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Recent progress in the assessment of irradiation effects for in-vessel fusion materials: tungsten and copper alloys

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DEMO and fusion power plants beyond it require robust materials to ensure durable and safe operation as well as commercially competitive construction and dismantling design. One of the main challenges in the development of those materials is assessment of irradiation effects, originating from the nuclear fusion reaction which generates 14 MeV neutrons damaging the material's atomic lattice. So called in-vessel materials will experience the most severe neutron exposure being far beyond the damage limits acquired by currently operating nuclear power plants. The task of development and qualification of the in-vessel materials thus boils down to securing that the degradation of mechanical, thermal and physical properties will remain within acceptable limits, which are in turn driven by the design of components and operational scenario. Overall, three main functions of the in-vessel materials can be singled out, such as: structural, armour and heat sink.

Within European material's programme, the portfolio of baseline materials for DEMO contains the following items: (i) EUROFER(97), a 9Cr Reduced Activation Ferritic Martensitic (RAFM) steel, as structural material for the breeding blanket, (ii) commercially pure tungsten as plasma facing component armor material, and (iii) copper chromium zirconium (CuCrZr) alloy as heat sink material for the divertor coolant interface [1.]. This contribution reviews the efforts done towards the assessment of the irradiation effects and operational temperature window performed over the last several years in the frame of the European fusion programme [2.] focusing on the armour and heat sink materials.

Based on the already available knowledge gained in FP6 and FP7 programmes, the operational conditions for the baseline in-vessel materials are tentatively determined as illustrated on the Figure. For each of the baseline material, the lower temperature bound is defined by the embrittlement (fracture without plastic deformation), while the upper temperature bound is determined by softening of the material (reduction of the yield point). Accordingly, the main challenges in the formulated irradiation programmes were linked to: (I) assessment of the ductile-to-brittle transition temperature (DBTT) of baseline tungsten and advanced tungsten alloys; (ii) investigation of baseline tungsten under irradiation at very high temperature, reflecting operational conditions in divertor; (iii) assessment of the mechanical properties of reinforced CuCrZr alloys. The choice of the advanced materials is driven naturally by the need to extend the operation temperature/fluence window to extend the design space.

Although the fusion neutron spectrum implies an important difference in the transmutation reactions compared to fission spectrum, the current R&D programme utilizes available Material Test Reactors (MTRs), while dedicated fusion neutron sources are under construction. This limitation is especially important for the assessment of RAFM steels and tungsten, given that MTRs conditions do not yield to the same generation rates of gases in steels and rhenium in tungsten, which are known to contribute to embrittlement. Accordingly, the neutron exposure fluences and design of irradiation devices are defined to ensure the relevance of the executed programmes.

Driven by the technological priorities, the irradiation tests campaigns were arranged in two waves. The first one involved baseline materials focusing on delivery of the engineering design data and the second one targeted screening irradiation of the advanced materials. Execution of the irradiation programmes was realized in Europe on BR2 reactor, while other reactors were involved for the irradiation of RAFM steels.

Extraction of the properties of the neutron exposed materials involved extensive post irradiation examination (PIE) campaigns. Unique nuclearized facilities in Germany, Belgium, and Greece were involved to deliver thorough information on the performance of the neutron exposed materials in terms of: mechanical, microstructural, chemical and physical properties. The most important results signifying our current understanding of the operational limits (see Figure) are reported in this contribution. The performance of the advanced materials is also assessed and presented, which already at this stage allows drawing some important conclusions. In summary, we provide an outlook for continuation of the research programmes involving irradiation facilities as well as technological and research material matrices within next 5 years.

[1.] G. Pintsuk, Fusion Engineering and Design 146 (2019) 1300–1307; https://doi.org/10.1016/j.fusengdes.2019.02.063

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