Fusion Neutron Source Blanket: Requirements on Calculation Accuracy and Benchmark Experiment Precision

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Abstract. In this report the requirements to the calculation accuracy of the main parameters of the fusion neutron source and the thermonuclear blankets with the DT fusion power of more than 10 MW are formulated. To conduct the benchmark experiments the technical documentation and calculation models were developed for two blanket micro-models: the molten salt and heavy water solid-state blanket. The calculations of the neutron spectra and 37 dosimetric reaction rates that are widely used for the registration of thermal, resonance and threshold (0.25−13.45 MeV) neutrons were performed for each blanket micro-model. The MCNP and MCU code and the neutron data library ENDF/B-VII were used for the calculations. All the calculations were performed for two kinds of the neutron source: I is the fusion source, II is the source of neutrons generated by the ^{7}Li target irradiated by protons with energy 24.6 MeV. The spectral indexes ratios were calculated to describe the spectrum variations from different neutron sources. The obtained results demonstrate the advantage of use of the fusion neutron source in future experiments.

1. Introduction

Currently, projects of subcritical systems with external neutron sources for transmutation of nuclear waste are designed in all countries with the developed nuclear power. The base Russian project is a fusion neutron source which neutrons are generated in the (d,t) reaction. Now a conceptual design of a demonstration fusion neutron source (DEMO-FNS) with the fusion power of at least 10 MW is worked out at the Kurchatov Centre of Nuclear Technologies in the National Research Centre "Kurchatov Institute" [1-3]. The work on the project showed that there are significant differences between the required and achieved accuracy of calculations of the main DEMO-FNS parameters (see table). The analysis of the literature is indicated that there is a small number of benchmark experiments with different models of blankets that can be applied to verification of software used for justification of nuclear and radiation safety of the full-scale subcritical blankets. Their virtual absence has made relevant the problem of preparation and justification of such experiments. A complex composition of nuclides of the blankets and the need to maintain the necessary low level of criticality requires the development of a specific approach to these experiments. For this purpose two types of thorium fusion micro models of the blankets were considered and analyzed. There are a salt and heavy water one.

TABLE: REQUIREMENTS TO CALCULATIONAL ACCURACY OF BASIC PARAMETERS OF DEMO-FNS AND BLANKETS.

Fusion Neutron Source		
Parameter	Calculational accuracy of parameters	Required accuracy of parameters
Heat power of fusion reaction in tokamak	20 %	20 %
Neutron yield	20 %	20 %
Average power density of reactor core	< 25 %	< 25 %
Radiation resistance of construction materials	>100%	30%
Parameters of power density in central rod of tokamak	<20%	10%
Activation of construction materials of tokamak	40%	40%
Blanket		
Parameter	Calculational accuracy of parameters	Required accuracy of parameters
Heat power transferred in blanket	5-6%	3%
K_{eff} ~ 0.95	2-3%	0.5-1.0%
Neutron flux for • thermal spectrum • fast spectrum	25-30% 12-17%	10% 5%
Tritium generation rate	15%	5%
Rate of generation of basic functional for ^{233}U, ^{233}Pa	15%,10%	7%,5%
Rate of transmutation : • for fissionable minor actinides • for minor actinides with threshold energy	~10% ~30%	5-7 %

2. Description of calculational models

2.1. Molten salt model (Model I)

The general view of the model is shown in *FIG. 1*. It consists of a coaxial internal tank (Ø230x58 mm) filled with melt flibe made from thorium fluoride salt (LiF(67%) + BeF_2(18%) + ThF_4(15%)). It has three channels for detectors with radii of 46.5 mm, 72.0 mm and 96.5 mm. Around the internal tank there is a coaxial external tank (Ø738x234 mm) that can be filled with various moderators (D_2O, H_2O, or C). This tank is used for the generation of a neutron spectrum similar to a spectrum of a fusion thorium blanket. The height of both tanks is 522 mm. The internal and external tank is made from hastelloy. The central rod is shown in *FIG. 2*. It is consisted of four coaxial bushings (Ø55x36 mm, h=522 mm). The external one is composed of hastelloy. The material of the next ones is Al, 6Li2O, and Al.

