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Deterministic safety analysis of the reference accidental sequence for the European HCPB TBM system

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ABSTRACT

In order to investigate the accidental behavior of the helium cooled test blanket module and its auxiliary systems, a particular sequence has been selected for the deterministic analyses in the frame of the EFDA licensing task for ITER. This sequence starts from an ex-vessel loss of coolant with simultaneous assumed failure of the plasma shutdown system. This paper presents the study of this sequence with the use of various assumptions and code-dependent modeling (RELAP5, MELCOR and ANSYS). Two different variants of the sequence are analyzed depending on the assumption of the failure of water-cooled component of ITER. The resulting transients show the effect of the exposure of the Be pebble beds on air and on a mixture of air and steam.

1. Introduction

The helium cooled pebble bed (HCPB) blanket concept, developed by the Forschungszentrum Karlsruhe, is one of the two European blanket concepts foreseen to be tested in ITER [1]. Test blanket modules (TBM) derived from this concept will be located in a horizontal port of ITER facing directly the burning plasma with its first wall (FW) that constitutes 1 m^2 of the whole ITER FW. A failure mode and effect analysis (FMEA) has been performed by ENEA [2] for this TBM and its auxiliary systems (helium coolant system (HCS) and tritium extraction system (TES)) to identify the main postulated initiating events (PIE) and the most demanding accident sequences; the PIEs are the most representative accident initiators, in terms of radiological consequences, between a set of elementary events challenging the plant in similar way and producing equivalent fault plant conditions. Among these cases, a particular sequence, namely a loss of coolant accident (LOCA) in ex-vessel with failure of the plasma shutdown system, has been selected for the deterministic analyses in the frame of the EFDA licensing task. This has been done by the best-estimated analysis.

The evolution of the selected sequence and the related analysis can be divided in three phases. Phase 1 ("He blow-down") starts with a double-ended pipe break in a large diameter pipe of the HCS in the tokamak cooling water system (TCWS) vault during the plasma burn. This leads to the complete loss of TBM He cooling in very short time. In phase 2 ("delayed plasma shutdown"), it is assumed that the detection of ex-vessel LOCA fails to trigger the fusion power shutdown system (FPSS). As the heat removal capability of the HCS goes to zero due to the lost of the coolant inventory, the TBM is heated up by the plasma burn. As the PIE is assumed under long pulse (more than 1000 s), the heating continues until EUROFER melting point (1450 °C) on the FW surface is reached. Hence the structural integrity of the FW channels cannot be ensured any more and the FW confinement fails allowing air from the TCWS vault to ingress into the VV, which causes abrupt plasma shutdown followed by a major disruption. A short transient (1 s) with a heat flash from the plasma disrupting of 2200 kW/m^2 concludes this phase. Phase 3 ("long-term behavior") begins at this point. The heat removal for the TBM is now ensured mainly by heat irradiation on the surrounding structures. Heat sources are the decay heat and the possible Be chemical reaction with air or steam that can enter the VV. The high FW temperature caused by heating-up in phase 2 leads to a failure of the TBM box and consequent exposition of the internal Be beds to the VV atmosphere. Without the failure of water-cooled component of ITER, the impact of the internal bed with air ingress will be analyzed in scenario A. The additional fault of a water-cooled ITER system (shielding blanket or divertor) due to the disruption with a probability of $\sim 10^{-2}$ per severe disruption is analyzed in scenario B. Here the product of Be–steam reaction is H_2 introducing (together with the presence of air) the risk of explosion with failure of the VV containment function. In the following each

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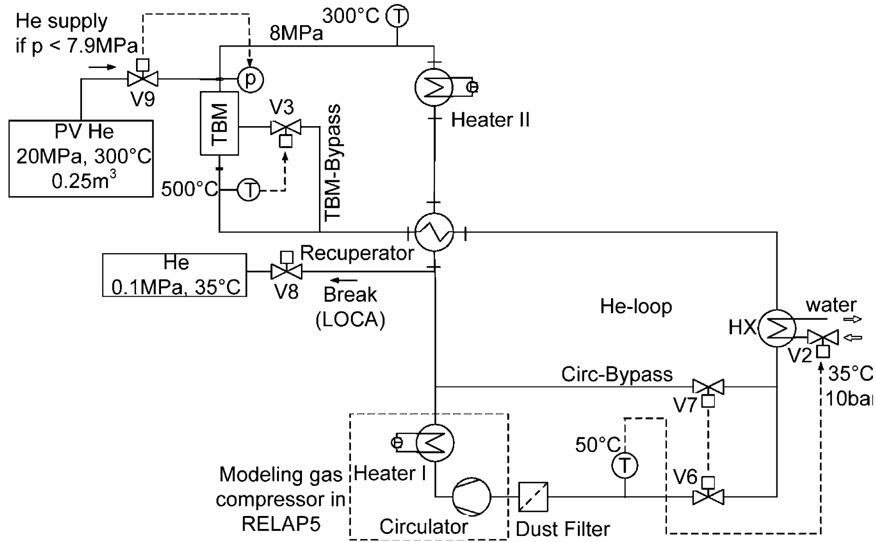

