

DESIGN STATUS AND FUTURE RESEARCH PROGRAMME FOR A SUB-CRITICAL ASSEMBLY DRIVEN BY A PROTON ACCELERATOR WITH PROTON ENERGY 660 MEV FOR EXPERIMENTS ON LONG-LIVED FISSION PRODUCTS AND MINOR ACTINIDES TRANSMUTATION (SAD)

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Abstract

Report presents project for the construction of a low power integral system on the basis of the proton accelerator of energy 660 MeV and sub-critical MOX blanket with uranium-plutonium fuel. Installation includes sub-critical core with a nominal thermal power of 15-20 kW. Multiplication coefficient $k_{\text{eff}} = 0.95$ and the accelerator beam power of 0.75-1 kW. The experimental programme for SAD will be focused on solving different aspects of reactor physics, reaction rates measurements and benchmarking. The first conceptual design of the SAD experiment is completed in the form of the ISTC Project Proposal #2267. Realisation of the SAD facility may be expected in about 3-4 years.

Introduction

After unprecedented development of a nuclear physics and technology in the first half of 20th century seemed, that the processes of fission in nuclear reactors and synthesis in thermonuclear ones will provide mankind with practically inexhaustible source of cheap and enough safe energy. To the end of the last century it became clear, that the thermonuclear power engineering as is far from creation of production plants, as well as 50 years back, and atomic engineering at all advantages hides in itself enormous dangers and main of them – radioactive waste. So the total amount of radwaste on the nuclear complex plants of Russia makes size of more 600 millions cubic meters with activity more than 10^{20} Bq. The radioactive waste derivated at all technological stages of nuclear fuel cycle – at production and processing of uranium ore, at manufacture and usage of nuclear fuel, regeneration of the irradiated fuel, decommissioning of nuclear objects. For the sake of justice it is necessary to mark, that the radwaste derivated not only in nuclear fuel cycle, but also in traditional thermal power engineering. So in a petroleum industry of USA in 70th-80th years of the last century was annually derivated about 450 thousand tons of the radwaste and for 20 years total amount has made more than 8 millions tons the similar situation took place and for the oil refining complex of Russia. [1] However all sources of the radwaste irrelevant with nuclear fuel cycle and military applications, make some percents from total volume of radwaste.

At nowadays none of the countries transferred to usage of technologies permitting completely remove all concerns connected with spent nuclear fuel and the radwaste. The various concepts of different systems for long living plutonium isotopes, minor actinides (MA) americium, neptunium, curium and long lived fission products (LLFP) incineration are now examined. These are Advanced Liquid Metal Reactor (ALMR) with metallic and oxide fuels, Molten Salt Reactor (MSR) and sub-critical systems driven by proton accelerator (ADS). The experimental information on behaviour of such systems is insufficient, so creation of the small-scale prototypes of production plants is the priority task, as the complete understanding of features of behaviour of such installations cannot be reached on the basis of model calculations. The advanced comparative reviews of fast reactors, ADS and respective strategies are given in [2-8].

SAD basic data

SAD basic features are determined with “Phasotron” JINR proton accelerator and usage as a basic fuel elements (FE) serially released in Russia MOX FE of a BN-600 reactor. Rather modest proton current of accelerator (maximum value is 3.2 μ A) positions the SAD facility within the section of prototype installation between zero power facilities and industrial scale ones, which are designed now. Basic data are listed in Table 1.

SAD facility will be equipped with experimental channels permitting installation and extraction in different parts of sub-critical assembly, reflector and shielding different detectors and isotopic samples. At present time SAD potential user are requested to propose their requirements for locations, dimensions and design features of such channels.

Table 1. SAD basic data

| | |
|------------------------------------|---|
| Thermal power | 15-20 kWt |
| Protons energy | 660 MeV |
| Beam power | 0.75-1 kWt |
| Proton beam / target orientation | vertical |
| Fuel elements orientation | vertical |
| Criticality coefficient | $k_{\text{eff}} < 0.95$ |
| Fuel | MOX, UO ₂ + PuO ₂ |
| Cladding tubes maximum temperature | 400° C |
| Spallation target | replaceable: Pb, Pb-Bi, W |
| Reflector | Pb |
| Coolant | Air |

Proton accelerator parameters are listed in Table 2.

