Two-zone Sub-critical Reactor Driven by a High-intensity Neutron Generator as a Research Facility for Nuclear Waste Transmutation - 10124

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ABSTRACT

In regard to intensive development of accelerator driven system (ADS) in the past 20 years and a promising possibility of radioactive waste transmutation in such systems, we have proposed the physical project of a sub-critical research reactor driven by an external neutron source. The basis of such a research reactor is a good optimized two zone sub-critical assembly. The results of calculations of the simple homogeneous models of such assemblies are presented in the paper, and the two zone (fast and thermal) heterogeneous model has been designed on the base of these calculations. The main details of design and physical characteristics of such a model are also presented. Special attention is paid to the choice of effective external neutron source. The disadvantages and advantages of different types of accelerators and power neutron generators are considered.

INTRODUCTION

The long-term hazard of radioactive wastes arising from nuclear energy production is a matter of continued public discussion in many countries. Using the transmutation of the actinides and some long-lived fission products, the radiotoxicity of the high-level waste and, possibly, the safety requirements for its geologic disposal, can be reduced. Studies of different authors [1-3] show that the construction of accelerator-driven sub-critical systems (ADS) is a very promising field in nuclear power engineering. Such systems provide a possibility to improve the safety level and to develop effective methods of transmutation of long-lived radioactive waste. Active projects for ADS exist in USA, Japan, France, Spain, Belgium, Italy, Russia and Belarus [4-9]. The research in these countries mainly comprises the basic studies of the different aspects of ADS, although some of these projects are directed towards a pre-engineering design phase within the next few years. An operating research assembly has been created in Belarus (Yalina) [10-11].

THE TRANSMUTATION OF THE NUCLEAR WASTE

There are now 436 nuclear power reactors operating in the world. In addition to electricity, they produce spent nuclear fuel containing a large quantity of Plutonium (Pu), minor actinides (MA) – Neptunium (Np), Americium (Am), Curium (Cm) – and long lived fission products (first of all ^{99}Te and ^{129}I). Partitioning and transmutation (P&T) are considered at this time to be possible alternative to geological disposal of nuclear wastes [8, 9, and 13]. If one extracts Plutonium and minor actinides from spent nuclear fuel and fission them, then the radiotoxicity of nuclear wastes can be decreased sufficiently. The nuclear transmutation is itself the irradiation of nuclear wastes by intensive neutron flux in order to transform transuranics, in particular (Pu, MA), and long lived fission products to short-living and stable isotopes. If one could completely extract Pu and transmute it, the radiotoxicity can be lowered by an order of magnitude. In addition, if one can transmute MA, the general radiotoxicity will be one hundred times even lower. If one could transmute all radioactive wastes, their activity will become lower than the activity of natural uranium ore approximately in 500 years. Transmutation can be performed in all types of nuclear reactors with high neutron flux, but the transuranics including MA can be transmuted in fast reactors more effectively. In electro-nuclear systems (ADS) both transuranics and fission products can be effectively transmuted. So the real possibility to decrease the quantity of radioactive wastes arises with the help of ADS. However, the natural question will arise: what is the cost of such a transmutation? What usage charge should society pay for this idea realization? At the present stage of the conceptual research, one can make only coarse estimates of the economical effectiveness of transmutation processes in ADS. In any case, the question of ADS cost reduction still remains. Therefore it is expedient at the present stage to study the main physical characteristics of ADS and the possibility of creation of a research sub-critical facility with an external neutron source as a base of design for an industrial transmutation installation. In the next sections we consider the physical properties and preliminary design of such a research facility.

STUDY OF THE SIMPLE MODELS OF SUB-CRITICAL ASSEMBLIES

The first stage of our research studied the simple models of sub-critical assemblies (see Fig. 1) [14]. The main objective of our investigation was to establish the basic laws of the behavior of the amplification factors of neutron flux and energy depending on primary features of the assembly - such as nuclide composition, energy of neutrons of the external source, effective multiplication factor of the system, and ratio of nuclear concentrations in different zones and their sizes. Study of such model assemblies is of interest for a better understanding of amplification properties of more complicated systems and for their parameters optimization. Even such simple systems show a number of nontrivial properties concerning the amplification of neutron flux, in particular the amplification factors have non-monotonic behavior depending on the uranium enrichment and ratio of nuclear concentrations (H/U). We choose the physical systems to be slightly sub-critical, namely, we fix the value of neutron effective multiplication factor of each system to be equal k_{eff}=0.99.