Fig. 1. Scheme of RELAP5 modeling for the HCS.

phase will be studied using qualified codes regarding assumptions and modeling.

2. Phase 1: He blow-down

The blow-down phase has been analyzed using the thermo-hydraulic system code RELAP5/MOD3.2 [3]. Fig. 1 shows the HCS modeled by RELAP5. Detailed modeling of the HCPB TBM and the corresponding HCS is reported in [4] for normal operation analyses. Pipe break is located between pump outlet and recuperator for a pipe with inner diameter 96.7 mm. The pressure control system (PCS) for the HCS is modeled as a pressure vessel (PV). The ex-vessel LOCA decreases the pressure level below 7.9 MPa and ∼4 kg He from the PV can be supplied to the HCS. The blow-down begins during the normal operation at steady state, when TBM inlet works at 8 MPa and 300 °C and the plasma is burning with the nominal surface heat load 270 kW/m^2.

Pressure decrease at TBM inlet shows a time constant of 1.05 s (i.e. when 63% pressure drop is reached). He blow-down goes very fast and is almost insensitive by the changes in the arrangement of the main components. Pressurization in the TCWS vault and T release into the vault are the possible consequences of the blow-down. If the total He mass (∼36 kg in the HCS and PCS) is lost into the free volume of the vault (∼23,223 m^3 [9]), He pressure in the vault can increase by ∼977 Pa, which is irrelevant compared with atmosphere pressure. The primary coolant contains at maximum 1 mg of T at the design partial pressure of HT of 0.3 Pa [5]. This small amount released in the vault is largely inside the maximum allowable values.

3. Phase 2: delayed plasma shutdown

In phase 2 the thermal analysis is performed using a 3D ANSYS model. The aim of this calculation is to determine the maximum possible delay of the plasma shutdown and the temperature level that the TBM material can reach in order to estimate the possible damages in the structure. Fig. 2 shows the ANSYS model of a radial cell cut out of the HCPB TBM. ANSYS calculation [6] is started with steady state regarding: the plasma burn by the nominal surface heat load; radial distribution of nuclear power density [7]; temperature of the FW cooling channels at 330 °C and its heat transfer coefficient (HTC) α_{FW} = 5000 W/(m^2 K) [4]; temperature of the cooling plates in breeder units (BU) at 450 °C and its HTC α_{BU} = 3000 W/(m^2 K) [4]; material properties for EUROFER [8], Be-cover, Be pebble in He and breeding ceramic in He [9]. The followed transient calculation simulates heating-up. Coefficients α_{FW} and α_{BU} are ramped down within 3 s based on the time constant obtained in phase 1. Heat is transported from the FW to TBM back plate by heat conduction and radiations on the breeding unit (BU) back plate and TBM back plate (Fig. 2).

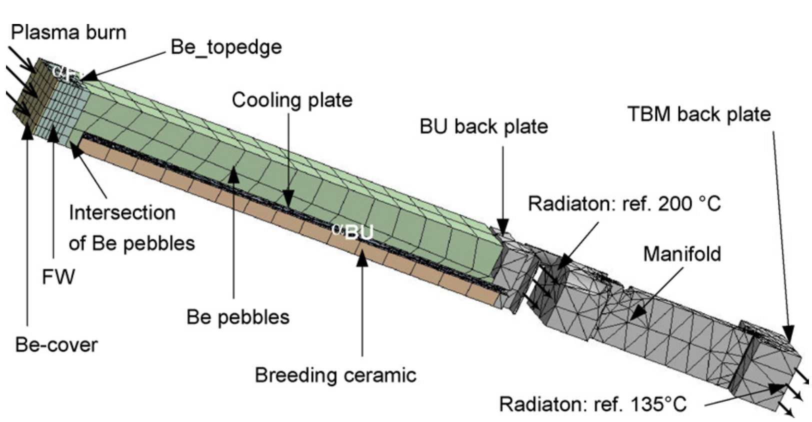

Fig. 2. ANSYS model for the thermal analysis in phase 2.