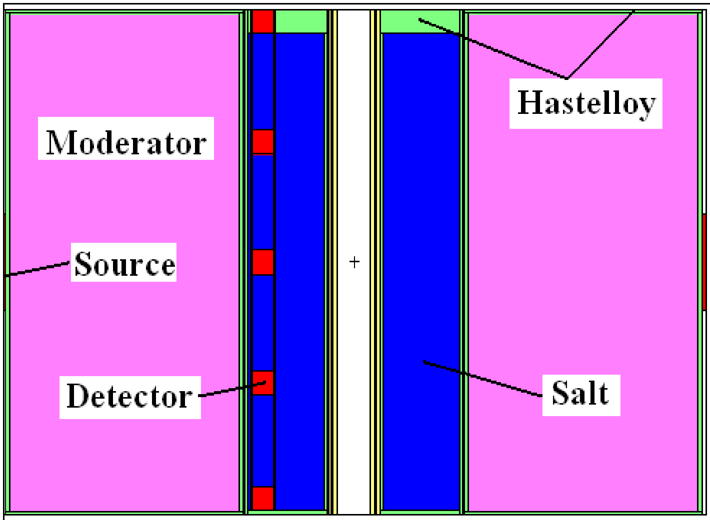

FIG. 1. The vertical cross section view of the molten salt model.

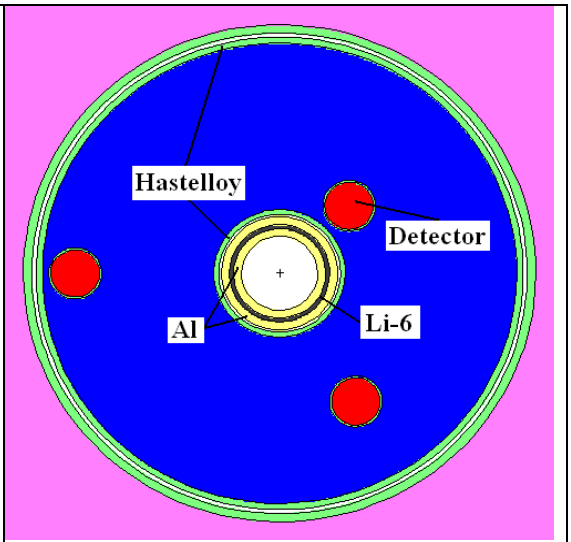

FIG. 2. The central rod and detector locations.

The channels are hastelloy tubes (Ø25x23 mm) inside which there are hastelloy pencil cases (Ø21.5x18.5 mm) filled with blocks composed of melt flibe with thorium fluoride which composition is specified above. The dosimetrical detectors are between the blocks.

2.2. Solid fuel model (Model II)

The general view of the model is presented in *FIG. 3*. The only difference between the model I and II is a composition of the internal tank. In the model II there are fuel channels instead of the one with the molten salt. The fuel channels are zirconium tubes (Ø25x23 mm) filled with blocks consisted of metallic thorium inside aluminium coatings. The tank is filled with D_2O, H_2O, or C. Zirconium is used as a constructive material instead of hastelloy.

The fuel channels are arranged in an upper and lower remote lattice inside the tank and form two rings (*FIG. 4*). There are 12 rods on the inner ring (I-st row) with the radius of 57 mm and 18 rods on the outer one (II-nd row) with the radius of 87.5 mm. The whole model has the rotational symmetry of 60 degrees.

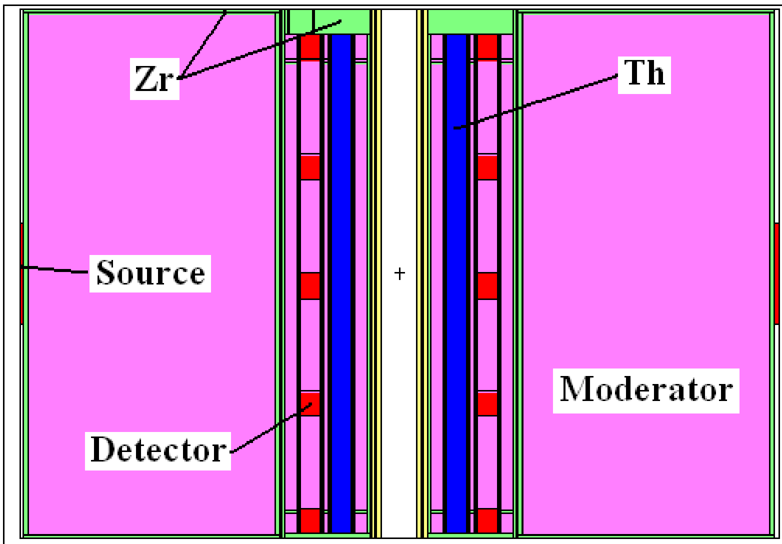

FIG. 3. The vertical cross section view of the solid fuel model.

