Fusion Engineering and Design 87 (2012) 885–889

Contents lists available at SciVerse ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Study of ceramic pebble beds in Post Irradiation Examination of the Pebble Bed Assemblies irradiation experiment

S. van Til*, A.V. Fedorov, A.J. Magielsen

Nuclear Research and Consultancy Group, Westerduinweg 3, Postbus 25, 1755 ZG Petten, The Netherlands

ARTICLE INFO

Article history:
Available online 13 March 2012

Keywords:
Lithium ceramics
HCPB
Pebble bed
Irradiation
DEMO

ABSTRACT

The irradiation experiment Pebble Bed Assemblies (PBA) consists of four mock-up representations (test elements) of the EU Helium Cooled Pebble Bed (HCPB) concept. The four test elements contain a ceramic breeder pebble bed sandwiched between two beryllium pebble beds and are regarded as one of the first DEMO representative HCPB blanket irradiation tests, with respect to temperatures and power densities. The design value of the PBA were to irradiate pebble beds at a power density of 20–26 W/cc in the ceramic breeder, to a maximum temperature of 800 °C.

Two test elements contain lithium orthosilicate pebbles (Li_4SiO_4; FZK/KIT) and were irradiated with target temperatures of 600 and 800 °C, respectively. The other test elements have lithium metatitanate (Li_2TiO_3; CEA) with different grain sizes and were both irradiated with a target temperature of 800 °C. The PBA have been irradiated for 294 Full Power Days (12 cycles) in the High Flux Reactor (HFR) in Petten to a total neutron dose of 2–3 dpa in Eurofer, and an estimated (total) lithium burnup of 2–3% in the ceramic pebbles.

This work presents results of Post Irradiation Examinations (PIE) on the four HCPB test elements. Using e.g. SEM, the evolution of compressed pebble beds and pebble interactions like swelling, creep, sintering, etc., under irradiation and thermal loads are studied for the candidate pebble materials Li_2TiO_3 and Li_4SiO_4. (Chemical) interactions between ceramic pebbles and Eurofer (e.g. chrome diffusion) are observed. Looking at different sections of the pebble beds, correlations between temperatures and thermal–mechanical behaviour are clearly observed.

1. Introduction

The irradiation experiment Pebble Bed Assemblies (PBA) consists of four mock-up representations (test elements or TEs) of the EU Helium Cooled Pebble Bed (HCPB) concept for DEMO. The four test elements contain a lithium ceramic breeder pebble bed sandwiched between two beryllium pebble beds, separated by floating Eurofer-97 plates, see Fig. 1. The plates are 'suspended' by a bellow spring to avoid excessive stress build-up. The experiment is regarded as one of the first DEMO representative HCPB component irradiation tests, with respect to temperatures and power densities [1] with the objective to study the thermomechanical behaviour of HCPB pebble beds. Irradiation has been successfully performed in 2003 and 2004. Dedicated dismantling and preparation procedures have been developed during the Post Irradiation Examination (PIE) campaign in 2005 [2,3]. In preparation, all TEs have been impregnated in a resin and cross sections of the regions of interest have been cut. An extensive optical microscopy and SEM study has been performed on different areas of the different pebble beds in each mock-up. A selection of the findings is presented in this paper.

2. Materials, preparation and irradiation

The goal of PBA was to irradiate four HCPB blanket mock-ups with combined ceramics and beryllium pebble beds up to a DEMO-relevant power density of 20–26 W/cc in the ceramic breeder, reaching temperatures of ~800 °C [1]. Two test elements, TE#1 and TE#4, contain lithium orthosilicate pebbles (Li_4SiO_4 or "OSi") and were irradiated with target temperatures of 600 and 800 °C, respectively. The Eurofer floating plates had average temperatures of 400 °C in TE#1 and 530 °C in the other three TEs. The OSi pebbles are produced by melt-spray method by FZK (now KIT). The other test elements, TE#2 and TE#3, contain lithium metatitanate (Li_2TiO_3 or "MTi") and were both irradiated with a target temperature of 800 °C. The MTi pebbles are produced by sol–gel method and sintered at different temperatures (1040 °C and 1100 °C, respectively), resulting in different grain sizes. The ceramics pebble beds have a diameter of 45 mm and a height of 11 mm. All TEs have been precompressed in steps up to 3 MPa and heated to 350 °C for 18 h to establish a well-defined thermomechanical starting condition, with

* Corresponding author.
E-mail address: vantil@nrg.eu (S. van Til).

0920-3796/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.fusengdes.2012.02.052

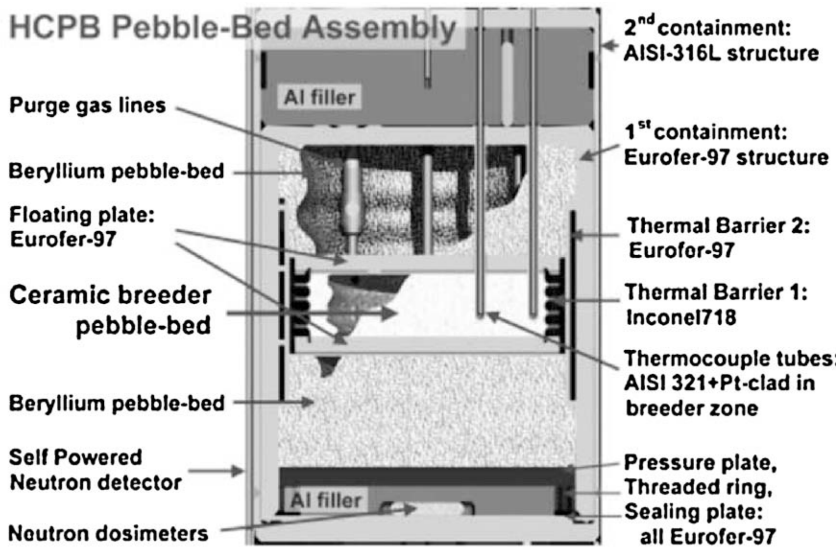

Fig. 1. A cross section schematic of one of four test elements of PBA.

