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Comparison of MCB and FISPACT burn-up performances using the HELIOS experiment technical specifications

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ABSTRACT

The objective of the HELIOS experiment was to test innovative, uranium-free nuclear fuel containing americium and to study helium release and fuel swelling behaviour during irradiation. The experiment consisted of irradiation of five fuel samples, each containing various initial concentrations of Pu and Am in different inert matrices. The irradiation was performed in the High Flux Reactor (HFR) at Petten during nine cycles (i.e. about nine months) for a total duration of 240 equivalent full-power days.

The neutronic calculations play an important role in preparation and analysis of the irradiation experiments. Therefore, this paper presents an explicit burn-up analysis of the HELIOS samples using two numerical tools, the MCB and FISPACT codes. The focus of this calculation is on the concentrations of Pu, minor actinides (MAs) and He during irradiation time and on total sample power due to nuclear reactions and decay. Particular attention was paid to Am242m, the fission cross-section of which is significant in the thermal neutron spectrum. The MCB code incorporates an improved method of producing this, which was subsequently tested and qualified. The sensitivity of the nuclide evolution to the choice of JEF2.2 and JEFF3.1 transport cross-section libraries was also investigated.

1. Introduction

The HELIOS experiment was performed as part of the EUROTRANS project sponsored by the Sixth Euratom Framework Programme (D'Agata, 2009). The objectives of the EUROTRANS project included generic conceptual design of a modular European Facility for Industrial Transmutation (EFIT) and advance design of an experimental facility demonstrating the technical feasibility of transmutation in an accelerator-driven system (ADS). The main goal of HELIOS was to investigate the in-pile behaviour, in terms of fission gas release, of uranium-free fuels with addition of MAs. The main criterion for designing innovative fuels containing long-lived Am241 is its resistance to the embrittlement caused by He formation. Therefore, the influence of fuel microstructure and temperature on fuel swelling induced by He produced from Am241 transmutation is of major interest for the scientific community.

The previous irradiation of inert matrix fuels containing an americium fraction was performed at the HFR in Petten as part of the collaboration on the Experimental Feasibility of Targets for Transmutation (EFTTRA) (Konings et al., 1998). In the beginning, two experiments (EFTTRA-2 and EFTTRA-2bis) were designed to test the behaviour of $MgAl_2O_4$ (spinel), $Y_3Al_5O_{12}$ (YAG), Al_2O_3 and CeO_2 inert matrices without presence of fissile material (Klaassen et al., 2002). As a result, spinel and YAG were chosen as the best candidates as a support material for actinide transmutations. The follow-up experiment (EFTTRA-3) aimed at irradiation of sixteen targets based on MgO, $MgAl_2O_4$, $Y_3Al_5O_{12}$, Al_2O_3, CeO_2 and Y_2O_3 inert matrices. Eight of the targets contained a UO_2 or $(U,Y)O_x$ component, the others concerned irradiation of just an inert matrix material (Nefft et al., 2003). The post-irradiation examination (PIE) of the EFTTRA-3 uranium targets ruled out $Y_3Al_5O_{12}$ as a suitable material for an inert matrix due to its high diametrical swelling. MgO, CeO_2 and Y_2O_3 displayed the best resistance to irradiation conditions. $MgAl_2O_4$ had shown sufficient swelling resistance, but other experiments indicated intensive swelling at high uranium densities (Nefft et al., 2003). Nevertheless, it was chosen as an inert matrix material in the EFTTRA-4 and EFTTRA-4bis experiments (Konings et al., 2000). The EFTTRA-4 and EFTTRA-4bis targets were the first in the EFTTRA series containing a 10–12 wt% Am241 fraction. PIE of them indicated high swelling caused by helium production. To investigate this phenomenon in greater depth, a new experiment was designed – HELIOS.

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This paper presents the results of the numerical burn-up analysis of the HELIOS experiment. Exact interpretation of HELIOS requires reliable reconstruction of the conditions in the reactor core during irradiation. For this reason, a new method, featuring different stages with separate calculations, was developed and applied at Joint Research Centre, Institute for Energy. For the comparative analysis of the predicted nuclide concentrations, the FISPACT (Forrest, 2003a) and MCB (Cetnar et al., 1999) codes were used. The MCB code may use many types of transport cross-section libraries. To investigate sensitivity to different cross-section libraries, calculations were performed with JEF2.2 (JEF2.2, 2000) and JEFF3.1 (Koning et al., 2006) nuclear data tables. Considerable effort was put into estimating the evolution of the power of fuel samples by means of the MCB code using different options for heating calculations. A new method of calculation for the branching ratio to the metastable states of Am242m and Am244m was introduced. The influence of this new approach on nuclide concentration and sample power is described.

Section 2 describes the HELIOS experiment in detail. Section 3 explains the method applied and includes descriptions of the general calculation schema, numerical tools used for burn-up analysis, treatment of metastable isotopes and the method of heating calculations and source calculations. Section 4 presents the results obtained in terms of nuclide concentrations and sample power. Section 5 contains conclusions and describes the activities planned for further analysis of the HELIOS experiment.

