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The application and comparison of ^{97}Zr and ^{92}Sr in the absolute determination of the contribution of power density and cladding activation in a VVER-1000 Mock-Up on the LR-0 Research Reactor

Michal Košťál*, Marie Švadlenková, Ján Milčák

Research Center Rez Ltd., Husinec-Rez 130 250 68, Czech Republic

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ABSTRACT

^{97}Zr is a relatively high-yield fission product that can be used for zero reactor power determination. The technique is not widely used because in the case of reactors that use zirconium metal in the fuel cladding, it is not only a fission product but is also produced by activation. In an appropriately chosen time interval, results obtained using ^{97}Zr can be compared to those of power determination performed using ^{92}Sr. The knowledge of the ratio between fission-induced ^{97}Zr and the portion of ^{97}Zr activated in the cladding can be used not only for power-density determination but also as an important indication of fuel failures.

1. Introduction

Pin-wise power density is an important quantity that must be monitored during reactor operation. It is necessary not only for the adequate assessment of fuel conditions but also for the assessment of core structures and reactor pressure-vessel conditions. During reactor operation, the pin-wise power density is often calculated using diffusion codes. For code-validation purposes, the pin-wise density can be experimentally determined by means of fission density because the fission density and the power density in various parts of the core are nearly proportional [3].

The fission density can be determined via gamma spectroscopy of the irradiated fuel. This approach is based on the proportionality between fission-product activity and fission density. Sometimes, the total gamma radiation emitted by the collimated part of the fuel pin is measured [12]. In this case, NaI(Tl) scintillation spectroscopy is employed. The fission density is then derived by comparison with a reference fuel pin. The measured result must be corrected for the radioactive decay of gamma emitters in the irradiated fuel pins. In this case, a semi-empirically determined solution is applied. Such solution uses experimentally determined coefficients, which arise from the least-squares fit on gamma emission decay measurements.

In another method, only the Net Peak Area (NPA) of selected nuclides is measured. In this approach, when only one nuclide is studied, an analytical formula can be employed. The application of NaI (Tl) spectroscopy on the 1596 keV line of ^{140}La was reported in [7], but more often HPGe spectroscopy is used. Depending on the irradiation condition (power level, irradiation time and subsequent cooling time), various nuclides can be studied. The half-life of most dominant fission products is comparable to the time of irradiation and the subsequent cooling time. For an irradiation time on the scale of hours and a short cooling time, fission products with half-lives on the scale of hours, such as ^{92}Sr, ^{91}Sr, ^{135}I, ^{133}I, and ^{143}Ce, dominate in the spectrum [1]. When the irradiation at higher power lasts for days and the measurement is started at some cooling time after which short-lived isotopes have decayed, products with half-lives on the scale of days, such as ^{140}La, dominate in the spectrum [8]. When the irradiation takes months or years, ^{137}Cs dominates in the spectrum, and ^{95}Zr and ^{95}Nb can also be measured (see, for example [5]).

The presented method is particularly relevant for the experimental determination of the fission density in zero-power reactors. Its main advantage is its relatively long usable time because of the relatively long ^{97}Zr half-life, which is 16.749 h [11].

2. LR-0 reactor

The LR-0 reactor, operated by the Research Center Rez (the Czech Republic), is a pool-type zero-power light-water reactor. For the

* Corresponding author. Tel.: + 420 266172655.
E-mail address: kostal@cvrez.cz (M. Košťál).

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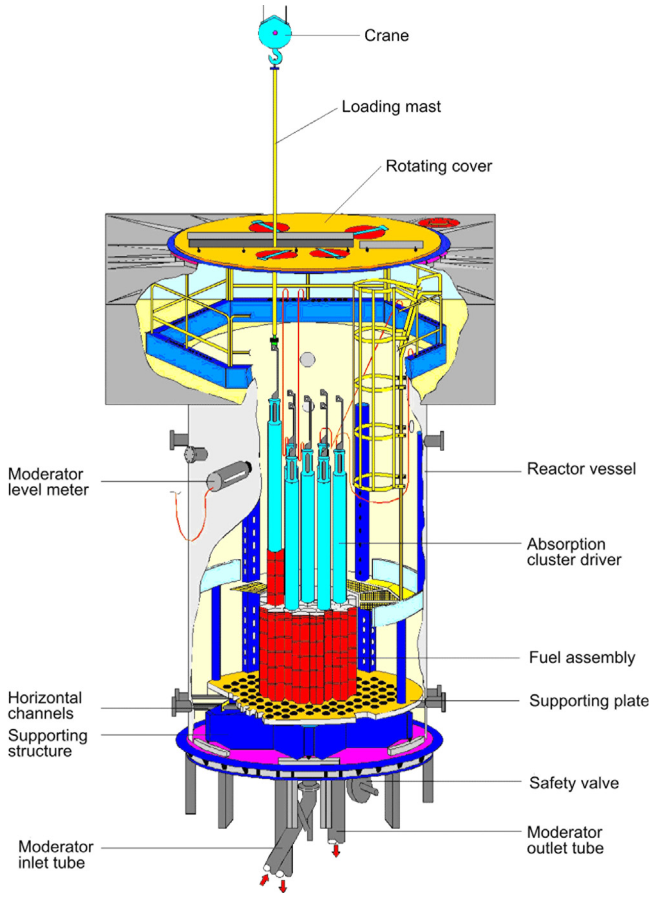

