EFFECT OF HIGH FLUENCES ON THE EMBRITTLEMENT OF LOW COPPER VVER 440 SURVEILLANCE SAMPLES

M. K. Miller*, K.F. Russell*, J. Kocik** and E. Keilova**

**Microscopy and Microanalytical Sciences Group, Metals and Ceramics Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6376, USA.*

***Nuclear Research Institute Rez plc, 250 68 Rez near Prague, The Czech Republic*

An atom probe tomography microstructural characterization has been performed on low (0.06 at. %) copper surveillance samples from a VVER 440 reactor that were exposed to high fluences in order to evaluate the susceptibility of these pressure vessel steels to embrittlement during service and plant life extension. The 15Kh2MFAA base and 10KhMFT weld specimens were each examined in three conditions: unirradiated, thermally aged (10 and 5 years, respectively at 295 °C) and neutron irradiated at 275°C to fluences of 1 x 10^{25} m^{-2} and 5 x 10^{24} m^{-2}, E > 0.5 MeV, respectively. The results from Charpy V-notch tests, and the measured ultimate and yield strengths were similar for both unirradiated and thermally aged materials. However after neutron irradiation, significant shifts (>100°C) in the ductile-to-brittle transition temperatures and increases in the yield and ultimate tensile strengths were found in both the base and weld materials.

Atom probe analysis revealed no significant differences between the copper contents of the matrix and the bulk compositions. In addition, the intragranular copper-enriched precipitates previously detected in neutron irradiated higher copper pressure vessel steels were not observed in these low copper materials. Three-dimensional atom probe compositional measurements revealed enrichments of manganese, silicon, phosphorus, copper and carbon at dislocations in neutron irradiated materials. The solute distribution around the dislocation was not uniform and the silicon and manganese were located in different regions of the dislocation. This behavior would be expected because the silicon atoms are undersized and manganese atoms are oversized compared to iron atoms and therefore, they would be accommodated more efficiently in different regions of the stress field. Some spherical features were also observed which could arise from solute segregation to small dislocation loops or other small defects, such as vacancy clusters or nanovoids. Another possibility is that some of the spherical features initially form through the clustering or precipitation of copper atoms and these embryos then attract or act as a sink for the other solutes or vacancies. A ~5 atom copper core has been observed in some of the features. All these solute-enriched regions can significantly impede the motion of dislocations and thereby account for the observed changes in the mechanical properties at high fluences.

These experimental results clearly demonstrate that low copper pressure vessel steels that are used in Russian VVER 440 reactors are susceptible to embrittlement during neutron irradiation.

Research at the Oak Ridge National Laboratory SHaRE User Facility was sponsored by the Division of Materials Sciences and Engineering, U.S. Department of Energy, under contract DE-AC05-00OR22725 with UT-Battelle, LLC and by the Office of Nuclear Regulatory Research, U. S. Nuclear Regulatory Commission under inter-agency agreement DOE 1886-N695-3W with the U. S. Department of Energy.