7th International Conference on Modelling and Simulation in Nuclear Science and Engineering (7ICMSNSE)
Ottawa Marriott Hotel, Ottawa, Ontario, Canada, October 18-21, 2015

7ICMSNSE-020

Neutronic Design for a 100MW$_{th}$ Small Modular Natural Circulation Lead or Lead-alloy Cooled Fast Reactors Core

Chong Chen, Hongli Chen, Haoran Zhang, Zhao Chen and Qin Zeng
School of Nuclear Science and Technology, University of Science and Technology of China,
Hefei, Anhui 230027, China
shchshch@ustc.edu.cn, hlchen1@ustc.edu.cn, kulah@mail.ustc.edu.cn,
zchen214@mail.ustc.edu.cn, zengqin@ustc.edu.cn

Abstract

Lead or lead-alloy cooled fast reactor with good fuel proliferation and nuclear waste transmutation capability, as well as high security and economy, is a great potential for the development of fourth-generation nuclear energy systems. Small natural circulation reactor is an important technical route lead cooled fast reactors industrial applications, which has been chosen as one of the three reference technical for solution lead or lead-alloy cooled fast reactors by GIF lead-cooled fast reactor steering committee. The School of Nuclear Science and Technology of USTC proposed a small 100MW$_{th}$ natural circulation lead cooled fast reactor concept called SNCLFR-100 based realistic technology. This article describes the SNCLFR-100 reactor of the overall technical program, core physics calculation and analysis. The results show that: SNCLFR-100 with good neutronic and safety performance and relevant design parameters meet the security requirements with feasibility.

Keywords: LFR, natural circulation, lead-alloy cooled, SNCLFR-100

1. Introduction

Small Modular Reactor (SMR) are ideal for providing the electricity to countries with small, limited, or distributed electricity grid system. In recent years, due to their attractive advantages such as reduced capital costs and enhanced safety, small modular reactor has attracted particular attentions and been attracting considerable attention around the world such as been developed in the USA, Russia, China, Japan, Korea, France, and other countries. Several small module natural circulation lead or lead-alloy cooled fast reactors (LFRs) have been developed in the past decades due to the good natural circulation performance of lead or lead-alloy. In 1990s, Rubbia [1] proposed using a natural circulation LFR to serve as a sub-critical reactor for an Accelerator Driven System (ADS) in European Organization for Nuclear Research (CERN). In the early of 2000s, MacDonald and Todreas [2] carried out some research works on the natural circulation Lead–Bismuth Eutectic (LBE) cooled reactor for actinide burning and low cost electricity producing in Massachusetts Institute of Technology (MIT) and Idaho National Engineering and Environmental Laboratory (INEEL). In the late of 2000s, Sienicki [3,4] developed several small modular natural circulation LFR concepts in

Argonne National Laboratory (ANL), including SSTAR [3,5] and SUPERSTAR [4]. In 2011, Seoul National University designed a 100MWt/35MWe lead–bismuth-cooled small modular reactor called PASCAR[6] that is targeted to be the first generation of small modular reactor system as a long-life robust power unit[7,8]. At the same time a small natural circulation LFR has been developed to serve as an ADS research platform under the supported of the Chinese Academy of Sciences (CAS) Strategic Priority Research Program named ‘‘Advanced Nuclear Fission Energy-ADS Transmutation System’’[9-11].

Small natural circulation of lead-cooled fast reactor using a full natural circulation cooling circuit, during operation does not require an active circuit pumps and other mechanical equipment, and the reactors with good passive safety features. In addition, a small natural circulation lead cooled fast reactors can avoid a series of manufacturing and running problem come from lead-based materials pump, which can effectively reduce the lead cooled fast reactor material performance requirements, reduce the difficulty of engineering construction, and improve reactor project feasibility. But at the same time, compared with the more mature forced circulation cooling technology, all-natural circulation cooling small natural circulation lead cooled fast reactors need to face a new series of technical challenges, such as the natural circulation cooling is closely related to thermal-hydraulic phenomena, safety characteristics and so on.

