STUDY OF A POSSIBILITY OF EXPLOITATION OF SUBCRITICAL ASSEMBLY WITH THE ELECTRONS BEAM

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The possibility of exploitation SAD (Subcritical Assembly at Dubna) system using an electron beam was investigated. The spectrum of neutrons in the experimental channel located near various targets irradiated by 200 MeV electrons was calculated. The comparison of calculated neutron spectra in experimental channel for different targets irradiated by a 660 MeV proton and 200 MeV electron beam shows that the neutron spectrum changes from fast neutron (which are useful for study of the transmutation of actinides) to epithermal neutrons (suitable for studying the transmutation of fission products). The time dependent activity of 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. The radioactive isotopes productions in the tungsten target were calculated with MCMPX and FLUKA codes. Time dependent activity during irradiation and cooling of the tungsten target were calculated by two methods. First method was elaborated in JINR, while the second method is based on FLUKA code. We find good agreement between these methods.

I. INTRODUCTION

At present the problem of safe nuclear energy is a topical issue of the day. So, the study and creation of various types of subcritical systems is rather important. The accelerator driven subcritical system SAD (Subcritical Assembly in Dubna, Refs. 1 and 2) is projected for 660 MeV protons in the Joint Institute for Nuclear Research (JINR). Possibility of construction of the SAD system using electrons beam was investigated.

Besides energy production subcritical systems open perspectives for the reprocessing of spent nuclear fuel (SNF) as well as any other radioactive wastes (RAW) by means of transmutation into 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 for minor actinides subcritical systems are capable to destroy fission fragments. Main problem is coming from the long lived fission fragments (LLFF) such as ^{99}Tc and ^{129}I which are the most dangerous from the point of view of their long-term safe storage (several thousand years).

High fluxes of energetic neutrons 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 high life period $T_{1/2}$=2.14 · 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 capture one or two neutrons and finally stay stable.

II. DESCRIPTION OF THE FACILITIES

The lead target of the subcritical assembly SAD (Ref. 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 and pressure tight lid and bottom welded to them also made of stainless steel. The volume is filled with lead. Lead blocks are placed around the target (Ref. 2)

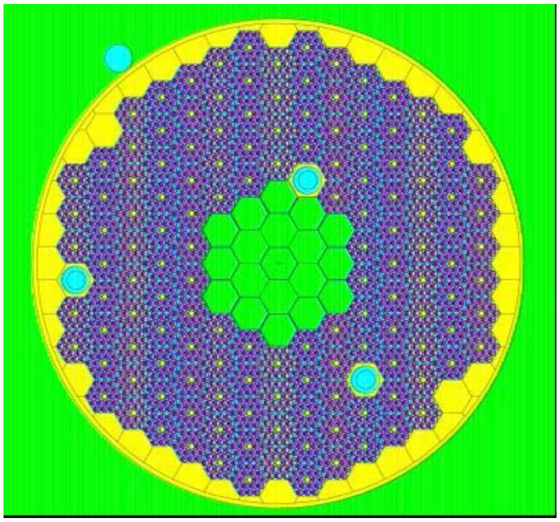

Fig. 1. Schematic view of vertical cross section of the sub critical assembly SAD. (The distance between centers of hexagonal blocks is 36 mm)

Hexagonal lead block consists of a hexagonal stainless steel tube and 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. The 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).

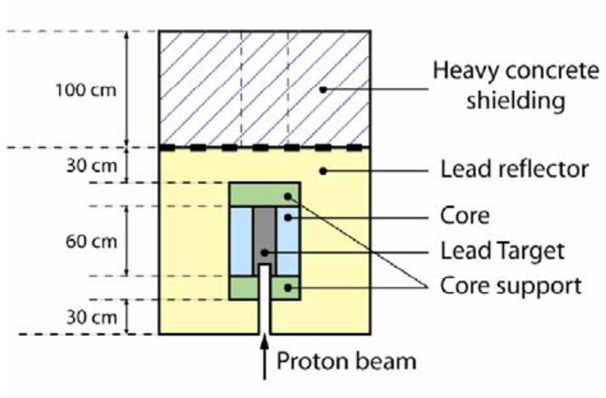

Fig. 2. Schematic view of horizontal cross section of the sub critical assembly SAD.

