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Neutron-Physical Characteristics of Blanket of Hybrid Fusion Neutron Source Based on Solution of Thorium Nitrate and Minor Actinides in Heavy Water

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INTRODUCTION

In the Russian Federation, the creation of a fusion neutron source (FNS) is a priority in the implementation of the federal target program for the development of new-generation nuclear energy technologies. The Kurchatov Institute considers the Tokamak T-15MD as a prototype source of thermonuclear neutrons. The development of a hybrid blanket for a fusion neutron source is an important part of the tasks being solved.

PURPOSE OF STUDY AND TASKS

The purpose is to study the possibilities of transmutation of minor actinides (MA) and the production of nuclear fuel (uranium–233 and tritium) in a FNS blanket consisting of a solution of thorium nitrate in heavy water.

The following tasks were set:

- Justification of the use of thorium nitrate solution in heavy water as a FNS blanket material;
- Comparison of the calculated neutron-physical characteristics of a heavy-water blanket with thorium dioxide and a blanket with thorium nitrate;
- Calculation of the production of nuclear fuel (uranium-233 and tritium) in the FNS model when loading minor actinides;
- Calculation of the transmutation of minor actinides in an aqueous blanket.

METHOD

The Monte Carlo MCNP-4 code and ENDF-B-VII nuclear data were used.

CALCULATION MODEL

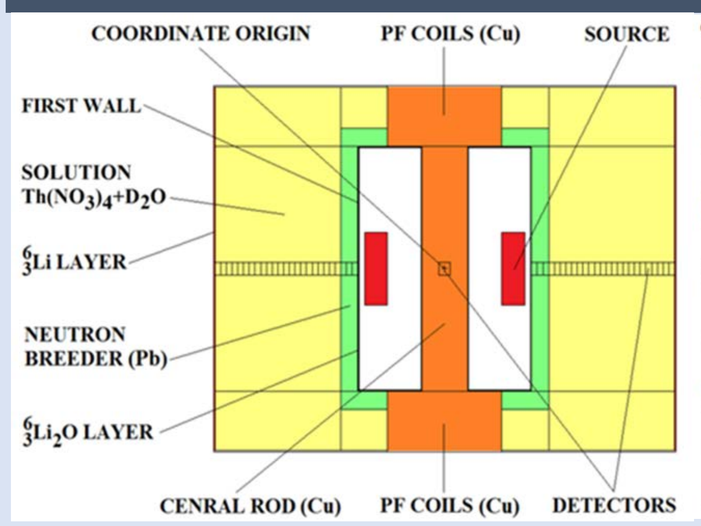

Fig. 1. View of the central vertical cross-section of the FNS model.

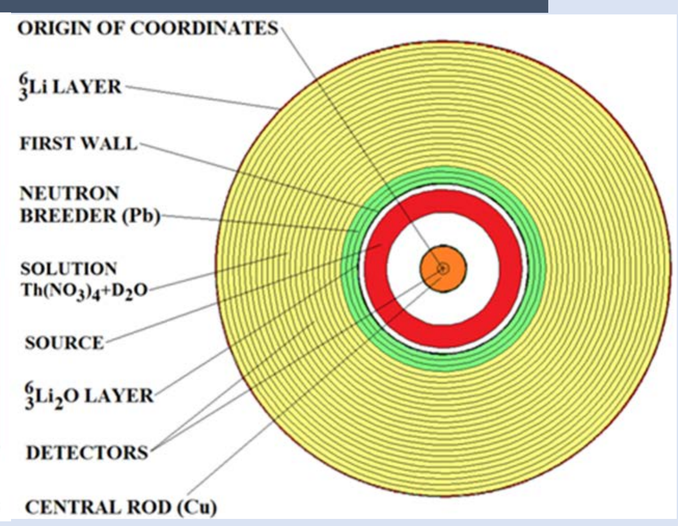

Fig. 2. View of the equatorial horizontal cross-section of the FNS model.

OVERAL DIMENSIONS: R = 201.8 cm, h = 301.6 cm;
FUSION NEUTRON SOURCE: 14.1 MEV D-T, isotropic ; R=70 cm r=50 cm, h=60 cm;
EMISSION RATE: 5 МВт (1,775× 10^{18} n/s);
CENTRAL RODE: Cu, R=20 cm, h=201.6 cm;
VACUUM VESSEL: R=75 cm, r=20.8 см, h=200 cm;
PF COILS: Cu, R=50 cm, h=50 cm;
FIRST WALL: 3 mm Mo, 1 mm Cu, 1 mm Cu-Cr-Zr; 3 mm H_2O; 1 mm, V92-Ti4-Cr4;
$^6Li_2O$ SHELL AROUND THE FIRST WALL: thickness of 1 mm;
^{6}LI SHELL ALONG THE OUTER CONTOUR OF FNS: thickness of 1 cm;
SOLID-STATE BLANKET: Pb**;**
AQUEOUS BLANKET: solution of $Th(NO_3)_4$ in D_2O with ^{233}U and minor actinides;
26 DETECTORS: R-r=5 cm, h=10 cm;
DETECTOR IN CENTER:
R=5 cm, h=10 cm.

