THE NEW RESEARCH SUBCRITICAL REACTOR DRIVEN BY A HIGH-INTENSITY NEUTRON GENERATOR FOR TRANSMUTATION OF THE NUCLEAR WASTE

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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 effective methodology of preparation of tritium in the subcritical core for the external neutron source is proposed.

1. Introduction

We must solve two main problems for further development of nuclear energy: the safety of nuclear power plants and the removal of radioactive waste. The attention to safety of nuclear power is increased after incidents at Three Mile Island's nuclear power plant and at Chernobyl. There is the very good level of safety of nuclear energy now. Many projects of third and forth generation of nuclear reactors are developed lately. These projects may improve the safety of nuclear power plants in the near future [1].

Nuclear transmutation is considered as a possible mechanism for reducing the volume and hazard of radioactive waste. Nuclear transmutation is the conversion of one chemical element or isotope into another, which occurs through nuclear reactions. 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. For solution of this idea require to develop the method of extraction of transuranics from the high level waste and to build a nuclear reactor with high neutron flux. The project of the research subcritical reactor driven by external neutron source for the transmutation of radioactive waste is proposed in this article [2, 3].

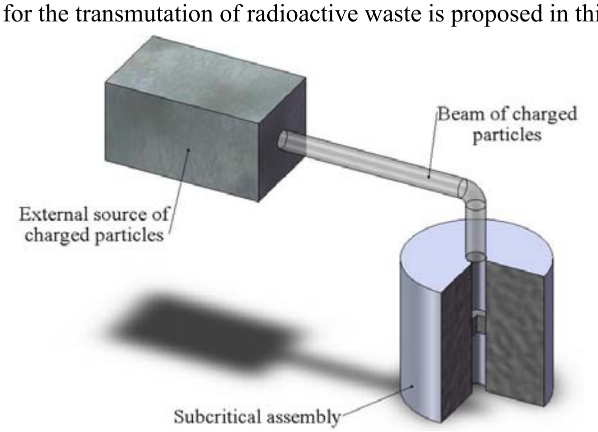

Fig. 1. Simplified scheme of ADS.

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 [4-6]. The Carlo Rubbia's research group at CERN proposed the energy nuclear system for transmutation of plutonium and another minor actinides at nineties of the twentieth century ("Energy Amplifier" (EA)) [7]. The "Energy Amplifier" is the subcritical core with fast neutron spectrum driven by a proton accelerator. Thus, the principal scheme of ADS is the subcritical core driven by an external neutron source (Fig. 1).

A subcritical assembly is a nuclear fission assembly that produced fission without achieving criticality. Instead of a sustaining chain reaction, a subcritical assembly uses additional neutrons from an external source. For solution of this idea require to optimize a subcritical system and to select optimum external neutron source.

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.

2. Optimization of subcritical assembly

Daniel and Petrov [8] in the one-group approximation of the neutron diffusion equation for two-zone reactor showed efficiency of using the two-zone system, where the first, small booster reactor with $k_{\infty 1}>1$ serves as a neutron multiplier for a second, big reactor. The first reactor obtains neutrons from a spallation source and delivers more neutrons to the second reactor. Both reactors are subcritical. They showed that the total power gain factor for a typical reactor system of such type may achieve magnitude $N \sim 400$ in this case.

We have studied various homogeneous subcritical reactor systems for the past few years [9, 10]. Systems with different geometry, chemical composition and subcriticality level were analyzed with the help of neutron-physical codes

MCNP 4c and Scale 4.4a. The main optimization parameter for this case is the neutron amplification factor q of the external source because the main goal of constructing research reactors is obtaining of high neutron fluxes. This factor may be defined as the ratio of the total number of neutrons crossing external boundary surface per second N_S to the strength of neutron source I_0: $q = N_S/I_0$. Energy amplification factor G defined as the ratio of the energy released in the reactor to the energy of source neutrons is also important physical characteristic of such systems.

The main conclusions made on the basis of these calculations are the following. 1. The two-zone subcritical reactor system is really more effective in neutron flux amplification than the one-zone system. 2. The most optimal arrangement of zones is the following – the fast neutron spectrum zone (including external neutron source) is located at the centre of the core and the thermal neutron spectrum zone is surrounding the fast neutron spectrum zone. 3. Amplification factor in the well-optimized subcritical system may achieve values of a few hundred units.

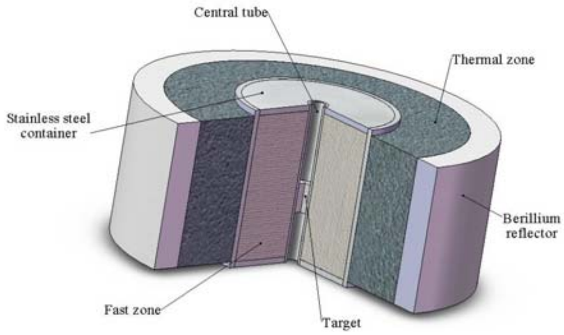

Fig. 2. The simplified sub-critical assembly.

