Possibility of Subcritical Assembly Exploitation with Electrons Beams

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Abstract

A possibility of SAD system exploitation using electron beams was investigated. The neutron spectrum in the experimental channel located near various targets irradiated by 200 MeV electrons was calculated. Comparison of neutron spectra in experimental channel for different targets irradiated by 660 MeV protons and 200 MeV electrons beam shows that the neutron spectrum changes from fast neutrons (which are useful for study of transmutation of actinides) to epithermal neutrons (good for studying transmutations of fission products). The time dependent activity of a tungsten target irradiated by 200 MeV electron beam was calculated. The electron beam power was 10 kW and the total power of the system was 20 kW. Radioactive isotopes production in the tungsten target was calculated with MCMPX and FLUKA codes. Time dependent activity during irradiation and cooling of the tungsten target was calculated by two methods. A first method was elaborated at JINR, while a second one is based on FLUKA code. We find a good agreement between these methods.

I. INTRODUCTION

At present the problem of safe nuclear power engineering is a topical issue of the day. So, the study and creation of various type subcritical systems is rather important. An accelerator driven subcritical system (660MeV protons+MOX subcritical core) SAD [1,2] is constructed in the Joint Institute for Nuclear Research (JINR). A possibility of exploitation of SAD system using electron beam was investigated.

In addition to energy production, subcritical systems open_perspectives for reprocessing spent nuclear fuel (SNF) as well as other radioactive wastes (RAW) by means of transmutation into safe stable and short-lived isotopes. Evidently, it is impossible to utilize completely all minor actinides (MA) accumulated in large volumes without subcritical systems based on high current proton accelerators. The matter is that for these isotopes the number of delayed neutrons, which allow for stable control of conventional critical reactor is rather small. Besides minor actinides, subcritical systems are capable to destroy fission fragments. The main problem is coming from the long-lived fission fragments (LLFF) such as ^{99}Tc and ^{129}I which are most dangerous from the point of view of their long-term safe storage (several thousand years).

Powerful fluxes of high energy of protons are necessary to ensure effective transmutation of actinides. It follows from the fact that the atomic numbers of such elements are in the range of 89-102 and area of stable elements is finished at Z=82 (lead). Therefore, in order to burn MA, reactions of fission and reactions with emission of a large number of nucleons are needed. Situation is different with fission products. E.g., ^{99}Tc with a high life period of $T_{1/2}$=2.14 $\cdot$ 10^5 years after the radiation capture of low energy neutron is transmuted into a short-lived isotope ^{100}Tc ($T_{1/2}$=15,8 sec) which decays promptly into a stable ^{100}Ru which may overcome another capture of one or two neutrons and finally stays table.

II. DESCRIPTION OF THE FACILITIES

The lead target of subsritical assembly SAD [1] (see Fig.1) consists of two millimeter stainless steel casing, which appears in its external profile as a construction imitating assembly of seven hexagonal prisms, a pressure tight lid and a bottom welded to them and made of stainless steel. The volume is filled with lead. Lead blocks are placed around the target [2].

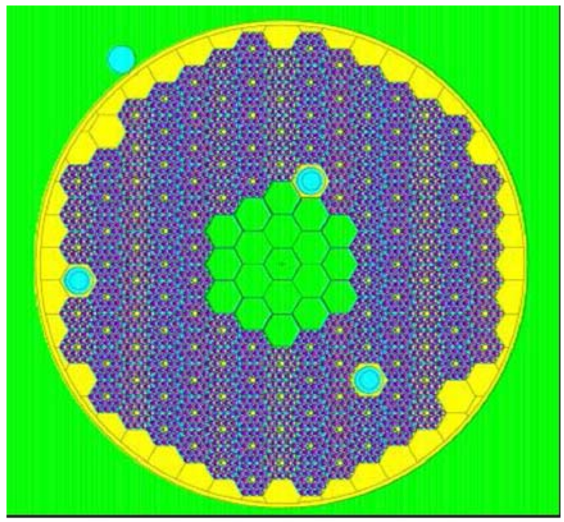

Fig. 1: Schematic view of vertical cross section of the sub critical assembly SAD

The hexagonal lead block consists of a hexagonal stainless steel tube and a hermetically welded shank and lid also manufactured from stainless steel. Internal cavity of the block is filled with lead. Mass of the target is 52 kilograms; mass of the lead block is 7,7 kilograms. Cylindrical cavity with diameter 58 mm and depth 179 mm is made at the entrance point of the beam into the target in order to develop optimal conditions for neutron generation (see Fig.2).

