Investigations of VNS for Minor Actinides Transmutation on the Base of Spherical Tokamaks with Aspect Ratio A=2

E.A.Azizov, V.N.Dokouka, I.A.Kovan, R.R.Khayrutdinov - TRINITI
A.V.Lopatkin, V.G.Muratov, - NIKIET, N.A.Obysov – Minatom RF
O.G.Filatov, V.A.Korotkov, V.A.Krylov, A.B.Mineev– Efremov Institute
Russia

Abstract

Concept of volumetric neutron source on the tokamak base dedicated for transmutation is proposed. JUST-T (JUST for Transmutation) concept has moderate parameters: aspect ratio A =2, dimensions R=2 m, neutron wall load p_n=0.4 MW/m^2 and also moderate physical consumption's. JUST-T subcritical blanket is effective for transmutation of minor actinides created during NPP work.

Key words: tokamak, aspect ratio A=2, volumetric neutron source, transmutation, subcritical blanket, minor actinides.

Introduction

Demonstration of practical application of fusion become now (after ~ 50 years of investigations) is a vital need. Moreover use, which can be estimated economically.

In this sense ITER-FEAT project (~5 B$, ~500 MW(thermal)), in spite of importance of complex demonstration of physical and technical realization of fusion, doesn’t have straight use in industry and energetic.

Elaboration of tokamak based volumetric neutron sources (VNS) for material investigations turn out to be “internal” task which helps mainly to ITER program of material investigations.

First step of practical use of fusion can be help to nuclear energy in solving its problems – mainly task of fission radioactive wastes transmutation. This problem (fusion’s help to fission wastes) stands many years, but only recently it acquired new impulse connected with possibility of:

- subcritical blankets utilization in fusion installations with level of energy amplification M_E ~ 100 and production of ~ 10 fission neutrons per one fusion neutron in it. Use of this subcritical blankets remove practically the problem of tritium reproduction and even the problem of first wall cover fraction by blanket (70-80% cover is enough);
- Minor Actinides (MA – Am,Np,..) transmutation.

These suggestions gives it possible solving of MA transmutation problem at the level of fusion power ~ 50 MW and blanket area ~ 100 m^2.

VNS on the tokamak base with d-t fuel is one of the main candidates for radioactive wastes transmutation due to detailed database of experiments, good understanding of physical phenomenon's and not far level of data extrapolation

Several generations of Tokamak VNS were analyzed. Let's note shortly their main peculiarities.

1). VNS generation of the beginning of 1990th ([1,2]).

The center of problems (between physics and engineering) was transported to engineering. In the result as a rule VNS had high levels of toroidal field B_t ~ 5 - 7 T and power supply; and relatively low normalized beta and bootstrap current fraction β_N ~ 2.6 – 3.6, f_{BS}~0.3 – 0.5. Plasma energy confinement corresponded to so called ITER-P89 scaling with enhancement factor H_{P89} ~ 2. The main goal of this VNS generation was material testing under irradiation, level of necessary fluence of fusion neutron was ~ 5 $MW{\cdot}y/m^2$.

2). VNS generation of the end of 1990th. The center of problems for this generation was transported to physics. This leads to strong decreasing of toroidal field level B_t ~ 1.5 - 3 T, increasing of high bootstrap current role f_{BS}~0.5 – 0.95 and importance of high normalized beta achieving β_N ~ 4 – 8. New plasma energy confinement scaling's was obtained (ITER-IPB(y,1), ITER-IPB(y,2) scaling) with enhancement factor H_τ ~ 1 – 2. The goal of this VNS generation was not only materials testing, but also transmutation. Some data of this projects is given in Table 1.

Modern Tokamak Based VNS parameters (end of 1990th) Table 1

	China 1998 [3]	China 1998 [3]	USA, M.Peng, 1998 [4]	USA, M.Peng, 1998 [4]	UK, Robinson 1998 [5]	USA, ARIES 2000[6]
Neutron wall load p_n, MW/m^2	1.02	0.5	1	4	1.5	0.23
Aspect ratio _	1.4	1.4	1.4	1.4	1.6	1.6
Major radius R, m	1.4	1.4	1.1	1.1	0.7	2.37
Elongation k	1.85	1.85	3	3	2.3	3.1
Safety factor q_{95}	5.5	7.5	9	9	3	3.1
Normalized beta β_N	6	5.5	4	7.6	2.6	5.04
Plasma current I_P, MA	9.2	7	10	10	10.3	12
Toroidal field at plasma axis B_t, T	2.5	2.5	2.1	2.1	2.94	1.54
Bootstrap current fraction f_{BS}	0.72	0.81	0.5	0.9	0.3 (*)	0.95
Drive power P_{AUX}, MW	28	19	40	70	46	47
Fusion gain Q	3.6	2.6	1.65	3.7	0.8	1.65
H_τ (*)	2.2	2.7	1.5	1.7	1.1	1.7