SNCLFR-100 is a Small, 100MWt, Natural Circulation, Lead or Lead-alloy cooled Fast Reactor (LFR) which is one of the potential candidates for LFR development. In this paper a preliminary conceptual neutronics design study for the SNCLFR-100 is presented. The core configuration with level of fuel rods has been developed meeting the foremost requirements of limiting the reactivity swing over the core lifetime and flattening the radial power profiles, and

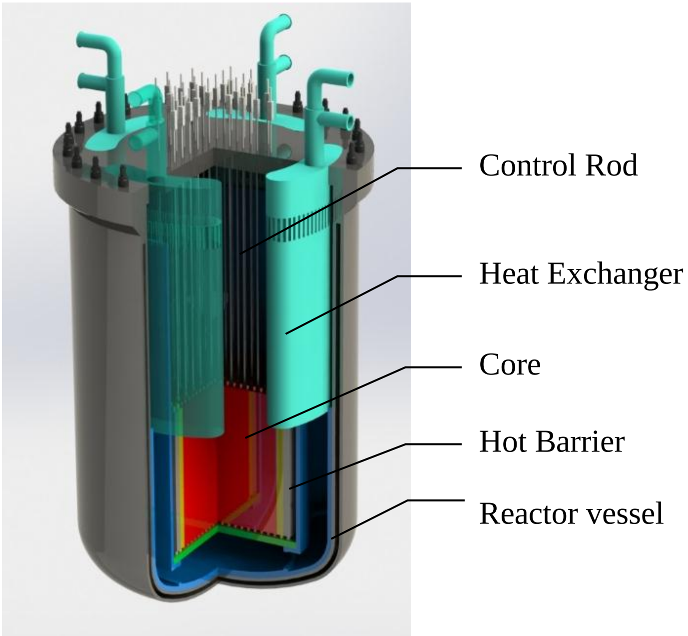


Fig 1 Illustration of SNCLFR-100

incorporating fissile self-sufficiency for efficient utilization of uranium resources. Reactivity coefficients and kinetic parameters have been evaluated for the reference beginning-of-life, middle-of-life and end-of-life core configurations.

2. SNCLFR-100 technical solutions

2.1 Overall technical parameters

SNCLFR-100 is designed based on the realistic technical small natural circulation lead cooled fast reactor, adopting an integrated arrangement, modular design and other advanced design concepts, with a simple system, flexible using, good economy, and high security features. The overall structure of SNCLFR-100 reactor is shown in Figure 1 and its overall technical parameters is shown in Table 1.

Table 1 Design parameter of reference rector for SNCLFR-100

Design factor	Design value
Core thermal power	100 MW_{th}
Metallic fuel composition	MOX（20 wt %）
Core lifetime	60 years
Refueling cycle	5 years
Core average burn-up	56 MWd kg^{-1} （HM）
Maximum reactivity swing	378 pcm
Size of the reactor	Φ6 m×10 m
Number of main heat exchanger device	4×Shell and tube heat exchangers
1st circuit coolant	Pb（l）
1st circuit operating temperature	400-480 ℃
1st circuit operating pressure	0.1 MPa
Drive	natural circulation
Loop height	4 m
1st circuit coolant flow	8528 kg/s
2nd circuit coolant	H_2O
2nd circuit operating temperature	330-430 ℃
2nd circuit operating pressure	18 MPa

2.2 Core design

The SNCLFR-100 reactor core considers the needs of whole natural circulation cooling by using a shorter axial height, a larger pitch to diameter ratio (P/D) and other methods to reduce the flow resistance of the core. The core is composed of 204 fuel assemblies, 36control rod assembly（24CR+12SR）, 48 reflective layer assembly and 84 shield layer assembly. There are three fuel zones district in the fuel layer assembly. The core is flat structure with 1m height and 2.8m equivalent diameter of the active area. As is shown, the core arrangement of SNCLFR-100 is shown in Figure 2 core design parameters in Table 2.