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

TABLE I. The basic characteristic of the SAD subcritical assembly driven by 660 MeV protons.

Characteristics	Description
Proton beam power	1 kW
Thermal fission power	25 kW
Fuel elements BN-600.	70.5%UO2+29.5 % PuO2
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 10^{12} cm^{-2} s^{-1}

Calculations have been carried out based on the parameters of the linear electron accelerator LUE-200: The energy of electrons is 200 MeV, power of the beam is 10 kW which is equivalent to the intensity of the beam 3.125 10^{14} e^-/sec. (Ref.3)

The traveling wave electron linac LUE-200 is designed at the Budker Institute of Nuclear Physics (BINP), Novosibirsk (Ref.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 II. Main parameters of the linear electron accelerator LUE-200.

Characteristics	Description
Beam average power	up to 10 kW
Electron energy	200 MeV
Pulse current	1.5 A
Pulse duration	≤ 250ns
Repetition rate	150 Hz
Average accelerating gradient	35 MeV/m
Operation frequency	2856 MHz
RF power amplifier	≤ 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 a significant increase of the beam power (its basic configuration power of the proton beam is 1 kW), and as a consequence the 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 doesn't solve the problems of heat removal from the target as a whole. However a technical solution of this major problem exist see, e.g., the project of tungsten target for the IREN installation (Ref.3).

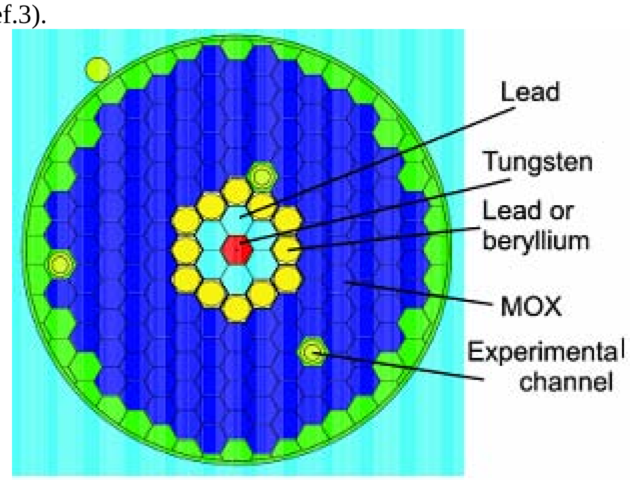

Fig. 3. Schematic view of the blanket

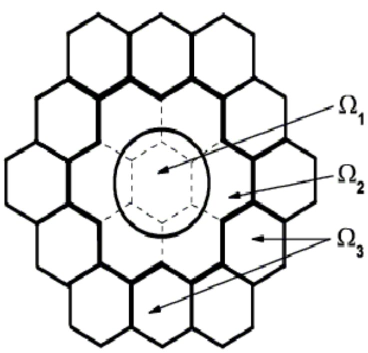

Fig.4. Target cross section. Regions Ω_1, Ω_2 & Ω_3

Secondly, as it has been shown before in (Ref.4) emission of neutrons through the side surface of the lead target develops quite intensively along the whole length accompanying irradiation of the target with proton beam at 660 MeV. 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.

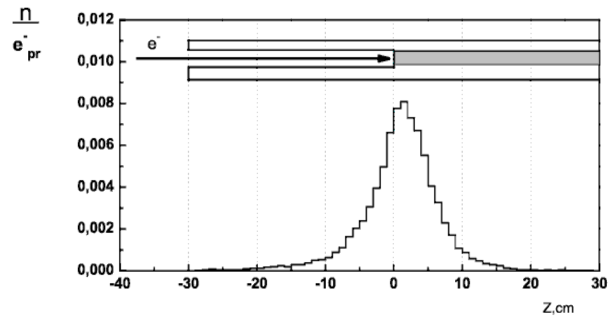

Fig. 5. Neutron emission through the side surface of the target with the tungsten inserts depending on the coordinate along the target axis. Origin of coordinates is placed in the interaction point of the beam with the target.

Calculation is carried out using the program FLUKA (Ref.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 the 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 melting 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.