Table 2. Parameters of JINR Phasotron

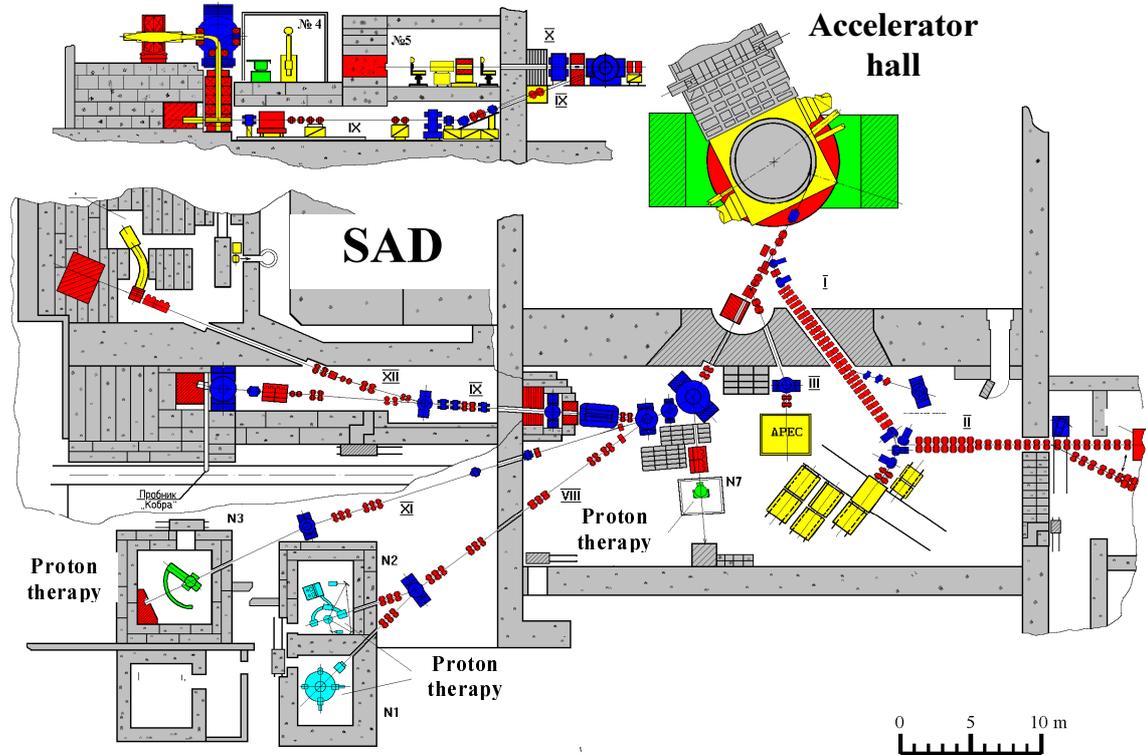
| | |
|---|--|
| Intensity of the extracted proton beam: | 3.2 μA ($1.997 \cdot 10^{13}$ protons/s) |
| Beam emittance: | $\Sigma_x = \pi(5.1 \pm 2.3) \text{ cm} \cdot \text{mrad}$ $\Sigma_y = \pi(3.4 \pm 1.4) \text{ cm} \cdot \text{mrad}$ |
| Time structure | |
| Fast extraction | |
| Frequency | 250 Hz |
| FWHM | 20 μs |
| Number of protons in pulse | $0.8 \cdot 10^{11}$ |
| Slow extraction | |
| Frequency | 250 Hz |
| Pulse width | 3 500 μs |
| Beam microstructure | |
| Micropulse FWHM | 10 ns |
| Micropulse period | 70 ns |

SAD present design status

Allocation of the installation

SAD facility will be located in new building will be constructed in a gap between existing accelerator and YASNAAP buildings (Figure 1).

Figure 1. General plan view of the JINR “Phasotron” accelerator complex (in the left upper corner side view of the neutron/meson therapy complex) SAD facility will be constructed between accelerator and YASNAAP buildings



General layout of the installation now supposes proton beam injection from the bottom of installation after 110° turn with strong bending magnets. So proton beam heats the target from below and it's necessary to have rather thick beam stop in straightforward i.e. top direction. The biological shielding properties will be determined by the highest neutron energy. The preliminary view of the SAD general layout is shown at Figure 2. Initially horizontal beam is deflected 20 degrees downwards inside accelerator hall and then turns 110° and hits spallation target, located inside fuel blanket. Such an allocation permits to avoid safety problems with possible water accidents, which exist in the case of beam injection from the top of the core. These problems are: accidental core flood with bending magnet cooling water or flood with a water from the nearest water reservoir in the case of accidental break of dam. Water level in the latter case will correspond building mark -0.5 m. Estimated volume of the structural concrete necessary to satisfy requirements of radioprotection standards is about $3\,000\text{ m}^3$.

