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Ageing assessment of RBMK-1500 fuel channel in case of delayed hydride cracking

G. Dundulis*, A. Grybenas, A. Klimasauskas***, V. Makarevicius****, R. Levinskas*******
**Lithuanian Energy Institute, 3 Breslaujos str., 44403 Kaunas, Lithuania, E-mail: gintas@mail.lei.lt*
***Lithuanian Energy Institute, 3 Breslaujos str., 44403 Kaunas, Lithuania, E-mail: agrybenas@mail.lei.lt*
****Lithuanian Energy Institute, 3 Breslaujos str., 44403 Kaunas, Lithuania, E-mail: arturas@mail.lei.lt*
*****Lithuanian Energy Institute, 3 Breslaujos str., 44403 Kaunas, Lithuania, E-mail: makarev@mail.lei.lt*
******Lithuanian Energy Institute, 3 Breslaujos str., 44403 Kaunas, Lithuania, E-mail: levin@mail.lei.lt*

1. Introduction

Ignalina NPP contains RBMK-1500 type reactors. RBMK reactors are graphite-moderated with a water-cooled reactor core. The fuel cell assembly is located in the centre of the moderator column and consists of a fuel channel into which the fuel element assembly is inserted and through which the coolant flows. Zirconium alloys are used as a constructional material for manufacturing both claddings of fuel assemblies and fuel channels (FC) [1]. Zirconium alloys can pick up hydrogen during operation as a consequence of corrosion reaction with water. Hydrogen redistributes easily at elevated temperatures migrating down the temperature or concentration gradient and up the stress gradient.

When the terminal solid solubility of hydrogen in zirconium alloy [2] is exceeded in a component such as pressure tube that is highly stressed for long periods of time, delayed hydride cracking (DHC) failures may occur. DHC is a phenomenon where a crack can propagate in stepwise fashion as a result of hydrogen redistribution ahead of the crack tip under stress level below the yield stress. The high mobility of hydrogen enables hydride to redistribute. If stress levels are sufficiently high the local hydrogen concentration can exceed the terminal solid solubility and the hydride platelets precipitate in the primary cracking direction.

The necessary conditions for DHC are the presence of the crack, a sufficiently high hydrogen concentration, tensile stresses and stress intensity factor (K_I) larger then the threshold value at the crack tip. The latter condition is called K_{IH}, - the threshold stress intensity factor in the presence of hydride, below which no crack growth occurs. At K_I values above K_{IH} the rate of cracking v, is essentially independent on K_I.

The ability to shut down the reactor before the pressure tube ruptures is the basis for leak before break (LBB). The information required to support LBB is knowledge of the length of the crack at leakage, critical crack length and the speed of DHC.

Tested RBMK zirconium tubes were manufactured using the heat treatment technology TMO-1.

The aim of this work was to estimate the FC capability to fulfil the LBB requirements for present and further time in case of possible DHC cracking.

2. Materials and methods of testing

Before machining the specimens, sections of the pressure tube were hydrided to produce the required hydrogen concentration using an electrolytic method and diffusion annealing treatment. Predetermined amounts of hydrogen ranging from 27 to 76 ppm were added to the unirradiated sections of the fuel channel tubes by electrolytically depositing a layer of hydride on the surface of the pressure tube material followed by dissolving hydride layer by diffusion annealing at elevated temperature [3].

From the hydrided pressure tube material curved compact toughness specimens were machined. Except for thickness and curvature of the tube, the in-plane dimensions of the specimens were in proportion described for compact the specimens in ASTM standard test method (E-399). Potential drop leads made of Zr-2.5Nb wire were attached to the crack mouth of the specimen by spot welding within 1 mm of either side of the crack mouth so as to average any irregularities of the crack front through the specimen thickness.

The CCT specimens have been fatigue precracked at room temperature to produce an initial crack length about 1.7 mm.

During DHC testing to monitor crack growth direct current potential drop technique has been used. DHC test has been completed after estimated crack growth of 1.5 mm.

DHC specimens were investigated using optical microscope (Olympus, MIC-11). Roughness height on the DHC surface was measured from the test specimen fracture surface.