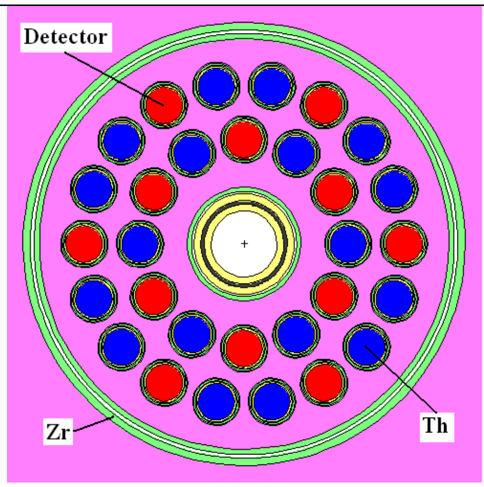

FIG.4. The locations of thorium channels and detectors.

3. Calculations of reaction rates, spectral indexes and neutron spectra

Two neutron sources were used in the calculations:
(i) the source that generates only the neutrons with the energy of 14.1 MeV;
(ii) the source based on the proton accelerator with the energy of 24.6 MeV and ^{7}Li target. The source generates neutrons with the spectrum presented in [4].

The results were obtained for 14 threshold detectors presented in [5, 6, 7] and 3 additional one (Mn, Lu and Au), which registered 37 products of the nuclear reactions.

The reaction rates R [1/(s·cm^3)] were calculated using the detector volumes V = 10.39 cm^3 for the molten salt model, and V = 47.12 cm^3 for the solid fuel one.

The normalized reaction rate RR [1/s] is obtained from the reaction rate R using the expression

$$RR = R \cdot V \qquad (1)$$

The spectral indexes were calculated according to the formula

$$SI_i = RR_i^{14MeV} / RR_i^{7Li} \qquad (2)$$

where SI_i is the spectral index obtained for the i–th reaction rate; RR_i^{14MeV} is the i–th reaction rate with the 14 MeV neutron source; RR_i^{7Li} is the i–th reaction rate with the ^{7}Li neutron source.

The neutron spectra and spectral indexes were calculated for the external tank filled with the D_2O, H_2O and C moderators.

As an example, *FIG. 5* shows the neutron spectra obtained for the molten salt blanket with the D_2O moderator. *FIG. 6* illustrates the spectra for the solid state blanket with the same moderator. The appropriate spectral indexes are shown in *FIG. 7* and *FIG. 8*. The calculations were performed using the MCNP [8] and [9] codes with the nuclear data library from the ENDF/B-VII files [10].

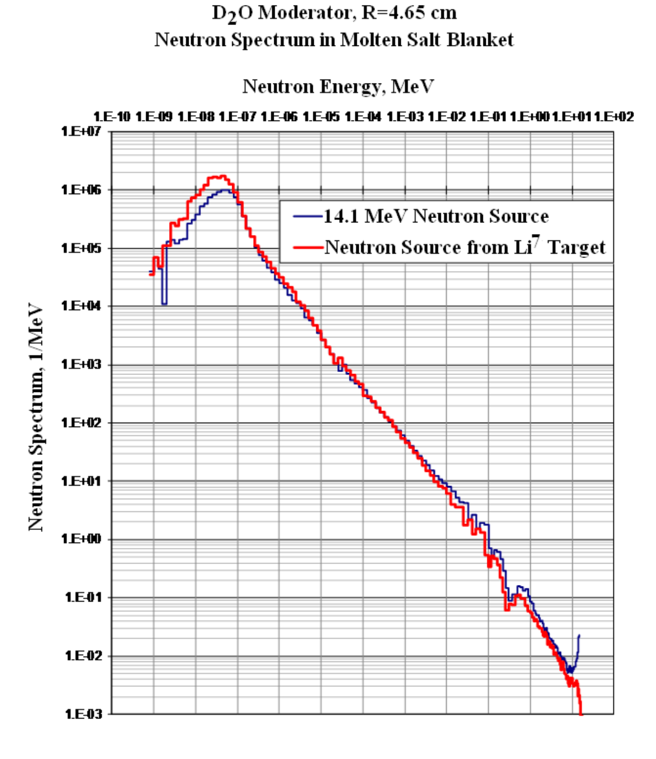

FIG. 5. *The energy spectrum in the molten salt blanket model with the heavy water moderator.*