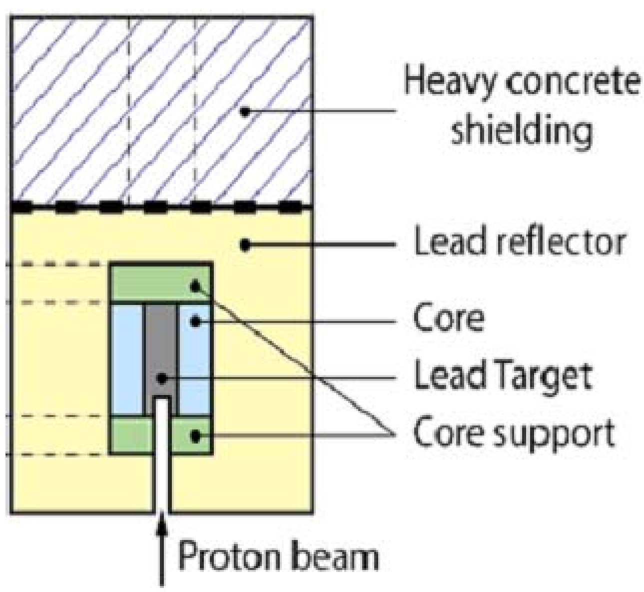

Fig. 2: Schematic view of horizontal cross section of the sub critical assembly SAD

The basic characteristics of the subcritical assembly SAD are resulted in TABLE I.

Table 1: The basic characteristic of the SAD subcritical assembly driven by 660 MeV protons

Characteristics	Destription
Proton beam power	1 kW
Thermal fission power	25 kW
Fuel elements BN-600	70.5%UO_2+29.5% PuO_2
Height of a fuel active part	580 mm
Mass of fuel in element	164.5 g
Number of fuel elements in assembles	18
Number of fuel assembles	133
Maximal gain factor	K<0.95
Heat-carrier	air
Reflectors	lead
Max neutron flux	$2.1 \cdot 10^{12}$ cm^{-2} s^{-1}

The performed calculations have been based on parameters of the linear electron accelerator LUE-200: energy of electrons is 200 MeV, power of the beam is 10 kW which is equivalent to the intensity of the beam $3.125 \cdot 10^{14}$ e^-/sec [3].

The traveling wave electron linac LUE-200 is designed at the Budker Institute of Nuclear Physics (BINP), Novosibirsk [3]. The linear electron accelerator consists of the following main elements: pulsed electron gun, S - band buncher, two accelerating sections, RF assembly on the basis of 5045 SLAC klystron, radio frequency (RF) power compression system SLED, two klystron modulators, focusing system, beam diagnostic system and wideband magnet spectrograph.

Its main characteristics are presented in TABLE II.

Table 2: Main parameters of the linear electron accelerator LUE-200

Characteristics	Destription
Beam average power	up to 10 kW
Electron energy	200 MeV
Pulse current	1.5 A
Pulse duration	$\leq$ 250ns
Repetition rate	150 Hz
Average accelerating gradient	35 MeV/m
Operation frequency	2856 MHz
RF power amplifier	$\leq$ 250ns
Number of accelerating sections	2

II.A. Modification of the construction of the target.

We have modified the construction of the target (see Fig.3) to ensure the best possible conditions for neutron generation with the electron beam. First of all, due to significant increase of the beam power (in basic option power of the proton beam is 1 kW), and as a consequence, increase of heat load in the target it is necessary to replace at least the central zone of the target with material with high melting temperature. Tungsten is chosen as such replacement which except for the high melting temperature is also characterized by higher density which allows for the reduction of unwanted loads in the elements of construction due to gamma radiation. Evidently, such modification does not solve the problems of heat removal from the target as a whole. However, a technical solution of this major problem exists. See, e.g., the project of the tungsten target for the IREN installation [3].

