CN-115-29

The subcritical assembly at DUBNA (SAD): coupling all major components of an accelerator driven system (ADS) for nuclear waste incineration

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Abstract. Various concepts of accelerator driven systems (ADS) for the incineration of nuclear wastes like minor actinides (MA) and long-lived fission products (LLFP) are under investigation now worldwide. Creation of large subcritical accelerator driven systems ADS should precede experimental checks of the theoretical predictions and estimation of technological features of such systems.
To resolve some questions an ADS with thermal power of several kW is sufficient. At the present time the project on creation of the 27 kW ADS with U-Pu MOX fuel is under realization at JINR. Existing 660 MeV proton accelerator will drive subcritical core of the SAD installation. Project objectives, technical description and current status are presented.

1. Introduction and overview

The construction of large subcritical accelerator driven systems (ADS) should be preceded by experimental verifications of the theoretical predictions and of the technological features of such systems [1]. The most important issues to be addressed are:

- Substantiation of operational safety of sub-critical systems;
- Reliable calculation and measurement of the ADS power;
- Development of methods for reliable monitoring of the subcriticality k_{eff};
- Measurement of the contribution of the high-energy part (E >10 MeV) of the neutron spectrum, being particularly important for the design of radiation protection.
- Engineering of the coupling of an accelerator with a sub-critical reactor system;

Experimental ADS with thermal power of about 20-30 kW, as proposed in the SAD project, can deliver reliable substantial answers to these problems.

In JINR experimental and theoretical research activities focusing on coupling of proton accelerators with fissile targets/cores have been conducted since the middle of the 50-s' under the scientific label "*electronuclear*" research [2, 3,]. Neutron yields and spectra in lead and uranium targets have been measured, as well as neutron cross-sections for a number of isotopes, important for the estimation of the efficiency of various modes of transmutation [4, 5, 6]. For the analysis of the *electronuclear* systems properties, mathematical models with appropriate databases and software have been developed [7].

2. Basic data

The SAD project basic features are determined by the characteristics of the “PHASOTRON” proton accelerator at JINR – driving accelerator for the SAD facility [8] – and by the choice of the regular Russian MOX fuel elements of the BN-600 reactor type [9]. The proton current (maximum value is 3.2 μA) and the corresponding power dumped in the spallation target determine together with the value of the multiplicity k_{eff} of the core, the total thermal power of the installation.

The basic data of the SAD-facility, and the MOX fuel characteristics are listed in the following tables:

TABLE I: SAD INSTALLATION BASIC DATA

Parameter	**Value**
Thermal power	up to 30 kW
Proton energy	660 MeV
Beam power	up to 1 kW
Proton beam / target orientation	Vertical
Fuel elements orientation	Vertical
Criticality coefficient	$k_{eff} \approx 0.95$
Fuel - see table below for details on composition	MOX, $UO_2 + PuO_2$
Cladding tubes maximum temperature	400°C
Spallation target	Replaceable: Pb, W
Reflector	Pb
Coolant	Air

TABLE II: BASIC FEATURES OF THE SAD CORE FUEL

Parameter	**Value**
Fuel composition	$(UO_2 + PuO_2)$
Plutonium dioxide content in the fuel, %(mass)	up to 30*
^{239}Pu content in Pu %(mass), not less than (with accuracy not worse than 10^{-4} for basic isotopes)	95
Fuel density, g/cm^3	10.4 ±0.2
Fuel pellet diameter, mm	5.95*

*– parameters become defined more accurately during FE design

3. Subcritical assembly

The sub-critical blanket of SAD (Figure 1) is placed within a biological shielding, which is made of heavy concrete and placed in radial and top directions from the active core (AC). Pipes are foreseen in the shielding blocks to provide the allocation of the cooling loops for the target, the core, the experimental channels (vertical and horizontal), the power control channels, the proton guide etc. The upper part of the biological shielding will provide access to the blanket and to the experimental channels during fuel loading/reloading operations and to experiments with detectors and samples. The SAD core consists of 141 fuel assemblies; each assembly by itself combines 18 fuel pins, separated by wire spacers, and welded onto the cladding tube in helical manner. The fuel assembly does not have sidewalls, but only lower and top frames where the FE are fixed. A central supporting rod made of stainless steel achieves the integrity. The low specific energy release in the system allows the usage of air-cooling, both for the target and for the active core.

