ADS with HEU in the Vinča Institute

Milan Pešić
Vinča Institute of Nuclear Sciences
Belgrade, Yugoslavia
mpesic@rt270.vin.bg.ac.yu

Nikolai Sobolevsky
Institute for Nuclear Research of Russian Academy of Science
Moscow, Russia
sobolevs@cpc.inr.ac.ru

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Abstract

The "Conceptual design of ADS" is a new project proposed in the Vinča Institute for the next three years. In this paper, an option in the project - an idea of high-enriched uranium (HEU) - H_2O low-flux ADS is shown. Preliminary results of design study and calculations of the beam-target interaction and neutronics of proposed sub-critical system are given.

1. Introduction

The Federal Assembly of the Federal Republics of Yugoslavia accepted a law in 1994 that forbids design and construction of nuclear power plants. The decision of the state to abandon nuclear energy option was initiated by the greenpeace movement in late eighties. This initiative was supported by strong influence of (wide and powerful) part of scientific and engineering community that promote energy production in coal power plants and hydro-power plants. Their arguments were based on relatively reach natural resources of coal and hydro-potentials of rivers in Yugoslavia. The law also includes penalties for prison up to five years for work on planning, site examination, design or construction of nuclear power plants or processing plants for irradiated fuel or storage of high-level radioactive waste in Yugoslavia. According to the law, only research in nuclear field is allowed.

Therefore, due to the law, currently there is no possibility to design a full scale ADS for power production or transmutation of radioactive waste and transuranium nuclides. On the other hand, quantities of irradiated fuel in Yugoslavia are (relatively) low compared to many other countries that use nuclear energy. The major quantity of irradiated fuel is stocked at the research reactor RA in the Vinča Institute because of the reactor operation in period 1959-1984. There is no plant, even on the laboratory scale, for processing of irradiated fuel in the country. Thus, the economy reasons do not support design and construction of ADS for transmutation of the irradiated fuel.

However, actual (political and economic) situation in the country, as well as the consequences of the last war in 1999, open again the question of power production sources. A 30% shortage in electricity power production in the country is estimated, as a result of damages in electricity power plants and transportation lines and due to facts that some coalmines and associated power plants at

Kosovo region are currently unattainable. Nuclear power plants for electricity production may become, beside electricity import, a real option in prospective. Therefore, the proposed experimental low-flux ADS, beside its usage as a valuable research machine, may contribute to following and developing new nuclear technologies in the country useful for eventual nuclear power option in future.

The current concept of the Vinča Institute of Nuclear Sciences proposes six new scientific programs for future research. The nuclear program – "Nuclear Reactors and Waste Management" - comprises, among the other projects, the "Conceptual design of ADS." Beside its contemporaneous concept and the reasons mentioned above, the idea of research of a sub-critical reactor driven by an accelerator beam is supported (Pešić et al., 1999) by facts that:

- Construction of the TESLA Accelerator Installation (Nešković et al., 1992) in the Vinča Institute is in the final stage,
- A rich experience in design, construction, operation and maintenance of both research reactors RA and RB in the Institute is acquired during the last 40 years (Pešić et al., 1999a), and
- A significant amount of fresh HEU fuel elements could be available for that purpose.

The TESLA Accelerator Installation is a multi-purpose facility for production, acceleration and use of ions. Its construction began in September 1992 in co-operation with the international scientific centres at the CERN (Switzerland) and DUBNA (Russia). The installation comprises (Fig. 1):

- A compact isochronous cyclotron - the VINCY Cyclotron,
- An electron cyclotron resonance heavy ion source the - mVINIS Ion Source,
- A volume light ion source - the pVINIS Ion Source, and
- Several low and high-energy experimental channels.

The ion sources are already in operation, while the first beam extraction from the VINCY Cyclotron is scheduled to September 2000. Designed parameters of the accelerator are set 10 years ago and regarding the ADS for energy production or transmutation of transuranium nuclides are not favourable. The cyclotron can deliver to the target either protons with maximum energy of 75 MeV and current of 5 μA, or deuterons with maximum energy of 73 MeV and current of 50 μA. These particle energies and beam current are far away from those ones necessary for creation of a neutron rich spallation source. This accelerator could be used only as the first stage in a multi-cyclotron section of a high power ADS. Thus, one of the main tasks in the project will be theoretical and experimental examinations of interaction of the beam particles with different materials in order to choose and design an optimal target in respect to escaping neutron spectrum and yield.

