PROBABILISTIC ASSESSMENT OF FUEL CHANNEL BEARING TRAVEL AND END OF BEARING TIME

Fernando Camacho[1], Rex Lam[2], Jason Goldberg[3], Larry Micuda[3], David Cho[3]
[1] DAMOS Inc., Toronto, Ontario, Canada
[2] AMEC NSS, Toronto, Ontario, Canada
[3] Bruce Power Inc., Tiverton, Ontario, Canada

Abstract

Operators in Ontario have been assessing fuel channel elongation in nuclear generating units to ensure fuel channels remain on bearing at least until the next inspection in accordance with CSA N285.4. These assessments have so far been performed deterministically and, among other conservative assumptions, use the worst stack-up of tolerances for all relevant fuel channel components to calculate the end-of-bearing (EOB) times. Since the probability of having the worst stack-up of tolerances occurring is extremely small, a deterministic assessment provides a very conservative representation of the unit condition. The probabilistic assessment presented in this paper provides a more realistic representation of elongation and channel end-of-bearing times.

For a given reactor, the probabilistic assessment used Monte Carlo techniques to generate values for fuel channel component dimensions, current fuel channel elongations, future elongations and elongation measurement errors from specified distributions. The simulated values are then used to obtain a distribution of EOB times at each lattice position in the reactor. The expected number of fuel channels reaching EOB in a given operating interval can then be compared to pre-established acceptance criteria to determine if the operating interval is acceptable.

The methodology is illustrated with an example reactor. The results from 100,000 simulations at each lattice position show that the EOB times calculated in the deterministic assessment corresponded to a very low percentile of the EOB times calculated in the probabilistic assessment. This indicated that the deterministic assessment was very conservative. For the example reactor, no elongation maintenance would be necessary for approximately one year (8,000 effective full power hours) after the latest outage.

1.0 Introduction

In accordance with CSA N285.4-94 [1], the operator for an example reactor has been assessing fuel channel elongation to ensure fuel channels remain on bearing at least until the next inspection. These assessments have so far been performed deterministically and, among other conservative assumptions, use the worst stack-up of tolerances for all relevant fuel channel components to calculate the end-of-bearing (EOB) times. Since the probability of having the worst stack-up of tolerances occurring is extremely small, the deterministic assessment provides a highly conservative representation of the unit condition.

In this paper, a conservative probabilistic assessment of fuel channel elongation is provided for the example reactor. The probabilistic assessment utilises distributions for the relevant parameters in order to provide a more realistic representation of the channel configuration.

2.0 Methodology

In the probabilistic assessment of fuel channel elongation, an approach based on Monte-Carlo simulation of every channel in the example reactor core was used. The assessment methodology was very similar to the deterministic assessment, except for the use of distributed parameters. The expected number of fuel channels going off bearing per year was calculated in the probabilistic assessment. Fuel channel component positions and dimensions were simulated to obtain a distribution of available bearing travel (ABT) for the fuel channel at each lattice position. A distribution of end-of-bearing (EOB) times was then calculated using simulated fuel channel elongations and the ABT distributions at each lattice position. Based on the distributions of EOB times for all lattice positions, the annual EOB frequency, i.e., number of channels reaching EOB per 8,000 equivalent full power hours (EFPH) was calculated.

2.1 Acceptance Criterion

The allowable failure frequencies for different reactor core types with various numbers of known in-service degradation mechanisms were provided in Annex C of CSA N285.8 [2]. Since the example reactor was considered to be a Type II core, the total allowable failure frequency was 0.033 events per year. One half of the allowable frequency was held in reserve for unknown degradation mechanisms. The allowable frequencies for each known degradation mechanism for different numbers of known degradation mechanisms could be found in Table 1.

As specified in CSA N285.8, probabilistic assessments must address all degradation mechanisms. A probabilistic assessment of delayed hydride cracking (DHC) initiation and leak-before-break (LBB) for the example reactor identified two degradation mechanisms: debris fretting flaws and bearing pad fretting flaws. For the probabilistic assessment of fuel channel elongation, off-bearing operation was considered to be the third degradation mechanism. It was very conservatively assumed that a fuel channel going off bearing would immediately result in a pressure tube rupture. Thus, from Table 1, the allowable failure frequency per mechanism per year was 0.00550 for 3 known degradation mechanisms. Therefore, the allowable frequency for fuel channels going off bearing was 0.00550 per year for the entire core.

