Assessment of Gas Gap evaluation for the Ignalina NPP RBMK-1500

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Abstract: This paper presents core lifetime analysis of the Ignalina NPP Unit 1 RBMK-1500 reactor, which started to operate in 1983. The rate of closure of the approximately 1.5 mm gaps between the fuel channels (pressure tubes) and the graphite blocks is largely a function of accumulated fast neutron dose and graphite operating temperatures.

The previous statistical analysis based on linear regression contains many uncertainties, including lack of graphite brick hole diameters measurements, initial fuel channel tubes and bore-holes manufacturing tolerances, material property uncertainties for both graphite and the pressure tubes. The prediction accuracy problem was also raised by Safety Analysis Report of the Ignalina NPP completed in 1996.

The task of this paper was a development of strategy and methodology for gas-gap closure evaluation. The probabilistic model for the gas-gap evaluation was created. Performed detailed analysis of the pressure tube - graphite gas-gap closure in the Ignalina-1 RBMK-1500 reactor concluded that for choosing channels for inspection it is recommended to accept probabilistic approach strategy.

The graphite moderated brisk behavior was analyzed. Deterministic analysis of graphite changes show that linear trend is very conservative approach and can not be used for longer forecast. Mean change of graphite diameter behaves non linear but according to curves estimated using graphite behavior modeling code ABAQUS.

The gas gap closure forecast was performed for the year 2003. Probability that there will be no channels with zero gaps in reactor unit 1 until 2003 is not less than 0.98. The estimate probability of gas gap closure until 2003 is close to boundary probability. The sensitivity analysis was performed. The results show that the most contributing factor is data variance. It is recommended to improve gas gap closure evaluation methodology and perform calculations whether new direct graphite measurement will be necessary to perform in 2002.

Introduction

The RBMK reactor is designed to use a graphite moderator in the form of graphite bricks which surround Zirconium-Niobium channels (or "pressure tubes") containing the nuclear fuel and coolant. The pressure tube is initially positioned in place by a series of graphite rings that are alternately in contact with the inner bore hole of the graphite bricks and the outer perimeter of the pressure tubes. The initial design was to provide a nominal 2.5-3 mm gap between the pressure tubes and the rings, filled with 10% helium and 90 % nitrogen gas mixture.

It is well known that the initial gaps will contract as a result of radiation induced shrinkage of the graphite and outward creep of the pressure tubes. An in-service inspection program has been in place at Ignalina NPP, which is focused on monitoring the rate of gap exhaustion.

The gas gap closure problem at the Ignalina NPP-1 RBMK-1500 reactor was first identified by Safety Analysis Report in [1] and the following review RSR [2]. Further, the problem was studied by LEI [4, 6], AEAT, LAP [3] and other. LEI also developed graphite inspection strategy [5] in accordance with the conclusions of the workshop, held at VATESI office in early 1999 [7].

One common feature of the models developed by different teams until 1999 was that dimensional change model of the graphite bore inner and FC outer diameters were assumed to be linear. It is agreed that linear model is correct for the expansion of the FC tube diameter, but experimental data and known physical phenomena contradicts the linear graphite shrinkage model. This phenomenon was not accounted in any of the previously used models and caused wrong long-term future projections.

This report describes probabilistic model of the gas gap closure accounting for the non-linear graphite behavior. The model is used to estimate the gap closure probability and timing.

Technical description

A typical single fuel channel cell consists of a 7 meters high stack of graphite moderator bricks being located together by the cup and cone arrangements. There are steel bricks at the top and bottom of the column. At the base of the column the bricks are located on a spigot and the top of the column is located in line with a hole in the upper biological shield by means of a telescopic joint. The vertical joints between graphite moderator bricks are staggered in adjacent channels to avoid any horizontal planes of weakness. To prevent the oxidation of the graphite and to improve the thermal efficiency the core is contained in a 90% Helium 10% Nitrogen mixture.

The pressure tube is located in the moderator brick central hole by a system of graphite split rings. Each ring is alternately tight on the pressure tube or tight in the moderator bore as shown in Figure 1.