(*) – result of our reconstruction

1. Key parameters of JUST-T concept

JUST-T (JUST for transmutation) is the development of our previous JUST ideology [7] for the radioactive wastes transmutation. Let's discuss arguments for the choice of JUST-T key parameters.

1). *Fusion gain* $Q = P_{FUS}/P_{AUX}$

Achieved level of the fusion gain is Q = 0.3 – 1 within several seconds. ITER project had the evolution from Q = ∞ (FDR stage, up to 1998) to Q = 10 (FEAT stage). So, reasonable level of extrapolation Q = 1 – 2 (for steady state regime of plasma burn) in the medium sizes tokamak with major radius R ≤ 3 m

2). *Neutron wall load* p_n

Note that for pure fusion reactors the reasonable level of neutron wall load $p_n \geq 3$ MW/m^2, for fission-fusion reactors (with energy multiplication factor M_B~10) $p_n \geq 1$ MW/m^2, for the case of subcritical fission-fusion reactors (with M_B~50-100) possible value of neutron wall load can be $p_n \sim 0.5$ MW/m^2.

3). *Aspect ratio A.*

Aspect ratio is one of the main parameters, which define physical and engineering philosophy of tokamak.

For the case of ultra low aspect ratio's (A~1.2-1.6) plasma scenario is fully noninductive, central solenoid (CS) is absent; high values of plasma current I_P~10 MA, plasma elongation k~3 and normalized beta $\beta_N \geq 4$ are desirable in this concept. Plasma configuration for such high elongation's must be double null type (DN). Plasma disruptions must be excluded.

In opposite case of high aspect ratio's A>>1 tokamaks peculiarities: CS and inductive (or hybrid) plasma scenario are desirable, elongation and normalized beta are moderate (k < 1.5 – 2, β_N < 2 – 3). Plasma disruptions are normal events.

A=2 range . Interest to this range was stimulated from one side by our R&D during development of project of Kazakhstan Tokamak for Material Investigations [8,9]. From another side - by tokamak reactor analysis (see, for example [10].

For A=2 some features of ST can be applied (k, q_{95}/q_I); main part of ITER database also can be used and some details of ITER ideology can be taken – SN configuration with k~1.7, moderate values of normalized beta β_N~2.5-3. CS is desirable even as Starter Solenoid. Plasma disruptions are possible, so high plasma currents advantages becomes not to be so obviously.

It must be noted that ST experimental database is not sufficient yet, specially concerned with normalized beta β_N and plasma confinement. So ITER database of plasma confinement is reasonable to use for A=2 tokamaks.

4). *Steady state operation.*

This regime becomes more and more attractive. It gives necessity of

$$f_{BS} + f_{CD} \approx 1$$

($f_{BS} = I_{BS}/I_P$ is bootstrap current fraction; $f_{CD} = I_{CD}/I_P$ is current drive fraction); necessity of high resource NBI system development; stationary cooling of VV and EMS etc.

Specific of work at A=2 and moderate normalized beta $\beta_N \leq 2.5–3$ is in not very high value of bootstrap current fraction $f_{BS} < 0.4 – 0.6$, so current drive fraction can be high $f_{CD} > 0.4 – 0.6$.

Note that in accordance with ITER Physical Basis [11] it is used the following limit for β_N:

$$\beta_N/q_{95} < 0.7 – 0.8$$

5). *Energy confinement* τ_.

ITER-IPB(y,1) scaling for plasma confinement is taken. In accordance with JT-60U recent data [12] the enhancement confinement factor $H_\tau=\tau_E/\tau_{IPB(y,1)}$ can be as high as $H_\tau=1.4$ if $n_e/n_{GW} < 0.8$.