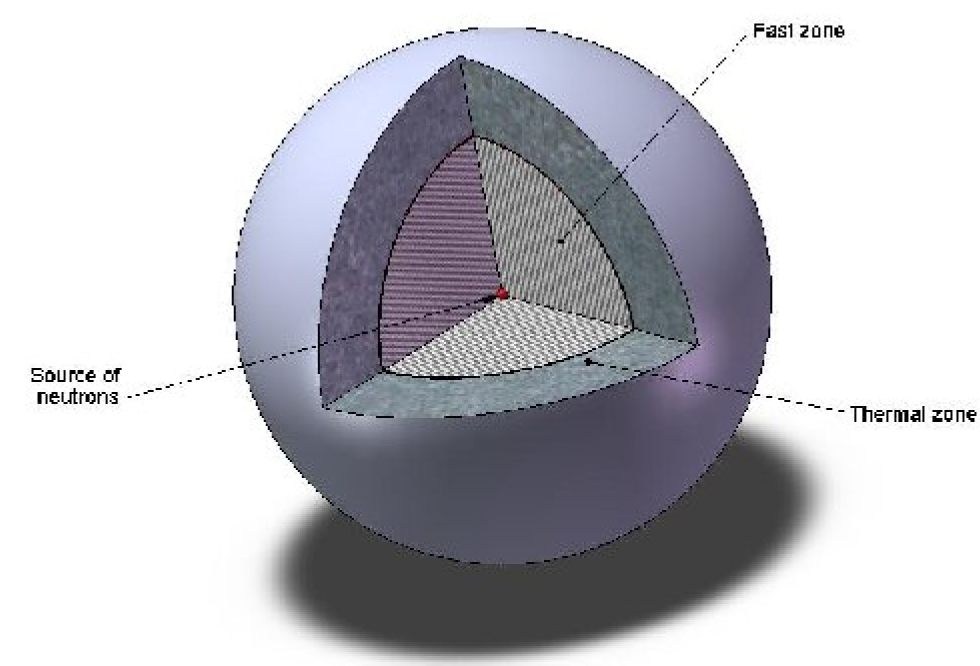

Fig. 1. The simple spherical two-zone subcritical model.

We have considered a point isotropic source of neutrons with energy of 14 MeV to be the "external" source, which is located at the centre of spherical sub-critical assembly (see Fig. 1). Actually, realistic neutron sources from D-T reactions are neither isotropic nor mono-energetic, however the simplified model we use is rather typical and frequently used. The geometric dimension (radius) of the assembly is fixed by the requirement for the effective multiplication factor of the system to be equal to a certain specified value, which is slightly less than unity, i.e. the assembly should be slightly sub-critical. Calculations of the amplification factors and other physical characteristics of the systems under consideration were done with the help of the neutron Monte Carlo transport code MCNP-4C [15], which employs the latest ENDF/B-VI nuclear data library.
It was shown in several papers, in particular [16], that the two-zone sub-critical systems with inner enriched booster are able to effectively amplify the source neutron flux. Therefore we have considered two-zone system, where the inner zone consists of enriched uranium, and outer zone consists of pure ^{238}U. The thickness of the outer zone is given in the range from 1 cm to 20 cm, and enrichment of the inner zone varied from 8% to 100%. For every enrichment the dimension of the inner zone was selected in the way to provide k_{eff} of all system to be equal to 0.99. The neutron amplification coefficient q was the main characteristic of the sub-critical system (see Figure 2). We define the neutron amplification factor q as the ratio of the total number of neutrons passing through the close surface in a time unit N_S, to the intensity of the neutron source I_0, i.e. to the number of neutrons emitted by the source in a time unit $q = N_S/I_0$.

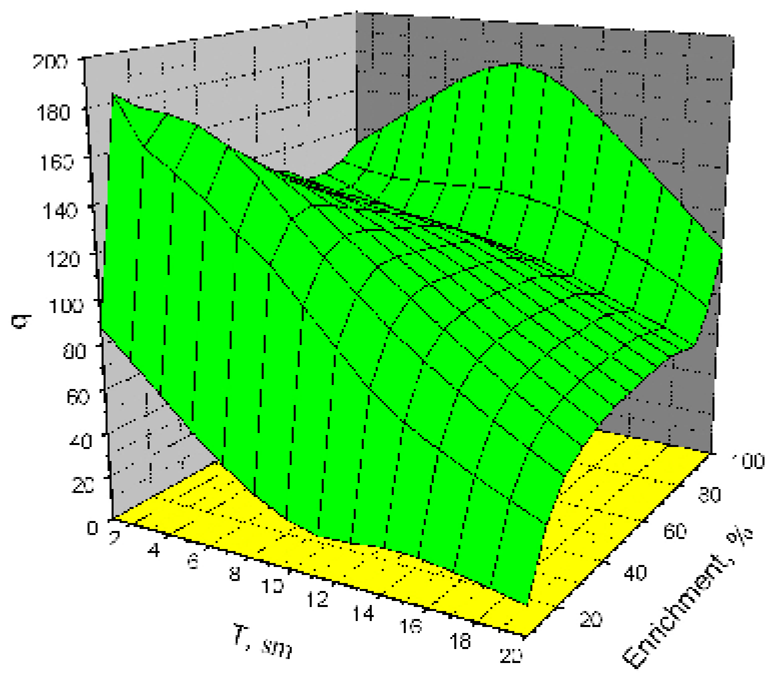

Fig. 2. The neutron flux amplification factor for the external boundary surface versus the uranium enrichment for the different thickness of the outside zone (T).