Another possible interpretation of the criterion in CSA N285.8 was that pressure tube rupture was the only degradation mechanism, as opposed to the different causes of pressure tube rupture each being a degradation mechanism. Therefore, the maximum allowable combined frequency of rupture from debris fretting flaws, bearing pad fretting flaws and off-bearing operation together would be 0.0165 events per year.

This paper assumed that the first interpretation of the criterion (0.00550 events per year) applied because of the frequencies of rupture due to debris fretting flaws and bearing pad fretting flaws were not available.

2.2 Types of Distributions Used

In the simulations, three types of distributions were utilised depending on the quantity being sampled. These were the uniform, normal and Student's *t*-distributions.

2.2.1 Normal Distribution

The normal distribution was used for all quantities that included measurement errors (e.g., raw elongation measurements). In those quantities, the extent of measurement error was based on engineering judgment and operating experience. The probability density function for the normal distribution with mean zero and standard deviation of 1 could be found in Figure 1. Its shape was commonly known as the "bell curve".

2.2.2 Uniform Distribution

In the absence of manufacturing and installation data, the uniform distribution was used for quantities where design values and tolerances were available (e.g., dimensions). Most manufacturing and installation processes produced normally distributed outputs, but assuming a uniform distribution would create larger variations in the sampled quantities. An example probability density (pdf) function for the uniform distribution could be found in Figure 2. Note that the pdf for the uniform distribution was larger than the normal distribution at the tails of the distribution. As such, using the uniform distribution was conservative.

2.2.3 Student's *t*-Distribution

The scaled and shifted Student's *t*-distribution was used to simulate quantities modelled by linear regression. This distribution was used when model parameters were estimated from a limited number of data points (e.g. fuel channel elongation models). The distribution was similar in shape to that of the normal distribution and was dependent on the degrees of freedom (dof), which was a function of the sample size used to estimate the model parameters. The Student's *t*-distribution would become narrower around the mean as dof increased and approached the normal distribution as $dof \to \infty$. The pdf for the Student's *t*-distribution for various dof could be found in Figure 3.

2.3 Temperature and Pressure Expansion Allowances

The temperature and pressure expansion allowances in the ABT calculations were assumed to be constants. Since they were calculated assuming the most punishing circumstances (e.g., the fuel channel was assumed hot while all other components were assumed cold), they were conservative.

3.0 Results and Discussion

The results presented in this section were from 100,000 simulations at each lattice position in the example reactor.

3.1 Simulated Bearing and Journal Gaps

In the deterministic assessment, the gap between the end fitting and journal ring and between the lattice tube and bearing were assumed to be zero. In the probabilistic assessment, these gaps were randomly sampled using the uniform distribution from the maximum available gap calculated from other sampled reactor component dimensions. The location of these gaps could be found in Figure 4.

The histograms of the simulated journal gap and bearing gap could be found in Figure 5 and Figure 6, respectively. For the journal and bearing gaps, the distribution at the smaller gap values approached uniform while at the larger gap values, the distribution tailed off similar to that of the normal distribution. This was expected because obtaining large gap values required both a large maximum available gap as well as a large sampled gap.

The histogram of the combined journal and bearing gap could be found in Figure 7. The combined gaps added an average of 0.52 mm to the ABT.

3.2 Deterministic and Simulated Available Bearing Travel Comparison

The histogram of the simulated available bearing travel at the last inspection for a fuel channel in the example reactor could be found in Figure 8. The deterministic ABT was also marked in the figure for comparison. The results showed that the ABT calculated in the deterministic assessment corresponded to a very low percentile of the ABT calculated in the probabilistic assessment.

3.3 Deterministic and Simulated End-of-Bearing Times Comparison

Since the deterministic ABT was shown to be a very low percentile of the ABT calculated in the probabilistic assessment, the same pattern could be expected when comparing the EOB times. The results in Figure 9 for the same example fuel channel showed that this was indeed the case. The results from Section 3.2 and Section 3.3 confirmed that the deterministic assessment was more conservative than the probabilistic assessment.

3.4 End-of-Bearing Frequency

The mean and 97.5 percentile bound on the expected number of fuel channels in the example reactor reaching EOB at 8,000 EFPH (yearly) increments from the last outage could be found in Table 2. Comparing the results to the acceptance criterion of 0.00550 occurances/year, the results in Table 2 showed that no elongation maintenance would be necessary for the example reactor until approximately one year (8,000 EFPH) after the last outage.