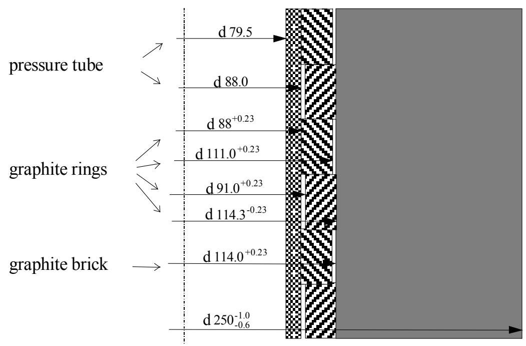

Figure. 1. Graphite and Zr-2.5%Nb pressure tube interaction zone.

The slots in these rings are aligned together to allow the He/N_2 mixture to pass along the channel. The fuel element which consists of an outer ring of 12 and an inner ring of 6 zirconium clad uranium dioxide fuel elements are contained within the pressure tube supported by a central tie bar.

The interaction of the fast neutrons leads to dimensional changes in the graphite and the pressure tube materials. For example, in the graphite-moderated reactors, initial accumulation of the fast neutron dose produces a gradual shrinkage of the graphite blocks. For the RBMK reactors this results in a decrease of the bore diameter through which the fuel channel passes. For the pressure tube made of a Zirconium and 2.5% Niobium alloy, the effect is opposite, due to thermal and irradiation effects the tube diameter increases. As a result, the gap between the pressure tube and the graphite, which has a nominal thickness of 1.5-mm, is gradually diminished leading to an eventual closure of the gap.

Previous analyses and comparison of results

The gas gap closure problem at the Ignalina NPP-1 RBMK-1500 reactor was first identified by Safety Analysis Report in [1] and the following review RSR [2]. Further, the problem was studied by LEI [4, 6], AEAT, LAP [3] and other. LEI also developed graphite inspection strategy [5] in accordance with the conclusions of the workshop, held at VATESI office in early 1999 [7].

It is included the forecast of first gap closure. As an outcome from these results joint group consisting from LAP, LEI and INPP [7] came into a mutual agreement and concluded that:

- With high confidence there will be no gas-gap closure until year 2000,
- For further gas-gap closure forecast it is needed to make extended control on graphite bore taking measurements during the next planned preventive maintenance.

Statistical analysis of the graphite bore and pressure tube outer diameters measurement data

Graphite bore diameter and pressure tube diameters are subject to continuous inspection and measurements. An in-service inspection program has been developed recently at the Ignalina NPP, which is focused on monitoring the rate of gap closure.

1. Measurement data

Quantity of all kind of measurements performed at the INPP-1 since the start of the operation is shown in Table 1.

Table 1. Type and quantity of graphite and pressure tube measurements

Year	Type and quantity of inspection					
	Pressure tube					Graphite
	Visual inspection	Ultrasound inspection	Inner PT diameter	Dimensional change	Pending	Inner diameter
	Initial inspection before start of operation					
1983	29	-	53	238	15	54
	Operational inspection					
Until 1997	147	80	186	64	21	16
1997	*	*	299	*	*	5
1998	*	*	550	*	*	48
1999	*	*	330	*	*	
2000			30			100

* - data is not available.

2. Data Analysis

In the next sections a new probabilistic approach to deal with the gap closure problem is presented. It is based on the actual gap data analysis. The main feature of the probabilistic gas-gap closure model is that it estimates the gap in each channel separately and investigates the gap in each graphite brick along the channel. The actual gap is calculated as the difference between the graphite blocks diameters and the pressure tube outer diameters at the same channel and the same axial position. This approach eliminates unnecessary conservatism, which arise from comparing extreme diameters.

Actual gap in the channel is illustrated in Figure 2. This figure shows the graphite block internal diameter and the pressure tube internal diameter plotted against the distance from the lower zirconium-steel adapter, for the channel 12-10, extracted during the measurements program in 1998.

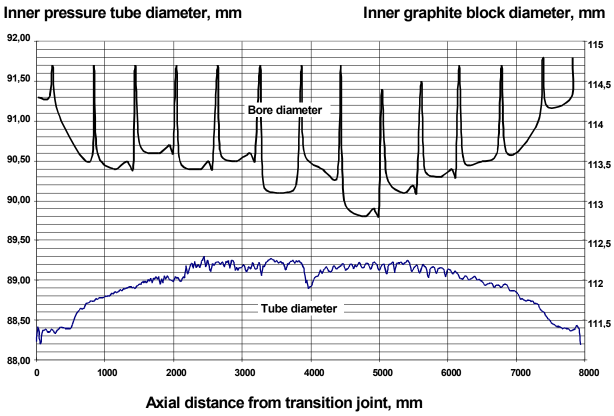

Figure. 2. Measurements of inner pressure tube diameter and graphite bore diameter in 12-10 channel, recorded in 1998.