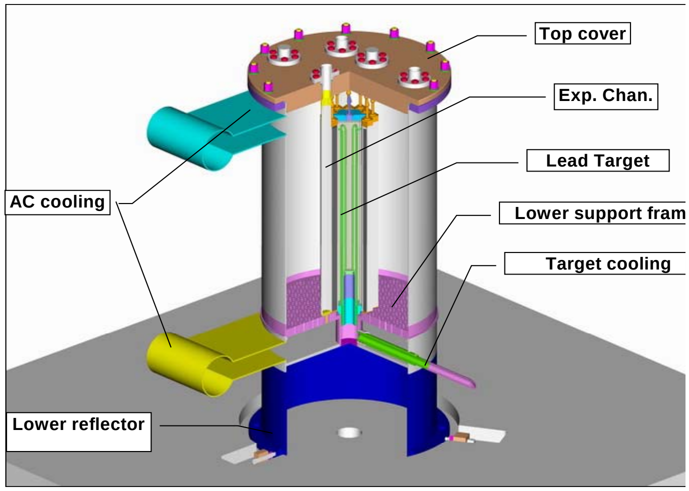

Figure 1: SAD core general view, fuel assemblies and lead reflector not shown.

A cross section of the SAD active core is presented in Figure 2.

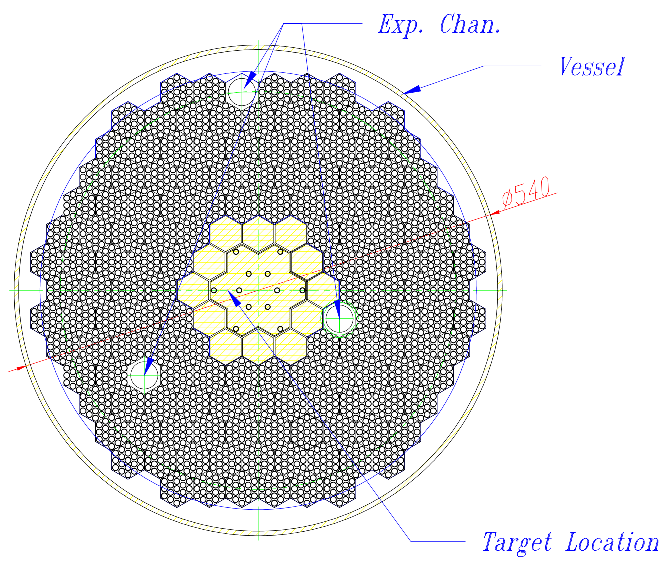

Figure 2: Cartogram of the SAD core (141 fuel assemblies x 18 fuel elements), 395 kg of UO_2 - PuO_2 MOX fuel. 29.5 weight percents of PuO_2.

The lead target assembly consists of a set of hexagonal lead prisms with air-cooling of the central 7 prisms (Figure 3). Other materials than lead and other dimensions will be used for the target in the course of the SAD experimental program.
The active core is surrounded by a lead reflector of 60 cm thickness in radial direction and of 20 cm in axial direction at the top and at the bottom. The lead density is 11.15 g/cm^3. A B_4C layer of 3 cm thickness to reduce the number of low energy neutrons in the concrete and shorten neutron lifetime in core is located between the lead reflector and the concrete shielding in radial direction.