3. DHC testing results and discussions

The DHC velocity is sensitive to the temperature history; the maximum value is attained by cooling from a temperature higher than the solvus temperature of hydrogen in the specimen. Thus, a standard procedure for measuring the cracking velocity was applied. Specimens were heated at 5ºC per min to a peak temperature, soaked for 1 h and cooled down at 1.5 C per min to the test temperature with a minimum 30ºC temperature drop without any under cooling. The hydrogen concentrations in the samples were chosen so that solubility limit at the test temperature was exceeded about 25 ppm. Peak and test temperatures for DHC velocity measurements are in Table 1.

To maintain heating and cooling at the given rates an electric furnace was equipped with programmable temperature controller. Temperature measurements were performed using thermocouple mounted on the specimen surface near the crack tip.

Table 1

DHC testing conditions

DHC test temperature, °C	283	250	144
Peak temperature, °C	335	315	275
Hydrogen concentration, ppm	76±3	54±3	27±3
DHC length, mm	1.2-1.5	1.3-1.9	1.5-1.6
K_I initial, MPa·m$^{1/2}$	15.7-17.3	14.5-16.5	15.1-15.8
K_I final, MPa·m$^{1/2}$	20-22.5	18.9-24.2	19.9-21.8
Number of specimens	6	6	3

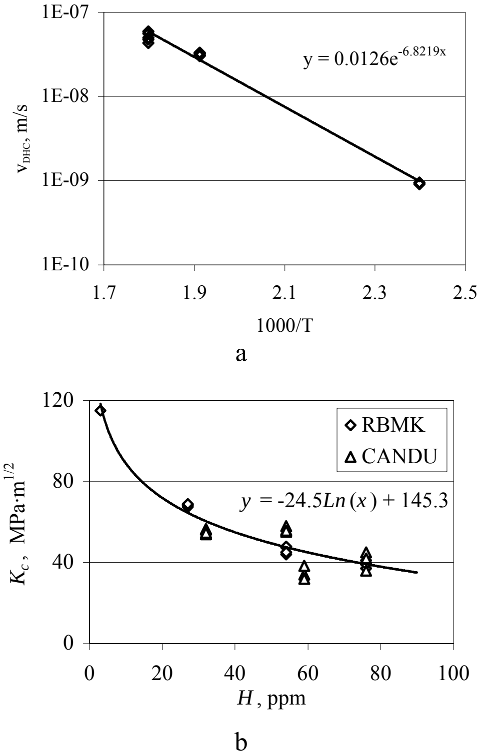


Fig. 1 DHC velocity as a function of temperature (a) and crack resistance at 20°C as a function of hydrogen concentration (b) for RBMK TMO-1 pressure tube material

After holding specimen at the test temperature for 35 min, a constant load was applied. DHC started after a short incubation time and was allowed to grow to an estimated crack length. After completion of DHC test actual crack length was measured from the fractographs. The DHC velocity was determined from the average DHC-length measured from the fracture surface photograph for one half of the fractured specimen using DHC-area method. The K_I was calculated using the following equation from ASTM E399

$$K_I = P_Q/(B \cdot W^{1/2}) \cdot f(a/W) \tag{1}$$

where P_Q is the applied load, N; B is the specimen thickness, m; W is the specimen width, m; a is the crack length, m; $f(a/W)$ is calculated using the equation

$$f(a/W) = (2+a/W) \cdot [0.886+4.64 \cdot (a/W)-13.32(a/W)^2+ +14.72 \cdot (a/W)^3-5.6 \cdot (a/W)^4]/(1-a/W)^{3/2} \tag{2}$$

The average v_{axl}, m/s, has been determined by dividing average DHC length l_D, mm, by DHC time t, min, as follows

$$v_{axl} = 10^{-3} l_D \cdot /(60t) \tag{3}$$

DHC velocity data as a function of 1000/T is plotted in Fig. 1, a, fracture toughness depending on hydrogen concentration is in Fig. 1, b.

To estimate more accurately leak through the postulated flaw, roughness height on the DHC surface was measured from the fractured test specimens.

