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Analysis of attractiveness of nuclear materials as applied to the on-site fuel cycle of inherently safe fast reactors

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Abstract

As of the present moment a fairly well-established concept of "attractiveness of nuclear materials" is widely used in scientific publications. This term implies that nuclear materials which are involved in the civil fuel cycle may be used for fabricating primitive nuclear explosive devices or even nuclear weapons. This concept serves as an instrument for comparative analysis of various nuclear materials as pertains to their possible diversion for unauthorized application. Attractiveness of nuclear materials is determined in the first place by the neutronics properties inherent to these materials. These properties include the capability of the material under examination to initiate self-sustained chain reaction because otherwise this material will be absolutely unattractive for the above-mentioned purposes. Besides that, the main properties and important characteristics of nuclear materials influencing their attractiveness are the intrinsic neutron background and heat release. The present paper presents the analysis of fuel compositions involved in the fuel cycle of inherently safe BR-1200 fast reactors (BREST-1200) incorporating on-site NFC infrastructure in terms of their attractiveness. The object of investigation are the elementary systems in the form of spheres containing nuclear materials of the BR-1200 fast reactor fuel cycle both without neutron reflectors and surrounded with such reflectors made of different materials. Here, critical conditions are defined for each system for which the main properties characterizing the attractiveness of nuclear materials are calculated taking into account the reflector material and thicknesses.

Keywords: BR-1200 fast reactor; Attractiveness of reactor fuel for unauthorized applications; Uranium nitride; Mixed nitride uranium-plutonium fuel; Critical system with neutron reflectors; Beryllium; Tungsten.

Introduction

Chemical activity of sodium coolant which until the present moment was regarded as the main option for application in fast reactors led the researchers working in the field of development of fast reactors to the attempts to find alternative coolant for fast reactors which would be inert when in contact with air and water. Such coolant and the design of fast reactor was suggested by the group of researchers headed by V.V. Orlov and E.O. Adamov. The project was given the name BREST—an acronym standing for the Russian abbreviation for inherently safe lead-cooled fast reactor loaded with dense mononitride fuel with 1200 MW(e) power. This project was under development from the end of the 1980s after special bidding announced by the State Committee for Science and Technology of the USSR. Later the project was given the name "Proryv" (the Breakthrough) within the framework of which low-power pilot and demonstration reactor BREST-OD-300 was developed as well. The concept of the "Proryv" Project incorporated all the main achievements in the field of fast reactor design which, in the opinion of the designers, allows ensuring safety of the fast reactor at deterministic level.

The concept of on-site nuclear fuel cycle ensuring closing of the fuel cycle with utilization of lower actinides and minimization of radioactive waste was also developed.

The decision on the construction of pilot demonstration power generation complex (ODEK) consisting of the

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BREST-OD-300 reactor facility with on-site nuclear fuel cycle [1] on the territory of the Siberian Chemical Combine (Seversk) was made for experimental substantiation of the main technical solutions adopted within the "Proryv" Project.

Several years ago, Professor V.V. Orlov came up with and substantiated the idea of putting into operation fast reactors loaded with enriched uranium with gradual involvement in its fuel cycle of plutonium and minor actinides generated in uranium fuel in the process of its irradiation in the reactor. Upon reaching steady-state fuel composition after certain number of fuel residence campaigns the reactor will work on the basis of intrinsically renewable uranium–plutonium fuel with breeding ratio approximately equal to unity.

On the one hand, deposits of cheap uranium explored by the present moment are sufficient for ensuring functioning of nuclear power generation during extended periods of time based on the existing comparatively low rates of its development. And, as it seems, putting into operation nuclear reactors loaded with uranium fuel will not lead to the deficit of uranium. However, on the other hand, such approach completely ignores the continuously increasing volumes of spent fuel of thermal reactors which are being already accumulated which require addressing and resolution of this problem within the nuclear power generation system. Besides the above, plutonium accumulated during the initial stages of use of uranium fuel in the nuclear reactor core contains small amounts of even isotopes [2,3–6]. It appears as the result that by rejecting the use of external blankets within the BREST reactor concept because of accumulation there of plutonium "dangerous" from the viewpoint of ensuring non-proliferation of nuclear weapons, accumulation of such plutonium is transferred instead to the reactor core characterized with much higher rate of breeding as compared with blankets. This problem requires further detailed investigation.

