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HTR-PM fuel pebble irradiation qualification in the high flux reactor in Petten

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ABSTRACT

NRG has performed a High Temperature Reactor fuel qualification test in the framework of the Chinese HTR development for INET – Tsinghua University, as a part of the qualification process of Chinese fuel for use in the HTR-PM (High Temperature Reactor-Pebble bed Module). Fuel qualification is an essential part of the licensing process of the HTR-PM, currently under construction in the Shandong province in the People's Republic of China.

The design of the INET irradiation setup for irradiation in the High Flux Reactor is performed by NRG. In the design of the irradiation rig, the pebbles are encased in graphite half shells to form a solid cylindrical stack. Within the graphite, thermocouples are located for temperature monitoring, and neutron fluence monitor sets for neutron fluence verification. Next to the temperature measurements, the online monitoring consisted of fission product release measurements. These measurements were performed with the Sweep Loop Facility, designed and built by JRC-IET.

Post Irradiation Examinations are performed and consisted of gamma scanning, dimensional and weight measurements and visual inspection. In April 2016, the pebbles were transported from Petten to Karlsruhe, Germany where the second required step of fuel qualification will be performed, namely heating tests in the KÜFA facility.

This paper describes the global lay-out and functionality of the irradiation facility. The online data generated and irradiation parameters are reported, with focus on the measured fission product release behavior of the fuel. The paper also presents non-destructive post irradiation examinations.

1. Fuel pebble description

The Institute of Nuclear and New Energy Technology of Tsinghua University in Beijing, (INET) has requested NRG to qualify Chinese HTR fuel for application in the HTR-PM (High Temperature Reactor – Pebble bed Module), currently being built in the Shandong province in the People's Republic of China. Fuel qualification is an essential part of the licensing process for the HTR-PM. Ten HTR Fuel pebbles were fabricated by INET and delivered to NRG in January 2012. The HTR fuel pebbles consist of a molded carbonaceous matrix of 60 mm diameter that contains the coated particles in an inner zone of 52 mm diameter and with a fuel free shell larger than 4 mm thickness. In Fig. 1 an X-ray image of one of the pebbles is presented, showing the fuel particles and fuel free zone. The coated particles themselves consist of a central LEU UO_2 fuel kernel and a TRISO coating as presented in Table 1.

2. Irradiation targets

The irradiation is performed in the High Flux Reactor (HFR) in Petten, the Netherlands. The HFR can irradiate a wide variety of materials or fuel under well-controlled conditions. For qualification, the pebbles were required to reach central temperatures of 1050 ± 50 °C, with a pebble surface temperature as homogeneous as possible.

The irradiation duration was determined such that the upper four pebbles reached a burnup higher than 100 MWd/kgHM. During the irradiation the gas mixture of helium and neon flowing through the first containment was continuously swept and measured by gamma spectroscopy to quantify the release of gaseous fission products. A dedicated Sweep Loop Facility (SLF) was used for this purpose (Laurie et al., 2012).

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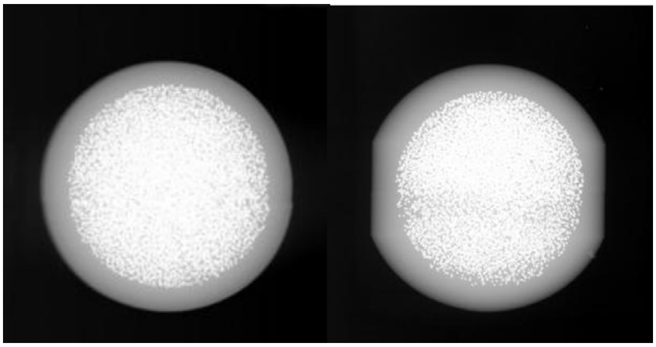

Fig. 1. X-ray image of the top- and side view of a pebble, showing the TRISO particle distribution.

Table 1
Nominal characteristic data of INET pebbles.

Pebble properties	
Particle batch	1
Kernel composition	UO_2
Kernel diameter [µm]	500
Enrichment [U-235 wt%]	17
Thickness of coatings [µm]:	
low density graphite (buffer)	95
inner high density Pyro lytic	40
Carbon or "PyC"	35
high density SiC	40
outer high density PyC	
Particle diameter [µm]	920
Pebble	
Heavy metal loading [g/pebble]	7
U-235 content [g/pebble]	1.19
Number of coated particles [−]	
per pebble	12000
Matrix graphite grade [−]	A3-3
Matrix density [g/cm^3]	1.75
Temperature at final heat treatment [°C]	1900

3. Design

Fuel irradiation experiments can be performed in the HFR in different in-core position with different fluences in the standardized irradiation rigs which acts as the 2nd containment. The inner part of the irradiation rig is custom made to meet the specific irradiation requirements. When assessed in the safety analysis, the sample holder can therefore be placed in any in-core irradiation position. For this irradiation, the design was based on experience from the German HTR fuel qualification program and from more recent European HTR fuel irradiation tests in the HFR (Fütterer et al., 2004).