2. The HELIOS experiment

The radiotoxicity of spent nuclear fuel can be reduced significantly by burning MAs in fast spectrum reactors. To fulfil this objective, a more comprehensive knowledge of the in-pile behaviour of MAs bearing fuel, especially Am, is needed. Results obtained in the previous experiments (EFTTRA-T4 and EFTTRA-T4bis) indicate that one of the key issues for designing MA fuels is trapping or releasing He produced due to nuclear transmutation and decay. The former concerns providing enough open porosity and trapping He in the fuel pellet, while the latter is related to the He release and accumulation in the pin plena.

Analysis of He release at an early stage of irradiation was one key objective of HELIOS. He release strongly depends on in-pile fuel temperature and burn-up. Therefore one way to achieve efficient release of He is to add Pu to the initial fuel mix. This increases the fuel temperature and causes faster He release, starting from the beginning of life (BOL). The other way is to introduce a novel inert matrix with open porosity that creates He release paths in fuel pellets. Both methods mentioned were applied in the HELIOS experiment for the particular fuel samples.

The basic properties of the five fuel pins irradiated in the HELIOS experiment are set out below:

- Pin no. 1 made of $MgO + Am_2Zr_2O_7$, CerCer composite pellets (particles in the range of 5–50 μm), fabricated by CEA, open porosity introduced in MgO inner matrix.
- Pin no. 2 made of $(Am,Zr,Y)O_2$, solid solution pellets, fabricated by the JRC-ITU.
- Pin no. 3 made of $(Pu,Am,Zr,Y)O_2$, solid solution pellets, fabricated by the JRC-ITU.
- Pin no. 4 made of $(Am,Zr,Y)O_2 + Mo$, CerMet composite pellets (particles in the range of 65–125 μm), fabricated by the JRC-ITU.
- Pin no. 5 made of $(Pu,Am)O_2 + Mo$, CerMet composite pellets (particles in the range of >150 μm), fabricated by the JRC-ITU.

Details of the densities and material properties are given in Section 3.4 (Table 2).

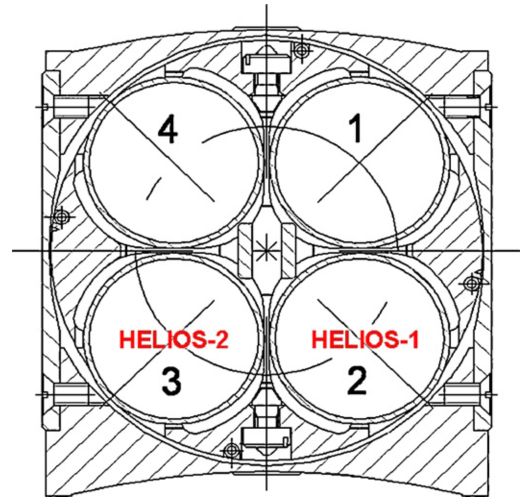

Fig. 1. QUATRO 129 rig with four irradiation channels.

The irradiation was carried out during nine reactor cycles with a total length of about 240 full-power days from April 2009 to February 2010 in position G7 at the HFR in Petten. The reactor power during irradiation was constant at the level of 45 MW. The reloadable QUATRO 129 rig (see Fig. 1) was used as outer containment for the experiment. The QUATRO 129 capsule contains, by default, four irradiation channels, but in HELIOS only two of them were filled with specimen holders (HELIOS-1 and HELIOS-2). The remaining two channels contained aluminium dummies. The orientation of the QUATRO 129 capsule was changed by 180° every cycle to give a uniformly distributed neutron flux. The vertical displacement unit (VDU) makes it possible to change the axial position of both specimen holders together. Its maximum operation range is 150 mm. The irradiation started at the lowest possible position but in further cycles the specimen holders were moved upwards to obtain the required temperature, using the effect of flux buckling. The specimen holder stands for the inner experiment containment. The gap between containments was filled with inert-gas mixture, mainly He, Ne and N, in order to adjust the experiment temperature during burn-up. The instrumentation used for connection between out-of-pile and in-pile devices was placed in the head of the QUATRO 129 rig. The molybdenum shroud containing fuel pins and some additional instrumentation, like thermocouples and fluence detector sets, was placed inside the specimen holders. The shroud, along with the fuel pins, was immersed in a sodium bath to improve the thermal heat transfer. Fuel pellets in one He atmosphere were permanently sealed inside fuel pins (D'Agata, 2009).

A total of five fuel samples were irradiated in the HELIOS experiment, samples 1 and 3 in HELIOS-1 and samples 2, 4 and 5 in HELIOS-2. Samples 2 and 3 were situated on the top of the specimen holders and equipped with central thermocouples, placed in a central hole in the upper part of the fuel pellets. The material composition of these samples was similar although, in order to increase temperature and investigate its influence on He production, Pu had been added to sample 3. A detailed comparative post-irradiation examination of samples 2 and 3 is planned.

3. Method

3.1. Calculation schema

The method of numerical analysis of the HELIOS experiment consists of three main steps (see Fig. 2). In the first step, stochastic Monte Carlo transport calculations using the MCNP code (X-5 Monte Carlo Team, 2005) were performed to obtain the