4. Deterministic LBB analysis

The deterministic LBB analysis was performed according to the Guidance for the application of Leak Before Break concept at Ignalina NPP RBMK-1500 reactors VD-E-98-03 [4].

The basic requirement of the given document is that the flow of coolant through through-wall crack must be detected before the crack will reach critical sizes. According to [4] analysis is performed for the postulated through-wall crack, which parameters should meet the following requirements:

- length of the postulated defect should not exceed half of critical through-wall crack length;
- the leak through the postulated through-wall crack should 10 times exceed the leak, which can be detected by leakage monitoring systems in 1 hour of normal operation;
- the postulated crack should remain stable in case of load increment in 1.4 times;
- the response time of leak detection systems, including reactor shutdown, should be less than the time of crack propagation from initial (postulated) length up to the critical sizes; the influence of degradation and fatigue mechanisms should be taken into account.

4.1. Sensitivity of leak detection systems

The reactor channel integrity monitoring system is capable to detect less than 1 kg/h leak, but warning signals are activated and sent to the Gas Circuit Control Room and in the Main Control Room when the leak rate in reactor cavity increases up to 10 kg/h. According to the requirements of guidance [4], performing deterministic LBB analysis the safety factor equal to 10 on this value is used. It means that the calculated leak rate through the postulated crack should exceed 100 kg/h.

4.2. Tube dimensions and the loads

The minimal allowable wall thickness with the biggest possible diameter was taken for deterministic LBB analysis:

- minimal wall thickness of the tube – 3.6 mm;
- outside diameter of the tube – 90.0 mm.

Under normal operation conditions (NOC) the absolute static pressure in FC of maximal power at the entrance is equal to 7.81 MPa, at the exit – 7.08 MPa according to the results of analysis performed using thermohydraulic code RELAP5 [5] at reactor operation on a thermal power 4200 MW, when in operation there are three main circulation pumps with output 8000 m^3/h each on each side of the main circulation circuit (MCC) [6].

Under accident conditions (AC), the highest absolute pressure equal to 8.94 MPa is reached at loss heat sink accident at the reactor power 4200 MW and the main circulation pumps output 8000 m^3/h [6].

4.3. Material properties

In 2001 the company Studsvik Nuclear AB (Sweden) performed the determination of mechanical characteristic of Ignalina NPP Unit 1 fuel channel zirconium tube with heat treatment TMO-1 [7]. The tested fuel channel operation life was 17 years.

The hydrogen concentration for the tested pipes was at the level only few ppm that does not have influence on fracture toughness at high temperature when zirconium hydride is dissolved. The results of performed investigations show that hydrogen concentration has the influence on crack resistance at 20°C (see Fig. 1, b).

The main influence on reduction of fracture properties has the size of solid hydrides in the matrix of the base metal. At higher temperature the solid hydrides dissolve, i.e. become smaller and fracture toughness increases. It was conformed by performed investigations [8] for Canadian material Zr – 2.5% Nb. These data has a good agreement with the results presented in Fig. 1, b. The reduction of fracture resistance at higher temperature is associated with the change of main tensile material properties.

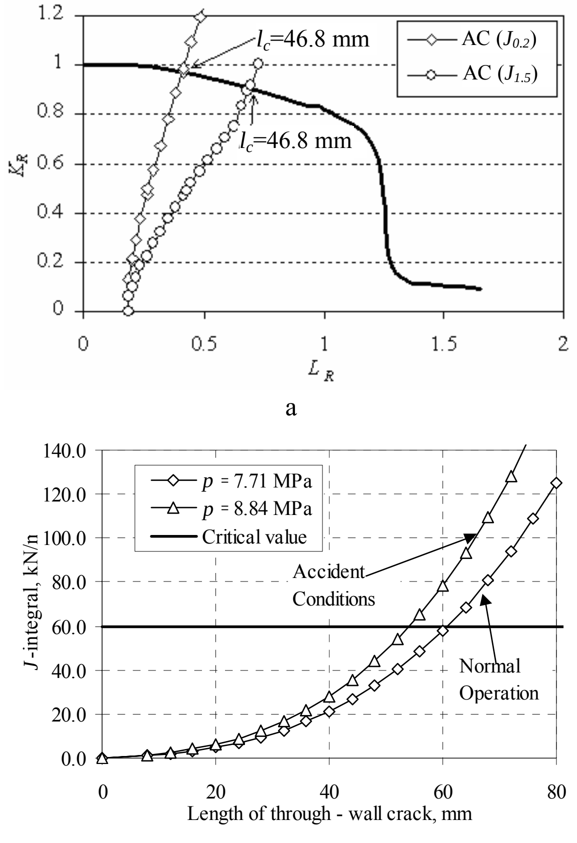
4.4. Determination of trough-wall crack critical length