RESULTS

Table 1. Production of nuclear fuel in FNS model with $^{232}ThO_2$ and $^{232}Th(NO_3)_4$ blanket (0% ^{233}U) without minor actinides at a D-T neutron source intensity of 1.775×10^{18} n/s.

Material of the aqueous blanket	$^{232}ThO_2$ (34.95 g) + D_2O (100 g)	$^{232}Th(NO_3)_4$ (61.43 g) + D_2O (100 g)
Volume of the aqueous blanket, m^3	15.6987	
Total amount of ^{6}Li, kg	341.255	
^{233}U enrichment (wt. %)	0	0
Loading of MA, kg	0	0
Loading of ^{232}Th, kg	5.137×10^3	5.116×10^3
Loading of ^{233}U, kg	0	0
Neutron yield per 1 fission of the ^{232}Th nucleus	3.189	3.232
k_{eff}	<<1	<<1
Leakage	1.097×10^{-2}	6.849×10^{-3}
^3H production, kg/year ($^6Li_2O$)	9.967×10^{-2}	1.652×10^{-1}
^3H production, kg/year (^6Li)	8.221×10^{-2}	1.062×10^{-2}
^3H production, kg/year (total)	1.079×10^{-1}	1.760×10^{-1}
^3H consumption, kg/year	~3.000×10^{-1}	~3.000×10^{-1}
Reproduction rate of ^3H	3.598×10^{-1}	5.867×10^{-1}
^{233}U production, kg/year	1.443×10^1	1.874×10^1
^{233}U consumption, kg/year	0	0
Reproduction rate of ^{233}U	0	0
Thermal power of the ^{232}Th blanket, MW	1.679	7.151×10^{-1}
Electrical power, MW	5.597×10^{-1}	2.384×10^{-1}
Thermal power density, MW/m3	1.070×10^{-1}	4.555×10^{-2}
Maximum statistical uncertainty, %	0.08	0.4

RESULTS

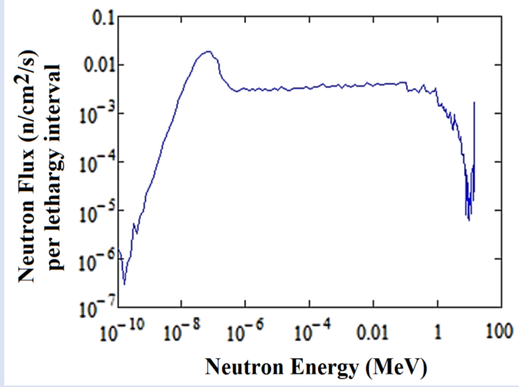

Fig.3. The averaged neutron flux energy spectrum in the heavy water blanket ($Th(NO_3)_4$ + D_2O) at keff = 0.95 (1.7% ^{233}U) at a neutron source power of 1 n/s.

Table 2. Production of nuclear fuel in $^{232}Th(NO_3)_4$ heavy-water blanket depending of ^{233}U enrichment for 1 year (365 d) of machine operation at neutron source intensity of 5 MW (1.775×10^{18} n/s).

The mass of minor actinides in a thorium blanket with a total load of 21 kg is 9.345 of ^{237}Np, 10.214 kg of ^{241}Am, 1.281 kg of ^{243}Am, 4.2×10^{-3} kg of ^{243}Cm, 1.554×10^{-1} kg of ^{244}Cm				
Material of the aqueous blanket	$^{232}Th(NO_3)_4$ (61,43 g) + D_2O (100 g)			
Volume of the aqueous blanket, m^3	15.6987			
Total amount of ^{6}Li, kg	341.255			
^{233}U enrichment (wt. %)	0	1.6	1.7	1.8
Loading of ^{232}Th, kg	5.095×10^3	5.014×10^3	5.009×10^3	5.004×10^3
Loading of ^{233}U, kg	0	8.153×10^1	8.662×10^1	9.172×10^1
k_{eff}	0.004	0.926	0.952	0.983
Reactivity $\rho = (k_{eff} - 1)/k_{eff}$	—	–0.079	–0.050	–0.017
Neutron yield per 1 fission of the ^{233}U nucleus	—	2.498	2.498	2.498
^{233}U production, kg/year	1.588×10^1	$1,097\times10^2$	$1,755\times10^2$	$4,449\times10^2$
^{233}U consumption, kg/year	0	1.087×10^2	1.842×10^2	4.926×10^2
Reproduction rate of ^{233}U	0	1.009	0.953	0.903
^3H production, kg/year	0.188	0.417	0.553	1.117
^3H consumption, kg/year	~3.000×10^{-1}	~3.000×10^{-1}	~3.000×10^{-1}	~3.000×10^{-1}
Reproduction rate of ^3H	0.627	1.390	1.843	3.273
Thermal power of the ^{232}Th blanket, MW	1.931	2.442×10^2	4.123×10^2	1.100×10^3
Electrical power, MW	6.437×10^{-1}	8.141×10^1	1.374×10^2	3.667×10^2
Thermal power density, MW/m^3	1.230×10^{-1}	1.556×10^1	2.626×10^1	7.007×10^1
Maximum statistical uncertainty, %	0.1	0.8	1	3