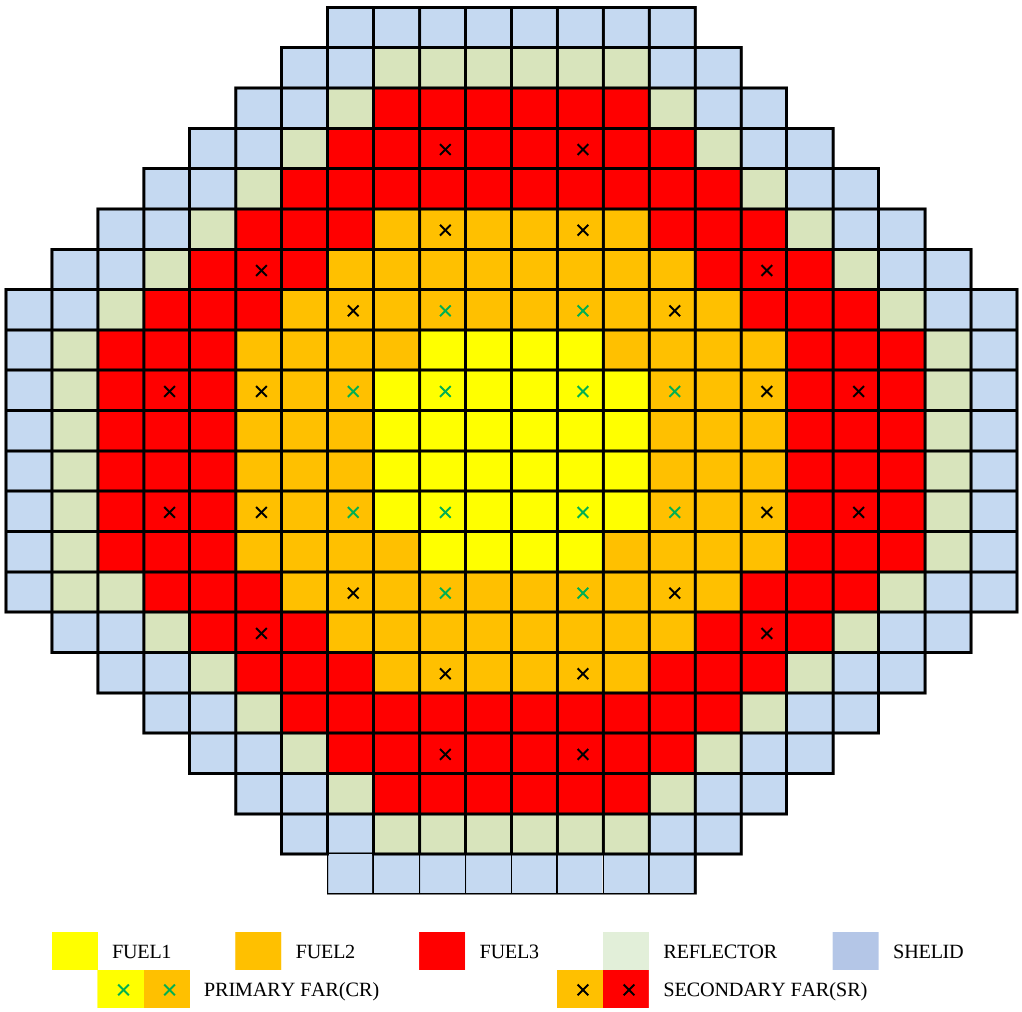
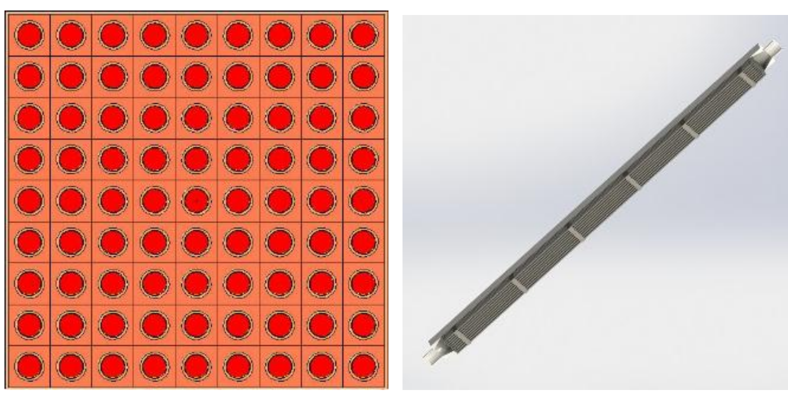