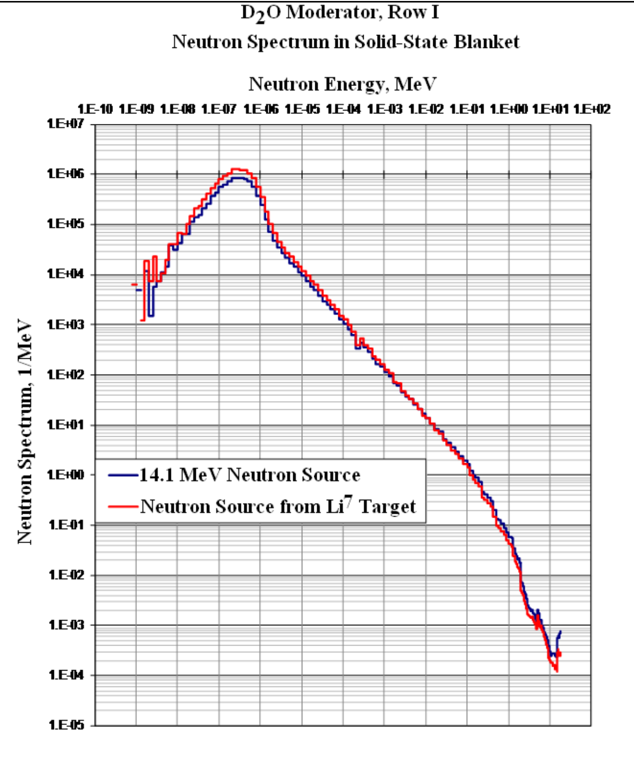

FIG. 6. *The energy spectrum in the solid fuel blanket model with the heavy water moderator.*

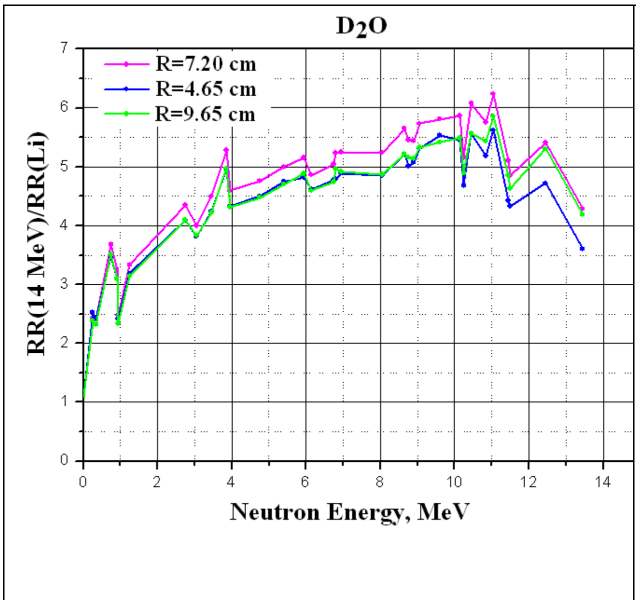

FIG.7. The spectral indexes in the molten salt blanket model with the heavy water moderator.

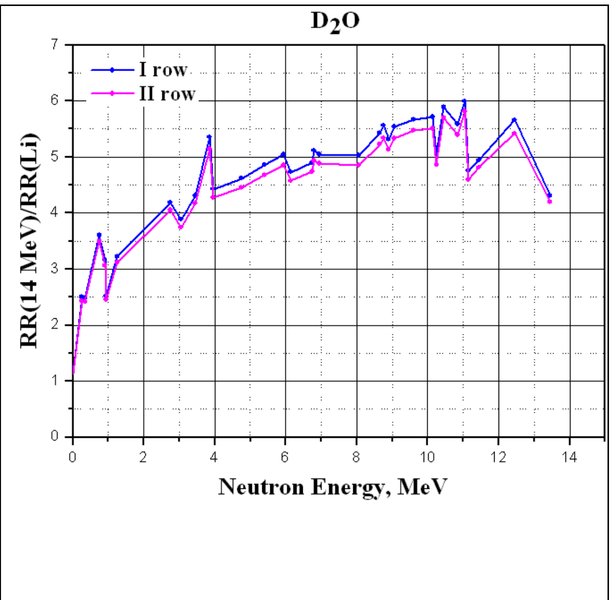

FIG. 8. The spectral indexes in the solid fuel blanket model with the heavy water moderator.

