Safety Issues of Zr-2.5Nb CANDU Pressure Tubes and their Surveillance Examination

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1. Introduction

Zr-2.5Nb pressure tubes that function to carry fuel bundles and coolant of heavy water inside are the most critical components to the safety and capacity factors of heavy water pressurized water or CANDU reactors. The safety issues are their degradation during operation in reactors by corrosion and hydrogen pick-up, delayed hydride cracking (DHC), irradiation embrittlement and dimensional changes such as irradiation creep and growth. For example, the enhanced creep rate of the pressure tubes after an approximately 20 year operation has forced a CANDU plant to operate with a reduced power lower than the full power. Thus, it is very important for the safety and availability of the CANDU reactors to establish their degradation rate with a very high confidence level based on the operational experiences. To this end, CANDU utilities and AECL have tried to collect in-reactor performance data of the Zr-2.5Nb pressure tubes since 1970s by conducting material tests on the pressure tubes that were periodically withdrawn out of the oldest CANDU plant. Up to date, 26 pressure tubes have been subjected to surveillance examination[1]. Though a considerable in-reactor performance data of the irradiated Zr-2.5Nb tubes has consequently been procured mainly by AECL, the size of their performance data base is undoubtedly very small compared to that of cladding tubes used in fuel rod design and analysis. This accounts for many unresolved issues related to the degradation rate of the pressure tubes with time and about how to correlate it with the reactor operating conditions and the as-fabricated variables of the Zr-2.5Nb pressure tubes.

As the in-reactor performance data of the Zr-2.5Nb pressure tubes have been growing, it is recognized that the in-reactor performance data taken from the oldest tubes may not be representative of all the pressure tubes operating in CANDU type reactors. This rationale may come from wide operating experiences of the utilities that the degradation rate of the pressure tubes strongly depends on the operating condition such as the capacity factors, coolant temperatures, the fuel loading modes, power distributions in the core and along the tube axis and so on. This leads the Canadian Standards Association to strengthen the code for periodic inspection of CANDU nuclear power plant components (CSA N285.4) in 2005[2]

2. Pressure Tube Surveillance Examination

Clause 12 of CSA N285.4-05 is related to surveillance examination of pressure tubes to monitor pressure tube properties. The general requirements related to pressure tube surveillance examination stipulate that the licensee shall prepare a material property surveillance program for each reactor unit but a reduction in the extent of material property testing is acceptable provided that an integrated material surveillance program is prepared and accepted by the regulatory authority. In the case where more than one type of pressure tube materials is used, material surveillance for each material type shall be determined independently of other material types. The material property tests for the surveillance examination are measurements of fracture toughness (K_c), delayed hydride crack growth rate and isothermal threshold stress intensity factor for the onset of DHC initiation from a crack (K_{IH}). To establish the variation in material properties along the length of the pressure tube, a sufficient number of measurements are to be preformed. As to the intervals for material surveillance program, 5 runs of material property testing shall be carried out during 30 year design life: the 1st run shall be completed within 12 to 15 years after the first net power date and the 2nd to 5th runs shall be conducted every 4 year since the 1st run.

3. R&D for pressure tube surveillance examination

Since the pressure tubes to be examined for monitoring their degradation are highly radioactive, all the tests must be conducted remotely in hot cells. With an aim to development of basic technology related to pressure tube surveillance examination, a research project has been conducted since 1997 as one of the mid-term and long-term nuclear R&D projects under the auspices of the Ministry of Science and Technology (titled "Development of evaluation technology of pressure tubes integrity")[3]. 3 pressure tubes removed from Wolsong Unit 1 after around 10 year-operation due to a DHC concern were subjected to material testing in hot cells in Korea Atomic Energy Research Institute. For the first time in KAERI, we installed an electric discharge machine that was built on a special order for a remote use in the hot cells and successfully cut test specimens with various shape from the highly radioactive pressure tube. Using those specimens remotely made in the hot cells, material tests have been conducted: tensile tests, delayed hydride cracking tests to determine the crack growth rate and the threshold stress intensity factor for the onset of delayed hydride cracking, fracture toughness tests to evaluate the fracture toughness resistance with temperature and neutron fluence, and microstructural analysis using transmission electron microscope, scanning electron microscope and optical microscope. Figs 1-3 showed typical experimental results for one of Wolsong 1 tubes examined.