The neutron amplification factor spatial distribution dependent on inner enrichment was calculated for the given model (Fig. 3), and in addition the evaluation of such reactor power with neutron source intensity of 10^{15} n/s was made (thermal power is about 3 MWt). All data at the figures are reduced to single source neutron. We finished the investigation of heterogeneous systems now, but results of the latest investigation will be published in another journal.

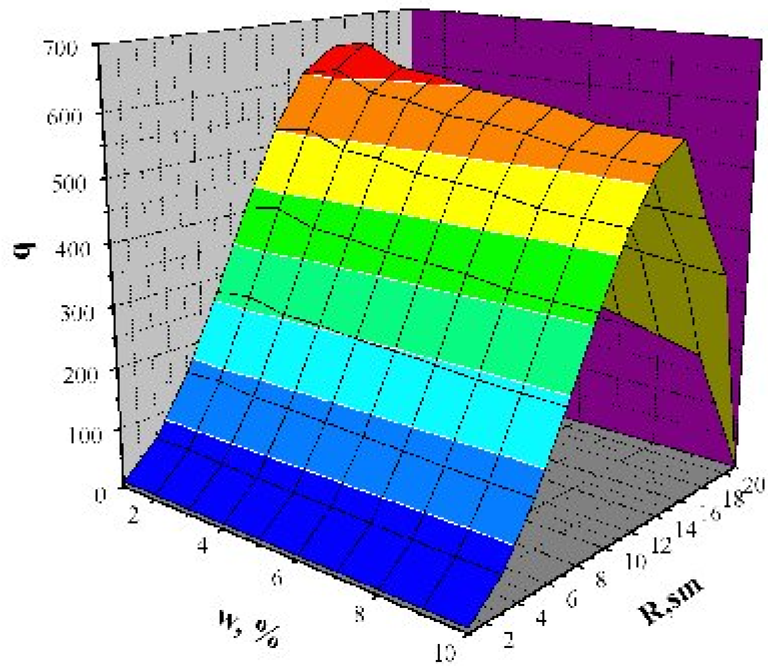

Fig. 3. The neutron flux amplification factor spatial distribution calculated to single source neutron at different enrichment of the inner zone.

RESEARCH OF THE HETEROGENEOUS TWO-ZONE SUB-CRITICAL ASSEMBLY

Our assembly was designed as a two-zone multiplying sub-critical system with fast (inner zone) and thermal (outer zone) neutron spectra, which are also necessary for effective transmutation of nuclear wastes. These two zones were arranged in such a way that the effective multiplication factor in the assembly is equal to 0.97, i.e. the assembly is slightly sub-critical. The multiplication fission reaction in the assembly is supported by the external neutron source which is a neutron generator (see for example [17]). This neutron generator creates the flow of deuterons directed to the titanium target saturated by tritium which is located at the center of sub-critical assembly. The D-T reaction is originated in the target:

$$^{2}H + ^{3}H \rightarrow ^{4}He + n \qquad \text{(Eq. 1)}$$

As a result we have a neutron flow with mean energy about 14 MeV. In order to model such sub-critical assembly, we have divided it into 9 zones, as shown in Figure 4. Let us consider these zones in detail. The zone 1 is the evacuated tube in which the flow of deuterons is moved from top to bottom toward the target. The zone 2 is a thin plate made of titanium saturated by tritium. The reaction (Eq. 1) is originated inside this zone and neutrons are created. The zone 3 is the copper substrate for the target; a tube of stainless steel with water heat carrier removes heat from inside this zone. The zone 4 is the stainless steel container in which the fast assembly is located.

