediate over-heating, °C	250
Calculating pressure in condenser, kgf/cm^2	0,04
Turbine maximum capacity, MW	856
Specific heat flow rate, kW/kWh	2,395
Turbine mass, t	1800
Condenser mass, t	1300
Turbo-drive for feeding pump capacity, MW	23,2
Feed water temperature, °C	210

Table 8.
The evaluative calculation results of scheme thermal technical parameters.

	Value
Helium mass flow rate in loop, kg/s	600.6
Steam generator:	
capacity, MW	528.3
coolant mass flow rate, kg/s	480.7
Blowers:	
gas heat-up (ε=1,035), °C	11.2
inlet temperature, °C	288.8
outlet temperature, °C	300
capacity, MW	36.36
Heat exchanger-accumulator:	
capacity, MW	133.1
coolant mass flow rate, kg/s	121.1



1 - cassette; 2 - extruder; 3 - jacket;
4 - thermal insulation.

Fig. 12. Cross-section of SG module

The preliminary evaluations shown that it is reasonable to use two identical parallel modules of direct-flow steam generators. The steam generating element is a steeply-bended tube ($\varnothing$16×2 mm) with 80 mm middle diameter of tube arrangement, spiral slope of 4°33'. Thew internal extruder is a tube $\varnothing$56×3 mm. The elements (18) are collected (the step is 100 mm) in the hexagonal cassette in the jacket with the dimension for wrench of 504 mm It is necessary to locate 19 cassettes in the steam generator cross-section by the traditional hexagonal arrangement.

The cross-section of SG module is shown on fig.12. The tubes beam (19 cassettes) is located in the cylindrical jacket (2600 mm internal diameter and 12 m cylindrical part length without the ellipse bottoms account). The jacket external part is cover with thermal insulation. It is preferable to perform the heat exchangers-accumulators in the same jackets as the SG modules (for example as the steel spheres pebble-bed). The steel spheres have 15-20 mm diameter with natural porosity of ε=0,4. The used blowers are the single-stage centrifugal unit (0,5 m wheel diameter) jointed on the single axis with electrical induction engine (12,1 MW capacity, 6000 rpm frequency) in the steel jacket for 10 MPa pressure. The electrical efficiency factor (net) of the considered scheme is 34.2 %.

7. DEMO materials

7.1. Structural material

The ferrite-martensite steel is used as structural material for helium-cooled blanket of DEMO reactor. The chemical composition of this grade steels is presented in table 9. Table 10 contains the physical mechanical properties of 9CrMoVNb. The chromium ferrite and ferrite-martensite steels are susceptible to the cracks formation (due to its capability to harden on air) in the volumes near the welds. The danger of these cracks formation increases with the carbon content increasing. The 9CrMoVNb steel has the perfect weldability. The hand, automatic and argon-arc welding are can be used for 9CrMoVNb steel 9CrMoVNb steel.

Table 9.

Chemical composition of ferrite and ferrite-martensite steels

Steel grade	Chemical elements contents, %									
	C	Si	Mn	Ni	Cr	S	P	V	Mo	Nb
9CrMoVNb	0.8-0.12	0.17-0.34	0.3-0.6	<0.5	8.6-10	<0.025	<0.03	0.1-0.2	0.6-0.8	0.1-0.2
9CrW –0.5	0.02-0.06	0.15-0.3	0.3-0.6	1,2-1.6	11-12	<0.01	<0.015	-	0,8-1.0	-
9CrW -1	0.14-0.18	1.0-1.3	0.5-0.8	0.5-0.8	10-12	<0.02	<0.03	0.2-0.4	0.6-0.9	0.2-0.4
9CrW -2	0.10-0.15	<0.6	<0.6	<0.3	12-14	<0.018	<0.018	0.1-0.3	<1.63	0.25-0.55
F82H	0.20	0.17	0.57	0.51	12.1	0.003	0.016	0.28	1.04	-

Table 10.

Physical mechanical properties of 9CrMoVNb steel

Property	Testing temperature, °C							
	20	100	200	300	400	500	600	700
Heat conductivity coefficient, J/cm^2·s·K	0.272	0.276	0.276	0.280	0.284	0.284	0.289	0.289
Normal elasticity modulus, E, GPa	220	215	210	203	194	184	178	171
Thermal expansion coefficient, 1/K, 10^6	-	-	10.6	10.9	11.2	11.5	12.0	12.5

The chromium content reducing from 13 down to 9-10% and structural state optimization by melting method, heat treatment and precision micro-alloying selection cause to the lower shift of ductile-brittle transition temperature after irradiation. The other reasons have the significant influence on the low-temperature radiation embrittlement of ferrite-martensite steels (damage dose, helium breeding, irradiation temperature). The ferrite and ferrite-martensite steels with 9-12% of Cr have a few advantages such as producibility and high resistance to radiation swelling. However it should be noted that these steels have some features that can strongly restrict the operation parameters of DEMO reactor.

