Available online at www.sciencedirect.com
ScienceDirect
Nuclear Energy and Technology 1 (2015) 170–173
www.elsevier.com/locate/nucet

Sensitivity coefficients of the neutron and physical reactor parameters to the fuel inventory parameters

I.V. Demeneva*, V.A. Eliseev, L.V. Korobeynikova

JSC «SSC RF-IPPE»1, Bondarenko sq., Obninsk, Kaluga Region 249033, Russia

Available online 21 March 2016

Abstract

Required properties of fast reactor core with nitride fuel are reached only if the fuel it is loaded with is plutonium-based and has strictly determined (equilibrium) isotopic composition and strictly determined plutonium mass fraction (plutonium enrichment). It is suggested to use fuel composition representing mixture of nitrides of uranium and plutonium (U-Pu)N with power generation grade composition as the starting reactor core fuel load. It is known that at present extracted plutonium is stored in Russia at the "MAYAK" PA where it is kept packed in containers. It is not possible to predict exactly isotopic composition of plutonium which will be obtained after blending different batches of plutonium. Therefore, measures must be anticipated allowing compensating for the deviations of fuel isotopic composition and enrichment from the designed values. Algorithm accounting for such deviations is required for the purpose. Such algorithm can be built by calculating sensitivity of physical characteristics to the deviations of reactor fuel load. Two approaches to the calculation of sensitivities of reactor parameters to the variation of plutonium isotopic composition are examined. Numerical illustrations are presented as applied to fast nuclear reactor of BREST-300 type.

Keywords: Sensitivity coefficient; Plutonium isotopic composition; Neutron multiplication factor; Breeding ratio.

Introduction

Combination of properties of heavy liquid lead coolant and dense nitride fuel creates conditions for achieving enhanced breeding of fissile nuclides in the reactor core and stabilization of breeding properties of the reactor, which allows operating the reactor at low and stable reactivity margin [1].

However, required properties of the reactor core, namely, the reactivity margin close to zero for burnup compensation are achieved only when the core is loaded with plutonium-based fuel with strictly determined (equilibrium) isotopic composition and with strictly determined plutonium mass fraction (plutonium enrichment). It is planned to use as the starting core fuel load the fuel composition representing mixture of nitrides of depleted uranium with power grade plutonium (U-Pu)N obtained after 20-year cooling down and subsequent re-processing of spent fuel of VVER reactors. Plutonium extracted from spent light-water reactor fuel after batch re-processing of irradiated fuel assemblies has varying isotopic composition because of dependence of the latter on the burnup depth and on the original enrichment of uranium light-water reactor fuel. Beside that decay of ^{241}Pu ($T_{1/2} =$ 14 years) takes place during plutonium long-term storage which leads to the additional dispersion of relative concentrations of plutonium isotopes.

Non-uniformity of plutonium isotopic composition predetermines the need to implement studies and to develop an algorithm allowing accounting for the effects of plutonium isotopic composition on the reactor physical parameters and, in the first place, on the criticality parameters.

Such algorithm can be built having a set of coefficients [2] characterizing sensitivity of physical parameters to the deviations of the fuel load.

Let us examine two such characteristics, effective neutron multiplication factor (k_{eff}) and breeding ratio (BR), and

* Corresponding author.
E-mail addresses: idemeneva@ippe.ru (I.V. Demeneva), eliseev@ippe.ru (V.A. Eliseev), ikorobeynikova@ippe.ru (L.V. Korobeynikova).
Peer-review under responsibility of National Research Nuclear University MEPhI (Moscow Engineering Physics Institute).
http://dx.doi.org/10.1016/j.nucet.2016.01.002

respective sensitivity coefficients:

$$SC = (\Delta k_{eff}/k_{eff})/\Delta C \text{ or } SC = (\Delta BR/BR)/\Delta C, \quad (1)$$

where SC is the sensitivity coefficient; Δ_{keff} is the deviation of the effective neutron multiplication factor; ΔBR is the deviation of the breeding ratio, and ΔC is the relative deviation of the fuel load parameter.

The above refers both to the manufacturing fuel for the starting load of the reactor core, and to the reactor operation within closed fuel cycle when continuous evolution of plutonium isotopic composition will be taking place with plutonium composition tending to get closer to the equilibrium one.

