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Interaction of Pb -16Li melt with EUROFER97 under higher temperature and neutron irradiation

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ABSTRACT

The behaviour of ferritic-martensitic steel EUROFER97 was evaluated after its exposure in a liquid Pb-16Li environment under neutron flux simulating the conditions of operating parameters of the HCLL test blanket module using a test train inserted into the LVR 15 research reactor in CV Řež. The interaction of the Pb-16Li alloy with neutron flux results in radioisotope formation due to transmutation reactions. The formation of tritium and polonium was measured and compared with calculated values. The Pb-16Li corrosion effect leads to dissolution of steel matric. Two reaction layers were observed on the exposed EUROFER97 surface. The first continuous surface layer is characterized by uneven thickness, the second subsurface layer confirms that dissolution of the metal matrix takes place along martensitic lath boundaries. The performed examinations proved that the mechanism of corrosion in the liquid melt was volume dissolution of steel.

1. Introduction

The development of the European HCLL (Helium-Cooled Lithium Lead) Test Blanket Module (TBM) concept uses reduced activation ferritic-martensitic steel (RAFM) EUROFER97 as a structural material, Pb-16Li liquid alloy as a breeder and neutron multiplier, and pressurized helium as a coolant. In the view of further development it is of a high importance to investigate the behaviour of the Pb-16Li breeder in contact with EUROFER97 structural material under neutron irradiation and conditions simulating those of the HCLL TBM. In this very important area the results of investigating the synchronous radiation and corrosion effect have not been published yet. The effects of irradiation only on the diffusion coefficient and the tritium permeability changes of EUROFER97 steel have been examined under high flux reactor (HFR) conditions [1,2]. The aim of our investigation was to construct and operate the irradiation equipment under conditions corresponding to operating parameters at 520 °C and to evaluate the result of transmutation reactions and the interactions of Pb16Li melt with the EUROFER 97 steel. The performed experiment has been linked with the previous evaluation of EUROFER97 steel under similar conditions without irradiation [3,4].

2. Experiments

The experiment has been carried out on the Pb-16Li eutectic alloy which was made of 99.99 wt% of pure lithium and 99.9 wt% of lead in a molybdenum crucible. The chemical composition of the alloy containing about 0.654 wt% of lithium is shown in Table 1.

EUROFER97 steel plates of 24 mm thickness used for the specimens preparation, were heat-treated: hardening 980 °C/27 min/air, tempering 760 °C/90 min/air [5]. The chemical composition of EUROFER97 is given in Table 2. Two types of specimens were irradiated. The plain corrosion specimens of 1.5 × 8 x 38 mm have been used for the examinations.

An irradiation rig was designed and three mock-up experiments were carried out to verify, whether target temperatures in the range of 500°- 520 °C and 300°- 320 °C were reached. The COSMOSFloWorks computer code has been used to verify the rig design and to calculate the temperature distribution in the experimental rig (e.g. internal dimensions, the cooler design, number of specimens etc.). The results indicated a good agreement between the measured and calculated values in both temperature ranges [6].

The irradiation experiment was performed in the in-pile rig (Fig. 1), the inner part of which consists of EUROFER97 field tube, liquid alloy and corrosion specimens. The outer part was under helium overpressure

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Table 1
Content of selected elements of the Pb-16Li eutectic alloy, wt%.

Element	Bi	Co	Cr	Fe	Li	Mn	Mo
Content	0.0040	0.0001	0.0001	0.0011	0.654	0.0002	0.0001
Element	Ni	Sn	Ta	Ti	V	W	Zr
Content	0.0011	0.0563	0.0020	0.0003	0.0002	0.0002	0.0002

of 180 − 200 kPa, the inner part containing melts under helium pressure of 100 – 120 kPa. Different pressures of two gas systems were monitored, which has enabled checking the tightness of the inert gas systems. The irradiation experiment was carried out in the research reactor LVR-15, operated at Research Centre Rez, at power 8 − 9 MW for the period of 5950 h (247 EFPD), when total neutron fluence was $5.75 \times 10^{20}\ cm^{-2}$ and a radiation damage level of 1.45 dpa (displacement per atom) were achieved. The fluence rates in four energy groups are listed in Table 3. The number of atoms displacements in EUROFER97 steel was calculated using the damage energy cross-section.

