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ScienceDirect
Nuclear Energy and Technology 000 (2016) 1–5
www.elsevier.com/locate/nucet

Analysis of the attractiveness of materials as applied to the fuel cycle of high-power fast reactor of Bn-type

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Abstract

Nuclear fuel cycle of fast reactors contains materials which potentially can be used for fabricating nuclear explosives or nuclear weapons. It is customary to apply to such materials in addressing the problem of non-proliferation of nuclear weapons and nuclear terrorism the concept of attractiveness allowing evaluating potential possibility of their use in clandestine activities. Attractiveness of nuclear materials is evaluated, first of all, according to their neutronics properties. Results are presented of analysis of attractiveness of different types of fuel compositions as applicable to fuel cycle of fast sodium-cooled high-power nuclear reactor of the BN-1200 type for different options of its starting fuel loads and utilized regimes for reaching steady-state fuel composition. The object of the present study were the simplest systems containing fuel compositions of fast reactor of BN-1200 type in the form of bare spherical assemblies without neutron reflector and assemblies surrounded with simplest neutron reflectors. Criticality conditions were determined for each system and main neutronics properties of the fuel compositions under examination were determined for these criticality conditions.

Keywords: Non-proliferation of nuclear weapons; Attractiveness of nuclear materials; Fast sodium-cooled high-power reactor; Uranium oxide fuel; Uranium nitride fuel; Mixed oxide uranium–plutonium fuel; Mixed nitride uranium–plutonium fuel; Critical assembly; Neutron reflector; Critical mass; Beryllium; Tungsten.

Introduction

Power units equipped with fast reactors are capable to significantly expand the fuel resources for nuclear power generation and to reduce the volumes of accumulated radioactive wastes due to the organization of the closed nuclear fuel cycle. Only very few countries possess fast reactor technologies with Russia being the world leader in this field. It is sufficient to note the successful operation by the Beloyarskaya NPP during 35 years of BN-600 - the only working fast reactor in the world, which is, indisputably, the world class achievement. Construction of fast sodium-cooled BN-800 reactor on the Beloyarskaya NPP site, its connection to the power grids and operations for reaching 100% power level conducted as of the present moment demonstrate new progress achieved by Russia in the implementation of fast reactor technologies [1-5]. BN-800 reactor in contrast to BN-600 will be operated with MOX-fuel load and elements of the closed fuel cycle will be developed [2,6].

Nuclear fuel cycle (NFC) of fast reactors contains materials which can potentially be used for fabricating primitive nuclear explosives (NE) and, with certain additional processing, for fabricating nuclear weapons (NW) as well [3,7]. It has to be taken into consideration here that potential proliferators at the level of state will attempt to develop functional and powerful enough nuclear weapon with comparatively moderate mass and dimensions in order to be able to deliver the weapon beyond the limits of the country. [3,8–10]. Such state will, evidently, be developing technologies for additional significant processing of the nuclear material extracted from fuel cycle of nuclear power generation because without implementation of additional processing such materials have

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Peer-review under responsibility of National Research Nuclear University MEPhI (Moscow Engineering Physics Institute).

Russian text published: Izvestia Visshikh Uchebnikh Zavedeniy. Yadernaya Energetika (ISSN 0204-3327), 2016, n.2, pp. 35-44.

http://dx.doi.org/10.1016/j.nucet.2016.07.003

Please cite this article as: E.M. Lvova, A.N. Chebeskov, Analysis of the attractiveness of materials as applied to the fuel cycle of high-power fast reactor of Bn-type, Nuclear Energy and Technology (2016), http://dx.doi.org/10.1016/j.nucet.2016.07.003

comparatively large values of critical mass. On the other hand, it can be assumed that the purpose of sub-national and/or terrorist groups is to fabricate primitive nuclear charge from stolen nuclear materials without their preliminary serious technological processing, because deployment of such nuclear charge is intended on the territory of the country in question and its transportation to the place of the act of terror will be achieved using all available means [4,11–15].

Nuclear materials capable to sustain chain fission reaction with comparatively modest values of critical mass are, certainly, of interest for the present analysis. Existence of critical mass is the key property of the material and is the necessary but not sufficient condition of "attractiveness" in the selection of material for its unauthorized use [16].

Besides the critical mass which must have certain realistic value allowing performing transportation of the nuclear explosive by this or that available means to the place of criminal act, neutron background and level of heat release are the important characteristics of nuclear materials from the viewpoint of their diversion. Neutron background of nuclear material is generated due to the spontaneous fission of heavy nuclei, for the most part of uranium and plutonium. Additional neutron yield takes place due to (α-n) reactions on light elements, for the most part on oxygen. With high enough neutron background the probability of initiation of nuclear explosion accompanied with significant energy yield is very low because high neutron background will inevitably result in the premature initiation of chain fission reaction, i.e. in the pre-detonation, which practically excludes the possibility of obtaining the nominal energy yield [17].

Heat release, i.e. heating of nuclear material, takes place, for the most part, due to α-decay and other processes of decay of heavy isotopes contained in the material. Significant heating of the material makes it difficult to handle it, but the main factor here are the effects of high temperature on the layer of chemical explosive directly adjacent to the nuclear material. At sufficiently high temperature this explosive loses its properties and destroys functionality of the nuclear charge. Undertaking different tricks is possible for reducing the temperature, but, however, they inevitably lead to the loss of simplicity of the design [18].