Attractiveness of fuel composition of BR-1200 fast reactor is examined in the present study. Uranium nitride and mixed uranium–plutonium nitride fuel (MUPNF) are examined as such fuel compositions to be used as starting fuel loads of BR-1200 reactor. Calculation studies of main characteristics of spherical systems containing fuel compositions of the reactor under study both without the reflector and in the presence of such reflector made of different materials were conducted using MMKKENO computer code supported with ABBN 93 neutron data complex.

All the data pertaining to loads of BR-1200 reactor and data on the concentrations of isotopes in the fuel compositions under investigation used in the present study were kindly provided by V.N. Leonov, Head of the Chief Designer's Department of the Private Enterprise, Innovation Technological Center of the "Proryv" Project, for which the authors of the present paper with to express to him their sincere gratitude.

On certain aspects of the "Proryv" complex project

Development and substantiation of design of BR-1200 fast reactor goes at the present moment through its final phases. Use of dense mononitride fuel and lead coolant allowing ensuring steady-state fuel composition is the new and, essentially, innovative solution adopted in this reactor. It is planned to incorporate in the power unit two-loop configuration for removal of heat from the reactor core and the option with supercritical parameters of water steam directed to the turbine is examined for the purpose.

The "Proryv" is the complex project and implies not only the development of the NPP with one or several nuclear reactors included in its composition but, as well, incorporation of the whole infrastructure of closed nuclear fuel cycle. This allows reducing time expenditures and the distance covered during fuel transportation which enhances radiation and physical safety of such transportation operations. As the final result, the costs of transportation of nuclear materials will be reduced as well. In fact, transportation of nuclear materials inside the protected area removed from populated areas minimizes the risk of contamination of the population and ecosystems in the case of development of emergency situations accompanied with releases of radioactivity. Because of the same reasons, practically absolute physical protection, and, consequently, preservation of nuclear materials are ensured, since potential attempts of their theft by criminal and/or subnational groups during transportation of such materials along the generally accessible transportation routes cannot be completely excluded [7–11].

On the other hand, according to the opinion of Academician E.N. Avrorin, who is the well-known expert in the field of nuclear weapons, concentration of all necessary production facilities within the nuclear fuel cycle on the same site may be associated with risk of conspiracy plotted by employees with dishonest intentions and members of criminal and/or terrorist organizations aimed at the production of non-declared materials. In such case selection and control of personnel employed for conducting works inside such protected areas, i.e. the human factor, attain special importance.

The concept of "inherent safety" is the distinguishing feature of the project. Ensuring nuclear and radiation safety due to the utilization of natural laws and properties of the applied materials which will allow reaching convincingly provable safety at the deterministic level is understood under this term. This concept is widely used in nuclear power generation during already several decades and is called the "inherent self-protection" in regulatory documents [12]. The concept of "inherent safety" can be regarded as further development of the stable trend in the design of nuclear reactors and, possibly, as the qualitative breakthrough in this direction [13,14].

Combination of natural properties of lead coolant, mononitride nuclear fuel, physical characteristics of nuclear reactor, design solutions adopted in designing the reactor core and cooling loops brings the BR-1200 reactor on the qualitatively new level of safety and ensures its stability (nuclear safety) without tripping active emergency protection systems in the case of extremely severe accidents which cannot be mitigated by any of already existing nuclear reactors and reactors under design including the following: self-triggering of all control elements; switching off (jamming) of all pumps of the primary and secondary cooling loops; loss of integrity of