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.

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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
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 $\Delta K_{th}$ (threshold stress intensity factor range) should be determined below which the fracture propagation stops. $\Delta K_{th}$ 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 fatigue 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:

$$\Delta K_{th} = \Delta K_{th}^0 (1 - 0, 7R),$$  \hspace{1cm} (1)

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

At $T \leq 450 ^\circ C$, $\Delta K_{th}^0 = 6.5 \text{MPa m}^{1/2}$; at $T > 450 ^\circ C$ $\Delta K_{th}^0 = 17.0237 \text{MPa m}^{1/2}$, 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 $\Delta K_{th}$. 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.

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 $\Delta K_{th}$. Thermal treatment removes all structural changes caused by aging thus allowing the material to be considered as the initial one. Testing followed resulting in $\Delta K_{th}$ 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 $\Delta K_{th} = \Delta K_{th}^0 (1 - kR)$ 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
\( \Delta K_{th} \) value obtained in protection block material testing thus indicating significant thermal ageing of the tube sheet metal. This might be due to higher temperature during tube sheet metal service life and presence of a substructure attributable to production technology.

Processing of data on the impact of \( R \) on \( K_{th} \) for the tube sheet metal demonstrates the linear character of \( K_{th}(R) \) relationship with the factor of \( k = 0.65 \) and 0.60 for the protection block metal.

Comparison of the data obtained with [5] shows that the computational relationship (1) for the aged tube sheet metal needs to be adjusted. In this case the lower envelope for the data should be used (see Picture 2), the equation for it looks as follows

\[
(\Delta K_{th})_{ ageing} = (\Delta K_{th}^0)_{ ageing}(1 - 0.65R),
\]

where \( (\Delta K_{th})_{ ageing} = 6 \text{MPa m}^{1/2} \) at \( T \leq 450 \degree C \).

Linear relationship \( DK_{th}^0(T) \) of the \( K_{th}^0(T) = 16.575 - 0.0235 \cdot T \) type, where \( T \) is in °C, is suggested to determine the threshold value of \( \Delta K_{th}^0 = \Delta K_{th}(R=0) \) at 450 < \( T \leq 650 \degree C \) for aged metal.

\( \Delta K_{th}(450 \degree C) = 6 \text{MPa m}^{1/2} \) and \( \Delta K_{th}(650 \degree C) = 1.3 \text{MPa m}^{1/2} \) values where used to build it as the lowest available data in literature for austenitic stainless steel.

Fractographic study of the surface of the specimens tested and cracks found in the tube sheet was performed to identify the failure mechanisms. Conclusion was made that failure mechanism for the cracks found in the tube sheet is identical to the one obtained from the specimens tested in the \( \Delta K_{th} \) threshold value range. In both cases the intergranular failure prevails typical for the material loading close to \( K_{th} \), thus attesting to the termination of further crack growth. The result makes it possible to speak about crack initiation and propagation in the IHX tube sheet in the high-cycle fatigue region at relatively low-level strain ranges and stress intensity factor ranges (SIF).

**Heat exchanger UTS temperature analysis under thermal pulsation**

Analysis of the crack network formation causes showed that these resulted from the thermal cycle stress caused by the “cold” coolant from the reactor vessel cooling system (temperature of 390°C) and “hot” primary circuit sodium (temperature of 546°C).

Crack formation and propagation is determined by the following parameters:

- temperature difference between the ‘hot” and “cold” coolants (thermal cycle range) equal to 156°C;
- heat transfer factor from sodium to shell calculated via known empirical relationships [7] and equal to 4000 W/m² °C; and
- temperature pulsation frequency.

The temperature condition of the heat exchanger was calculated in order to determine the kinetics of the stress–strain state in the UTS area in view of the thermal cycle stress.

![Picture 3. Results of the analysis of the temperature condition in the IHX UTS area obtained via ANSYS: 1–3—temperature pulsation range in the shell depending on thickness at frequencies of 0.1; 0.3 and 1 Hz, respectively.](image317x462to558x726)
temperatures in the coolant contact area was 56, 35 and 16 °C, respectively. The depth of temperature pulsations with frequencies of 0.1; 0.3 and 1 Hz was 12, 8 and 3 mm, respectively.

### Analysis of crack formation and propagation in the heat exchanger UTS

The following creep equation describes the properties of the UTS material in the course of long-term operation under \( T > 450 ^\circ \text{C} \):

\[
\sigma_{eq} = \left[ \left( \varepsilon_{eq}^c \right)^{1-m_c} / \left[ a_c \left( 1 - m_c \right) \tau \right] \right]^{1/m_c},
\]

where \( \sigma_{eq} \) – equivalent stress; \( \varepsilon_{eq}^c \) – equivalent creep strain in a moment of time.; \( \tau, a_c, n_c, m_c \) – creep constants of the material.

Strain–stress state calculation results corresponding to temperature distributions for the frequency of 0.1 Hz are shown in Picture 4 in the form of change of equivalent creep strain \( \varepsilon_{eq}^c \) and main strain \( \sigma_1 \) for the center of temperature pulsation area (with maximum equivalent stress \( \sigma_{eq} \)) per 1000 h of stress. As seen from the picture there is significant growth of equivalent creep strain and, correspondingly, sufficiently decrease in the tensile stress (from 280 to \( \sim \)100 MPa) with the transfer to saturation stage at more than 1000 h of operation. Tensile stress \( \sigma_1 \) relax quite quickly for frequencies of 0.3 and 1 Hz.