3. Correlation analysis

A number of correlation calculations were performed in order to investigate possible dependencies of the gas gap to extraction forces, burn-up and other parameters. The results are summarized in Table 2.

Table 2. Analysis of the gas gap correlation.

Correlation type	Correlation coefficient
PT Diameter– extraction force	-0.28
Gap – extraction force	-0.30
Graphite Diameter – Gap	0.88
Graphite Diameter – burn-up	-0.13
Graphite Diameter – Diameter PT	-0.01
PT Diameter – Gap	-0.49
Burn-up – Gap	-0.24

The correlation analysis confirmed high dependence of the remaining gas gap and graphite bore diameter and pressure tube (PT) diameter, but no other dependencies were identified.

Probabilistic gas gap closure model

1. Model assumptions and uncertainties

Based on the experience of all teams participated in the investigation of the gas gap problem LEI developed the probabilistic gap closure model to estimate the remaining gap and closure time.

The main feature of the probabilistic gas gap closure model is that it estimates the gap in each channel separately and investigates the gap in each graphite brick along the channel. The probabilistic gas gap closure model is based on the following assumptions:

- The model accounts for the gas gap in each single graphite block of the graphite brick. Eight middle blocks were used for the calculations, as the rest 6 has quite small burn-up.
- Diameters of the graphite and PT are distributed normally. Graphite mean values are obtained from the deterministic calculations and variation is calculated from the statistics. PT diameter mean value is obtained from the linear trend line and variation is calculated from the statistics. Statistical data compliance with normal distribution was verified using χ^2 criterion. Data compliance with normal distribution hypothesis was accepted with high confidence.
- Gap closure criteria in the channel is gap closure in at least one graphite brick.
- Probability of the gap closure is calculated for each channel.
- For future projections non-linear graphite model is used, calculated by ABAQUS code.

The model is affected by the following sources of uncertainty:

- Measurement errors are 0.01-0.1 mm
- Initial values of PT outer diameter and graphite bore diameters have considerable manufacturing margins: 0.8 mm for PT and 0.23 mm for the graphite.

2. Gap closure probabilistic model

Probability of the gap closure in a single graphite brick is calculated by

$$P_i = 1 - \int_{-\infty}^{Zr_i} \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{(t-G(x))^2}{2 \cdot \sigma^2}} dt \qquad (1)$$

Zr_i	- maximal outer PT diameter of the graphite brick
G(x)	- graphite shrinkage trend function (non-linear, calculated by the ABAQUS code)
σ	- standard deviation of the graphite brick non-linear trend function. The average standard deviation value 0.149 was used for all the bricks.

$$\sigma = \sqrt{\frac{n \cdot \sum (d_i - G(x_i))^2 - \left(\sum (d_i - G(x_i))\right)^2}{n \cdot (n-1)}} \qquad (2)$$

x	- burn-up of the bricks
d_i	- graphite bore diameter measurement
n	- number of graphite bricks in the reactor

The model is illustrated in Figure 3. The gap closure probability is an area below interception of two normal distributions of graphite and PT diameters.

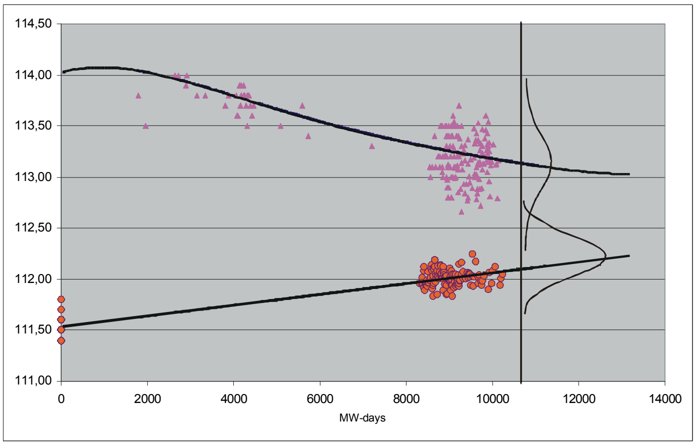

Figure. 3. Illustration of the gas gap closure probabilistic model.