Fig 2 SNCLFR-100 core layout with location of primary (black) and secondary (green) FAR systems,

SNCLFR-100 fuel assemblies using 9 ×9 quadrangle arrangement for fixed 6-layer lattice fixed and the total length is 3.4 m, as shown in fig 3. Control rod assembly arrangement using 9 ×9 quadrangle, but in the center of 3 ×3 region is replaced with B_4C, as shown in fig 4. In order to overcome the problems of buoyancy caused by liquid lead, when do the mechanical design of the fuel assemblies and control rod assemblies need to consider the weight program, such as using heavy metals or other tungsten counterweight.

Table 2 SNCLFR-100 core design information

Design factor		Design value
Number of fuel assemblies		204
Number of control assemblies		24
Number of 2nd shutdown assemblies		12
Number of fuel rods		19116
Number of reflection assemblies		48
Number of shielding assemblies		84
total height of the core		3.4 m
Total core radius		1.73 m
Active core height		1 m
Active core radius		1.4 m
fuel	1st	$PuO_2$16%+$UO_2$84%
	2nd	$PuO_2$19%+$UO_2$81%
	3rd	$PuO_2$24%+$UO_2$76%
Fuel pellet diameter		9.8 mm
Fuel rod outer diameter		12.2 mm
Pin pitch		17.4 mm
Pitch to diameter ratio（P/D）		1.43



（a）2D （3）3D

Fig 3 Structure diagram of fuel assembly for SNCLFR-100 core

The fuel comes from the reprocessing of PWR spent UO_2 fuel burnt up to 45GWd/t, with a 4.5% initial enrichment in ^{235}U and 15 years of cooling period has been performed in [12,13].

The nature isotopic composition for Pb is reported in [14]. The lead density depends on the temperature as [15]:

$$\rho\ [kg/m^3]=11367-1.1944\times T[K]$$

For 400 ℃ and 480 ℃, this corresponds to 10.56 g/cm^3 and 10.47 g/cm^3 respectively.

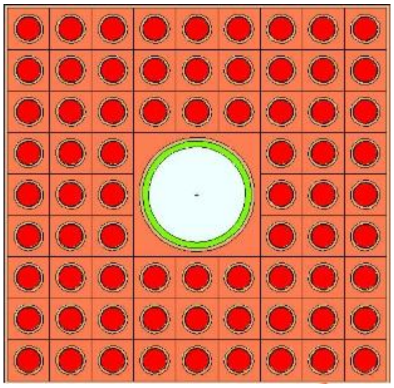


Fig 4 Structure diagram of control assembly for SNCLFR-100 core

3. Neutronic calculate and analysis

3.1 Tools and modeling

Neutronics analyses have been performed by means of MCNP[16] coupled with JEFF-3.2 [17] data library and the code for automatic generating of multi-temperature continuous-energy neutron cross section libraries[18].

3.2 Control system

Table 3 Control system worth.