4.0 Conclusions

A probabilistic elongation assessment was carried out using the methodology described in this paper. The estimated mean and 97.5 percentile bounds on the expected EOB frequency were based on the results from 100,000 simulations at each lattice position in an example reactor. The results from the deterministic calculation of EOB, which used the worst stack-up of tolerances, corresponded to very low percentiles of the probabilistic calculation of EOB, which was a more realistic representation of the condition in the example reactor. This demonstrated that the deterministic assessment was more conservative than the probabilistic assessment.

The results also showed that for the example reactor, no elongation maintenance is necessary for one year (8,000 EFPH) beyond the latest outage.

5.0 References

1 Canadian Standards Association, "Periodic Inspection of CANDU Nuclear Power Plant Components", CSA Standard N285.4-94, December 1994.

2 Canadian Standards Association, "Technical Requirements for In-Service Evaluation of Zirconium Alloy Pressure Tubes in CANDU Reactors", CSA Standard N285.8-05, June 2005.

Table 1: Allowable failure frequencies for a type II reactor core with various number of known in-service degradation mechanisms.

Allowable Pressure Tube Failure Frequency per Mechanism per Year	Number of Known In-Service Pressure Tube Degradation Mechanisms, g					
	g = 0	g = 1	g = 2	g = 3	g = 4	g = 5
	0.03300	0.01650	0.00825	0.00550	0.00413	0.00330

Table 2: Mean and 97.5 percentile bound of the expected number of fuel channels reaching EOB for the given operating intervals

t_1 (Years after last outage)	t_2 (Years after last outage)	Mean	97.5 Percentile Bound
0	1	1.2876E-04	1.9909E-04
1	2	5.0378E+00	5.0484E+00
2	3	6.8927E+01	6.8956E+01

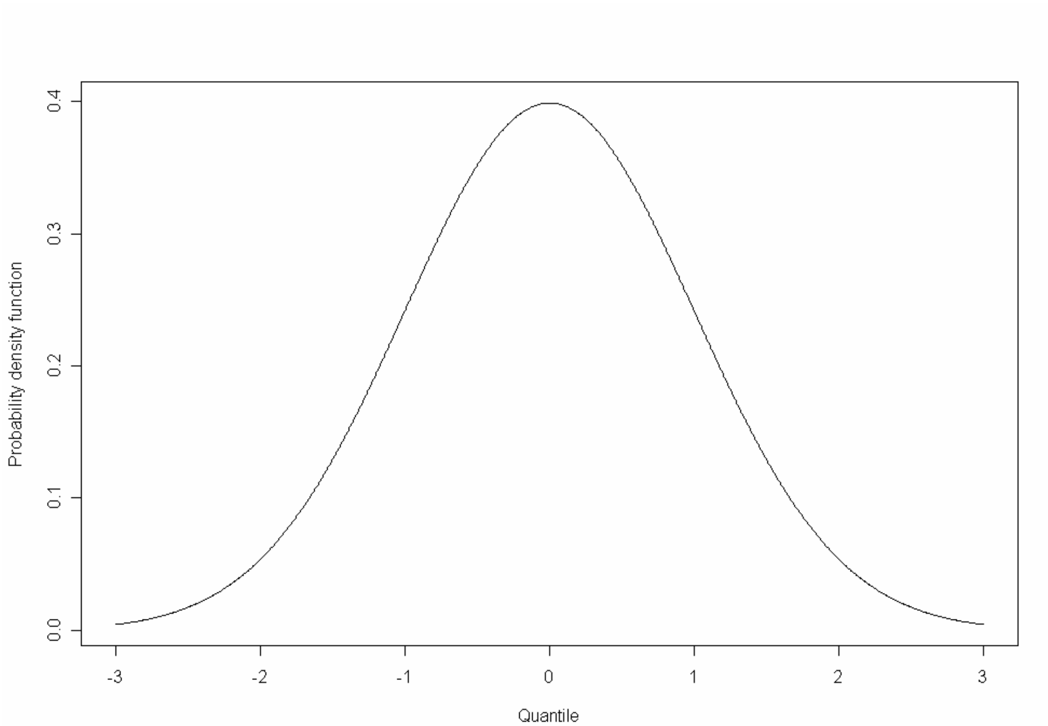

Figure 1: Example probability density function for the normal distribution with mean (μ) zero and standard deviation (σ) equal to 1.

