

Transport cask nuclide inventory calculations for spent pebble-bed reactor fuel

The Arbeitsgemeinschaft Versuchsreaktor (AVR) Jülich, a prototype pebble-bed high-temperature gas-cooled reactor (HTGR) operated from 1967 to 1988, was designed with the intent to demonstrate the feasibility of graphite-moderated, helium-cooled reactors with spherical fuel elements and for commercial power generation. AVR used three primary types of pebbles: fuel, moderator, and absorber spheres. Fuel pebbles contained coated fuel particles (initially BISO, later TRISO designs) embedded in graphite matrix. Uranium fuel with ^{235}U enrichment up to 17%, or high-enriched uranium up to 93% mixed with thorium to enable higher burnups, was used. Moderator pebbles, composed primarily of graphite, served to reduce spatial power density gradients within the reactor core, while absorber pebbles incorporated so-called “neutron poisons” to aid with the reactivity control. The distinct pebble geometry and material composition, together with the dynamic recirculation scheme, created reactor core conditions fundamentally different from those of light water reactors (LWRs).

Between 1993 and 2009, fuel elements, moderator and absorber spheres were loaded into 152 CASTOR® THTR/AVR dual-purpose casks for interim storage and transport. The design approval of this cask was last revised in November 2024 by the Federal office for the Safety of Nuclear Waste Management (BASE). The associated safety assessment is based on a covering inventory description, which was derived by the license holder, i.e. the Gesellschaft für Nuklear-Service (GNS), by performing depletion calculations using the SCALE code system. These results were subsequently validated by BASE, utilising both SCALE models, homogenised on the level of pebbles, and heterogeneous Serpent calculations with explicitly modelled TRISO particles. Additionally, for an individual pebble, gamma-spectrometry measurements of selected radionuclides were compared against model predictions, contributing to additional validation of the computational methods.

Compared with LWR fuel, AVR fuel pebbles typically have a higher initial enrichment and have a much smaller scale of heterogenisation. Operating conditions are also very different: a lower power density, a more thermalised neutron spectrum, larger temperature changes and gradients, continuous variation in boundary conditions from pebble circulation, higher achievable burnup, and substantially longer irradiation times. The sensitivity analysis showed that temperature variations of a few 100 K can lead to changes of up to 10% in higher actinide concentrations. Power density fluctuations strongly affect short- and medium-lived fission products, but only have a minor influence on production of important actinides. ^{244}Cm production in particular is sensitive to fuel density (at a constant total fuel mass). The radii of TRISO/BISO kernels influence ^{239}Pu and $^{241}\text{Pu}/^{241}\text{Am}$ production, though less so for ^{244}Cm . Graphite matrix density was identified as an important parameter, with sensitivity for ^{239}Pu production exceeding unity depending on fuel burnup and initial composition. Calculations using ENDF/B-VII.1 and ENDF/B-VIII.0 nuclear data libraries lead to consistent results, with differences in important nuclide concentrations of up to about 1%.

In August 2025 BASE issued the transport approval for the transport of all 152 casks from Jülich to interim storage facility in Ahaus, for which the validity of design approval of the CASTOR® THTR/AVR cask is a prerequisite. The findings presented above confirm on one hand the robustness of modern reactor physics tools for pebble-bed fuel analysis, and on the other hand show that the sensitivity to operational conditions and consequently also the overall uncertainties in important parameters of the spent fuel are significantly higher compared to SNF from conventional LWR systems. For the safety assessment of the CASTOR® THTR/AVR cask, these factors have been considered, leading to a reliable inventory description.

Country or International Organization

Instructions

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