Activities of the proposed ADS research are foreseen as a three-phase project for next three years with the aim to study the physics and development of the technologies needed to design a small (fast or thermal) sub-critical low-flux research reactor driven by an accelerator beam, as a mock-up of a full scale ADS.

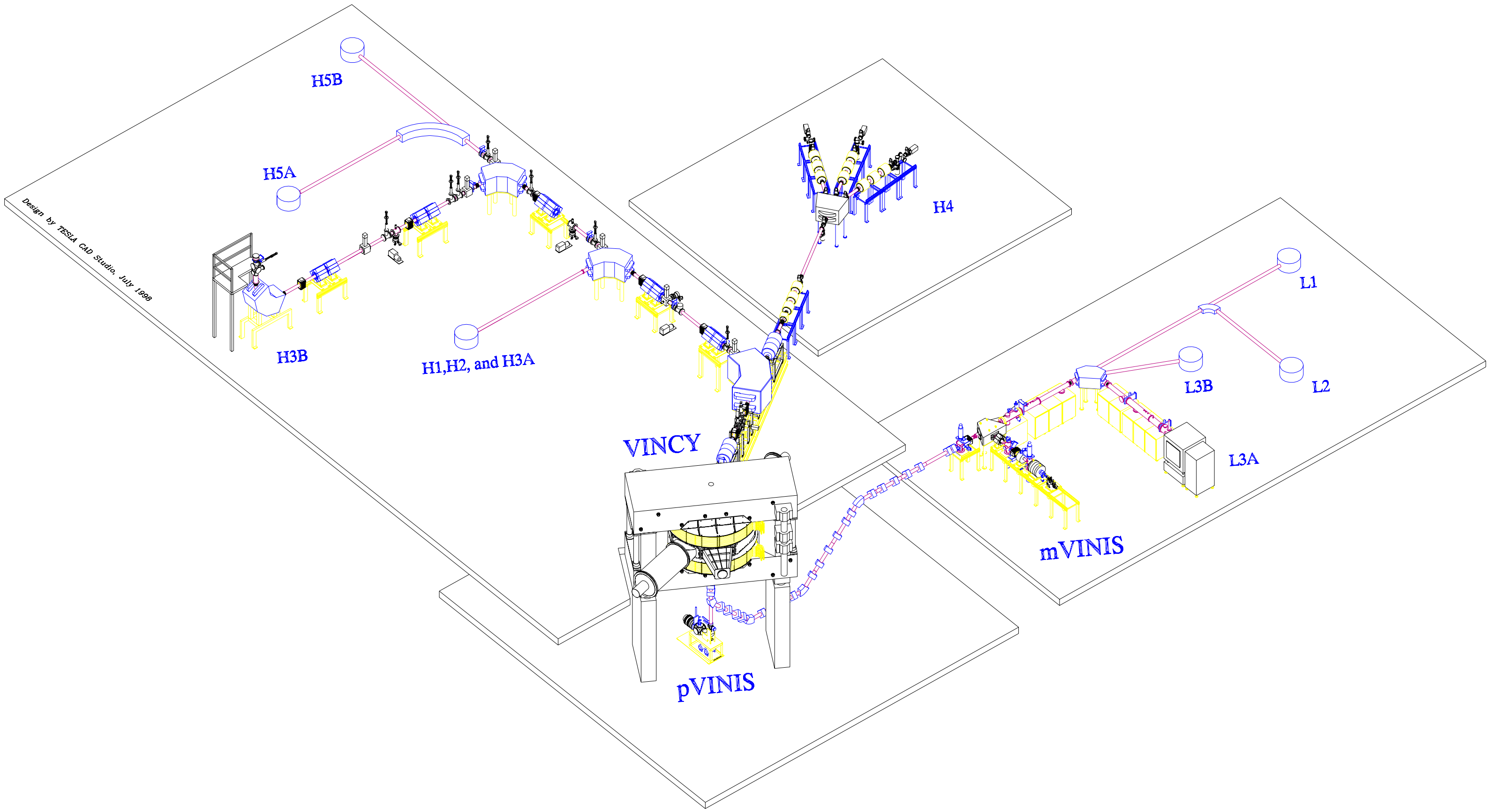

Figure 1.Scheme of the TESLA Accelerator Installation: VINCY Cyclotron, mVINIS Ion Source, pVINIS Ion Source, L1 - channel for physics of multiply charged ions, L2 - channel for surface physics, L3A - channel for modification of materials, L3B - channel for analysis of materials, H1 - channel for nuclear spectroscopy, H2 - channel for heavy ion nuclear reactions, H3A - channel for physics of thin crystals, H3B - channel for radiation research, H4 - channel for production of radioisotopes, H5A - channel for proton therapy, and H5B - channel for neutron research.