1. From the standpoint of physical and mechanical properties of chromium ferritic-martensitic steels their main shortcomings are the tendency to ductile-to-brittle at temperatures close to room ones and low temperature irradiation embrittlement (an increase of brittle fracture transition temperature, a sharp decrease of upper shelf stored energy, degradation of short-term mechanical properties and crack resistance parameters). These disadvantages restrict the lower operating temperature of the products.
2. These steels have the lower high-temperature strength than the austenite steels that could not provide the product reliable operation at temperatures higher than 620-650°C.
3. As for the technology of chromium steels the difficulties could appear due to the hardening cracks formation in the near-welds areas. This fact causes the necessity of welded joints heat treatment.
4. The use of at pure is preferable the chromium ferrite and ferrite-martensite steels mixture of raw materials melting in order to reduce the concentration of P and Cu. The above mentioned elements increase the low-temperature radiation embrittlement. The electroslag melting is used for chromium steels to receive the uniform structure. The 9CrMoVNb steel radiation embrittlement can be reduced not less that on 100°C at the high metal uniformity. The helium presence in steels on the level of 35 appm can increase (irradiation at 400°C by 40 dpa dose) the critical brittleness temperature of steel on 100-150°C. The increasing of irradiation temperature up to 500°C eliminates the helium influence
5. The 9CrMoVNb steel radiation embrittlement is determined by the dislocations density increasing. This radiation embrittlement is completely eliminated by the aging (550°C, 4 h). The radiation embrittlement eliminating for less pure and uniform metal requires more high temperature and aging duration.

7.2. Breeding material

The lithium orthosilicate is one of perspective materials for tritium breeding in fusion reactor blanket. This material has the following advantages as compared with another candidate breeding materials for DEMO-S helium-cooled blanket: (1) high content of lithium atoms; (2) low induced activity; (3) higher stability to hydration that Li_2O one in normal conditions; (4) investigation of properties and behavior at the tritium extraction. The significant disadvantage of lithium orthosilicate is chemical sorption of moisture from air at the normal conditions with further lithium carbonate formation. The other disadvantage is the high thermal expansion coefficient and that why the low resistance of products at the high thermal differences and thermal cycling. Moreover the lithium orthosilicate is thermal decomposing at temperatures higher than 1250°C that is negative factor for its radiation strength.

The initial materials for lithium orthosilicate fusion is natural lithium carbonate and silicon oxide. The silicon oxide is the strength sintered granules. For good distribution of mixture of raw materials components the silicon oxide is preliminary grinding with sifting through the sieve (0,1 mm cell). Figure 13 contains the technological scheme of fusion process. The mixturing of initial components with its further additional grinding is performed in the mill by the corundum spheres (∅18 mm). Taking into account the following fusion reaction $2Li_2CO_3+SiO_2 \rightarrow 2CO_2\uparrow+Li_4SiO_4$ the mass loss is 42,3%, the fusion extent could be determined by stages (weighting of reaction mixture of raw materials on the intermediate and final stages).