5. Conclusion

This study is the first step of the development of the benchmark experiment techniques to verify the nuclear data libraries necessary to the DEMO-FNS design. At this stage the technical documentation for fabricating the micro-models of the DEMO-FNS blankets is prepared, the mathematical models of the molten salt and solid fuel blanket are made, and their calculational analysis is performed. The results of the analysis showed the advantage of using the source which generates only the neutrons with the energy of 14.1 MeV over the source based on the proton accelerator. The reason of this is the difference in the calculated spectra for the neutron energies above ~ 100 keV. The increase of the values of the spectral indices quantitatively supports this conclusion.

Acknowledgments

This work is supported by the Russian Foundation for Fundamental Research according to the contract 14-08-90042.

References

[1] VELIKHOV, E.P., “Fusion-fission hybrid systems and molten salt technologies in large-scale nuclear energy”. Opening Report O/3, 25th IAEA Fusion Energy Conference, St. Petersburg, Russian Federation, 13-18 October 2014.

[2] KUTEEV, B.V., AZIZOV, E.A., ALEXEEV, P.N., IGNATIEV, V.V., SUBBOTIN, S.A., TSIBULSKIY V.F. ,”Development of DEMO-FNS tokamak for fusion and hybrid technologies”, Nuclear Fusion **55** (2015):073035.

[3] ZHIRKIN, A.V., KUTEEV, B.V., GUREVICH, M.I., CHUKBAR, B.K., “Neutronics analysis of blankets for a hybrid fusion neutron source”, Nuclear Fusion **55,** Number 11 (2015):113007.

[4] TITARENKO, YU.E., BATYAEV, V.F., PAVLOV, K.V., TITARENKO, A.YU, ALEKSEEV, P.N., GUREVICH, M.I., DUDNIKOV, A.A., ZHIRKIN, A.V., KUTEEV, B.V., KOLDOBSKII, A.B., KIEVITSKAYA, A.I., FOKOV, YU.G., “Benchmark Experiments for Verifying the Working Parameters of the Blankets of a Thermonuclear Neutron Source”, Atomic Energy (May 2016) DOI: 10.1007/s10512-016-0095-x.

[5] EZHOV, A. A., KNIZHNIKOVA, L. A., FRUNZE, V. V., “The effective threshold cross sections for the experimental determination of neutron fluxes in fusion reactor blankets”, VANT, Series: Nuclear constants, Issue **1**(**55**) (1984), pp. 29-34.

[6] SEVASTYANOV, V. D., KOSHELEV, A. S., GSSSD MR 182-2011. Methods of recovery of the neutron spectra of nuclear reactors and neutron CASCADE 200(176)

generators. Certified by Russian Scientific Technical Information Centre for Standardization, Metrology and Evaluation of Compliance, (FGUP "STANDARTINFORM") 03.05.2011. M.: "VNIIFTRI", 2011, 26 p.

[7] SEVASTYANOV, V. D., KOSHELEV, A. S., MASLOV, G. N., Characteristics of neutron fields, Reference book, Mendeleevo 2007.

[8] PELOWITZ, D.B., ed., “MCNPX User’s Manual, Version 2.6.0”, LANL report LA-CP-07-14 73 (April 2008).

[9] GOMIN, E.A., “MCU-4 Status”, Journal “Problems of Nuclear Science and Engineering. Series: Physics of Nuclear Reactors”, issue No.1, Moscow (2006), pp. 6-32.

[10] CHADWICK, M. B., et al., “ENDF/B-VII.1 Nuclear Data for Science and Technology: Cross Sections, Covariances, Fission Product Yields and Decay Data”, Nuclear Data Sheets, Vol. 112, Issue 12 (December 2011) Pages 2887-2996, http://dx.doi.org/10.1016/j.nds.2011.11.002.