Besides the above examined characteristics of nuclear materials affecting the dimensions, mass and functionality of nuclear charge, it is necessary to mention radioactive background which practically does not affect the dimensions and functionality but complicates handling such material by potential proliferators and, at the same time, makes it easier to detect such radioactive material.

Results of analysis of attractiveness of fuel compositions of fast sodium-cooled high-power nuclear reactor of BN-1200 type according to their main neutronics properties are discussed in the present paper. Technological factors associated with additional processing of materials within the NFC are the object for subsequent studies. Calculation studies were performed using the MMKKENO code.

Input data

Attractiveness of nuclear materials is determined by the neutronics properties inherent to these materials and allowing initiating self-sustained chain fission reaction [16]. The following properties were examined in the present study: critical mass (M); inherent neutron background (NB); heat release (HR); radioactivity (A). The following fuel compositions which may be utilized in loading the nuclear reactor under discussion were examined: uranium dioxide (UO_2), uranium nitride (UN), mixed oxide uranium-plutonium fuel ($(U+Pu)O_2$, MOX) and mixed nitride uranium-plutonium fuel ((U+Pu)N, MNUP).

Isotopic compositions were determined for the neutronics calculations of the fuel compositions for the following conditions: fresh fuel loaded in the reactor core and in the blankets (fresh fuel load); irradiated fuel unloaded from the reactor after the first completed fuel residence in the core (fuel unloading).

Isotopic composition of fresh UO_2 fuel (%) is following: ^{235}U 17.8; ^{238}U 82.2. Isotopic composition of UO_2 fuel unloaded from the reactor after the first completed fuel residence in the core (%): ^{235}U – 9.87; ^{236}U – 1.75; ^{238}U – 74.7; ^{238}Pu – $2.16\cdot10^{-2}$; ^{239}Pu – 4.6; ^{240}Pu – 0.354; ^{241}Pu – $1.74\cdot10^{-2}$; ^{242}Pu – $6.33\cdot10^{-4}$; ^{241}Am – $8.07\cdot10^{-4}$; ^{243}Am – $1.93\cdot10^{-5}$; ^{237}Np – 0.134; ^{239}Np – $1.45\cdot10^{-2}$; ^{235}U fission products – 9.56.

Isotopic composition of fresh UN fuel is following (%): ^{235}U – 14.4; ^{238}U – 85,6. Isotopic composition of UN fuel unloaded from the reactor after the first completed fuel residence in the core (%): ^{235}U – 7.81; ^{236}U – 1.26; ^{238}U – 79.0; ^{238} Pu – $1.36\cdot10^{-2}$; ^{239}Pu – 4.11; ^{240}Pu – 0.266; ^{241}Pu – $1.29\cdot10^{-2}$; ^{242}Pu – $3.91\cdot10^{-4}$; ^{241}Am – $6.08\cdot10^{-4}$; ^{243}Am – $1.11\cdot10^{-5}$; ^{237}Np – $9.59\cdot10^{-2}$; ^{239}Np – $1.27\cdot10^{-2}$; ^{244}Cm – $5.38\cdot10^{-7}$; ^{235}U fission products – 7.55.

Isotopic composition of fresh MOX-fuel (%) is following: ^{235}U – $8.18\cdot10^{-2}$; ^{238}U – 82.7; ^{238}Pu – 0.256; ^{239}Pu – 10.5; ^{240}Pu – 4.26; ^{241}Pu –1.3; ^{242}Pu – 0.852. Isotopic composition of MOX-fuel unloaded from the reactor after the first completed fuel residence in the core (%):^{235}U – $3.65\cdot10^{-2}$; ^{236}U – $8.99\cdot10^{-3}$; ^{238}U – 73.8; ^{238} Pu – 0.17; ^{239}Pu – 10.0; ^{240}Pu – 4.65; ^{241}Pu – 0.884; ^{242}Pu – 0.809; ^{241}Am – 0.146; ^{243}Am – 0.103; ^{239}Np – $1.7\cdot10^{-2}$; ^{244}Cm – $1.84\cdot10^{-2}$; ^{239}Pu fission products – 9.3.

Isotopic composition of fresh mixed nitride uranium-plutonium fuel (MNUP-fuel) (%) is following: ^{235}U 8.64·–10^{-2}; ^{238}U – 86.4; ^{238} Pu – 0.202; ^{239}Pu – 8.29; ^{240}Pu – 3.35; ^{241}Pu – 0.973; ^{242}Pu – 0.669; ^{241}Am – $4.76\cdot10^{-4}$. Isotopic composition of MNUP-fuel unloaded from the reactor after the first completed fuel residence in the core (%): ^{235}U – 0.785; ^{236}U – $4.18\cdot10^{-2}$; ^{238}U – $8.68\cdot10^{-3}$; ^{238} Pu – 0.145; ^{239}Pu – 8.78; ^{240}Pu – 3.63; ^{241}Pu – 0.672; ^{242}Pu – 0.63; ^{241}Am – 0.14; ^{243}Am – $7.23\cdot10^{-2}$; ^{239}Np 1.51·– 10^{-2}; ^{244}Cm – $1.11\cdot10^{-2}$; ^{239}Pu fission products– 7.43.

It has to be noted that in accordance with the calculation procedure accepted in the present calculation critical

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