

The SAD experiment as a milestone in the development of ADS

1. Background information

The SAD experiment was initiated at the ADTT'99 conference in Prague, after the presentation of a paper of a theoretical division at JINR, Dubna, proposing the coupling of the existing PHASOTRON accelerator at JINR with a new small fast spectrum sub-critical assembly. Although the proposed cost estimates obviously were too low, the idea was pursued by a number of interested scientists. After the first assessment, it was agreed to continue the project with the preparation of an ISTC proposal, based on MOX fuel with weapon grade Plutonium in order to match ISTC rules for support. The ISTC proposal was prepared efficiently by the dedicated project manager at JINR, Dubna, with small financial support by collaborators from CEA, CIEMAT, FZK and KTH. As a result, the ISTC proposal #2267 SAD was approved at the 27th ISTC Governing Board Meeting on 7-9 April 2002, as a three year project. The execution of the project is separated in two phases:

- a. Phase I – design and technology preparation and
- b. Phase II – construction of the facility.

Phase I started on November 1, 2003, for a period of six quarters. If funding is realised, Phase II can start immediately after finishing Phase I and will lead to an experimental installation, ready to perform first start-up tests in 2008, see e.g. short SAD leaflet for more details.

2. Concept of the SAD experiment.

The SAD experiment aimed from the beginning to be one of the first set-ups with the coupling of the essential components of future ADS for incineration of nuclear wastes: high energy proton beam, spallation target and fast spectrum sub-critical core. The existing PHASOTRON accelerator at JINR Dubna is well suited for physics experiments in a low power sub-critical system. The characteristics of the basic concept of the SAD experiment are

- a. Use of the existing PHASOTRON proton accelerator at JINR with 660 MeV energy and 3.2 μA maximum current. It can deliver a beam with up to 2 kW power that enables to have a total power of the sub-critical core, driven with such beam, at a level of more than 100 kW. The upper limit is determined by the maximum reactivity value $K_{\text{eff}} = 0.98$, the limiting value in the official documents for sub-critical assemblies in the Russian Federation. One has to note that this K_{eff} should be less or equal to 0.98 at all modes of operation, including anticipated accidents. So the normal mode of operation should be established at a lower value. In the current design the nominal value is chosen to be 0.95.
- b. Application of existing fuel elements with Uranium – Plutonium MOX fuel of BN-600 type in the sub-critical core, using weapon grade Plutonium. The production of the fuel pellets at the Mayak facility allows a relatively cost-effective solution with financial support of ISTC.
- c. Flexible layout of the target area in order to accommodate target investigations, like variation of geometry and target material. It should be noted that the moderate power of the PHASOTRON proton beam does not need extensive efforts for target cooling, like in power ADS. Here the MEGAPIE project will give first results for a Lead Bismuth Eutectic (LBE) target, but without coupling to a sub-critical core.

3. Objectives of the SAD experiment

In JINR experimental and theoretical research activities focussing on coupling of proton accelerators with fissile targets/cores has been conducted since the middle of the 50-s' under the scientific label "*electronuclear research*". The yields of neutrons and their spectra in Lead and Uranium targets of various types, neutron cross sections for a number of isotopes, important for an estimation of the efficiency of various modes of transmutation, have been measured.

JINR has the license for operation of nuclear research reactors with active cores made of metallic Plutonium and of Plutonium dioxide. Such reactors have been operated reliably and safely for more than 40 years. JINR has also a long-term experience with the operation of proton accelerators. This experimental background gives good prospects for setting-up and subsequently for operation an experimental ADS with MOX fuel at JINR in Dubna. Moreover, the JINR with its status as an international research centre allows joining financial contributions of the JINR member countries. The proposed project SAD will be the natural step on the way from experimental sub-critical zero power assemblies, driven by external neutron sources (MASURCA, BFS, YALINA, ..) to the proton beam driven LBE cooled medium-power proto-type XT-ADS, planned in the Integrated Project EUROTRANS of the European Community 6th Framework Program.

The main objective of the SAD experiment is to perform research for a future ADS for incineration of nuclear wastes by the coupling of the essential components: proton beam, spallation target and fast spectrum sub-critical core. The construction of this system will gather additional experience with coupling of the main components and will contribute to the preservation of know-how in nuclear engineering. In view of the moderate power of the PHASOTRON proton beam and of the possible level of sub-criticality in Russian sub-critical systems ($K_{\text{eff}} < 0.98$), currently a low power system with 20-25 kW is proposed. Utilizing upper limits for proton beam power and for sub-criticality level of the current design, a maximum of 100 kW can be reached in dedicated experiments.

4. Main characteristics of SAD experiment

The basic features of the SAD project are determined by the PHASOTRON proton accelerator characteristics and by the choice to utilize the regular Russian MOX fuel elements of the BN-600 reactor type. The proton current (maximum value 3.2 μA) and the corresponding power dumped in the spallation target, together with the criticality K_{eff} (< 0.98) of the sub-critical core, determine the total thermal power of the system.