Fig. 1. LR-0 overview [2].

layout of the reactor, see Fig. 1. All described experiments were performed using the VVER-1000 Mock-Up. This mock-up core consists of 32 assemblies with different enrichments of ^{235}U [6]. In the radial cross section, the assembly is identical to VVER-1000 fuel; axially, it is shortened with respect to regular VVER-1000 fuel. It contains 312 fuel pins, 18 stainless steel guide tubes for control clusters and a central zirconium-alloy instrumentation tube in a triangular lattice with a pitch of 12.75 mm. The fuel pin consists of UO_2 pellets in a zirconium-alloy cladding tube. In the center of each pellet is a hole with a diameter of 1.4 mm (range 1.4–1.6 mm). The inner and outer diameters of the cladding tube are 7.71 mm and 9.15 mm, respectively, resulting in a wall thickness of 0.72 mm. The length is optimized for the LR-0 reactor, and the length of the fissile column is 125 cm.

3. Experimental and calculation methods

3.1. Detector arrangement for measurement of fission rates

The fission products were induced during a 2.5-h irradiation at a power level of 9.5 W. The core layout, with the fuel assemblies and measured fuel pins indicated, is shown in Fig. 2. The experiments were conducted in four irradiation batches.

The basic device in the gamma-scanning system is a semiconductor HPGe coaxial detector in a streamlined horizontal configuration in a collimator assembly (Ortec GEM70, relative efficiency 70%, with a resolution of approximately 2.1 keV at $E_\gamma = 1333$ keV) and a multichannel analyzer (DSA2000, Canberra). The collimator tube consists of a central part and its surrounding shielding (see Fig. 3). The central part is a lead cylindrical pipe with a length of 10.14 cm

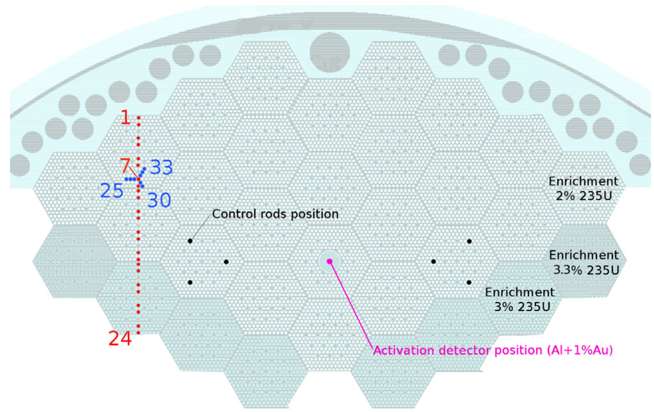

Fig. 2. Layout of LR-0 and measured pins.

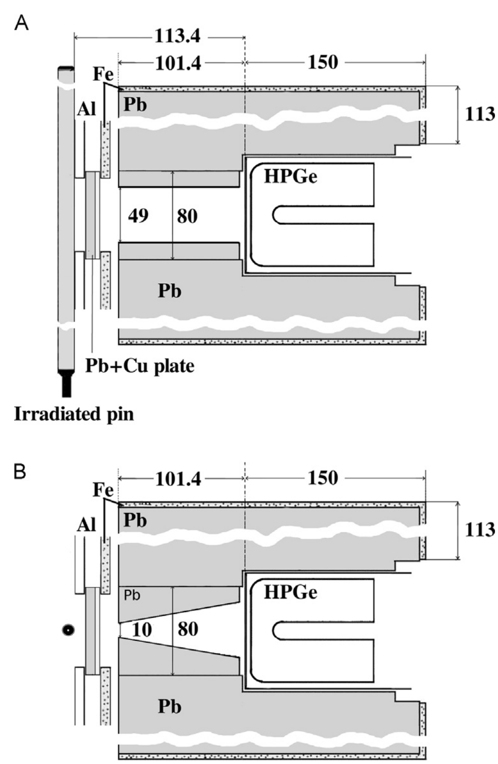

Fig. 3. HPGe detector arrangement, the distances are in [mm].

and an outer diameter of 8 cm. In this pipe, a collimator window that is centrally located with respect to the HPGe crystal was machined. The width and height of the window used in the experiment are 1.0 and 4.9 cm, respectively. The radial profile measurement was performed in the center of the pin fissile column, lying in the central horizontal plane of the reactor core. This corresponds to a region from 60.05 cm above the bottom of the fissile column to 60.05 cm below its top. The measured gamma spectra were analyzed using Genie 2 K software (Canberra) [13].

The HPGe pin measurement started at least 50 min after the reactor shutdown. In the acquired gamma spectra, the NPA (cps) of the energy peak at 743.4 keV was analyzed. This peak is formed by multiple gamma emitters (see Table 2), but the area of the ^{97}Zr peak at 743.36 keV is the quantity of interest. Because of the negligible lifetime of the mother nuclides (see Eq. (1), Table 1), a simple correction formula for the ^{97}Zr radioactive decay can be used (see Eq. (2)) to determine the contribution of ^{97}Zr to the mixed peak (see Eq. (3)). The fission ^{97}Zr peak can be obtained by