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Computational and experimental studies of the causes of crack network formation in the area of the heat exchanger tube sheet in the BN’600 reactor

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Abstract

In order to examine the condition of intermediate sodiumtosodium heat exchangers (IHX) and to substantiate their operation life extension to 45 years at the BN600 reactor plant at Beloyarsk NPP Unit 3, one of the six heat exchangers was removed from the reactor in April 2006. Inspection revealed cracks with 7 maximum depth of mm on the outer surface of the upper tubesheet (UTS) and adjacent shell.

To predict durability of substantially fatigued metal, verification of the existing relationship for the threshold stress intensity factor range for the 10Cr18Ni9 steel was needed. To this end, specimens of two structural elements in the IHX – upper tube sheet and protection block were tested.

To identify failure mechanisms, fractographic studies were performed on the surface of cracks detected in the tube sheet and produced in the specimens. The studies led to the conclusion that the failure mechanism for cracks detected on the tube sheet was identical to the mechanism generated in the test specimens. In both cases the intergranular failure prevailed that is typical for the material stress level indicative of crack growth termination. This result makes it possible to speak about crack initiation and propagation in the IHX tube sheet in the high-cycle fatigue region at low-level strain ranges and stress intensity factor ranges.

An analysis of causes of crack formation showed that the cracks could have formed as a result of the temperature pulsation effect produced by mixing of sodium flows having different temperatures – sodium entering the IHX inlet and sodium coming from the reactor vessel cooling system.

Computational analysis results showed that for all thermal pulsation conditions and crack propagation cross-sections under consideration, the leak-tightness condition is met for the upper tube-sheet and IHX outlet chamber shell that divide the primary and secondary coolant circuits.

The computational and experimental studies have proved that presence of these cracks does not limit the potential service life extension to 45 years for the IHX in the BN600 reactor plant.

Keywords: BN600; Intermediate heat exchanger; Computational and experimental studies; Temperature pulsations; Stress strained state; Stress intensity factor; Multicycle fatigue; Creep; Cracks.

Introduction

“Sodiumtosodium” intermediate heat exchangers (IHX) have been in operation at the Beloyarsk NPP (BNPP) Unit 3 reactor plant since 1980. Their assigned lifetime amounted to 30 years and expired in 2010. IHXs operate under high temperatures ranging from 367 to 550 °C in the primary circuit and 328 to 518 °C in the secondary circuit under low-level neutron irradiation. Repeated stress on the heat exchanger formed by the combination of the on-off modes, operation

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at power level and shutdown (planned and scram) is the major factor affecting the cumulative damage.

The heat exchangers are made of 10X18M9 austenitic steel. In April 2006 one of the six heat exchangers was removed from the BN600 reactor in order to study the IHX condition, obtain experimental data on the structural material mechanical characteristics change and validate the potential life extension of the IHX in operation to 45 years. Non-destructive testing revealed crack networks on the upper tube sheet and adjacent shell [1]. Major cracks were 4–7 mm deep with the opening of 50–130 μm. This work presents the results of the study of causes for crack formation and capability assessment for potential IHX service life extension to 45 years. Computational studies were performed with the help of ANSYS software.

Results of material studies of the heat exchanger UTS

Fatigue damage resulting from high-cycle thermal cyclic stress caused by cold and hot sodium flow is suggested as the main hypothesis for crack formation and propagation [2].

Computational methods developed within elastic fracture mechanics [3,4] are used to assess the material resistance to crack propagation under repeated stress. If the fatigue mechanism of crack formation is confirmed the threshold level for ΔK_{th} (threshold stress intensity factor range) should be determined below which the fracture propagation stops. ΔK_{th} value and stress strain behavior (SSB) can help answer the questions whether the cracks detected will develop and if IHX life extension is possible under high-cycle thermal cyclic stress.

Metallographic and fractographic studies of fractures have shown that they grow due to a mixed mechanism with a significant intergranular failure in the base metal.

In order to predict the durability of significantly fatigues metal we need to know the $\Delta K_{th}(R,T)$ relationship for this material, where R – load ratio; T – temperature, °C. According to regulatory documentation [5], $\Delta K_{th}(R,T)$ relationship looks as follows:

$$\Delta K_{th} = \Delta K^0_{th}(1 - 0,7R), \quad (1)$$

where $\Delta K^0_{th} = \Delta K_{th}$ at $R = 0$.