Absorber set	Reactivity worth（$）		
	Bol	Mol	Eol
Primary	12.56	12.49	12.68
Secondary	8.07	8.45	8.46

Control assemblies have three principal functions: (1) startup and shutdown capability; (2) reactivity compensation during a cycle; and (3) rapid shutdown for abnormal conditions. Neutron absorption material is natural boron in the form of B_4C. For a proper assessment of both control systems efficacy, a Monte Carlo method has been applied to the calculated FARs reactivity worth. The result is shown in table 3 and fig 5. The primary and secondary systems have shown a control worth of 12.56$ and 8.07$ respectively that is equivalent to 4.53%Δk/k and 2.91%Δk/k at BoL. Hence, each system alone can provide a sufficient shutdown margin. Both systems can be inserted together to give a total worth of 20.63$ or 7.44%Δk/k.

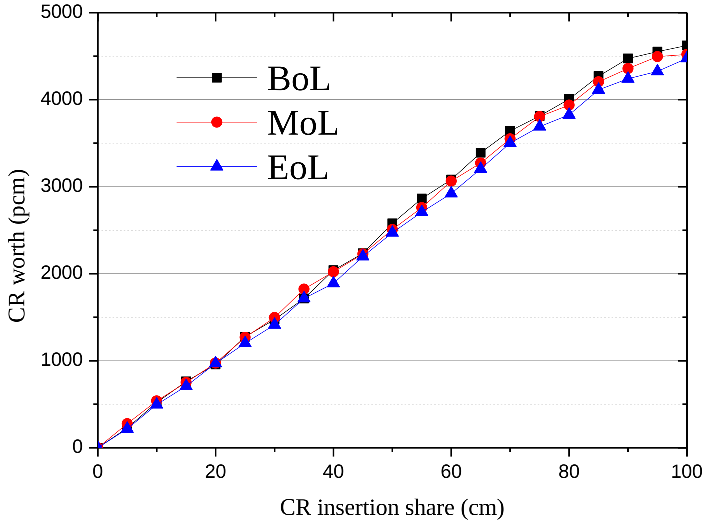


Fig 5 Reactivity worth of the primary control system at BoL, MoL and EoL

3.3 Key core performances

The key core performances, reactivity coefficients, and kinetic parameters of SNCLFR-100 are shown as follows:

Table 4 SNCLFR-100 key core performances.

Parameter	BoL	MoL	EoL	Units
k_{eff}	0.99989	1.00004	1.00006	-
Reactivity,ρ	-11	4	6	pcm
Primary FAR set insertion share	40.7	20.2	0	cm

Average power density	16.24	16.24	16.24	W cm^{-3}
Average linear power	52.3	52.3	52.3	W cm^{-1}
Average neutron flux	2.830E14	2.863E14	2.917E14	cm^{-2} s^{-1}

Table 5 Reactivity coefficients and kinetic parameters

Parameter	BoL	MoL	EoL	Units
Coolant Doppler coefficient*	-0.19	-0.57	-0.19	pcm K^{-1}
Fuel Doppler coefficient	-0.49	-0.64	-1.13	pcm K^{-1}
Axial expansion coefficient	-0.17	-0.13	-0.17	-
Radial expansion coefficient	-0.42	-0.51	-0.55	-
Delayed neutron fraction, β	368	362	353	pcm
Prompt neutron lifetime, Λ	552.06	552.42	542.08	ns

*Coolant temperature coefficient with the density change.

From the results of Doppler coefficient, lead density coefficient show that SNCLFR-100 has negative temperature reactivity effect which was conductive to the safety operation of the reactor. Negative expansion coefficient make the core remain steady state.

The thermal power density distribution of SNCLFR-100 core is shown in fig 6 and table 6. As it is shown, the peak position of the power density distribution is similar the same about the peak position of the neutron flux. As a result of the different fuels zones filled in different materials, the core produce different peak power values at the flux peak position, where the maximum axial power peak factor is 1.49 and the maximum radial power peak factor is 1.32.