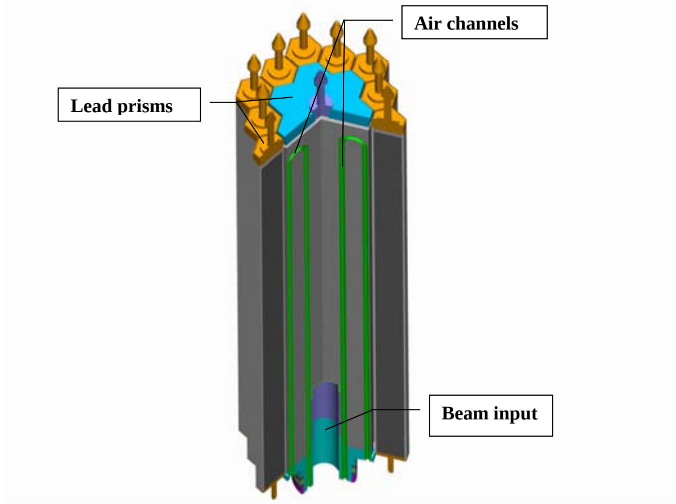

Figure 3: Lead spallation target design

The installation will be equipped with experimental channels (EC) and actuators, which will allow to place detectors and isotopic samples in different parts of the installation and to extract them after irradiation. Three vertical EC are located in the central part of subcritical assembly, substituting three fuel assemblies. One channel – in the vicinity of spallation target (EC1), next one in the middle of the core (EC 2) and the third one on the periphery of the core close to the Pb reflector (EC 3). Inner diameter of the channels 1-3 is equal to 33 mm. Another three vertical EC with inner diameter 60 mm are situated in Pb reflector.
The last vertical EC has diameter 45 mm and is placed in the top lead reflector on the beam axis.
Two horizontal EC with diameter 100 mm are located in the lower and side lead reflectors.
On the basis of the data, listed above, preliminary neutron spectra in experimental channels were calculated with MCNP[10]. The results for neutron spectra calculations for 3 vertical channels in the fuel part of the core (1-3) and for 3 vertical channels in the side reflector (4-6) are shown in Figure 4.

4. Accelerator and beam transport line

The proton accelerator PHASOTRON at JINR has 10 beam channels, used in various experiments. The normal beam losses at transition through the longest beam lines do not exceed 5%.
In the beam transportation system the standard for JINR deflecting magnets and quadruple doublet lenses will be used.
The beam transfer from horizontal into a vertical plane, entering from the bottom of the core, will be realised using two strong bending magnets which have to be designed and constructed.
The total number of magnetic elements in the beam line is about 40 including diagnostic elements and correction magnets. Beam current and spatial distribution will be monitored at different places along beam line using inductive sensors, ionization chambers and profilemeters. Beam current will be measured with high precision giving possibility for precise experimental monitoring of the core power to beam current ratio.