Proton beam

The beam transport system will contain two key elements: deflecting magnets OM-1 and doublets from quadrupole lenses ML-3, and also their different modifications. Both these units are exploited for a long time in beam transportation at Phasotron. Photos of the magnets and lenses are presented at Figure 3. Two strong bending magnets with 2 000 Ampere-turns coils (Figure 2) will be used to turn beam vertically. Because beam power is only 1 kWt there will no problems target window – $200\ \mu\text{m}$

aluminum foils will be used as window material. Existing infrastructure provides necessary distilled water supply for magnets/lenses cooling and power supply. Beam current losses are planned at the level not higher than 3% total. The power consumption of the beam line elements will make value of the order of 200 kW (about 10% of the total phasotron power consumption).

Figure 2. SAD building general layouts (side view), total volume of concrete shielding is about 2 000 m³

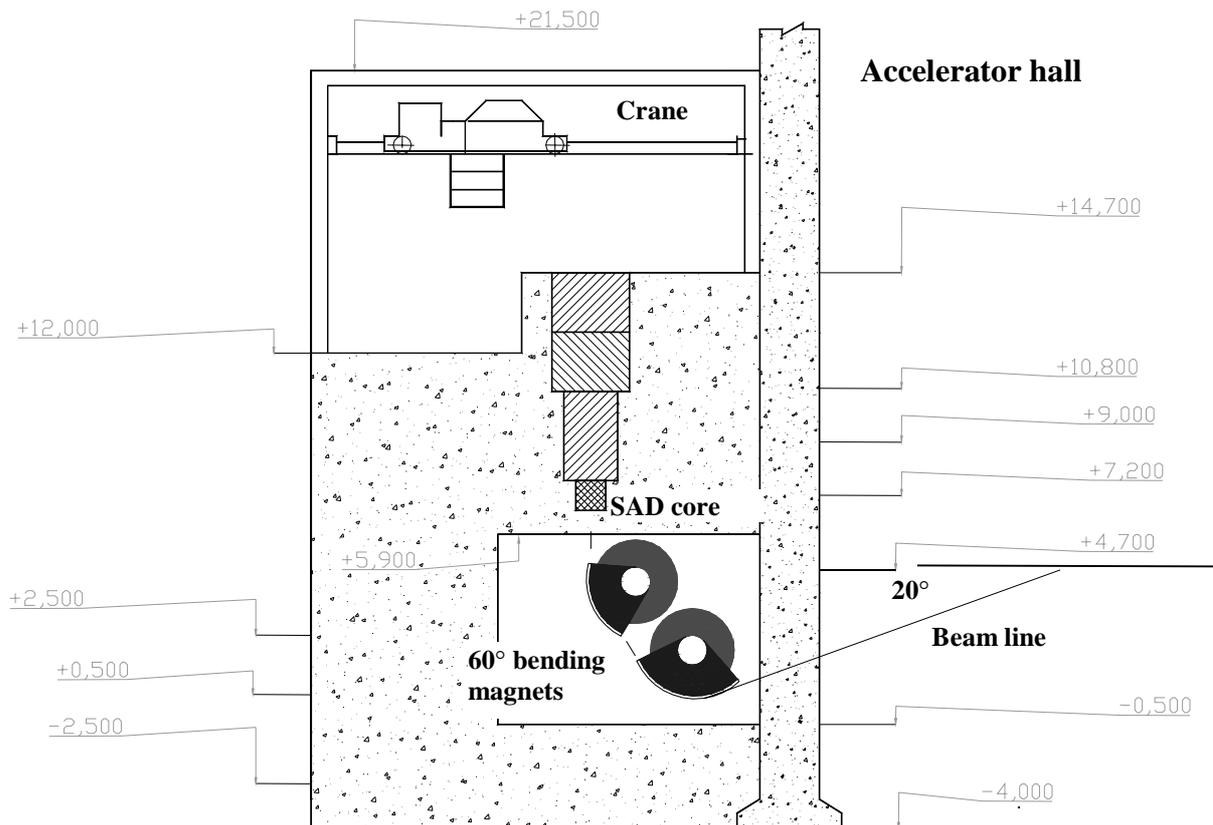
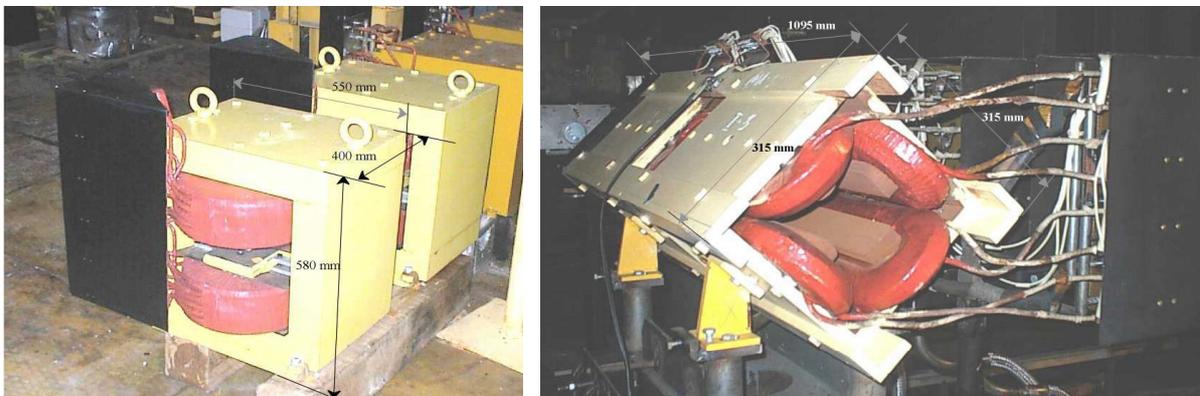