Determining sensitivity coefficients k_{eff} and BR is possible both using the perturbation theory and by performing direct calculation. Physical calculation of reactor performed using the TRIGEX software complex with neutron data library BNAB-93 and the neutron data preparation system CONSYST [3–5] were applied in the case under examination here. With comparatively small variations of isotopic composition within 1–2 abs. % both the above methods produce good agreement. Let us note here that the method of direct calculations (in contrast to perturbation theory) is richer in terms of the produced information and allows determining violation of linear dependence of variation of k_{eff} and BR on the evolution of fuel composition and, therefore, determining as well the boundaries of applicability of the sensitivity coefficients thus obtained.

Two approaches to performing calculation of coefficients of sensitivity of reactor parameters to the variation of plutonium isotopic composition were examined in the present study. Under the first approach sensitivity to variation of plutonium isotopic composition was estimated under the condition of compensation of this variation with uranium-238. Such approach was named the “conservative” approach. It corresponds to the technological process applied for plutonium correction in mixed fuel when plutonium composition deviates from the baseline one. Under the second approach variation of concentration of one of plutonium isotopes was compensated in the calculation of sensitivities by concentrations of other plutonium isotopes. Such approach was named the “vector” approach. This approach is in conformity with the proposed technology of plutonium fabrication when plutonium isotopic composition is formed on one technological process site, and plutonium mixing with depleted uranium takes place on the different production site. Overall loaded fuel inventory remained constant in both cases. For convenience sake we hereinafter applied the terminology of “sensitivity coefficients” to denominate the ratios of relative variations of the neutron multiplication factor and the BR to the relative variations of concentrations of isotopes in the mixture under the conditions stipulated above.

Coefficients of sensitivity to plutonium isotopic composition

Numerical values of “conservative” and “vector“ sensitivity coefficients for k_{eff} and BR calculated for lead-cooled reactor loaded with nitride fuel and with reactivity margin for compensating fuel burnup close to zero are illustrated in Table 1. As it has been already mentioned above, variation of concentration of one of plutonium isotopes was compensated under the “conservative” approach by uranium-238 concentration.

Table 1
Coefficients of sensitivity of k_{eff} and BR to plutonium composition.

Isotope	“Conservative” approach		“Vector” approach	
	% Δk/k, % abs.	% ΔBR/BR, % abs.	% Δk/k, % abs.	% ΔBR/BR, % abs.
^{238}Pu	0.49	−0.19	−0.11	0.90
^{239}Pu	0.78	−1.5	0.57	−1.4
^{240}Pu	0.13	0.1	−0.61	1.5
^{241}Pu	1.1	−1.8	0.51	−0.8
^{242}Pu	0.09	−0.14	−0.53	1.0

Under the “vector” approach variation of concentration of one of plutonium isotopes is compensated by concentrations of other plutonium isotopes in proportion to their weights in the initial composition. It can be seen that these coefficients are fundamentally different from each other not only by the value but in sign as well.

Values of sensitivity coefficients presented in Table 1 were obtained by direct calculations. However, “vector” SCs can be obtained as well without performing reactor neutronics calculations. In order to achieve this it is necessary to calculate “conservative” SCs and to know the deviations of the current isotopic composition from the prescribed one.

$$SC^i_{vect} = \sum \alpha^i_j \cdot SC^j_{cons} \quad (2)$$

where a^i_j is the deviation of isotopic vector (in % abs) from the vector preset with ith isotope concentration changing by 1% abs. Deviations by 1% abs. (and not 1% rel.) were accepted, because tolerances as applied to the fuel composition of nuclear reactors and to the fuel enrichment are established specifically in absolute percent.

Thus, having calculated once the “conservative” SCs for the initial plutonium composition we subsequently, with changing plutonium composition, determine the “vector” SCs using Formula (2) and, after that, the deviations of k_{eff} and BR.

The values of sensitivity coefficients presented in the table above are given for the initial reactor core configuration, i.e. for the special status of the reactor loaded with fresh fuel not containing fission products. Sensitivity of such reactor to deviations of parameters of the fuel load is maximal. Subsequently, in the course of reactor operation in the operation mode with uniformly spaced partial core reloading operations, sensitivity of the reactor to deviations of parameters of the next coming batch of fuel to be loaded will be several times less (depending on the time interval between partial reactor reloading operations).

Coefficients of sensitivity to fuel enrichment and fuel load

Coefficients of sensitivity to enrichment and fuel load indicated in Table 2 are needed as well for correction of fuel