The maximum hoop stresses in FC zirconium part are equal to 88.7 MPa at normal operation, 101.7 MPa at the most dangerous accident and 116.6 MPa at hydraulic testing conditions.

Critical length of through-wall crack was determined using the following two methods:

- method R6 Option 2 Category 1 using recalculated values of critical stress intensity factor [9];
- *J*-integral method using finite element method [10].

FC lower part was selected for the analysis, having the highest stresses and the lowest temperature, which results in the lower fracture resistance of material. The rupture parameters for FC are determined for NOC and AC. The calculation results are presented in Fig. 2. The results obtained using both methods are similar. However, the R6 method gives the more conservative results. Depending on the loading conditions, the critical crack length in FC is equal to 46.8 - 56.4 mm according to the method R6 (Fig. 2, a), and 54.0-61.0 mm according to *J*-integral method (Fig. 2, b). The performed sensitivity analysis has shown that in case of fracture toughness degradation of 1.5 times, critical length of the axial through-wall crack becomes shorter about 20%. Critical crack length becomes twice less than the length calculated in case if fracture toughness decreases more than 6 times. The results obtained using the R6 method give *K*-depended fracture in case of stable crack extension more up to 1.5 mm (Fig. 2, a).



a

b

Fig. 2 Critical crack size determination diagrams: R6 option 2 failure assessment diagram (a); *J*-integral versus length of through – wall crack under normal and accident conditions (b)

4.5. Modelling of crack opening function

The function of crack opening is one of the basic initial data for leak rate calculations. For modelling of the given function the elastic-plastic finite element analysis is performed. The function is modelled for the upper and lower parts of the FC using normal operation loading. The manometer pressure used in calculations is equal to 7.71 MPa. The result of analysis is presented in Fig. 3. In

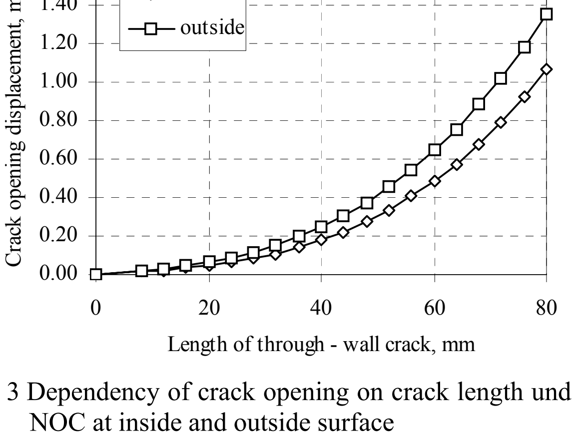


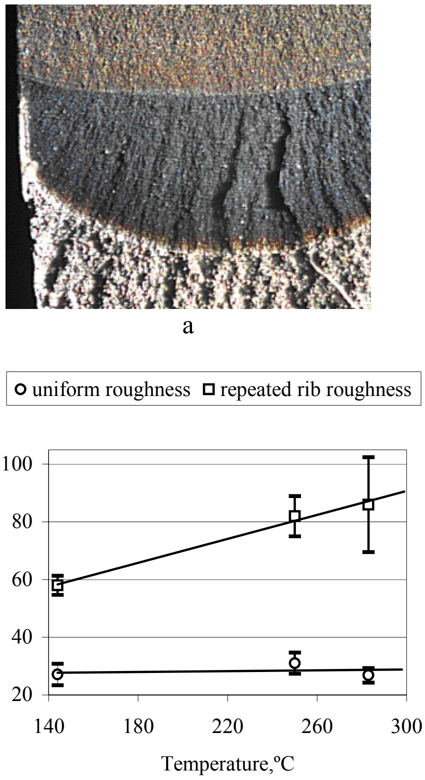
Fig. 3 Dependency of crack opening on crack length under NOC at inside and outside surface