Figure 3. General view of the deflecting magnet OM-1 (left) and doublet of quadrupole lenses ML-3



Sub-critical core and spallation target

Sub-critical blanket will be accommodated inside biological shielding made of heavy concrete (4.5 g/cm³) with thickness 1 200 mm (Figure 4). Inside a bulk of concrete expansion sleeves are made in vertical and horizontal directions for experimental channels, proton guide vacuum channel, cooling systems and power control system pipes. Upper part of the biological shielding is made is fabricated removable to provide access to the blanket and spallation target during charge/discharge operations. Blanket casing is made of stainless steel and provides housing for fuel blanket, spallation target and air flows for cooling them. Spallation targets are made plug-compatible, but of different materials: lead, lead-bismuth eutectic and tungsten. Each target represents the cylindrical core with spiral groove and six peripheral segments. Targets are placed inside manacle ring providing separate from the fuel blanket air-cooling. Fuel blanket consists of 129 fuel assemblies (FEA), installed in support grating with spacing 36 mm. Fuel assembly contains 19 fuel elements (FE) with MOX fuel. FE spacing is 7.95 mm. Fuel pellet is ceramic cylinder 5.95 mm in diameter and 10 mm height. Fuel parameters are listed in Table 3.

Figure 4. **Blanket cross-section: 1-fuel blanket; 2-spallation target; 3-lead reflector; 4-target loop; 5-blanket loop; 6-experimental channels**