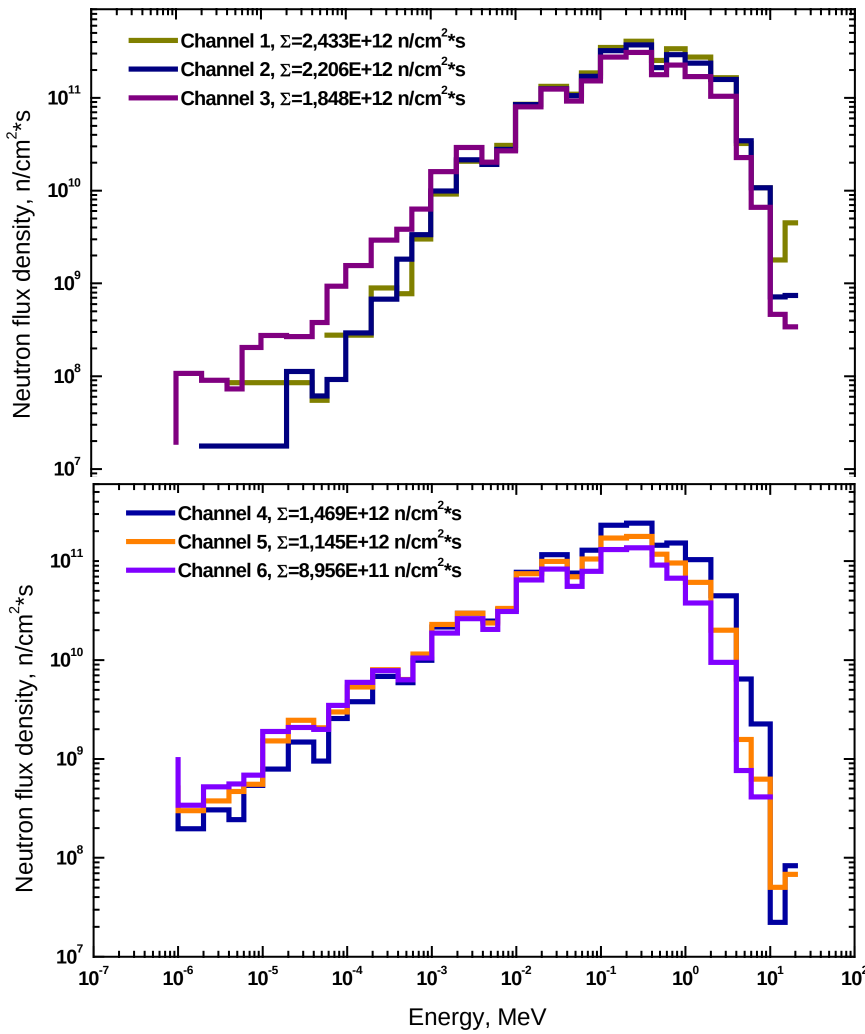

Figure 4: neutron spectra in the centers of vertical experimental channels 1-6. Integral flux density in n/cm^{2}s are: 1 – 2,433E+12 at 26 kW power; 2 – 2,206E+12; 3 – 1,848E+12; 4 – 1,469E+12; 5 – 1,145E+12; 6 – 8,956E+11.

5. Experimental program

Research program for SAD installation is forming in collaboration between scientific teams and design organizations. Experimentalist's requirements are reviewed by designers and receive evaluation from the point of view of reliability. Main points of the SAD experimental program are:

- Qualification of subcriticality monitoring, experiments with Pulsed Neutron Generator (PNG);
- Validation of the core power/beam current ratio;
- Tests and calibrations of the actual spallation target;
- Post-irradiation and on-line spallation products yields investigation;

– Transmutation reactions rates, integral cross sections and spectral indices measurements;
– Interpretation and validation of experimental data, codes validation, benchmarking;

Some experiments are also planned to assess the reactivity feedbacks for SAD facility. One of the most important tasks for subcritical assembly physics is the problem of reactivity measurements and monitoring at high subcriticality. Such investigations were performed at zero power subcritical assemblies with fast (MASURCA [11]) and thermal neutron spectra. The solution of this task is an extremely important step on the way to creation of the industrial scale ADS facilities, dedicated for radwaste transmutation, because reactivity fluctuations, proton beam parameters influence on reactivity characteristics of the subcritical blanket determine drastically the safety substantiation for such systems.

In SAD scientific program it is proposed to pay attention for experiments on measurements and monitoring of the k_{eff}. It is planned to measure k_{eff} average value by means of inverse multiplication, asymptotic period and other techniques. Time structure of the proton beam gives wide possibilities in application of the so-called pulse technique of reactivity measurements, in which one measures neutron flux decreasing time constant. That time structure also gives possibility to measure the influence of blanket surrounding (concrete shielding) on its neutronic properties.

The program on measurements neutron spectral flux densities and power release at different parts of the installation, prompt neutrons lifetime, and effective fraction of the delayed neutrons is planned.

To measure spatial and energy characteristics of the neutron field inside subcritical assembly one suppose to place in the target and fuel part of the core specially selected experimental samples, which permit to measure threshold reactions rates. To investigate neutron field in fast energy region absolute reaction rates will be determined for ^{209}Bi, ^{115}In (or ^{197}Au), ^{59}Co, and ^{27}Al.

Besides that, samples made of multi component alloy ^{55}Mn+^{63}Cu+^{197}Au+^{176}Lu will be used for measurements of (n,γ) reaction rates in thermal and resonance energy region (up to 1 MeV).

It is planned to measure also following spectral indices using ^{235}U, ^{239}Pu, and ^{238}U:

– ^{235}U(n,f)/^{238}U(n,γ);
– ^{239}Pu(n,f)/^{235}U(n,f);
– ^{238}U(n,f)/^{235}U(n,f).

A further experimental field of investigation at SAD facility will be actinides and U, Pu isotopes fission rates measurement.

May be the most important scientific task for the SAD installation will be to extent the experimental data base for testing computer codes and nuclear data used for ADS modeling. At present time some reaction rates calculated by different codes and databases, differ strongly, which is not acceptable for accurate calculation of physical characteristics and technology requirements for installations of industrial scale. At SAD design and manufacturing stages the basic task will be to describe with maximum precision isotope and element composition of SAD components and its geometry. It will enable to expect in future that all experiments described above could be compared with results of calculations, e.g. in benchmark investigations..

6. Project status

Within the design stage of the project all tasks determined by the working plan have been executed, namely – the technical design of SAD installation is developed, the safety analysis report is prepared, the technology of fuel pellets fabrication is prepared and the experimental batch of fuel pellets is manufactured.

7. Conclusion

Russian design institutes developed working plan for the stage of project realization. Project time schedule presumes about 4 years for putting SAD facility into operation in case of sufficient financing.

This work is supported by ISTC, project #2267.

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