6). *Plasma current I_P.*

For Q = 1 – 2 it is necessary to confine fast α-particles. This leads to the condition

$$I_P \geq 5.4 \cdot A^{-0.5} \cdot (1+k^2)/2k$$

which gives $I_P \geq 4.5$ MA (for A=2, k=1.7) and $I_P \geq 7.6$ MA (for _=1.4, k=3).

7). *Plasma heating/current drive power P_{AUX}.*

It is reasonable to use power, inputted into the plasma:

- as for plasma heating,
- for current drive,
- for fusion gain enhancement due to fast particles-plasma reactions.

In this case some exceeding of tritium concentration is preferable ($n_t/n_d \sim 1.5 - 2$)

The achieved level of absolute power input into the plasma by NBI is 40 MW (during 2 s) and 20 MW (during 8 s) [11]. In ITER-FEAT project the level of P_{AUX} is 50 MW.

For VNS it is reasonable to limit heating power at the level of $P_{AUX} \leq 40\text{-}50$ MW. One more limitation for specific heating is taken as $P_{AUX}/S_{pl} < 0.3$ MW/m^2 which also corresponds to the achieved level in tokamak experiments.

8). *Some technical details of the concept (see Fig.1)*

EMS is normal conducting on the Cu base with water cooling. Between TF and plasma at inboard 20 cm shield is situated (see also arguments concerned with 20 cm shield in [13]).

CS is surrounded near main torus axis, outside of TFC. PF coils are also outside TFC.

Blanket is surrounded at the outside between plasma and TFC.

2. Preliminary VNS parameters

In our project the following parameters and limitations were taken: R = 2 m, A = 2, a = 1 m, k_{95} = 1.7 (SN plasma configuration, X-point in the bottom), $\beta_{N,max}$ =3, $H_{\tau,max}$ = 1.4 (in relation to ITER- IPB(y,1) confinement scaling), P_{site} < 400 MW, $P_{AUX,max}$ = 40 MW ($p_{aux,max}$ = 0.3 MW/m^2). Reactions between fast particles of beam and plasma are taken into account.

Preliminary calculations leads to several options of VNS with A=2, presented in Table 2.

For both options presented in Table 2, fusion gain is Q = 1.4, fusion power is about $P_{FUS} \approx$ 56 MW, power in thermonuclear neutrons $P_N \approx$ 45 MW. Fraction of beam-plasma reactions in the total fusion power is about 60%. Confinement enhancement factor is $\_{\tau}$ = 1.2 – 1.4. Beam energy is about 140 keV.

Options of JUST-T main parameters Table 2.
(R = 2 m, A = 2, a = 1 m, k_{95} = 1.7 (SN↓), Q = 1.4, p_n = 0.4 MW/m^2
P_{AUX} = 40 MW, $P_{FUS,total}$ = 56 MW, $P_{FUS,\text{ beam-plasma}}$ =34 MW)

	I	II
Safety factor q	4	6
Total normalized beta β_N	2.8	2.8
Plasma current I_P, MA	6.5	5.3
Toroidal field at plasma axis B_t , T	3.2	3.9
Plasma density n_e, 10^{20} m^{-3}	1.2	1.2
Plasma average temperature T, keV	6	6
Bootstrap current fraction f_{BS}	0.3	0.55
Density to limit ratio n_e/n_{GW}	0.56	0.68
Confinement enhancem. factor to scaling IPB(y,1)	1.2	1.4
Part of fast α-particles pressure in beta $\beta_{f\alpha}/\beta_{total}$	4.5%	4.5%
Part of fast beam particles pressure in beta β_{fb}/β_{total}	6%	6%

3. Estimation of MA transmutation efficiency in VNS blanket

Term "MA transmutations" means fission of MA nucleus. Well known amount of MA annular production in LWR-1000 – 43 kg MA/(effective year) is used (40 years of cooling before transmutation is taken into account).

Calculations were given for following assumptions: 1D spherical geometry; 1.5 cm vacuum wall (zone 1); 20 cm thickness blanket (zones 2 and 3); 50 cm biological shield is beyond the blanket (zone 4); 80% of neutrons from plasma reaches the blanket.

General contain of blanket zones is shown in Table 3.

Blanket zones composition Table 3

Zone 1	50% Steel, 50% Coolant
Zone 2	15% Steel, 50% Coolant, 35% __
Zone 3	15% Steel, 40% Coolant, 45% __
Zone 4	75% Steel, 25% H_2O

Minor actinides (MA) are presented as dioxide with density 9 g/cm^3 and the following isotope contain:

Np^{237} – 30.8%, Am^{241} – 65.4%, Am^{241m} – 0.02336%, Am^{243} – 3.8%

This isotope contain corresponds to MA in irradiated fuel of LWR-1000 after 40 cooling.