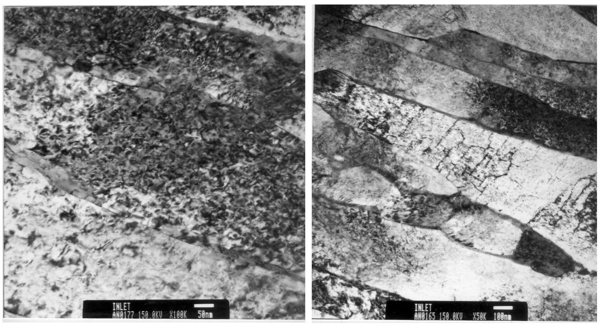

Fig. 1. (a) a-type dislocations and (b) c-type dislocations in a Wolsong 1 tube irradiated to neutron fluence of 8.9×10^{25} n/m^2 (E>1MeV).

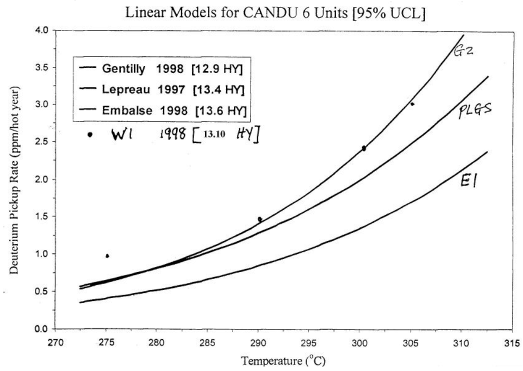

Fig. 2. Deuterium pickup rate of Zr-2.5Nb tubes with the reactors: the highest pickup rate was observed on tubes irradiated in Gentily 2 reactor and the Wolsong Unit 1 compared to those in other CANDU 6 reactors[4].

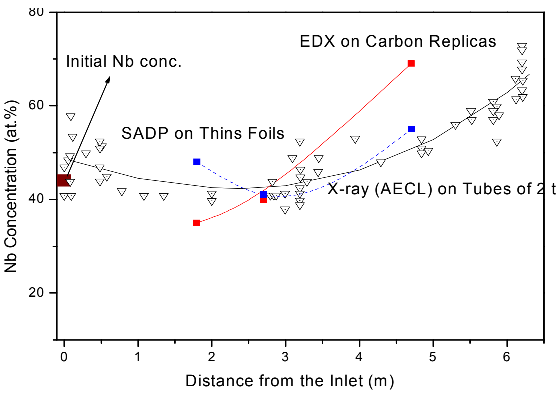

Fig. 3. Distribution of Nb concentration in the β-Zr phase along the axial length of the Zr-2.5Nb tube: all the data points except for the reverse triangle data were taken from the Wolsong 1 Zr-2.5Nb tube[5].

Microstructural analysis (Fig. 3) showed that the evolutions of microstruture for the Wolsong 1 tube are different from those of Zr-2.5Nb tubes that had been irradiated in Pickering and Bruce reactors. These results demonstrate that depending upon the operating conditions, the degradation behavior the Zr-2.5Nb tubes becomes different and even in the CANDU 6 reactors of the same design features. This fact provides a rationale that the degradation of the Zr-2.5Nb pressure tubes should be evaluated for each reactor unit, which is actually in accordance with the technical background of the revised version of CSA N285.4.

4. Conclusion and Further Works

The achievements of research and development related to pressure tubes carried out for 10 years since 1997 are establishment of basic technology for pressure tube surveillance examination in accordance with Clause 12 of CSA N285.4 and our understanding of delayed hydride cracking in Zr-2.5Nb pressure tubes[6,7] which had been reported in many Canadian reactors[8]. If our authority will decide to apply the technical standards of CSA N85.4-05, for a periodic inspection of CANDU nuclear power plant components, to Wolsong nuclear power plants, the first surveillance examination on pressure tubes should be carried out on the year of 2013 at the latest for Wolsong Unit 2. To this end, we have to further develop our basic technology being established by KAERI, the project of which should be accomplished in 5 years. The further research shall focus on establishment of the technologies related to surveillance examination of the pressure tubes such as quality assurance program, set-up of qualified equipment and experimental procedures for material surveillance examination in hot cells. Further work on a revision of DHC evaluation specified in CSA N285.8 is needed by accounting for Kim's DHC model[6,7].

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