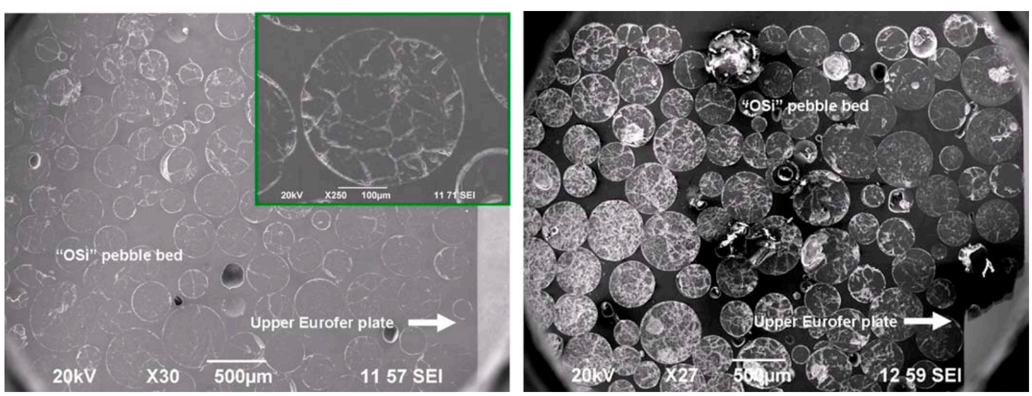

Fig. 2. Left: (SEM) Cross section of a non-irradiated OSi pebble bed from TE#0. Left inset: detail of a cross section of a non-irradiated OSi pebble from TE#0 Right: (SEM) Cross section of irradiated OSi pebble bed from TE#4. The middle of the pebble bed is on the lower left. From the top to the middle of the bed, a clear increase in (thermal) strains is visible (white shade by cracks in increasing brittleness of OSi). In both pictures the upper Eurofer plate is visible on the right side.

a minimal value for the thermal conductivity (especially of importance in the Be beds) [1]. For comparison, a fifth TE (TE#0, with an OSi pebble bed), has been precompressed, but not irradiated.

The PBA have been irradiated for 294 Full Power Days (12 cycles) in the High Flux Reactor (HFR) in Petten to a total neutron dose of 2–3 dpa in Eurofer-97, and a (total) lithium burnup of 2–3% in the ceramic pebbles, see Table 1 [4]. The different TEs were continuously purged with a reference purge gas (He + 0.1% H_2). The 4 outgoing purge gas lines are continuously monitored and measured for tritium content by the Tritium Measurement Station (TMS), installed next to the reactor. It has been shown that the thermocouple tubes function as a heat sink, leading to a structural underestimation of 50 °C in the ceramic pebble beds [5] (this correction is also shown in Table 1).

3. Observations

Using SEM, the evolution of the compressed pebble beds and pebble interactions like creep, and sintering under irradiation and thermal loads for the candidate pebble materials Li_2TiO_3 and Li_4SiO_4 are studied. (Chemical) interactions between ceramic pebbles and Eurofer (e.g. chromium diffusion) are observed. Looking at different sections of the pebble beds, correlations between temperatures and thermal–mechanical behaviour are observed in the form of sintering gradients in MTi and beryllium and increased cracking and fragmentation in OSi. Models have shown compaction strains after precompression and during start-up of irradiation, to be the largest in the centres of the ceramic pebble beds [1].

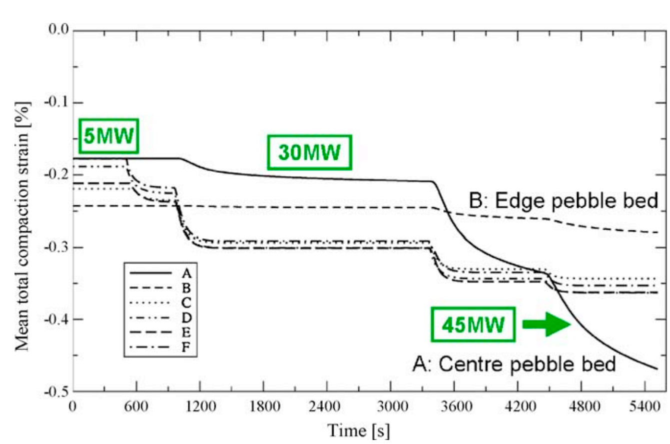

Fig. 3. Mean total compaction strain in the centre (A) and the edge (B) of the ceramics pebble bed of TE#4 during stepped reactor start-up (from 5 to 45 MW).