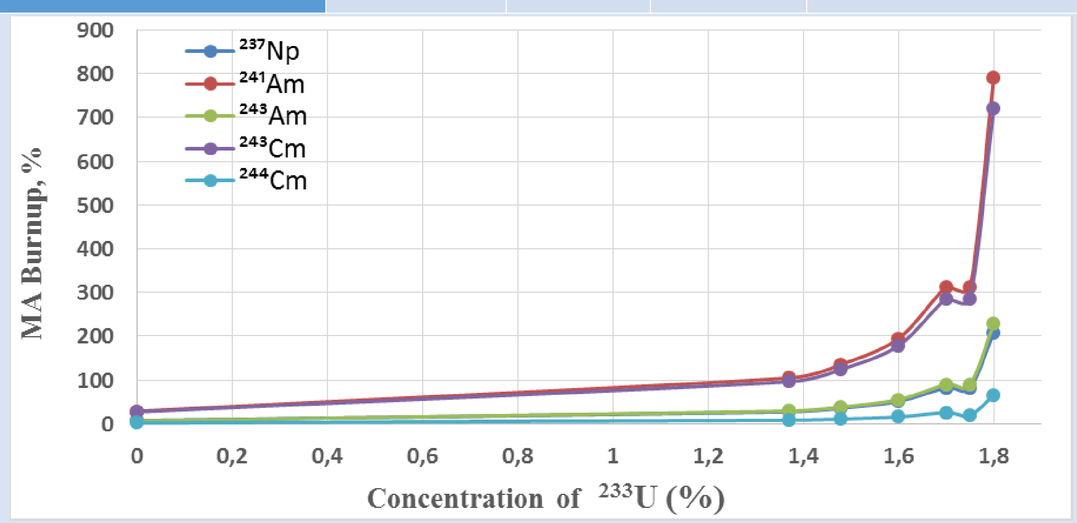

Fig.4. MA burnup in 365 days at a neutron source power of 5 MW (1.775×10^{18} n/s) depending on the degree of enrichment of the blanket with uranium-233.

CONCLUSION

- Thorium nitrate enriched with the isotope ^{15}N is able to successfully replace thorium dioxide, which has a high abrasiveness.
- The production of ^{233}U and tritium in a solution of thorium nitrate and minor actinides in the mode of the deep subcritical state of the blanket (keff ~ 0.95) makes it possible to achieve fuel self-sufficiency.
- At keff ~ 0.95, the machine has an electrical power of about 80–130 MW, which corresponds to the one of a low-power reactor.
- Transmutation in the FNS spectrum with a high proportion of thermal neutrons makes it possible to completely ignite the loading of neptunium-237 and americium isotopes in a safe mode (keff ~ 0.95) in 1.5–2 years. The values improve if the enrichment of the blanket with uranium-233 is increased.
- The ^{244}Cm isotope does not completely burn up. The calculations show that in the thermal spectrum, the ^{244}Cm load can be burned by 65%. As a result of α-decay with a $T_{1/2}$ period of 18.1 years, ^{244}Cm turns into plutonium, which can be returned to the fuel cycle.
- The utilization of MA in a fusion hybrid plant makes it possible to successfully ignite actinides due to the high thermal neutron flux density, which can be changed by varying the power of nuclear fusion. It is also possible to regulate the energy spectrum of neutrons by changing the ratio of fuel and moderator in the blanket.
- The state of the blanket (core) is controlled not by delayed neutrons, but by neutrons emitted by the plasma, which eliminates the loss of control over the blanket's thermal power.
- During the burning of MA, isotopes valuable in industry and medicine are formed in the radiation capture reaction. There are many fissionable ones among them, which can be ignited by recycling.

ACKNOWLEDGEMENTS / REFERENCES

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