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APT-studies of phase formation features in VVER-440 RPV weld and base metal in irradiation-annealing cycles

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Abstract

This paper presents a thorough APT study of VVER-440 RPVs WM and BM samples cut out from the inner RPV surface. The features of phase formation (number densities, sizes and composition) in VVER-440 RPV steels under primary irradiation, recovery annealing, re-irradiation, recovery re-annealing and subsequent accelerated re-irradiation are identified to justify its lifetime extension up to 60 years by recovery re-annealing.

It is shown that primary and re-irradiation is accompanied by formation of radiation-induced Cu-P-based precipitates whereas recovery annealing leads to their partial dissolution and coarsening of the undissolved ones. At this, for both WM and BM under primary annealing, Cu dissolves in the matrix, while under re-annealing Cu almost doesn't return to the matrix. In WM P fully dissolves in the matrix under annealing while in BM there is gradual matrix P depletion under operation (including recovery annealing) due to formation of P grain boundary segregation. Under the third irradiation cycle, Cu almost doesn't contribute to precipitation: in WM radiation-induced precipitates are P-based, enriched with Si, Ni and Mn, while in BM there are Si-based precipitates, enriched with Ni and Mn. In BM number density of precipitates is lower than in WM during all operation stages that causes its lower radiation embrittlement.

Keywords: Reactor pressure vessel steel, VVER-440, neutron irradiation, recovery annealing, Atom probe tomography, weld metal, base metal, precipitate

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1 Introduction

Reactor pressure vessel (RPV) steel operation under neutron irradiation at ~270 °C temperature leads to its properties' degradation caused by the nanostructural changes. Weld metal (WM) is the most susceptible to radiation embrittlement. In the 80-90s of the last century the WM annealing technology (recovery annealing) was developed. This technology allowed to restore the structure and properties of 1st generation VVER-440 RPV steels and extend its lifetime up to 45 years [1,2]. This extended period for a number of annealed power units ends currently. In this regard, re-annealing of these VVER-440 RPVs was proposed in order to extend their lifetime up to 60 years [3,4]. Fig. 1[1] demonstrates schematics of VVER-440 RPV property changes when extending the lifetime up to 60 years [3,4].

[1] Designations of the studied states are presented in Table 1