Thus, on the basis of computer simulation, we propose the following project of subcritical research reactor driven by the powerful neutron generator. Simplified scheme of subcritical assembly is shown in Fig. 2.

Let us consider this model in more detail. The flux of charged particles moving from top to bottom by the central tube hits titanium target saturated with tritium. D-T reactions occurring during interactions of deuterons with a tritium target produce neutrons with the energy 14 MeV. Titanium target is placed on a copper base cooled by the water, and in turn water cooling pipes are placed in the lower part of the central tube, under the target. Fast zone, surrounding the central tube, is placed in the tank made of stainless steel. Fast zone is composed of the reactor WWER-1000 fuel pins cooled by the helium coolant. Thermal zone, surrounding the fast zone, is also composed of the reactor WWER-1000 fuel pins, but cooled by the water coolant. Beryllium reflector is placed on the outside border of the reactor core.

Calculations were made for subcritical reactor model shown in Fig. 2 with the effective neutron multiplication factor fixed to be equal $k_{eff} = 0.97$. Point neutron source of the 14 MeV energy was placed in the centre of the assembly on the surface of the target. Geometrical dimensions of systems with different chemical composition were chosen to give fixed value of the effective multiplication factor. Calculations of amplification factors were performed with the help of Monte Carlo neutron transport calculation code MCNP-4c employing the ENDF/B-VI library of nuclear data. The main calculated physical characteristics of the system are neutron flux, neutron amplification factor and energy amplification factor.

First of all we have modeled the uranium enrichment variation in the fuel pins of the fast zone while the uranium enrichment of the thermal zone was fixed. Results of calculation show that optimal enrichment of uranium in the fast zone is 15 - 20 % in uranium-235. Secondly, gaseous coolant in the fast zone is proposed to use for the conservation of fast neutron spectrum. The most optimal gaseous coolants are helium and carbonic acid gases, in accordance with the world experience of the gaseous coolants usage. Results of calculation show unessential difference between these gases, so the final choice should be made based on thermalphysic and economic reasons. Thirdly, we have modeled variation of geometrical dimensions in order to determine optimal characteristics of the system height and radius. In this case we took into account statement of [15] that minimal leakage of neutrons through the surface of cylindrical reactor core takes place when the ratio of its height to diameter equals 0.8 - 0.9. This relationship is determined by the minimal surface area of cylindrical reactor core per unit volume. The above statement also holds true for the subcritical assembly. Taking into account this statement and the fact that cost of the materials increases depending on the volume of the fast zone, we choose the optimal value of the core height to be equal 50 cm. Fourthly, given the fast zone enrichment and height of the system, we obtain dependence of amplification factors on the uranium enrichment in thermal zone. Results of calculations show that optimal enrichment of the uranium in thermal zone comprises 4 % in uranium-235. More detailed results of modeling of heterogeneous subcritical reactor system will be given elsewhere.

3. The selection of the external neutron source

As to the choice of the external neutron source, the majority of the studies propose usage of accelerators of charged particles (both linear accelerators and cyclotrons) [12]. In this case beam of high-energy charged particles bombards heavy-metal target and yield of high-energy neutrons is a result of spallation process. We also consider some other possibilities of the choice of the external neutron source. First of all we consider powerful D-T neutron generators [13] employing nuclear reaction

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

Technique of the neutron generation on the basis of the plasma focus devices is actively developing in the last few years [14]. This technique also employs reaction (1) to produce neutrons. Plasma focus devices in prospect may become a worthy and more cheap and simple alternative to accelerators of charged particles.

3.1 The methodology of preparation of tritium in the subcritical core for the external neutron source

If we will plan to use high-intensity neutron generator for subcritical assembly, than appear one big problem: the receipt of tritium for targets by bombarded the beam of deuterons. The use of subcritical assembly for preparation of tritium is proposed. The tritium obtains in fission reactors with reaction (2)

$$^{6}Li + n \rightarrow T + {}^{4}He + E, \qquad (2)$$

From (2) lithium is sole industrial source of obtaining of tritium. But there is one problem. The half-life of tritium is promptly (12,3 years). It is mean, that all cycle use of tritium (obtaining of tritium in subcritical assembly, extraction, processing of lithium blocks, production of tritium targets) is promptly too. It should be noted for one atom of tritium requires spending the one atom of lithium. Therefore, some lithium blocks are implanted in subcritical assembly. There are lithium blocks above and below at beryllium reflector in renewed project.

4. 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. 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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