Three options of heat-transport medium were analyzed:

1 - liquid lead (Pb);
2 – liquid lithium (Li) with natural contain of Li^6, Li^7 isotopes;
3 – water (H_2O)

Integral blanket parameters are presented in Table 4.

Integral blanket parameters Table 4

Parameter	Option 1 (Pb)	Option 2 (Li)	Option _ (H_20)
Fission events per one fusion neutron:			
In zone 2	2.55	1.87	0.66
In zone 3	6.84	5.17	1.23
Total	9.40	7.04	1.89
Integral characteristics for fusion neutrons power 45 MW			
Total thermal power MW	6000	4470	1200
Amount of supported VVER[*]-1000 reactors	54	41	11

[*] VVER is the Russian analog of LWR

A large neutron surplus in all analyzed types of blankets takes place, so there is no difficulties with tritium reproduction. If it is necessary Li reproduction in blanket, thermal power in blanket is slightly decreased (3% decreasing in option 1 and 16% - in option 3).

Calculations allow to conclude that one specialized transmutator of VNS type with fusion power 56 MW can secure MA transmutation requirements in existing and prognosed (50 years) RF NPP energetic. One such transmutator during annular work can transmute MA which produced in 10 – 50 VVER-1000.

Indicated amount is upper estimation (ports and pipes are not yet to be taken into account; blanket is not now well designed).

Conclusions

Concept of VNS on the tokamak base for transmutation (named JUST-T) is proposed. Tokamak has moderate dimensions R = 2 m. The blanket is effective for transmutation of Minor Actinides which are created during NPP work.

Plasma part of JUST-T VNS is based on moderate physical assumptions for aspect ratio A=2 (confinement enhancement factor to scaling IPB(y,1) $H \leq 1.4$; normalized beta $\beta_{N(total)} = 2.8$; bootstrap current fraction $f_{bs} \sim 0.5$; plasma density to Greenwald limit ratio $n_e/n_{GW} < 0.7$; neutron wall load $p_n = 0.4$ MW/m^2; plasma current $I_P = 5 – 6$ MA; drive power P = 40 MW).

References

[1] M.Abdou et al. Phase 1 Report of the IEA Study on High Volume Plasma-Based Neutron Source (HPVNS), 1994, UCLA-FNT-94,UCLA-ENG-95-111

[2] A.B.Mineev, Analysis of the Tokamak Neutron Source (VNS) design and range of its parameters, Fusion Engineering and Design, 27 (1995) 307-315

[3] L.J.Qiu, Y.C.Wu, B.J.Xiao et al. A Low Aspect Ratio Tokamak Transmutation System, Proc. 17th IAEA Fusion Energy Conference, Yokohama, Japan, 19-24 Oct. 1998, IAEA-F1-CN-69/FTP/06(R)

[4] Y.-K.M.Peng, W.Reiersen, S.M.Kaye et al., Nuclear Fusion, v.40, no.3Y, 2000, p.583

[5] D.C.Robinson, R.Akers, S.J.Allfrey et al. Fusion Technology Applications of the Spherical Tokamak, ibid. as in [2], IAEA-F1-CN-69/FT1/12

[6], see also D.Steiner, E.Cheng, ZR.Miller et al., Fusion Neutron-Source Study, Univ. of California, San Diego, Preprint UCSD-ENG-083

[7] E.A.Azizov, N.Ja.Dvorkin, O.G.Filatov et al., JUST: Concept Development and Status, Plasma Devices and Operations, 1997, v.5, p.99

[8] E.A.Azizov et al. KTM Tokamak Conceptual Design and Basic Parameters, in Proc. 21st SOFT, Spain, 2000, paper D-02, p.310

[9] V.S.Shkol'nik et al. The Low Aspect Ratio Megaampere Tokamak for Material Researches (KTM), paper on International Workshop on the Spherical Torus'97, Russia, v.1, p.597

[10] C.P.Wong e.a. "Toroidal Reactor Designs as a Function of Aspect Ratio", 18th IAEA FEC, Sorrento, 2000

[11] ITER Physics Basis, Nuclear Fusion, v.39, no.12, 1999

[12] JT-60U Experiment Report no. 57, Demonstration of Non-Inductive Operation Scenario for ITER, January 15th, 2001