2. Description of the ADS with HEU fuel

In this initial phase of the Project, all possible options for the ADS type (neutron spectrum, fuel type, lattice pitch, target material, incident beam particle, ...) are open. As an example of options in the project – a concept of ADS with high-enriched uranium (HEU) fuel and light water moderator in the Vinča Institute is shown in this paper. Preliminary results of design study and neutronics calculations are given. Design is based on usage of HEU fuel (produced in ex-USSR) that is in regularly use at the RA and RB heavy water reactors in the Vinča Institute, since 1976. A three-dimensional (3D) view of the enriched uranium fuel slug is given in Figure 2. Its geometry shape and material composition are described elsewhere (e.g., Pešić, 2000). The fuel layer (2 mm thick) has inner/outer diameter (ID/OD) 31.0/35.0 mm and its total length is 100 mm. It is manufactured as 80%-enriched UO_2 dispersed in Al matrix. The fuel layer is covered by aluminium cladding, 1.0 mm thick on its inner side and 1.1 mm thick on its outer side. Top and bottom of the slug are covered by the 'Al stars' so that the total length of the slug is 113.0 mm. Inside the slug an 'Al expeller' is designed. It is a hollow cylinder (ID/OD 21.0/23.5 mm) that acts as a coolant intensifier during forced cooling (used at, e.g., the RA reactor). The aluminium, used in the HEU fuel slugs, is known as the SAV-1 alloy (98.5% w/o Al) with low contents of neutron high-absorbing impurities (e.g., B or Cd).

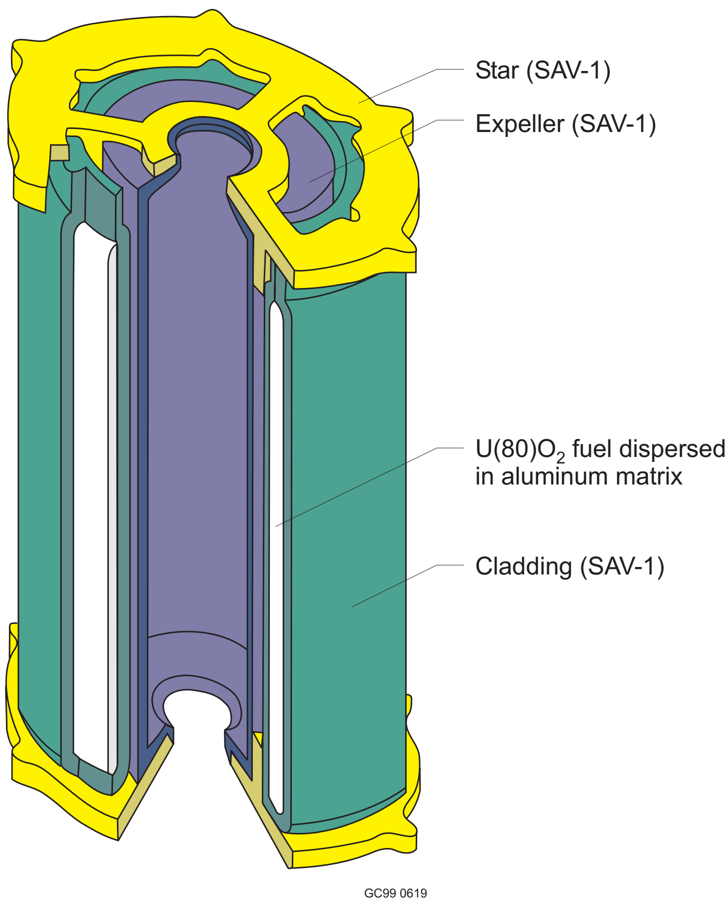

Figure 2. Three-dimensional view of HEU fuel slug used at RA and RB reactors in the Vinča Institute (Pešić, 2000, Figure: credit to the INEEL, USA)