this figure the maximum value of through-wall crack opening is presented. As it is seen from the results, crack opening on the outside is approximately 40% larger, than on inside. For critical crack length of 54 mm in FC lower part at NOC, the maximal crack opening becomes equal to about 0.37 mm on inside and about 0.50 mm on the outside surface.

4.6. Modelling of crack opening function

According to the requirements [4], determination of leak rate is performed for normal operation conditions. Absolute inside pressure equal to 7.81 MPa and outside pressure equal to 0.1 MPa under NOC were used in the calculations. It was assumed, that the coolant at the entrance to FC is under subcooled conditions: 263°C at absolute pressure of 7.81 MPa.

For more accurate assessment of the leak rate, irregularities of DHC fracture surface were measured. About 95% of all measured irregularities on DHC surface have uniform roughness height, which depends little on temperature. General view of such surface irregularities is shown in Fig. 4, a. The obtained measurement data show that with the increase of temperature several larger drops in height form on DHC surface. These ribs on the fracture surface are oriented along the crack growth direction. Maximum height of some individual ribs is 100 μm and more, average height at 283ºC is 86±16 μm (Fig 4, b). Average frequency of ribs with the height 55-110 μm in one specimen is 2-3. It was assumed in leak flow rate calculations through DHC split that a height of uniform roughness was 28 μm and repeated rib roughness with the frequency 3 in transverse direction was 90 μm.

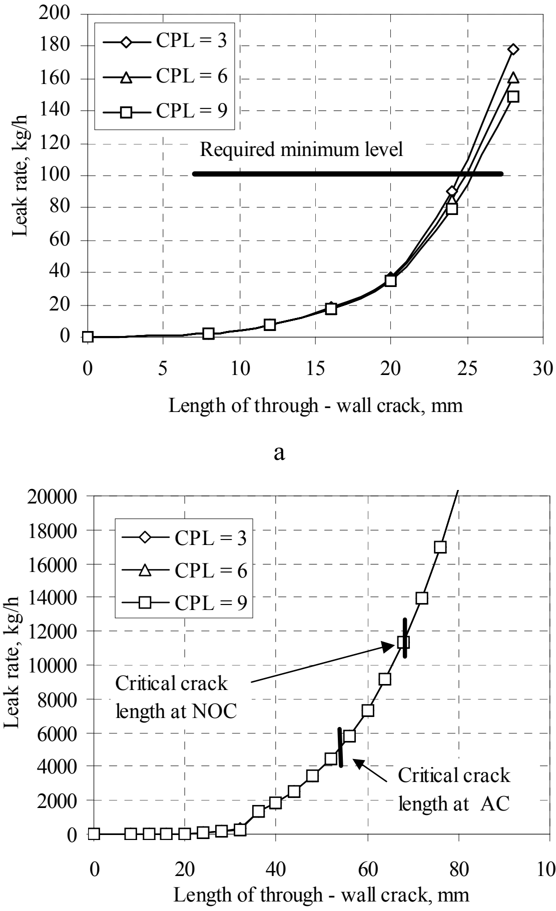


a

b

Fig. 4 DHC fracture surface, test temperature 283°C (a); average roughness height dependence on DHC testing temperature (b)

For leak rate calculations the computer program SQUIRT v.2.4 was used [11]. In calculations to construct a function of leak rate, the number of turns (CPL – Coefficient of Path Loss) equal to 3 for one rib was assumed. It was considered, that the crack opening is of elliptical shape, the wall thickness is equal to 3.6 mm, and discharge coefficient is equal to 0.95. The calculations are performed following the function of crack opening (see Fig. 3). Calculation results presented in Fig. 5, a show that the leak rate rapidly increases when the length of postulated crack exceeds approximately 15-20 mm. The leak rate equal to 100 kg/h is reached when the length of through-wall crack is about 24-25 mm. The CPL does not have substantial influence on the results at presented conditions.