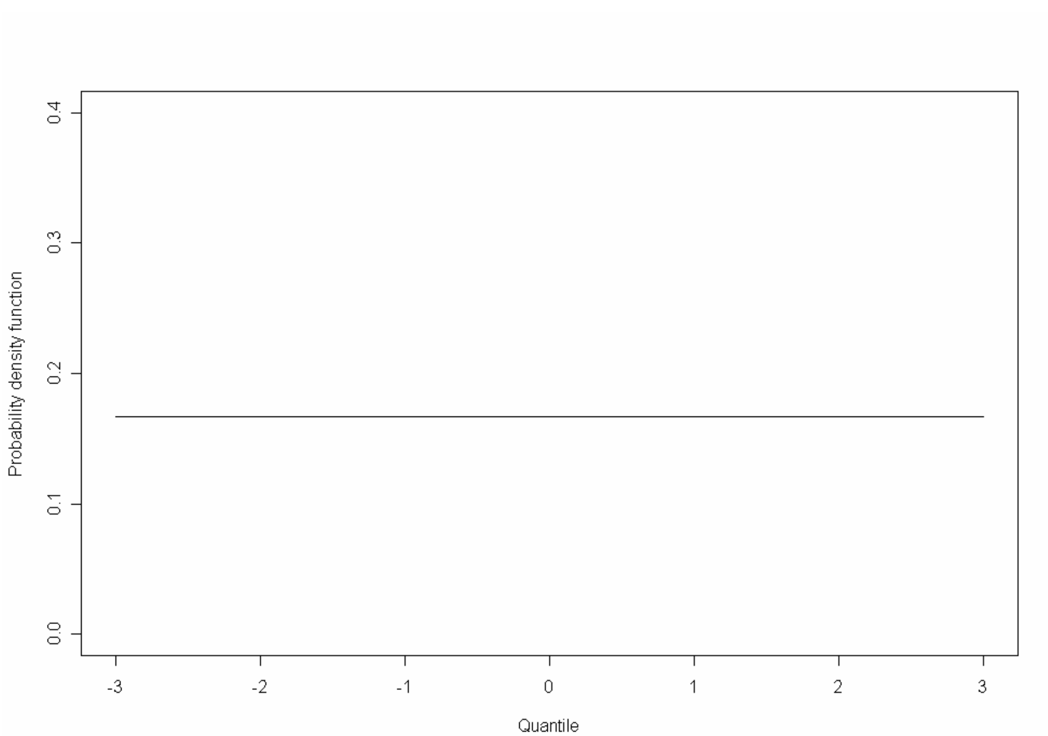

Figure 2: Example probability density function for the uniform distribution with lower and upper limits at -3 and +3, respectively.