Cyclical and long-term static damage (potential for crack formation via fatigue and creep mechanisms) in the area of IHX temperature pulsations was assessed based on the results of the SSS analysis using normative fatigue and long-term durability curves from [5]. Table 1 shows evaluation of minimum possible time for crack formation in the UTS area of the IHX removed from BN600 reactor for various temperature pulsation conditions.

It should be noted that the actual number of cycles and, respectively, the time to fatigue-induced crack formation can be much higher than calculated as the normative fatigue curves have higher margin factors for strain range \( n_e = 2 \) and number of cycles \( n_N = 10 \) as compared to the averaged ones.

The following approximating relationship was used to specify the calculation of time to crack formation \( t_f \) due to creep

\[
t_f = \exp \left[ 5.039 \left( 7.4017 - \ln (\sigma_{eq}) \right) \right],
\]

where \( \sigma_{eq} \) – equivalent true stress at the time of failure due to creep (long-term durability).

Conservatively taking the maximum value of \( (\sigma_{eq}) \) \( = \sigma_{cr} = 85 \) MPa (for 0.1 Hz) for the whole stress period in the cycle of 1000 h of stress, for the period \( t = 170,000 \) h (26 years) we get the creep-induced damage \( D_t = t/t_f = 0.057 \), which is negligible. For temperature pulsation ranges corresponding to the frequency of 0.3 Hz creep-induced damage will be even lower.

Method of [5, 10] was used to calculate crack propagation in the IHX element. This method presents the growth of the postulated defect in view of stress conditions. The postulated defect is located in the element in such a way that the crack grows in a most speedy way under the action of the stress factors.

The following formula [5] was used to evaluate the cyclical crack growth rate:

\[
\begin{align*}
\frac{d a}{d N} &= C_f \left[ \frac{\Delta K}{(1 - R)^{0.25}} \right]^n_f, \quad \text{mm cycle} \quad \text{for} \quad \Delta K > \Delta K_{th}(R, T), \\
\frac{d l}{d N} &= 0, \quad \text{for} \quad \Delta K \leq \Delta K_{th}(R, T)
\end{align*}
\]

where \( a \) – crack length; \( N \) – number of stress cycles; \( \Delta K \) – stress intensity factor (SIF) range in a cycle; \( R \) – cycle load ratio; and \( C_f, n_f \) – material constants.

Calculations of the crack growth rate at cyclical load for all above temperature pulsation conditions have shown that the maximum crack growth rate takes place at its initial calculated depth of 2 mm. While the crack grows in depth its rate declines non-linearly due to \( \Delta K \) decline (\( R \) grows simultaneously). However, even at this growth rate decline the crack could have grown to through-thickness at high-cycle load of 26 years of operation.

The threshold SIF range \( \Delta K_{th} \) – serves as the crack growth limiting factor. Its decrease terminates the cyclical crack growth. Maximum crack depth can be calculated by the equation

\[
\Delta K = \Delta K_{th}(R),
\]

where \( \Delta K \) depends on the crack depth, its semi-axes balance and load level and type (o temperature pulsation frequency in this case).

Evaluation of the maximum crack depth for the temperature condition corresponding to the pulsation frequency of
0.1 Hz provide inflated results as compared to the actual size not exceeding 7 mm, 35–38.5 mm for the upper tube sheet and 14 mm for the outlet chamber shell.

Maximum calculated crack depth for the temperature condition corresponding to the to the pulsation frequency of 0.3 Hz is 10.5–11 mm for the upper area of the tube sheet and 6.5 mm for the outlet chamber shell. These figures are close to the actual maximum crack depth found in the IHX UTS temperature pulsation area thus making it possible to view the frequency of 0.3 Hz a conditionally effective frequency of temperature pulsations.

Nevertheless, for all temperature pulsation conditions and crack propagation cross-sections under consideration the leak-tightness condition is met for the upper tube-sheet (63 mm thickness) and IHX outlet chamber shell (39 mm thickness) that divide the primary and secondary coolant circuits.

Fractographic study of specimen fractures made of upper tube sheet metal of the 5IHX RU BN600 and tested for cyclerack resistance showed that intergranular failure correlated to SIF ranges of $\Delta K < 10 \text{ MPa m}^{1/2}$, that in turn corresponds to temperature pulsation ranges with the frequency of $\sim 0.3 \text{ Hz} \ (\Delta K = 7–8 \text{ MPa m}^{1/2})$. At $\Delta K \geq 10 \text{ MPa m}^{1/2}$ crack profile in the specimens corresponded mostly to shift processes that correlates with temperature pulsation ranges with the frequency of $\sim 0.1 \text{ Hz} \ (\Delta K = 13–15 \text{ MPa m}^{1/2})$.

Hence, taking into account certain $\Delta K_{th}$ values, the frequency of 0.3 Hz is in line with the actual crack depths developing according to intergranular mechanism up to the termination of their growth.

Conclusion

The computational and experimental studies of the mechanism of crack formation in the IHX UTS area of BN600 reactor have proved that the cracks were formed due to high-cycle fatigue while the impact of creep was virtually non-existent.

Numerical assessment of crack propagation at pulsation frequency of 0.3 Hz shows best agreement with the actual depth of cracks propagating in line with the intergranular mechanism up to their growth is terminated. Minimum time to crack formation was 5.6 years. At temperature ranges corresponding to higher pulsation frequencies crack formation has very low probability.

For all temperature pulsation conditions and crack propagation cross-sections the leak-tightness condition is met for the upper tube-sheet and IHX outlet chamber shell that divide the primary and secondary coolant circuits.

Hence the studies have proved that formation of cracks found in the UTS is caused by temperature pulsations and presence of these cracks does not limit the potential for service life extension to 45 years for the IHX in the BN600 reactor plant.

References