a

b

Fig. 5 Dependency of leak rate on postulated crack length under NOC (a) and dependency of leak rate on critical through-wall crack length under NOC and AC (b)

When the length of through-wall crack reaches more than 35-40 mm, the change of two-phase flow to a single-phase flow occurs. It results the increase of leak rate. If the size of through-wall crack becomes close to the critical crack size, the leak rate will exceed 11 t/h for NOC and reach about 5 t/h for the most dangerous loading conditions (see Fig. 5, b).

4.7. Analysis of postulated crack growth and stability

In crack growth and stability analysis the postulated through-wall crack of the length equal to half of critical through-wall crack length, determined at the most dangerous loading, is evaluated. Such loading for FC is the loading at loss of heat sink accident. According to finite element analysis results, the length of the postulated crack for lower FC part is $l\_leak = l_c / 2 = 49.6 / 2 = 24.8$ mm, There *l_leak* is length of the postulated crack and l_c is critical length of the crack.

The crack growth rate was assumed equal to DHC rate in case of static loading. The crack growth rate v=3.37e-8 m/s at 263°C was used for analysis. This value was experimentally determined for zirconium alloy Zr - 2.5% Nb with heat treatment TMO-1.

The time t required to detect a leak and to shutdown the reactor in time is calculated according equation

$$t = (lc - l\_leak)/(7200V) \tag{4}$$

Thus this time t is 102.2 h or 4.26 day. According to the requirements [4], leak should be detected less than in 1 hour. During this time, the length of postulated crack can increase to 270 μm. As reported in [8] DHC velocities in irradiated pressure tube (fluence about $4.5 \cdot 10^{25}$ n/m) can be up to two times higher. But it does not have the major influence on the compliance to LBB requirements.

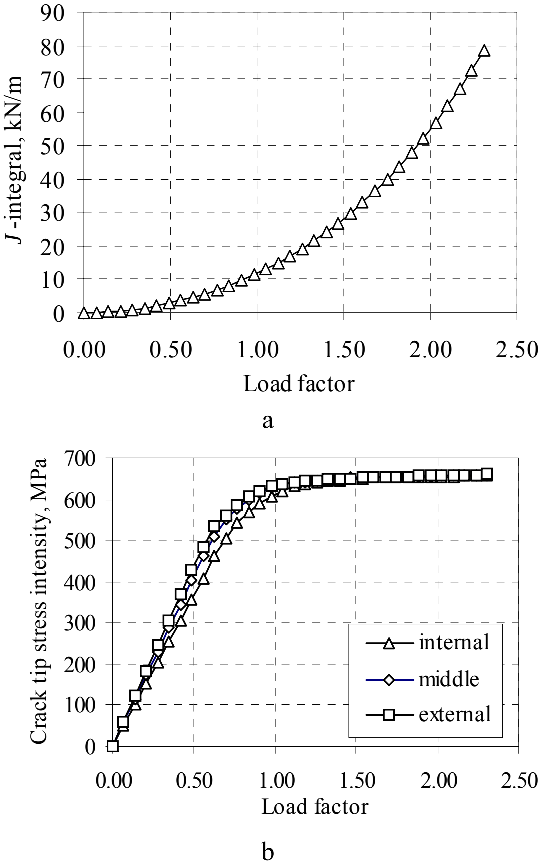


Fig. 6 Dependence of fracture parameters on load factor at *l_leak*: (a) *J*-integral versus Load factor; (b) crack tip stress intensity versus *J*-integral under accident conditions for inner, middle and external points

In Fig. 6, a the dependence of fracture parameters on load factor is presented. The presented results show, that if pressure increases 1.4 times (8.84·1.4=12.38 MPa), *J*-integral reaches 28.3 kN/m. It is almost 2.5 times less than critical value. The crack tip stress intensity is stable up to load factor 2.8 (Fig. 6, b). Thus, it is possible to conclude, that unstable growth of the crack of postulated sizes will not occur.