[13] F.Najabadi, S.Jardin, M.Tillack et al., The ARIES-ST Study: Assessment of the ST Concept as Fusion Power Plant, Proc. 17th IAEA Fusion Energy Conference, Yokohama, Japan, 19-24 Oct. 1998, IAEA-CN-69/FTP/08

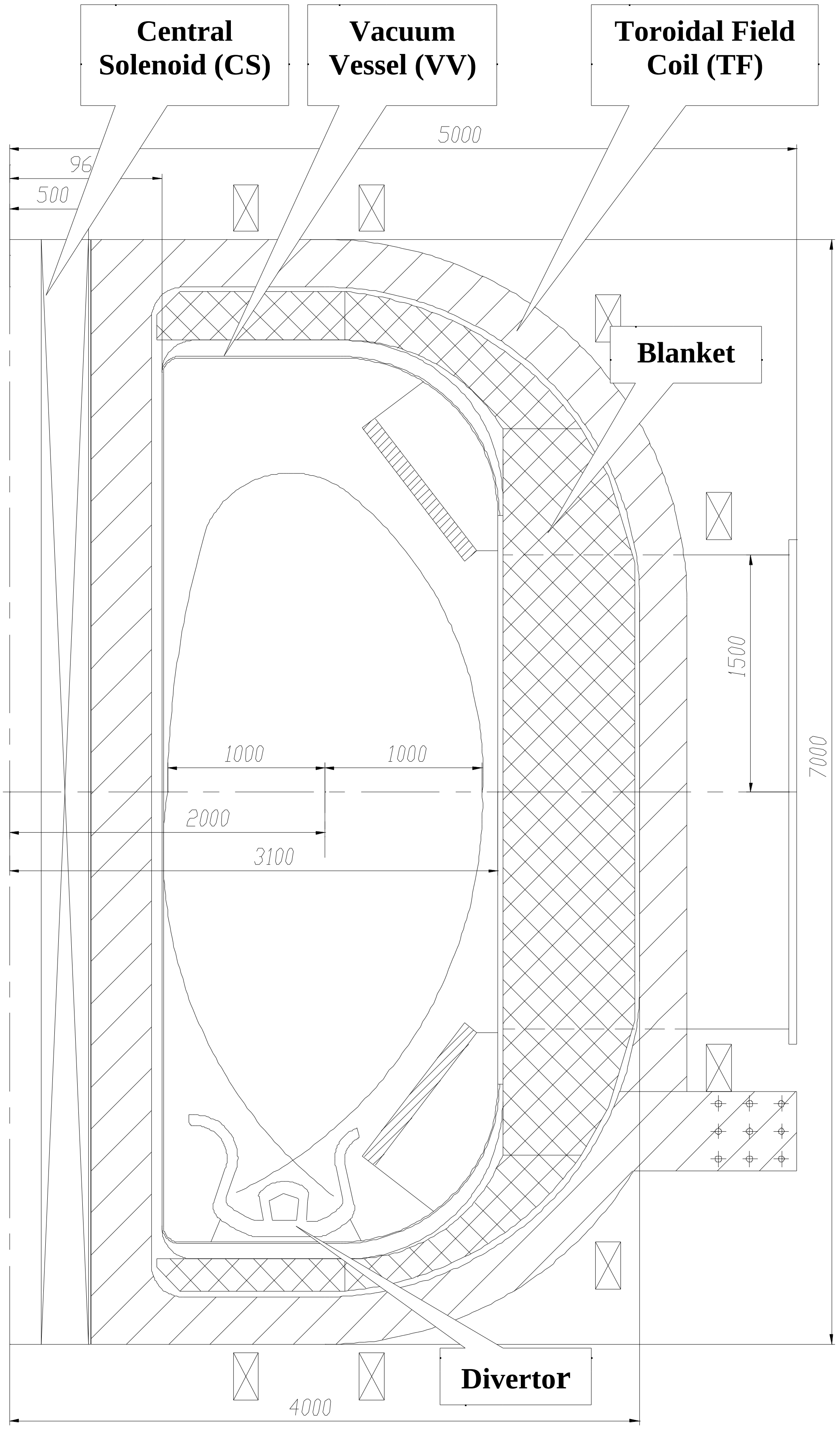

Fig.1. Principal view of JUST-T cross-section