In this example, a slightly modification of the HEU fuel is proposed in aim to obtain higher ratio of fuel to structural material. Both 'stars' (top and bottom) and 'expeller' are removed from the slug. The total length of so modified HEU slug (MHEU) is reduced to 107 mm, comprising just the fuel layer and Al cladding. These MHEU slugs are placed one above the other (up to the five ones) around an Al tube (ID/OD 26/28 mm) that passes through the slug's central hollow space (obtained by removing the stars and expeller). The 'fuel element', formed in that manner, is placed in the holes (40 mm diameter) drilled in a lead matrix and filled by water. The holes form a square lattice (11 x 11 matrix) with 50 mm pitch. Any fuel element can be replaced by, either a vertical experimental channel (Al tube, ID/OD 36/38 mm) or by a reflector element designed as a cylindrical lead rod (diameter 38 mm). To obtain ADS with dominant thermal neutron fission in bulk of the core, light water is proposed here as the primary moderator inside the fuel elements. In aim to simulate proposed high power ADS, a (natural) lead is used as moderator and reflector of the core. Radial reflector has average thickness about 210 mm, while top and bottom axial reflectors are 100 mm thick each. Entire core is designed in a stainless steel cylindrical tank (diameter 1000 mm and 735 mm total height of the core and both axial reflectors) with 25 mm wall thickness.

Particle beam, extracted from the VINCY cyclotron at the H5B channel, is introduced to the core by a separate stainless steel tube (ID/OD 12.6/13.6 mm, under high vacuum) entering the system through the top surface. A target is placed at the window of the beam tube, in the centre of the sub-critical core. In this initial stage of study, a lead cylinder (25 mm high and 25 mm diameter) is selected for the target material. Further research will be carried out to find out the optimal target material and shape in respect to beam characteristics (particle type, energy and current). The aim of that optimisation study is to achieve the maximum neutron yield and spectrum of leaking neutrons from the target surfaces, during interaction of the beam particles within target material.

Horizontal and vertical cross-sections (cut at planes at the target level) of the proposed ADS configuration with 97 fuel elements (each with five MHEU fuel slugs, except the central one) are shown in Figs. 3 and 4.