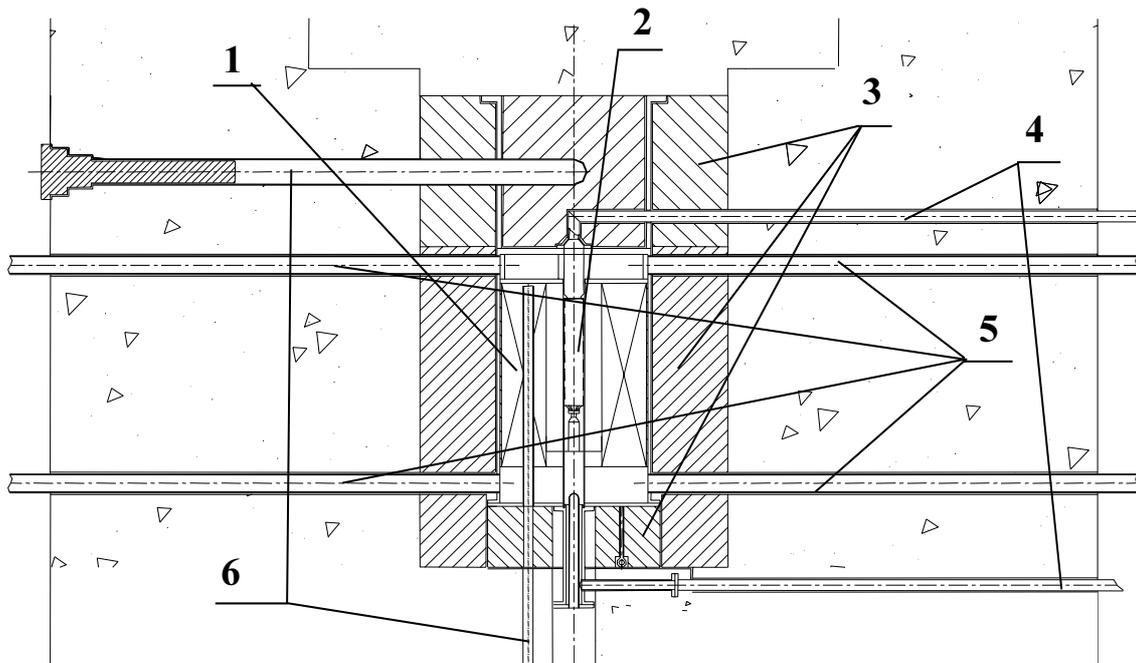


Table 3. **SAD fuel properties**

| | |
|---|------------|
| U and Pu fraction % by mass | ≤ 87.6 |
| ²³⁹ Pu fraction % from all Pu isotopes | ≥ 95.0 |
| ²³⁵ U fraction % from all U isotopes | ≤ 0.4 |
| Relative Pu fraction % from the sum of U and Pu | ≤ 30.0 |
| Density g/cm ³ | 10.4 ± 0.2 |

On the top of blanket casing air manifold is arranged to remove air from cooling systems. Between the blanket casing and biological shielding lead reflector is installed with thickness 250 mm to the side and 500 mm in beam direction. Inside blanket and reflector experimental channels are designed. Their design now is discussing with potential users of the SAD facility.

Cooling of the blanket and target is provided with two independent systems. Target is cooled with open loop and blanket with closed one. Blanket control and safety system includes part for controlling of the clad tubes impenetrability checking coolant in blanket loop.

Charging/discharging operations with fuel assemblies and removable spallation targets are conducted at fully stopped installation with removed upper part of biological shielding, top part of the reflector and casing closure head.

SAD future scientific programme

After realisation of the project on the basis of SAD installation it is planned to implement next research programme:

- Studying the operation modes of SAD in combination with the proton accelerator, measurements of the kinetic properties of the blanket.
- Studying the problems of target and SA integration, including influence of the target size and position on main SAD characteristics.
- Measurements of absolute value of the SAD power gain and reactivity, computer codes validation.
- Measurement of shielding efficiency (especially in a direction of a primary proton beam).
- Analysis of the neutron producing targets after long irradiation.
- Measurements of transmutation rates for MA and LLFP in different neutron spectra, computer codes validation.
- Deep sub-criticality measurements and monitoring.
- Studying the spallation products yields in target using He jet technique.
- Studying spatial and energy distributions of neutron field in target and fuel blanket.
- Measurements of the actinides and long-lived fission products transmutation rates.

SAD international co-operation

SAD project from the very beginning and in its future was and will be the project with extremely wide international co-operation. The leading institute – Joint Institute for Nuclear Research (JINR) in accordance with its statute is international intergovernmental organisation joining 18 member countries some of them are interested in scientific researches at SAD facility. Details of the JINR member countries participation are now negotiating with countries Plenipotentiaries.

The strong support for the project was rendered by four European leading centres: RIT (Stockholm, Sweden), CEA (Cadarache, France), CIEMAT (Madrid, Spain) and FZK (Karlsruhe, Germany). Due to collaboration with these institutes the conceptual design of the SAD facility was

prepared together with technical and economic assessment and cost estimating. It gave grounds for well-founded proposal to International Science and Technology Centre, which was finally approved for financing. The ISTC project implementation will start in the end of 2002. In acknowledgement of this support authors are tendering thanks personally to Waclaw Gudowski, Roland Soule, Enrique Gonzales Romero and Cornelis Broeders.

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