4.8. Compliance to LBB requirements

Performed deterministic LBB analysis confirmed, that the length of postulated crack, at which the necessary leak rate is reached, is less than half-length of the critical through-wall crack. Also it is confirmed, that the postulated crack remains stable at the most dangerous loading increase of 1.4 times with a safety factor of 2.5 on fracture toughness. The dependency of postulated through-wall crack length on material fracture toughness of is presented in Table 2.

The limiting factor for LBB requirements compliance can be the decrease of material fracture toughness due to the increase of hydrogen concentration. As presented in Fig. 7 the leakage crack size could significantly decrease in case when hydrogen concentration reaches more than 130 ppm. As shown in the Fig. 7 the leakage crack size is very close to the minimal acceptable leakage crack size. However it depends very strongly on leakage crack size safety factor *K_LBB* = 2.0 (*K_LBB* = *lc* / *l_leak*) which is conservatively assigned in regulations. When the *K_LBB* = 1.5 the limiting hydrogen concentration is about 200 ppm.

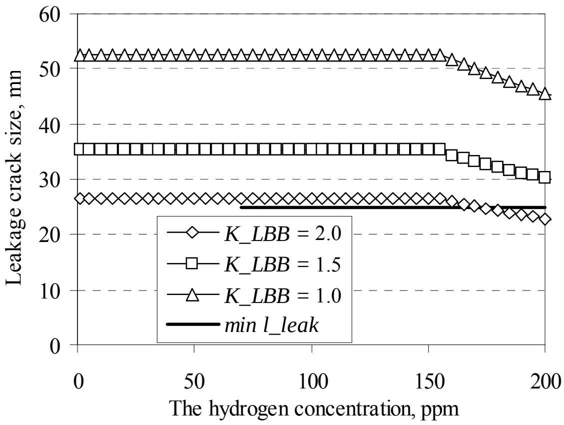


Fig. 7 Leakage crack size versus hydrogen concentration at different leakage crack size safety factors

Table 2

Dependency of postulated through-wall crack length on fracture toughness of material

l_leak (at 100 kg/h), mm	2 *l_leak*, mm	*J*-integral at 2·*l_leak*, kN/m	Critical *J*-integral, kN/m	Safety factor on fracture toughness, %
25	50	49	60	122.4

5. Conclusions

The performed deterministic LBB analysis confirmed, that the length of postulated crack, at which the necessary leak rate is reached, is less than half-length of critical through-wall crack. Also it is confirmed, that the postulated crack, remains stable at the most dangerous loading increase of 1.4 times with a safety factor of 2.5 on fracture toughness. The limiting factor for LBB requirements compliance can be the decrease of material fracture toughness 1.22 times which could be associated with hydrogen concentration more than 130 ppm.

Acknowledgments

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G. Dundulis, A. Grybėnas, A. Klimašauskas,
V. Makarevičius, R. Levinskas

RBMK-1500 KURO KANALŲ SENĖJIMO DĖL LĖTO HIDRIDINIO PLEIŠĖJIMO ĮVERTINIMAS

Reziumė

Straipsnyje pateikiamas RBMK-1500 kuro kanalų (TMO-1) senėjimo įvertinimas.

Vienas iš pagrindinių veiksnių, lemiančių kuro kanalų, pagamintų iš Zr-2.5%Nb lydinio, ilgaamžiškumą, yra korozijos metu ištirpusio vandenilio kiekis. Vandenilio koncentracijai viršijus tirpumo ribą, cirkonio lydinyje susidaro hidridai. Tam tikromis sąlygomis, tai sukelia lėtą hidridinį pleišėjimą (LHP) bei mažina šio lydinio atsparumą trapiajam irimui

LHP greitis TMO-1 kuro kanale nustatytas eksperimentiškai 283, 250 ir 144 °C temperatūrose, esant vandenilio koncentracijoms atitinkamai 76, 54 ir 27 ppm. Remiantis šiais duomenimis gauta LHP greičio temperatūrinė priklausomybė. Pagal ištirpusio vandenilio koncentraciją įvertintas cirkonio lydinio atsparumo trapiajam irimui pokytis, kurį gali sukelti hidridų susidarymas.