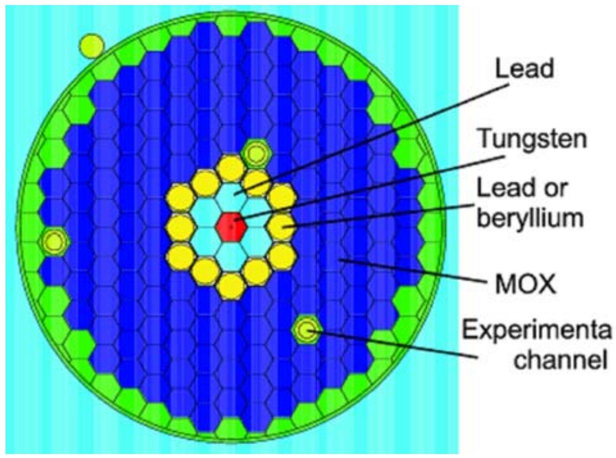

Fig. 3: Schematic view of the blanket

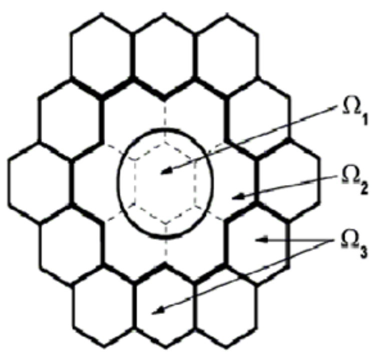

Fig. 4: Target cross section

Secondly, as it has been shown before in [4], the emission of neutrons through the side surface of the lead target develops quite intensively along the whole length accompanying irradiation of the target with 660 MeV proton beam. Free path of electrons with energy 200 MeV in the matter is much shorter; therefore, emission of neutrons from the side surface of the target will be localized. Therefore, it is reasonable to increase the length of the cylindrical cavity at the entrance point of the beam into the target to the mid-point of the target length to ensure that the maximum emission of neutrons is located in the central region of the reactor core. In this case the value of the neutron multiplication factor will be at maximum level. Neutron emission from the side surface of the target with the tungsten insert depending on the value of the coordinate along the target axis is shown in Fig. 5.

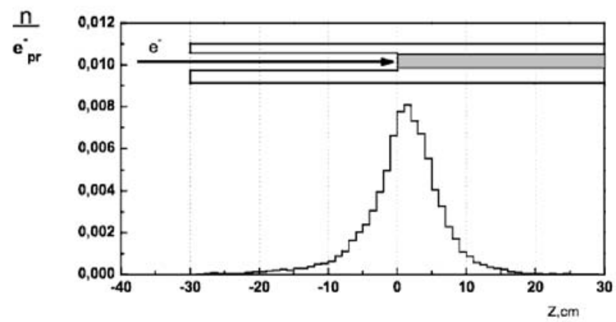

Fig. 5: Neutron emission through the side surface of the target with the tungsten insert depending on the coordinate along the target axis. Origin of coordinates is placed in the interaction point of the beam with the target

Calculation is carried out using the program FLUKA [5].

Total yield of neutrons from the target induced by the proton beam (beam power 1kW and energy 660 MeV) is equal to $1.14 \cdot 10^{14}$ n/sec, neutron yield induced by the electron beam is equal to $3.125 \cdot 10^{14}$ n/sec. Evidently, the share of high energy neutrons is reduced significantly which complicates the experiments to study transmutation of minor actinides. As it is well known, many LLFF, e.g. ^{99}Tc and ^{129}I demonstrate resonance structure in cross section of radiation capture of neutrons in the energy range from several eV up to dozens of keV. Therefore relative increase of the number of resonance neutrons in the spectrum improves the perspectives to study LLFF transmutation. Moreover, there is a possibility to further increase significantly the share of resonance neutrons in the spectrum, namely, the third modification of the concept assumes replacement of lead in the target and lead blocks surrounding the target by lighter elements such as graphite and beryllium which will further multiply neutrons emitted from the target and play a role of internal reflector for neutrons produced as a result of nuclear fission of fuel in the reactor core (RC). As a result of proposed modifications we are coming to the following configuration (see Fig. 4): Ω_1 – tungsten, Ω_2 and Ω_3 – graphite and beryllium. Let us notice that melting temperature of graphite and beryllium is much higher than meting temperature of lead which also shows assistance in solving the problem of cooling the target.