The required temperature of the eutectic melt was reached only by nuclear heating without external heating elements. The temperature of the melt in the samples area was controlled both by changing the heat transfer surface area by shifting the rig internals against the cooler shell and by changing the rig position depending on the reactor core height allowing to control the nuclear heating level. During the experiment the hot leg temperature was set mainly by rig vertical shift. The temperatures of the hot leg with samples and the cold leg were kept in the range of 500°- 520 °C and 300°–320 °C, respectively. The length of the specimen area was 200 mm, the field tube inner diameter 20 mm. Different pressures of two gas systems enable checking the tightness of the rig. The volume of the gaseous phase above the melt amounted to 0.08 dm^3, the alloy volume 0.044 dm^3, the alloy weight 465 g [7]. The flow of the melt around specimens was driven by natural convection in the range of 5 mm/s, evaluated by a computer modelling. The flow rate was calculated according to experimental conditions using a computer model [8].

After irradiation, the rig was dismantled and the field tube was cut into three sections (Fig. 1). The first cut was made above the melt level, the second one just below the corrosion samples and the third one above the cooler body plug. From the upper section was cut off 40 mm long segment. Corrosion specimens from upper section segments were loosed after removing of Pb-16Li alloy in a furnace under argon atmosphere and remaining lead was washed out in liquid sodium at the temperature above 250° C. The last step was removing sodium by washing in alcohol [9]. The Pb-16Li samples for optical microscopy and microanalysis were prepared during remelting in the furnace and casting into a crucible.

For the investigation of structural and surface properties of materials and their chemical composition a SEM, EDS (energy dispersive X-

Table 2
Chemical composition of EUROFER97, wt%.

Content	C	Mn	Si	P	S	Cr	V	W	Ta
Element	0.11	0.47	0.040	0.005	0.004	8.82	0.20	1.09	0.13
Element	Mo	Ni	Ti	Cu	Co	Nb	B	As	O
Content	< 0.005	0.022	0.005	0.0016	0.006	0.0016	0.001	0.005	0.001

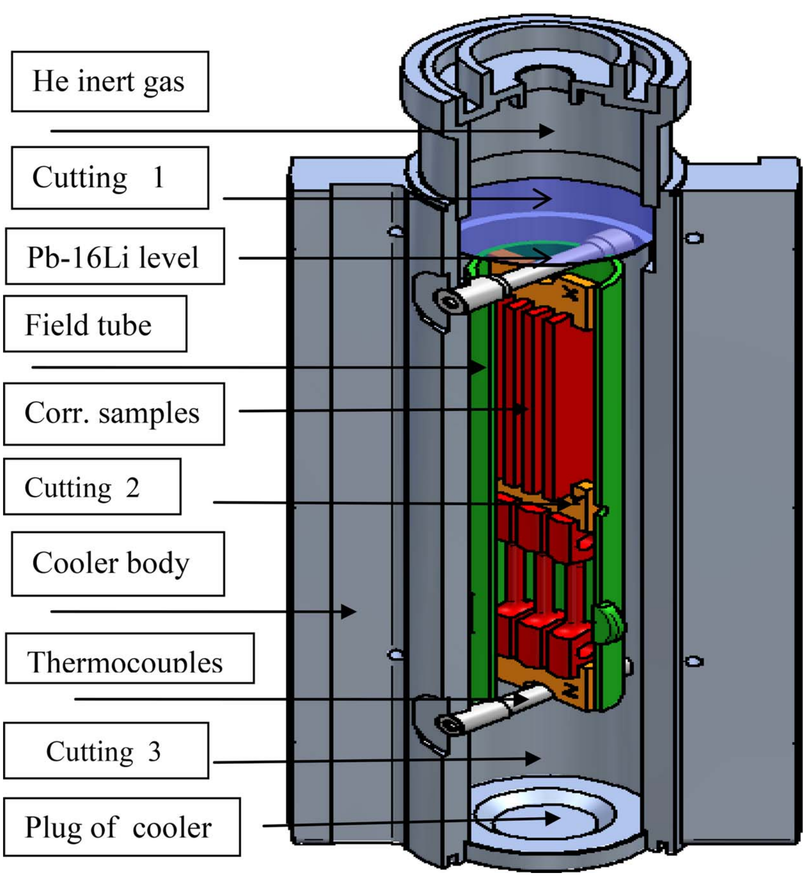

Fig. 1. IN-PILE irradiation rig. Positions of cutting during the rig dismantling are indicated.