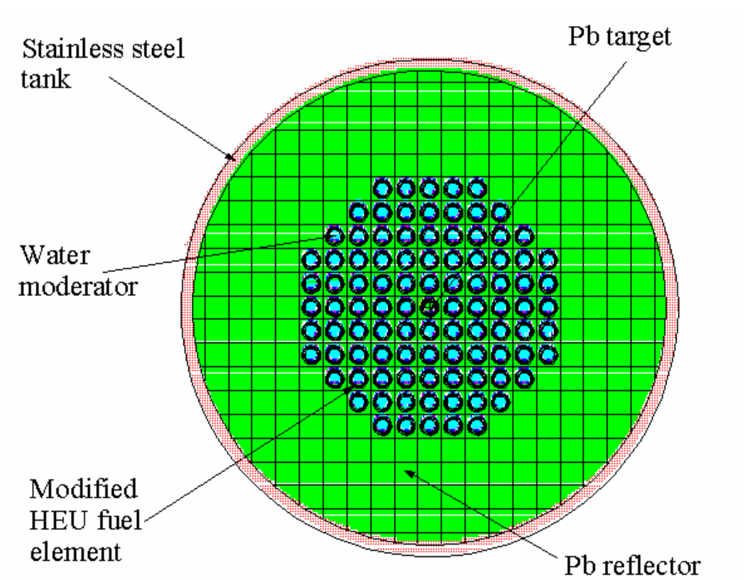

Figure 3. Horizontal cross-section (at the target plane) of the proposed ADS

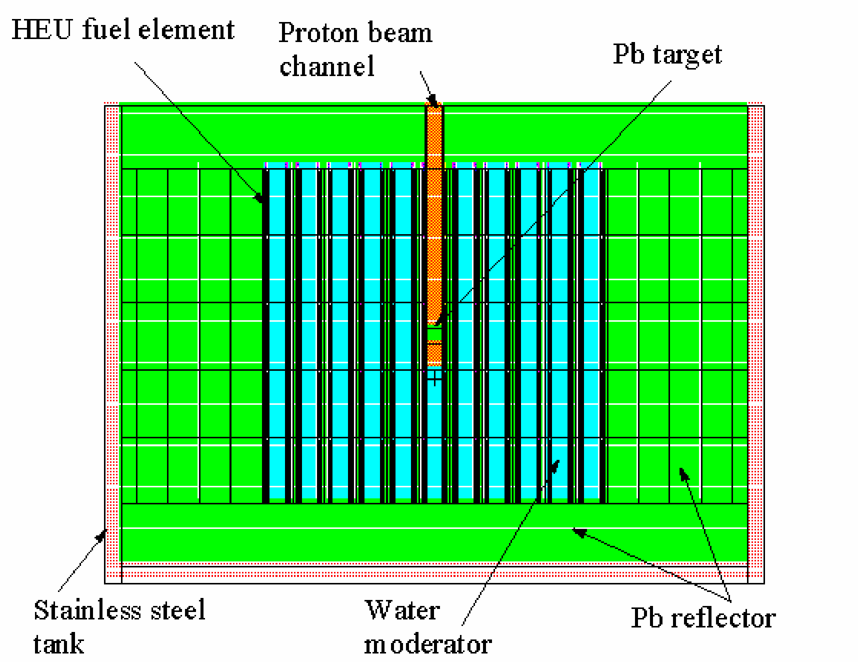

Figure 4. Vertical cross-section (at the target plane) of the proposed ADS

3. Calculation Tools and Initial Results

To estimate escape neutron spectrum and yield, an incident infinite thin ('pencil') proton beam with 75 MeV energy is assumed, for this study, to hit the top plane of the Pb cylindrical target along the cylinder axis. Interaction of the beam with the target material is calculated using the Monte Carlo based SHIELD code (Dementyev and Sobolevsky, 1999). This code is initially developed in the JINR, Dubna and modernised later in the INR RAS, Moscow. The code is validated against many experimental benchmarks and in several intercomparisons of high-energy hadron codes. SHIELD code calculates interaction of high energy particles with condensed matter, including hadron-nucleus interactions inside the target, generates and follows transport of secondary particles and computes deposition of energy and production of radionuclides in the target. Direct (analogue) Monte Carlo technique, as a rule, is applied for simulating of the interaction process.

Modern version of the SHIELD code allows simulation of the transfer of nucleons (including low energy neutrons), pions, kaons, antinucleons, and muons in energy range up to 1 TeV. Recently, the transfer of ions (arbitrary A, Z-nuclei) was added. The ionisation loss and straggling (optionally) are taken into account as well as the main modes of the meson decay. Hadron-nucleus interactions inside the target are simulated, using the exclusive approach, on a basis of the known Russian models of nuclear reactions. These models were jointed in the generator of nuclear reactions - the Multi Stage Dynamical Model (MSDM) (Botvina et al., 1997). The MSDM describes the cascade and precompound stages of the reaction as well as evaporation/fission, multifragmentation, and Fermi break up of residual nuclei. The transfer of neutrons with energies less than 14.5 MeV is simulated within multi-group ABBN neutron data system (Abagyan et al., 1981). In the SHIELD code, the complete storing of the hadron cascade tree during its simulation is realised. Therefore, after the simulation of the hadron cascade is finished, the cascade tree is fixed for following processing without any loss of physical information.

Simulation by the SHIELD code show that, for a number of protons with initial energy of 75 MeV that enter to the selected Pb target, near 95% will avoid inelastic interaction inside the target material. Leaking neutron spectrum from the target, calculated by the SHIELD code, is shown in Fig. 5. Total yield of escaping neutrons is about 0.19 neutron per proton. Within that number, only 7.4% of neutrons have energy in range 14.5 MeV-75 MeV. They are collected in 16 energy groups with equal bin width 3.75 MeV (from 15 MeV to 75 MeV) plus separate group 14.5 MeV-15 MeV. Below 14.5 MeV, neutrons are collected in 28 energy bins with borders equal to ABBN-78 multigroup data library structure. Peak of the leaking neutrons is in sixth and seventh energy group, i.e., in energy range between 0.2 MeV and 0.8 MeV. Leaking neutron spectrum does not contain neutrons with energies less than 0.465 keV, i.e., there is no thermalization of neutrons within the target material. It is consequence of a simplification made in this simulation, according which the target is placed in the vacuum (void) and so, return effect of slowing-down and thermalized neutrons in surrounding media in the core of the proposed ADS is not encountered in the neutron leakage spectrum.