The JINR PHASOTRON has 10 beam channels, used in various experiments. The normal beam losses at transition through the longest beam lines do not exceed 5%.

For the beam transportation system, standard magnetic elements will be used: deflecting magnets of type OM-1 and doublets of quadrupole lenses of type ML-3 with appropriate modifications. These standard magnetic elements have being designed and manufactured in many copies during the PHASOTRON exploitation. The beam transfer from horizontal into a vertical plane at the bottom-side of the SAD core, will be realised using two strong bending magnets, which have to be designed and created. The total number of magnetic elements in the beam line is about 20.

The basic data of the current SAD-design, parameters of the accelerator and the MOX fuel characteristics are listed in the following tables:

SAD installation basic data

Thermal power	up to 30 kW
Protons energy	660 MeV
Beam power	up to 1 kW
Proton beam / target orientation	Vertical
Fuel elements orientation	Vertical
Criticality coefficient	$K_{\text{eff}} \approx 0.95$
Fuel - see table below for details on composition	MOX, $\text{UO}_2 + \text{PuO}_2$
Cladding tubes maximum temperature	400° C
Spallation target	Replaceable: Pb, W
Reflector	Pb
Coolant	Air

Beam parameters

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	3500 μs
Beam microstructure	
Micropulse FWHM	10 ns
Micropulse period	70 ns

Basic features of the SAD core fuel

Parameter	Value
Fuel composition	($\text{UO}_2 + \text{PuO}_2$)
Plutonium dioxide content in fuel composition, %(mass)	29.5
^{239}Pu content in Pu, %(mass)	95
^{235}U content in U, %(mass)	0.4
Fuel density, g/cm^3	10.4
Fuel pellet diameter, mm	5.95

SAD system design parameters

System	Parameter	Value
Target	Number of elements	19 hexagonal prisms
	Material	Lead
	Pitch, mm	36
	Spacing between prisms, mm	1.5
	Height, cm	60
Active Core	Number of fuel assemblies	141
	Number of fuel elements per assembly	18
Fuel element	Pitch, mm	7.95
	Clad tube diameter, mm	6.9
	Clad tube thickness, mm	0.4
	Fuel pellet diameter, mm	5.95
	Fuel height, cm	58

5) Experimental program

In the current status of the SAD proposal, a detailed experimental program is not yet defined. Extensive discussions between experimentalists and designers are in progress, in order to establish specifications for experimental channels, auxiliary equipment, rooms and laboratories, etc. The SAD development team is currently requesting to interested researcher groups for most up-to-date proposals for ADS relevant experiments. Main possible experimental directions, already envisaged are:

- a) Measurements and monitoring of the sub-criticality level. In this important research area, synergy effects with the MUSE and YALINA experiments will be explored. Significant contributions for XT-ADS licensing may be expected.
- b) Measurements of typical core neutron physics parameters like:
 - i) spectral flux densities,
 - ii) power release at different parts of the installation,
 - iii) prompt neutrons lifetime,
 - iv) effective fraction of the delayed neutrons,
 - v) fission rates for minor actinides, U and Pu isotopes,
 - vi) transmutation rates for long lived fission products.
- c) Spallation products yields measurements inside the target.
- d) Preparation of experimental data for benchmarking available calculation procedures for ADS.

In the framework of IP EUROTRANS DM2 TRADE-PLUS, much attention is paid to the determination of the dynamic behaviour of ADS by temperature feedbacks. Indeed, the TRADE experiment with a TRIGA reactor, with thermal spectrum and Zirconium hydride fuel, has large fuel temperature reactivity coefficients, leading to large feedbacks at moderate power levels of about 200 kW. On the contrary, the temperature feedbacks from MOX fuel in a fast neutron spectrum, like in the SAD experiment, are much smaller and the SAD experiment is not well suited to investigate these effects. However, here it should be noted that future ADS for nuclear waste incineration very probably also will be operated with fast neutron spectra and with dedicated fuel with small temperature feedbacks. For this reason, in the SAD project it is planned to perform other types of experiments for the investigation of the dynamic behaviour of ADS. Currently, two experimental approaches are considered for the detailed design of the installation:

- a) Perturbation of the proton beam by current fluctuations,
- b) Perturbation of the sub-criticality level of the core by movement of absorber (or fissile) probes.

Generally, the dynamics behaviour of ADS and the role of the feedbacks between the components must be assessed carefully. In the case that temperature feedbacks need to be investigated, in the current SAD design system power around 100 kW is feasible for short term (several days) experiments. In this case a careful assessment of all aspects, like feedback coefficients and temperature behaviour, has to be carried out, including the control options and possible temperature ranges of the applied air-cooling systems.