Table 6 Peak power factor distribution of the rods for the hottest assembly（No.43）

0.99427	1.02642	1.01275	1.03199	1.03465	1.02968	1.05565	1.0392	1.05286
1.01207	1.0248	1.02199	1.02643	1.02901	1.04348	1.02974	1.05078	1.05561
0.98249	1.00491	1.01429	1.02333	1.02961	1.03432	1.02792	1.02151	1.01979
1.00143	1.01308	1.00756	1.02707	1.01186	1.02319	1.02009	1.03802	1.02944
0.99197	0.98832	0.99953	0.99953	1.02119	1.00708	1.01322	0.99479	1.01937
0.98925	0.99497	0.99493	0.9872	0.98375	0.99997	0.99927	0.99004	1.01062
0.95101	0.95213	0.99309	0.97507	0.98794	0.96489	1.00203	0.99967	0.98688
0.93725	0.97256	0.96593	0.96229	0.96871	0.99553	0.98479	0.98595	0.98899
0.92004	0.92513	0.94174	0.95512	0.95317	0.95931	0.96201	0.97027	0.95221

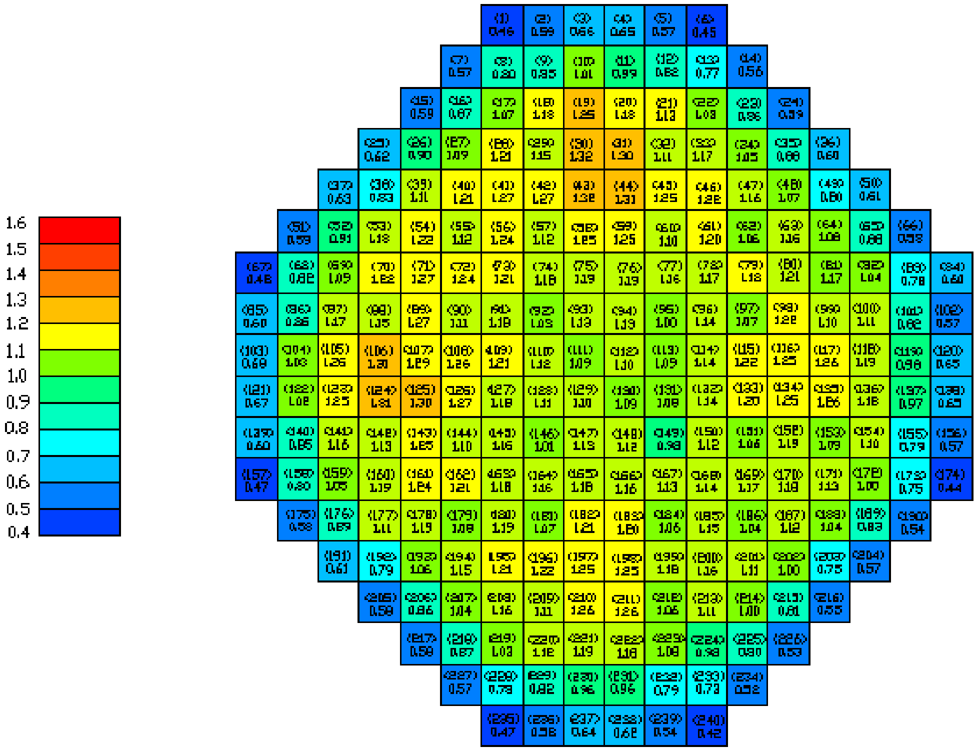


Fig 6 Power distribution of the fuel assembly along the radial（BOL）

4. Conclusion

Based on the viable technology, safety reliability and technology continuity requirements, the preliminary conceptual design of SNCLFR-100 has been developed which is related to the overall technical program design and core design. By computational analysis, the main properties of neutronics for the SNCLFR-100 core was completed. The results showed that: SNCLFR-100 has good neutronics, relevant design parameters to meet safety design requirements. In the future the core will be optimized.

5. Acknowledgment

This work is supported by the University of Science and Technology of China Youth Innovation Fund.