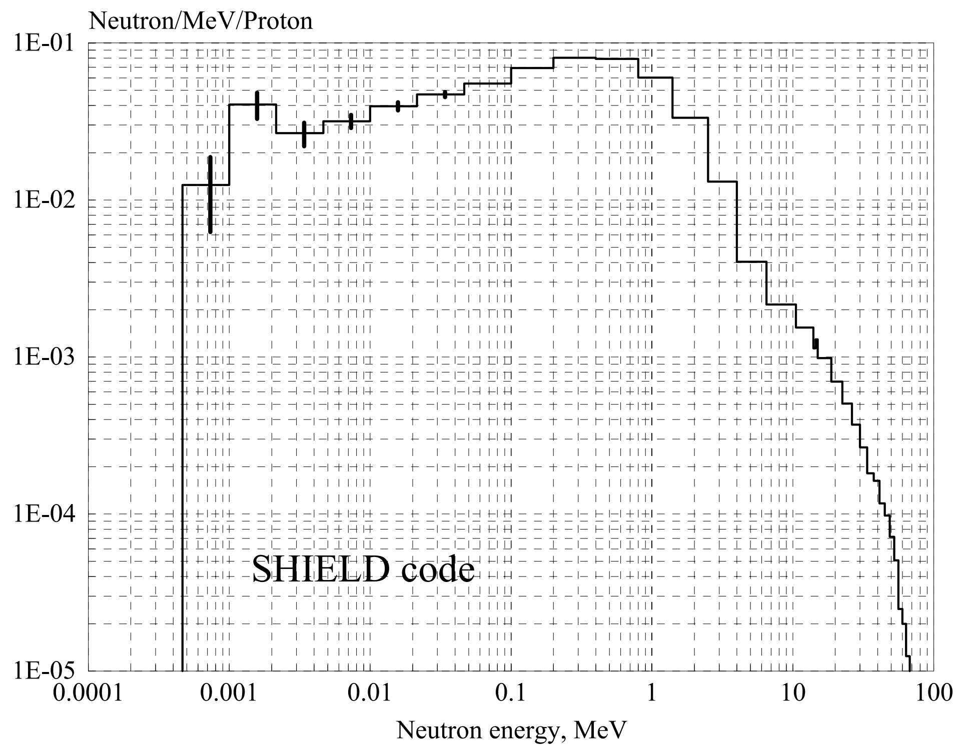

Figure 5. Escaping Neutron Spectrum from the Pb Target Calculated by the SHIELD Code

Preliminary neutronics criticality calculations of the proposed system are carried out using well-known MCNP™ (version 4B2) code (Briesmeister, 1997). Neutron nuclear data library, developed in the Vinča Institute (Milošević, 1998), based primary on the ENDF/B-VI (release 2) evaluation file, is used. Neutron scattering at hydrogen atoms connected in water molecules at thermal energies is encountered by the S(α,β) scattering law according to data given in the standard TMCCS library of the MCNP code. Three-dimensional model of the proposed ADS for usage with the MCNP code is developed. The MHEU fuel slugs are introduced in that model according to the 3D model of the real HEU slug (Pešić, 2000) developed for the RA and RB research reactors in the Vinča Institute.

In the first step calculation, carried out by the MCNP code, the particle source (SDEF) is defined as neutrons leaking the source volume with group spectra obtained in the SHIELD code. Slight modification is done due to limit of the highest neutron energy (20 MeV) in the VMCCS library. All neutrons above 20 MeV (less than 5.0 % of total yield) are inserted in two the highest neutron energy groups with boundaries 14.5 MeV – 18.75 MeV – 20 MeV. In further research, MCNP 'extended' data library for neutron energies up to 150 MeV will be used, so the simplification mentioned above will be avoided. The MCNP code is run for 7,000 neutron histories and a space distribution of neutron fission source in MHEU fuel slugs, sited in the system, is determined. The F4 tally with integration over fission cross-section by appropriate cell volume and neutron energy is used for that purpose.

The fission source distribution, obtained by the method described, is used for subsequent MCNP calculation of the system neutron effective multiplication factor (KCODE option). In this second step of calculation by the MCNP code, 500 neutron active cycles are run, after 15 initial ones, with assumed stationary neutron space and energy distribution in the system, and with 1,000 neutrons per cycle. Obtained value for the effective neutron multiplication factor in the system is 0.9821 ± 0.0011. Simultaneously, the prompt neutron lifetime in the sub-critical system is determined as $80.6 \pm 0.2\ \mu s$.