The basic characteristics of the subcritical assembly SAD driven by 200 MeV electrons are presented in TABLE III.

III. RESULTS OF CALCULATIONS

III.A. Calculations of neutron parameters for electron beam

As is shown in [1], effective neutron multiplication factor in the reactor core depends on the material of the target; therefore, changing the number of fuel assemblies we are capable to reach the level of $K_{eff}\approx 0,975$.

Thus, we investigated three possible concepts of the target to operate the SAD installation using electron beam. First option of the modification consists of adding a tungsten insert into the target, which shape is left unchanged. Of course, the shape and profile of the tungsten rod may differ under condition that most of electrons overcome reaction

Table 3: The basic characteristic of the SAD subcritical assembly driven by 200 MeV electrons

Characteristics	Destription
Electron beam power	up to 10 kW
Thermal fission power	up to 10 kW
Fuel elements in fuel assembles	18
Height of a fuel active part	580 mm
Number of fuel assembles	up to 132
Maximal gain factor	K<0.98
Heat-carrier	helium
Reflectors	lead

in tungsten; however, in calculations the volume of the central hexagonal prism (Ω_1) was completely filled with tungsten (see Fig. 4). The lead blocks surrounding the target are replaced with fuel assemblies. This option does not differ from the option considered in [1] except for the depth of the cavity at the entrance point of the beam into the target. In other words in this case there is a possibility to transfer the installation from the proton beam to electron beam which practically does not require any restructuring of the core as a whole. Use of the tungsten insert (Ω_1) is still assumed in the second option; however lead in the target (Ω_2) is replaced with graphite. Lead blocks surrounding the target (Ω_3) are replaced with analogous constructions made of graphite.

In this case we need a smaller number of fuel assemblies (by one or two assemblies) than in the option described above. Third option is different from the second one only by the replacement of graphite with beryllium and the number of fuel assemblies necessary to reach the required neutron multiplication factor is further reduced down to 116 assemblies in total. Calculation of parameters of the installation was carried out using the MCNPX package. Results of performed calculations are presented in TABLE IV.

Table 4: Results of calculations of neutron parameters

Target	K	Number of fuel assemblies	F_{tot}, n·cm^2·sec^{-1}	P_{heat},kW
W + Pb	0,974	132	$7{,}4 \cdot 10^{11}$	10,25
W + C + C	0,974	130	$5{,}9 \cdot 10^{11}$	8,57
W + Be+Be	0,975	116	$7{,}9 \cdot 10^{11}$	11,25

III.B. Neutron spectra in different modifications

Modeling of neutron spectra in experimental channels has been accomplished using the program MCNPX. Results of calculations are presented in Fig.6. Spectrum in the first experimental channel of the base installations is shown with dots for comparison. Let's remind that the base installation is designed for operation with the proton beam at energy 660 MeV and beam power 1 kW.

It is clear from the Fig.6 that the share of high energy neutrons is reduced significantly in comparison with the base installation. However, flux of thermal and resonance neutrons (E<10keV) is much higher in options with modified target. For example isotope ^{99}Tc