TABLE III. The basic characteristic of the SAD subcritical assembly driven by 200 MeV electrons.

Characteristics	Description
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

III. RESULTS OF CALCULATIONS

III.A. Calculations of neutron parameters for electron beam

As is shown in (Ref.1), effective neutron multiplication factor in the reactor core depends on the material of the target; therefore, changing the target we are capable to reach the level of K_{eff}≈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 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 (Ref.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 lesser number of fuel assemblies (by one or two assemblies) than in the basis option. The 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 the calculations are presented in TABLE IV.

TABLE IV. Results of calculations of neutron parameters

Target	K	Number of fuel assemblies	F_{tot}, $n \cdot cm^2 \cdot sec^{-1}$	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 options

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 of 660 MeV and a beam power 1 kW.

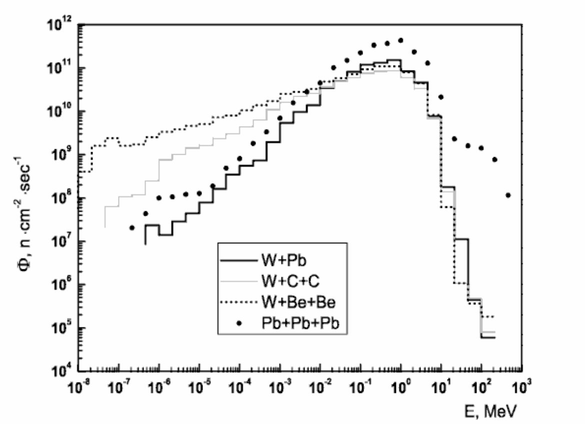

Fig. 6. Neutron fluxes of the installation with the modified targets and reflectors.

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 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 the electron beam is increased by thirty times. Isotope ^{129}I has a resonance in cross section of radiation capture for neutrons at energy 72.4 eV (603 b). Neutron flux when low Z materials are replacing lead at such energy is increased by one order. Let's point out that in the LLFF produced at power plants the main contribution 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 the electron beam

Method used for the calculation of the activation of the target BRPM irradiated by the proton beam is presented in Ref.7. Analogous calculations have been carried out for the electron beam. The rate of production of radioactive isotopes was calculated using the program FLUKA. The evolution of the activity of radioactive isotopes during the periods of operation and cooling down of the installation was calculated using two methods: method described in Ref.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 (Ref.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 in which the radioactive isotopes are produced is 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.

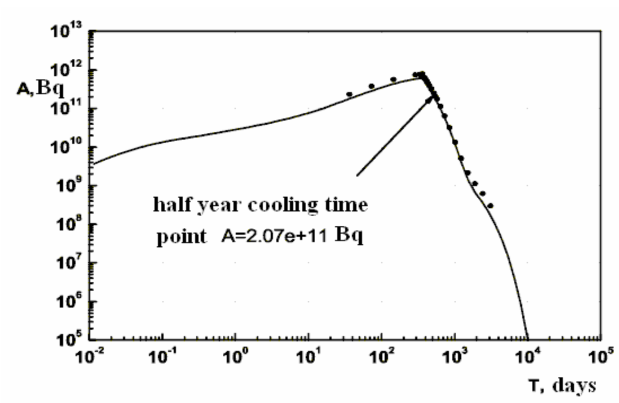

Fig. 7. Evolution of activity in the target with tungsten inserts. Calculation performed by using the FLUKA code is shown with dots; solid line demonstrates results of calculations based on the method from Ref. 7.

IV. CONCLUSIONS

The neutron generating target for the subcritical assembly allows for operations of the SAD using electron beams from the accelerator LUE-200 was calculated. Therefore, there is a possibility to study aspects of electronuclear method of energy production using one installation with different particle beams. Studies of the behavior of the same reactor core in different conditions and operation modes provides much better understanding of perspectives and modes of employment of the electronuclear method at the commercial scale.

The low energy of the electron beam limits the possibility of producing high energy neutrons in experimental channels of the installation. However, we have shown that 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 experimental program in the sphere of investigation of transmutation of the long lived fission fragments which are the most dangerous from the point of view of the long term safe storage of the radioactive wastes.

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