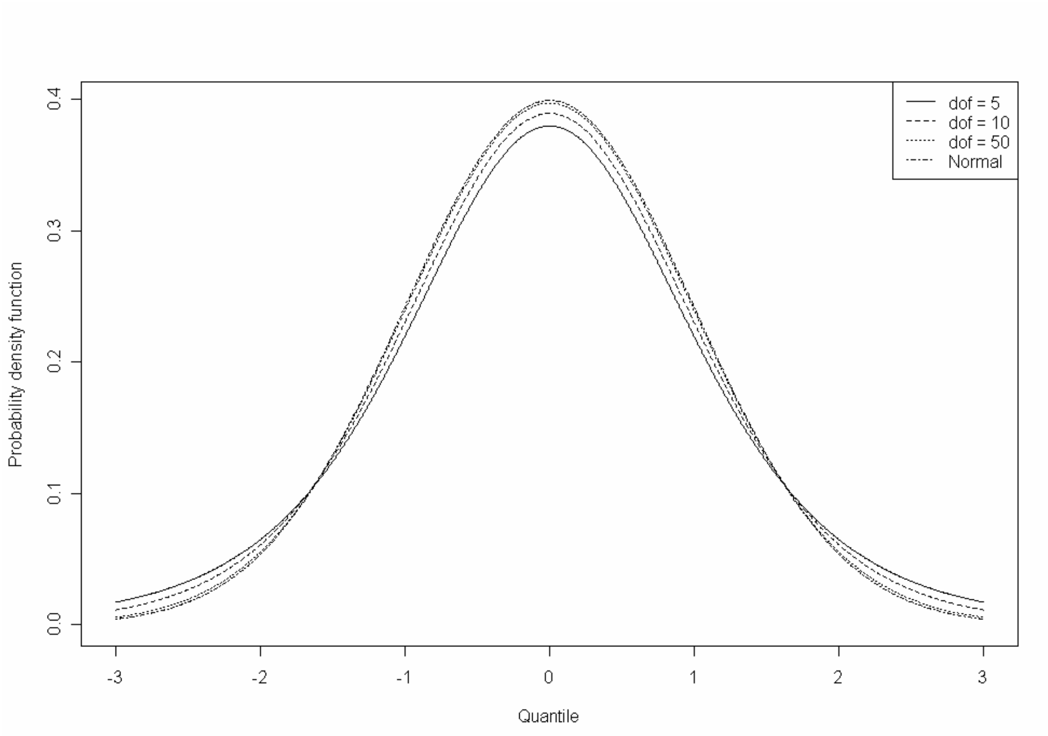

Figure 3: Probability density function for the Student's *t*-distribution for various degrees of freedom (dof). Not that as $dof \to \infty$, the distribution approached the normal distribution.

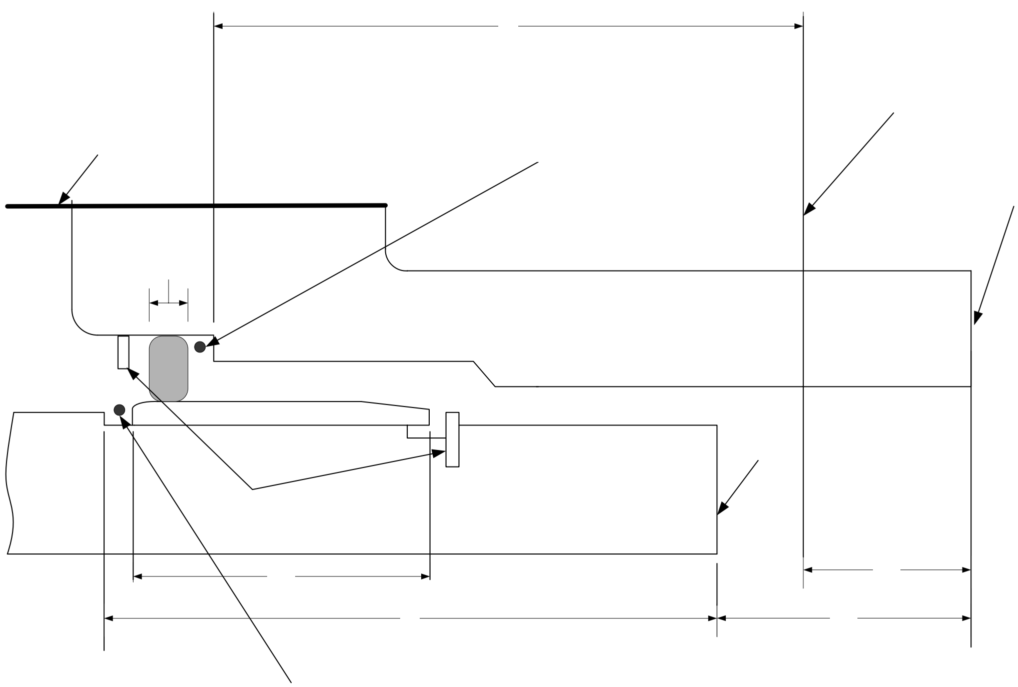

Figure 4: Schematic showing some of the dimensions used to calculate ABT.