„Tekėjimo prieš suirimą“ analizė atlikta remiantis gautais tyrimų rezultatais, literatūroje esančiais duomenimis bei normatyvinių dokumentų RBMK-1500 tipo reaktoriams reikalavimais. *J*-integralas ir plyšio atsivėrimo dydis apskaičiuotas taikant baigtinių elementų metodiką. Kritinis plyšio dydis nustatytas naudojant R6 ir *J*-integralo metodikas. Šilumnešio ištekėjimo pro postuluotą plyšį greitis apskaičiuotas naudojant SQUIRT programą.

Eksperimentinių tyrimų ir deterministinės analizės rezultatai patvirtino, kad kuro kanalai (TMO-1) tenkina „tekėjimo prieš suirimą“ reikalavimus.

G. Dundulis, A. Grybenas, A. Klimasauskas,
V. Makarevicius, R. Levinskas

AGEING ASSESSMENT OF RBMK–1500 FUEL CHANNEL IN CASE OF DELAYED HYDRIDE CRACKING

Summary

This paper presents the ageing assessment of RBMK-1500 fuel channel TMO-1.

One of the factors determining remaining lifetime of Zr-2.5% Nb fuel channel (FC) is the amount of hydrogen dissolved during corrosion process. When the concentration of hydrogen exceeds the terminal solid solubility limit zirconium hydrides are precipitated. As a result decreases resistance to brittle fracture and form necessary conditions for delayed hydride cracking (DHC).

The experimental investigations were performed to estimate DHC rates in RBMK TMO-1 pressure tubes. During the tests in average DHC values were determined at 283, 250 and 144 °C (with hydrogen concentrations correspondingly 76, 54 and 27 ppm). Resistance to brittle fracture depending on hydrogen concentration was evaluated.

Leak before break analysis was carried out according to requirements of RBMK 1500 regulatory documents. *J*-integral and crack opening were calculated with finite element method. Critical crack length was calculated using R6 and *J*-integral methods. Coolant flow rate through the postulated crack was estimated using SQUIRT software.

The results of experimental investigations and deterministic analyses have confirmed that the fuel channels (TMO-1) fulfil the LBB requirements.

Г. Дундулис, А. Грибэнас, А. Климашаускас,
В. Макарявичюс, Р. Лявинскас

ОЦЕНКА СТАРЕНИЯ ТЕХНОЛОГИЧЕС-КИХ КАНАЛОВ РБМК-1500 В СЛУЧАЕ ЗАМЕДЛЕННОГО ГИДРИДНОГО РАСТРЕСКИВАНИЯ

Резюме

В статье представлена оценка старения технологических каналов РБМК-1500 ТМО-1.

Одним из основных факторов, влияющих на долговечность технологических каналов, изготовленных из сплава Zr-2.5% Nb, является водород, который в процессе коррозии растворяется в сплаве. Когда концентрация водорода превышает предел растворимости, формируются гидриды циркония. В определенных условиях это приводит к замедленному гидридному растрескиванию (ЗГР), а также снижает сопротивление сплава хрупкому разрушению.

Скорость ЗГР в технологических каналах определена экспериментально при температурах 283, 250 и 144 °C и концентрациях водорода 76, 54 и 27 ppm соответственно. На основе этих данных получена температурная зависимость ЗГР. Определено влияние гидридов на изменение сопротивления циркониевого сплава хрупкому разрушению в зависимости от концентрации растворенного водорода.

Анализ «течи перед разрушением» выполнен используя полученные результаты экспериментальных исследований, литературные данные и основываясь на требования регулирующего нормативного документа реактора РБМК-1500. Для определения *J*-интеграла и величины раскрытия трещины в топливных каналах использован метод конечных элементов. Критический размер трещин рассчитан с использованием метода *J*-интеграла и метода R6. Скорость расхода течи через постулированную трещину определена используя программу SQUIRT.

Результаты экспериментальных исследований и детерминистического анализа подтвердили, что технологических каналов ТМО-1 соответствует требованиям «течь перед разрушением».

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