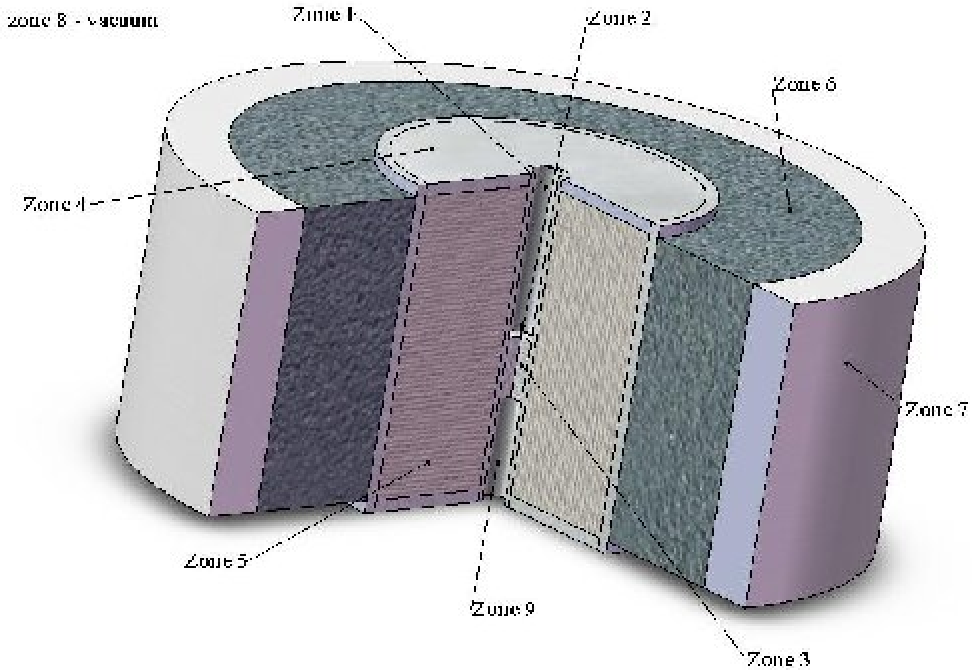

Fig. 4. The simplified sub-critical assembly with zone division.

The zone 5 is the fast assembly collected from the modern pins of reactor VVR-M (Kyiv Institute for Nuclear Research). This zone is cooled by a helium heat carrier. The thermal zone 6 is collected from the shortened pins of energy reactor VVER-1000, which are cooled by a water heat carrier. The zone 7 represents a beryllium reflector. The zone 8 is the vacuum. In the zone 9, the tubes for the heat carrier supply and removal from the zone 3 are located. Presently we are finishing the calculations of the physical characteristics of this assembly.

THE SELECTION OF AN EFFECTIVE AND OPTIMAL EXTERNAL NEUTRON SOURCE

The physical and economical effectiveness of the ADS are very dependent on the external neutron source selection. In the majority of the existing projects, the external neutron source is a proton or electron accelerator [4-9]. Let us try to compare the charged particle accelerators with neutron D-T generators.

There are two reasons that determine our choice of neutron source energy to be equal to 14 MeV. First, today we have two ways to obtain neutrons via the process of interaction of accelerated charged particles with matter, namely, with the help of D-T reaction and with the help of the spallation process. Spallation reactions give neutrons as a result of the interaction of fast charged particles (for example, protons with energy ~1 GeV) with nuclei of heavy metals (for example, with a mixture of lead and bismuth) [18]. Fusion reactions may be accomplished with the help of deuteron accelerators working at energies from 150 to 300 keV and currents of the order of an Ampere. Such a current is required to yield a neutron flux, which is equivalent to the spallation neutron flux produced by proton accelerators with energy ~1 GeV and current of about 1 mA. At the same time, a project based on the D-T reaction costs a few times less than the one based on spallation.

The second reason for our choice of neutron source energy to be equal to 14 MeV is that spallation neutrons have a rather wide energy spectrum with the maximum lying from 200 to 300 MeV. Neutron cross-sections in this region, however, are not known sufficiently well and they are not available for all nuclides needed. Since relevant cross-section libraries in this energy range are missing (except MCNPX, which we have none in our laboratory), the calculation with the neutron source from a spallation process is problematic. At the same time, the neutron source with energy of 14 MeV, resulting from D-T reaction, is available technically, and the neutron cross-sections in this energy range are well known and they are collected in corresponding libraries. In this connection, it is important to study the efficiency of transmutation with the "14-MeV neutrons" and to compare results with those, obtained with "spallation neutrons".

Recently, research has intensified on development and practical use of the facility of the Plasma Focus (PF) type. The PF devices may take the lead over the pulse neutron tubes used presently in industry both in absolute neutron output per pulse and full intensity. But the most important difference of PF from other sources consists of design simplicity (and consequently low price) and higher neutron radiation intensity. Presently the largest facility of the PF type has been developed in Poland [19, 20], which can create neutrons with intensity $5 \cdot 10^{12}$ n/s, and there is the plan to improve up to 10^{13} n/s. We suggest considering plasma focus as one of the possible neutron sources for sub-critical assemblies.

CONCLUSION

We have considered in this paper the preliminary physical project of nuclear research related to a sub-critical reactor with high neutron flux which can be used for experimental study of the possibility of nuclear waste transmutation, as well for traditional use as a research reactor. The optimization of the simple two-zone sub-critical system was performed which gives the possibility to develop the preliminary design of the real two-zone sub-critical heterogeneous system describing in the paper. The choice of the external neutron source is important question for effective operation of sub-critical system especially in economical sense. We hope that the project presented could be a good base for new type of research reactor with high neutron flux creation.

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