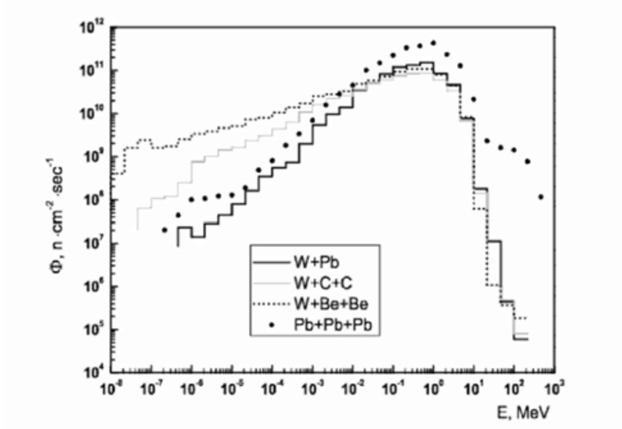

Fig. 6: Neutron parameters of the installations with modified targets

is characterized by resonance radiation capture cross sections at neutron energy 5,6 eV (4300 barn). Neutron flux at such energy in the first channel of the installation with beryllium internal reflector irradiated with electron beam increased by thirty times. Isotope ^{129}I has a resonance in cross section of radiation capture for neutrons at energy 72,4 eV (603 barn). Neutron flux at such energy is increased by one order. Let's point out that in the LLFF produced at power plants main contribution in total mass is coming from these two radioactive nuclides. Therefore the problem of investigation of transmutation for these two isotopes is especially sensitive.

III.C. Activation of the target with electron beam

The method used for calculation of the activation of the target BRPM irradiated by the proton beam is presented in [7]. Analogous calculations have been carried out for the electron beam. Rate of production of radioactive isotopes was calculated using the program FLUKA. Evolution of activity of radioactive isotopes during the periods of operation and cooling down of the installation was calculated using two methods: method described in [7], three and the method using the USRUWEV utilities provided together with the FLUKA package. Results of calculations are presented in Fig.7. for the following operation mode: installation is running with uniform load during one calendar year. During this period the beam is supplied to the target for 1000 hours, after that the installation is cooled down. It is assumed that the cooling time prior to refueling operations is equal to half a year, at this moment activity of the target is reaching $\approx 2 \cdot 10^{11}$ Bq which is approximately 5 times larger than the activity induced by the proton beam with power 1 kW. However, as it has been shown before [7] we have a thirty-fold margin in the equivalent dose rate. It is also worthwhile to mention that the width of the proton beam is equal to approximately 4 mm; therefore main volume of produced radioactive isotopes will be localized in the center of the target activated by the electron beam. Therefore the design limit for the dose rate for the personnel which is equal to 6 μSv/h is guaranteed within a safety margin. It means that the schedule of refueling operations and cooling time of the installation may be left without alteration.

IV. CONCLUSIONS

Thus, the concept of the neutron generating target for the subcritical assembly allows for operations of the SAD using electron beams from the accelerator LUE-200. Therefore, there is a possibility to study aspects of electronuclear method of energy production

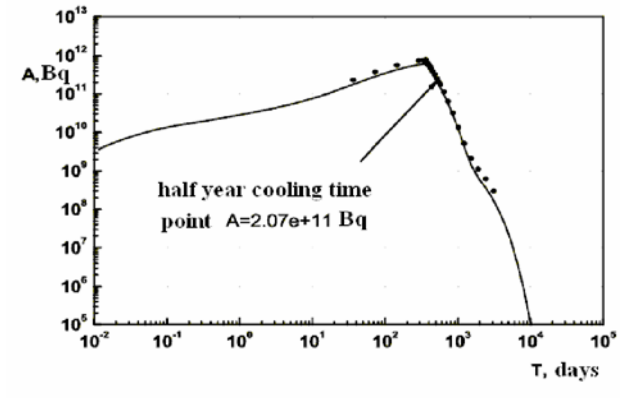

Fig. 7: Evolution of activity in the target with tungsten insert. Calculation performed by using the FLUKA code is shown with dots; solid line demonstrates results of calculations based on the method from [7]

using one installation with different particle beams. Studies of the behavior of the same RC in different conditions and operation modes provides much better understanding of perspectives and modes of employment of the electronuclear method at the commercial scale.

Low electron energy in the beam limits the possibility of producing high energy neutrons in experimental channels of the installation. However, using the internal reflector made of light materials makes it possible to provide the spectrum with higher density of the neutron flux in the resonance range. Thus, it is possible to expand the experimental program in the sphere of investigation of transmutation of LLFF which are most dangerous from the point of view of the long-term safe storage of the RAW.

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