6. References

[1] Rubbia, C., et al., “Conceptual Design of a Fast Neutron Operated High Power Energy amplifier”, CERN/AT/95-44 (ET), 1995.

[2] P. E. MacDonald and N. Todreas, “Design of an Actinide Burning, Lead or Lead-Bismuth Cooled Reactor that Produces Low Cost Electricity Annual Project Status Report”, INEEL/EXT-2000-00994/MIT-ANP-PR-071, 2000.

[3] J.J. Sienicki, “Status Report on the Small Secure Transportable Autonomous Reactor (SSTAR)/Lead-Cooled Fast Reactor (LFR) and Supporting Research and Development”, ANL-GenIV-089, 2006.

[4] J.J. Sienicki, et al., “SUPERSTAR: an improved natural circulation, lead-cooled, small modular fast reactor for international deployment”, Proceedings of the 2011 International Congress on Advances in Nuclear Power Plants (ICAPP 2011), 2011.

[5] C.F. Smith, et al., “SSTAR: the US lead-cooled fast reactor (LFR)”, J. Nucl. Mater. Vol.376, No.3, 2008, pp. 255–259.

[6] Sungyeol Choi, et al. , “PASCAR: Long burning small modular reactor based on natural circulation”, Nuclear Engineering and Design, Vol. 241, 2011, pp. 1486-1499.

[7] I.S. Hwang, M.H. Kim, H.G. Joo, et al., “Development of transportable capsule version of PEACER design”, ICAPP 08, Anaheim, California, USA, 2008 June 8-12.

[8] I.S. Hwang, M.H. Kim, H.G. Joo, et al., “Development of PASCAR (Proliferation resistant, Accident-tolerant, Self-sustainable, Capsular, Assured Reactor) design and safety analysis”, 10th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Mito, Japan, 2008 October 6-10.

[9] W. Zhan, et al., “Advanced fission energy program-ADS transmutation system”, Bull. Chin. Acad. Sci. , Vol. 27, No.3, 2012, pp. 375–381.

[10] H. Chen, et al., “Preliminary thermal-hydraulic design and analysis of china lead alloy cooled research reactor (CLEAR-I)”. The 9th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9), Kaohsiung, Taiwan, 2012 9-14 September.

[11] Z. Chen, et al., “Study of core flow distribution for small modular natural circulation lead or lead-alloy cooled fast reactors”, Ann. Nucl. Energy, Vol.72, 2014, pp. 76–83.

[12] V. Sobolev, “Preliminary design variants for fuel rod, assembly and core of ELSY-600”, DEL/07/05, ANS/826/07-15 SCK.CEN, Rev. 1, ELSY project, 2007-10-10.

[13] G. Van den Eynde et al. “XT-ADS Core Neutronics & Cycle Analysis”, IP EUROTRANS DMI(VI EU FP), WP1.2, Deliverable D1.34 & D1.35, Reference: ANS/RMS/GvdE/gvde.3910, B044123 825/09-08, March 2009.

[14] NIST(National Institute of Standards and Technology), http://physics.nist.gov/cgi-bin/Compositions/stand_alone.pl?ele=&ascii=html&isotype=some

[15] Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies, Edition, ISBN 978-92-64-99002-9, NEA No. 6195, OECD 2007.

https://www.oecd-nea.org/science/reports/2007/pdf/chapter2.pdf

16] X-5 Monte Carlo Team, "MCNP - A General N-Particle Transport Code, Version 5" , Volume II: User's Guide", LA-CP-03-0245 (April, 2003).

[17] Joint Evaluated File (JEF) Project, The JEFF-3.2 Nuclear Data Library, 2014, http://www.oecd-nea.org/dbforms/data/eva/evatapes/jeff_32/

[18] C. Chen, et al., "Development and Testing of the Code for Automatic Generating of Multi-temperature Continuous-energy Neutron Cross Section Libraries", Nuclear Science and Techniques, Vol.25, NO.050602, 2014.