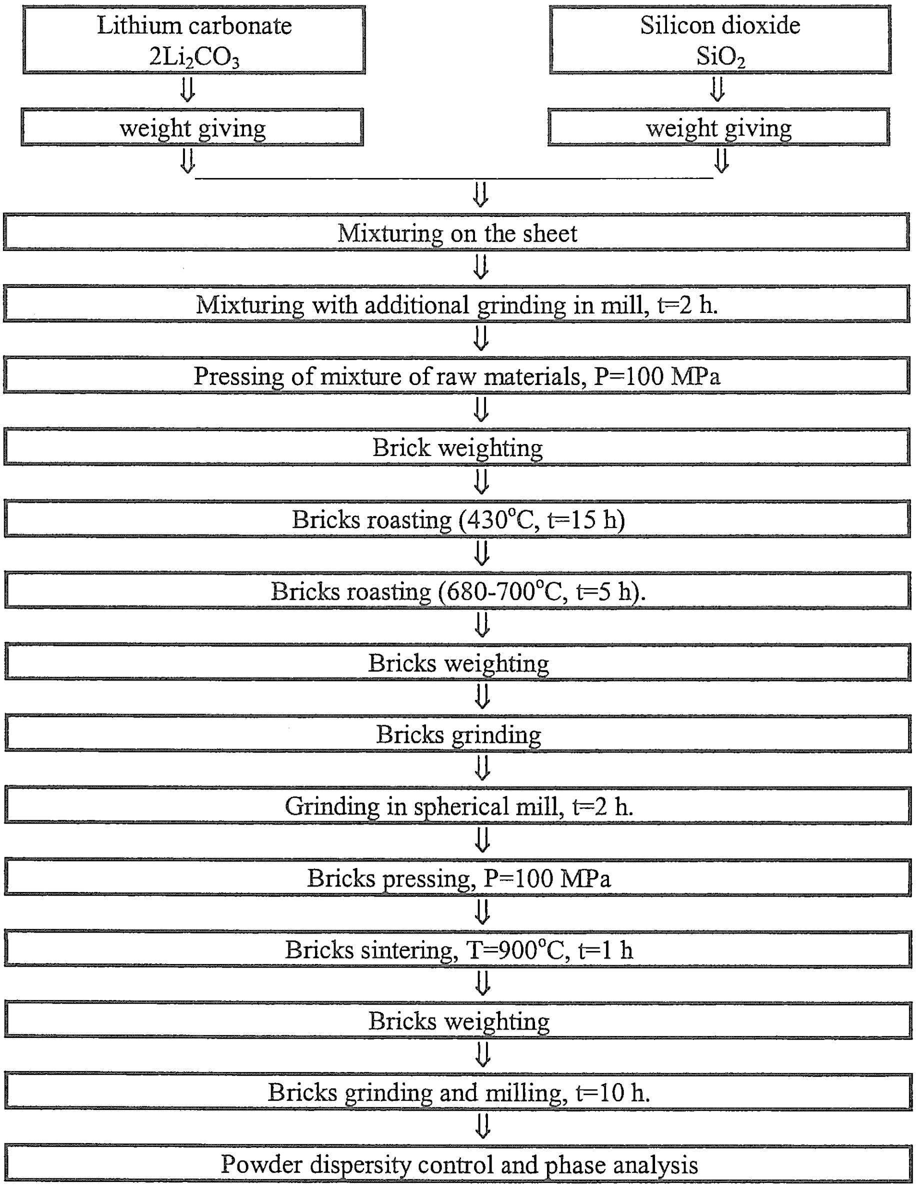


Fig. 13. Technological scheme of Li_4SiO_4. Fusion.

7.3 Neutron multiplier material

Beryllium is used as neutrons multiplier material for helium-cooled DEMO blanket with ceramic breeder. This material could be performed as pebble-bed with 20% porosity (reference option) or as the porosity beryllium blocks (alternative option) fixed on the breeding zone cooling channels.

The beryllium granules (∅0.5-1.0 mm) pebble-bed is proposed to use in DEMO blanket breeding zone. These dimensions are determined by the clearance between the coolant channels and by the required coolant temperature providing. The industrial technology to produce the spherical particles of the above mentioned dimensions (without the internal cavities and shrinkage pits) is absent now. That's why the working results of Bochvar Institute on the receiving of particles with relatively equiaxed shape. These particles could be received by the nodulizing of beryllium grinding groats. Basing upon the existing experience it is proposed to create the industrial technology of granules producing for breeding zone filling.

The developed in Bochvar Institute technological method allows to produce the porosity beryllium corresponding to the main requirements for multiplier material. This material could be received by the heat treatment of preliminary pressed mixture (metallic beryllium powder+beryllium hydride (BeH_2 powder) at temperature of 250-350°C. The ultra disperse beryllium is chemically high active and used as a connecting substance between the larger particles of metallic beryllium powder. The extracting hydrogen provides the formation of uniform micro-porosity structure with completely opened pores. The porosity of prodicing material could be regulated by the BeH_2 content changing in the initial mixture of raw materials. The required porosity could be received using the mixture of raw materials with BeH_2 content of 7.5-13.5 %.

The commercial powder of metallic beryllium and the powder of amorphous beryllium hydride are could be used as the initial materials for mixture of raw materials preparing. The characteristics of the above mentioned powders are presented in table 11.

Table 11.

Characteristics of initial materials for mixture of raw materials preparing

Material	Particles size, µm	Specific surface, m^2/g	Impurities content, % wt.	
			oxygen	spectrum determined impurities*
Be commercial powder	less than 30		0.7	less than 0,25
BeH_2O	1-250	0.6	0.8	less than 0,25

* the total content of following elements is presented: Si, Mn, Fe, Mg, Cr, Ni, Al, Cu, C,