To reach the irradiation targets a dedicated instrumented sample holder was fabricated. The internal part of the irradiation rig is fully optimized to reach the temperature and burnup specifications, and was connected to the Sweep Loop Facility (SLF), a dedicated system to supply the capsule with a gas mixture to control the temperature and to measure the activity release of the HTR-PM fuel pebbles.

The dimensional specification of the pebbles for use in the HTR-PM allows a certain variation in the outer dimensions. For the use in the pebble bed this is of no concern due to the fact that the whole core has relatively low temperature gradients. For the irradiation capsule however, the fabrication tolerances would lead to a higher degree of uncertainty for the temperature control in the qualification. The gas gaps around the pebbles determine not only the location of the pebbles in the irradiation rig, but also the thermal conductance to the outer containments. Since the requested accuracy in the irradiation capsule is larger than the fabrication tolerances, the outer graphite layer is modified for optimal thermal design (Fig. 2). A flat surface is fabricated for optimal radial heat flux, and the spherical surface is modified to have a well-defined contact surface. The radius was adjusted to 29.50 ± 0.02 mm.

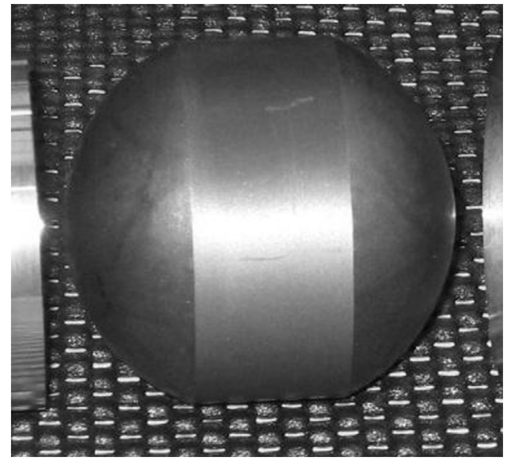

Fig. 2. A pebble before irradiation.

3.1. Sample holder design

A stack of five fuel pebbles was encased in graphite half-shells to form a cylinder (Fig. 3), irradiating the approximately 60.000 TRISO particles. The pebbles and the graphite half-shells were enclosed in a stainless steel containment, which acts as the 1st containment for the fuel pebbles. A total of 24 thermocouples were included in this containment for temperature measurements close to the pebbles and in the graphite half shells surrounding the pebbles. Within this containment, the gas was swept continuously for on-line fission gas release measurements.

For purposes of neutron metrology, 10 activation monitor sets were prepared. Each monitor set consists of the following activation monitor materials: an iron wire piece, a nickel–cobalt wire piece (1 wt% Co), a titanium wire piece, and a niobium wire piece (Mutnuru et al., 2010). The cobalt and iron pieces are the main indicators for the thermal and fast neutron fluences, respectively.

Homogeneous pebble surface temperatures were achieved by tailored gas gaps between the graphite half-shells and inner containment wall. Thermocouples and gas tubes penetrate the containment cap to reach the graphite half-shells. This penetration of the top cap is sealed by means of high-temperature brazing to form a gastight 1st containment.

The containment tube is enclosed in an aluminum shroud Fig. 4. This shroud holds another 24 thermocouples and acts as a spacer for instrumentation feedthrough. The section between first containment and the outer tube contains a second gas mixture that can be controlled separately.

Inside the cylindrical aluminum shroud, which surrounds the containment, thermocouples are guided in the sleeve. This shroud reduces

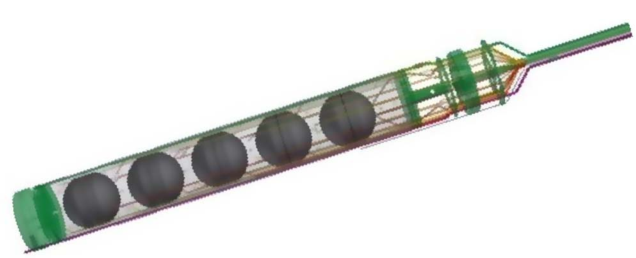

Fig. 3. The 1st containment of the irradiation capsule containing the pebbles and instrumentation.