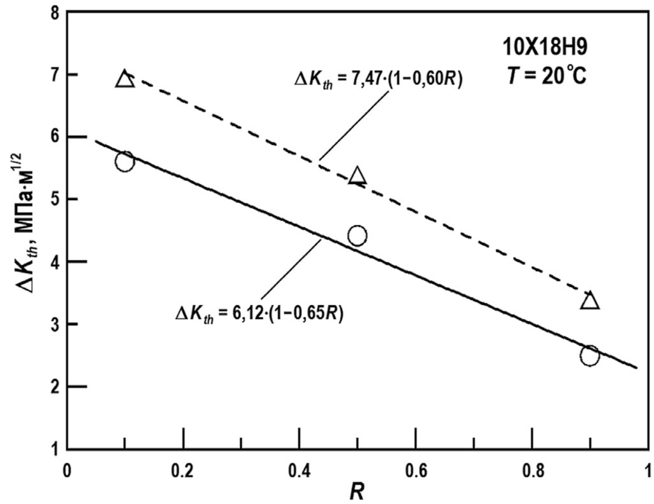
At $T \le 450\,°C$, $\Delta K^0_{th} = 6.5\,\text{MPa}\,\text{m}^{1/2}$; at $T > 450\,°C$ $\Delta K^0_{th} = 17 - 0.023T$, $\text{MPa}\,\text{m}^{1/2}$, where T – temperature, °C .

Relationship (1) was taken from the French standard RC-CMR [6] for austenitic chromium-nickel steels. The above standard does not state the state of steels (solution treated, aged, cold-worked) this relationship is valid for and what factual data it is based on.

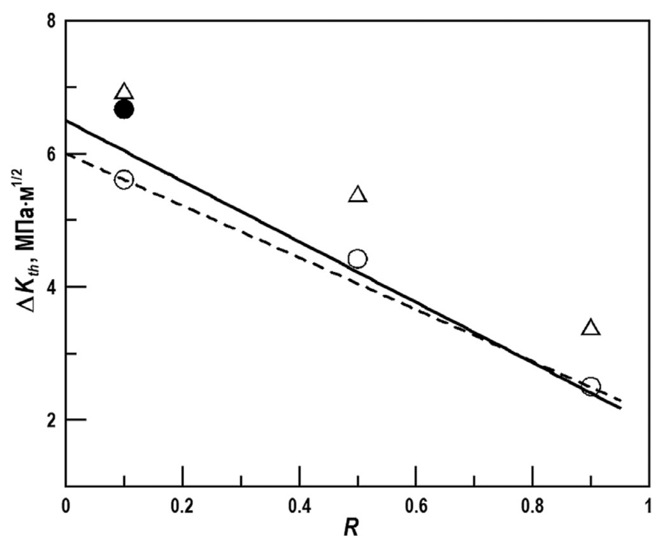
In view of the above the need arose to verify this relationship for 10X18M9 steel and to analyze the impact of aging on ΔK_{th}. The following studies were performed to this end.

10X18M9 steel from two structural elements was used as the subject for study:

- IHX upper tube sheet exposed to 550 °C in operation; and
- IHX protection block exposed to 520 °C in operation.



Picture 1. $\Delta K_{th}(R)$ relationship for 10X18H9 steel: o – tube sheet metal after service life; – protective shell metal; ––– relationship for the protective shell metal;; —— – relationship for the upper tube sheet metal.



Picture 2. Normative and adjusted $\Delta K_{th}(R)$ relationship for 10X18H9 steel: o – tube sheet metal after service life; – solution-treated tube sheet metal after service life; – protective shell metal; ––– adjusted normative curve; —— – normative curve according to [5].

Throughout the service life the structural element material was exposed to thermal aging. Part of the material under study was solution treated in order to find out the impact of thermal aging on DK_{th}. Thermal treatment removes all structural changes caused by aging thus allowing the material to be considered as the initial one. Testing followed resulting in ΔK_{th} values for aged and solution-treated metal at three load ratios. Results were assessed.

Picture 1 shows experimental data and their interpretation by linear relationship of $\Delta K_{th} = \Delta K^0_{th}(1 - kR)$ type built via least square method. Picture 2 shows the normative relationship for the same results according to [5] and also presents relationship adjusted for ageing of the material under study.

Results show that solution treatment of the tube sheet metal raises the threshold value for cyclical crack resistance to