For an incident beam of 75 MeV protons with current of 5 μA, the total power of 375 W is generated in the target. Cooling of the target material is necessary, but it is not analysed in this preliminary study Very simplified study of thermal energy generation shows that target temperature would increase at rate of near 20 K/s if heat transfer from the target to surrounding would neglected. That assumption is near to possible real situation due to the target position in the system.

The total neutron yield, according to the result of the SHIELD calculation, is about $5.9\ 10^{12}$ neutron per second, i.e., the average neutron flux leaking the target surfaces is $\sim 2\ 10^{11}$ n cm^{-2} s^{-1}. The MCNP calculation shows that neutrons are generated in the system dominantly by thermal fission ($E_n < 0.465$ eV). The fast fission ($E_n > 0.465$ eV) is only about 7% - 10% of all fission, depending on fuel position in the core. The statistical error (1σ) of determination of two-group average fission rate by the MCNP code in the lattice cells is about 5%. Average neutron flux in the lattice cells with HEU fuel slugs is dominantly fast ($E_n > 0.465$ eV) and about 3 times higher than the thermal one. This is consequence of small amount of light water and low energy decrement per neutron collision with lead. Peak of the fast neutrons is estimated, according to MCNP results, in the lattice cells near the target at value of $5.8\ 10^{10}$ n cm^{-2} s^{-1} with corresponding thermal neutron flux at value of $2.0\ 10^{10}$ n cm^{-2} s^{-1}. The statistical error (1σ) of determination of two-group average neutron flux by the MCNP code in the lattice cells is maximum 5% (in the core), i.e., maximum 10% (in the reflector).

4. Conclusion

A preliminary feasibility study based on neutronics criticality calculation has shown that the low flux ADS with existing HEU in the Vinča Institute and H_2O moderator in lead matrix is possible to design with neutron source generated by proton beam extracted from the TESLA Accelerator Installation.

References:

Abagyan, L.P., Bazazyants, N.O., Nikolaev, M.N., Tzibulya, A.M., 1981. *Gruppovye konstanty dlya raccheta reaktorov i zashchity – Spravochnik* (ed. M.N. Nikolaev), Moscow, Energoizdat

Botvina, A.S., Dementyev, A.V., Smirnova, O.N., Sobolevsky, N.M., Toneev, V.D., 1997. "MSDM - Multi Stage Dynamical Model" in International Codes and Model Intercomparison for Intermediate Energy Activation Yields, (by R.Michel, P.Nagel), NSC/DOC(97)-1, NEA/P&T No. 14, NEA OECD, Paris, p. 307.

Briesmeister, J.F., (editor) 1997. "*MCNP™ - A General Monte Carlo N-Particle Transport Code, Version 4B*," LA-12625, Los Alamos, NM, USA

Dementyev, A.V., Sobolevsky, N.M., 1999. "SHIELD - Universal Monte Carlo Hadron Transport Code: Scope and Applications," Radiation Measurements **30**, 553.

Milošević, M.J., 1998. "The VMCCS Data Library for MCNP™," Vinča Institute of Nuclear Sciences Bulletin, **3**(1-4), 11-14

Nešković, N., Ostojić, R., Susini, A., Milinković, Lj., Ćirić, D., Dobrosavljević, A., Brajušković, B., Ćirković, S., Bojović, B., Josipović, M., Toprek, D., Manasijević, M., Koički S., 1992. "TESLA Accelerator Installation," Proc. of the Third European Particle Accelerator Conference, Berlin, FRG, Frontiers, Guf-sur-Yvette, France, **1**, 415-417

Pešić, M., Nešković, N., Plećaš I., 1999. "ADS Project in the Vinča Institute," Proc. of the International Conference on Sub-critical Accelerator Driven Systems, SSC RF ITEP, Moscow, Russia, (October, 11-15, 1999) 27-33

Pešić, M., Cupac, S., Vukadin Z., 1999a. "Management of Ageing Research Reactors in the Vinča Institute," IAEA International Symposium on Research Reactor Utilization, Safety and Management, Lisbon, Portugal (September, 6-10, 1999), paper IAEA-SM-360/042P, 042.1-042.10

Pešić, M., 2000. "RB Reactor: Lattices of 80%-Enriched Uranium Elements in Heavy Water," in *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC(95)03/II, HEU-COMP-THERM-017, 2000 Edition, OECD/NEA, Nuclear Science Committee, Paris, France, Vol. **II**, 1-285, to be published