Probability of the gap closure in one channel is calculated by

$$P_{TK} = 1 - \prod_{i=4}^{11} (1 - P_i)\,, \qquad (3)$$

P_i - probability of gap closure in i graphite brick

Probability of the gap closure in at least one channel in the reactor is calculated by

$$P = 1 - \prod (1 - P_{TK_j}) \qquad (4)$$

P_{TK_j} - probability of gap closure in j channel

3. Strategy criteria for choosing channels

Taking into account that the number of the graphite bore measurements is strictly limited, it is necessary to choose them correctly. It may be thought that the main criteria might be the accumulated burn-up. Although, correlation analysis shows that diameter dependency upon the accumulated burn-up is very weak [5].

Taking into account that the gas-gap closure was estimated using the probabilistic approach it is natural to put the criterion of the gap closure probability into the first place for choosing channels to measure graphite bores.

The proposed strategy has significant advantage comparing with others (minimum gas-gap, highest accumulated burn-up, etc.) - using such a strategy ensures minimum probability of gas-gap closure in at least one channel in the reactor because channels to be inspected were chosen having the highest probability. When it was used pressure tube diameter change, mean statistical change of graphite block diameters, standard deviation of these data, then probabilistic approach is generalized sum-up characteristic.

This fact is the basis of strategy evaluation methodology. If there is used other mathematical model for gas-gap closure evaluation this methodology stays applicable.

Results

The main task of this paper was development of strategy and methodology for gas-gap closure evaluation. The probabilistic model for the gas-gap evaluation was created. Performed detailed analysis of the pressure tube - graphite gas-gap closure in the Ignalina-1 RBMK-1500 reactor concluded that for choosing channels for inspection it is recommended to accept probabilistic approach strategy.

Gas gap closure probability was projected for the period of two years – until the middle of 2003. Calculations were performed for each fuel cell individually and then transformed in to the total gap closure probability. Results of the probability estimation in the individual cells are shown in Figure 4.

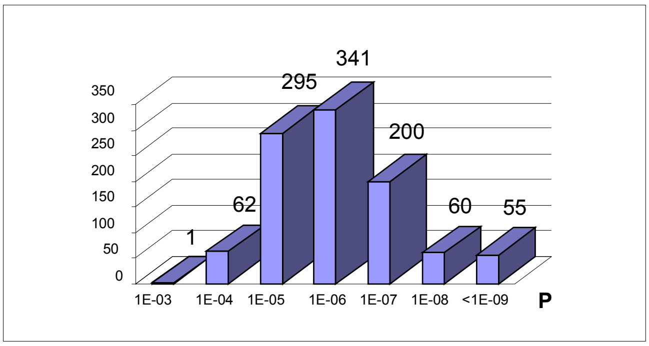

Figure. 4. Frequency diagram of the gap closure probability in individual cells until 2003.

The total gap closure probability calculations are shown in Table 3. Calculations included sensitivity study of the most important model parameters – variance of graphite and PT diameters. The results indicated that graphite variance is the most sensitive parameter in the model.

It is clear that operation of the reactor can be justified for the next period until 2003, as the gap non-closure probability is 0.98. The recently approved success criteria for gas gap non-closure probability is 0.95.

Table 3. Total gas gap non-closure probability until middle 2003 and sensitivity study results of the most important model parameters – variance of graphite and PT diameters.

$\sigma_{Gr}+10\%$	$\sigma_{Gr}+5\%$	σ_{PT} . σ_{Gr}	$\sigma_{Gr}-5\%$	$\sigma_{Gr}-10\%$
0.95	0.97		0.99	0.998
		0.98		
$\sigma_{PT}+50\%$	$\sigma_{PT}+20\%$		$\sigma_{PT}-20\%$	$\sigma_{PT}-50\%$
0.96	0.97		0.98	0.99

Conclusions

The results of the gas gap closure probabilistic modeling indicate that the gap non-closure probability is 0.98. The recently approved success criteria for gas gap non-closure probability is 0.95. Therefore operation of the reactor can be justified for the period until 2003.

In-depth probabilistic and engineering analysis of the gas gap closure is needed after graphite measurements are performed in the middle of 2003.

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