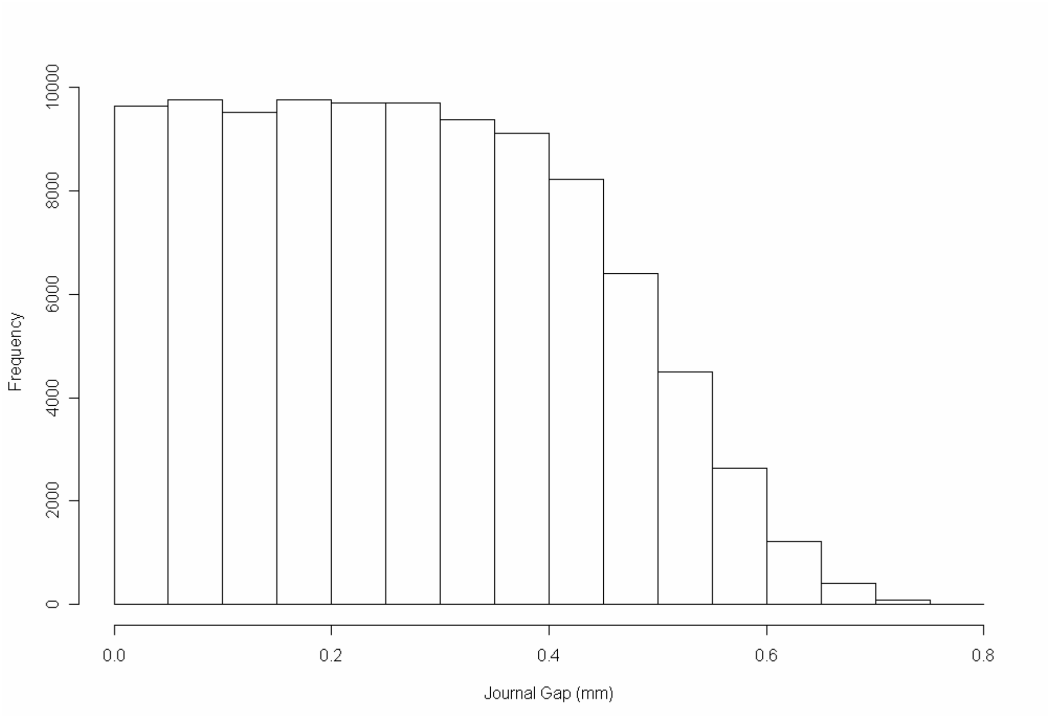

Figure 5: Histogram of the simulated journal gap.

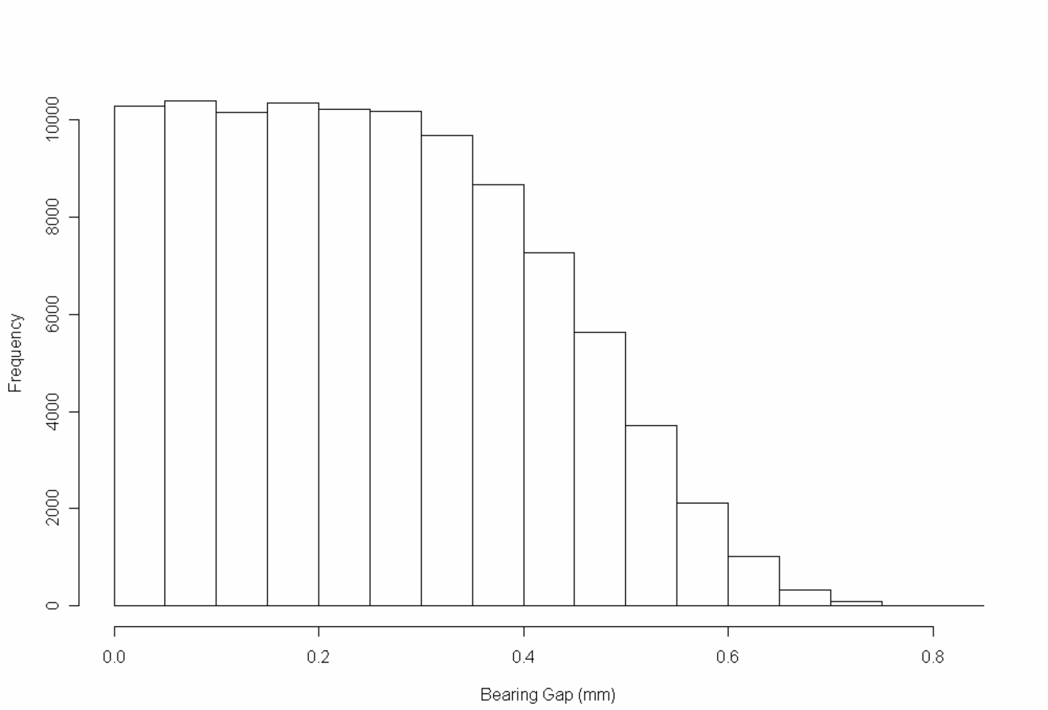

Figure 6: Histogram of the simulated bearing gap.

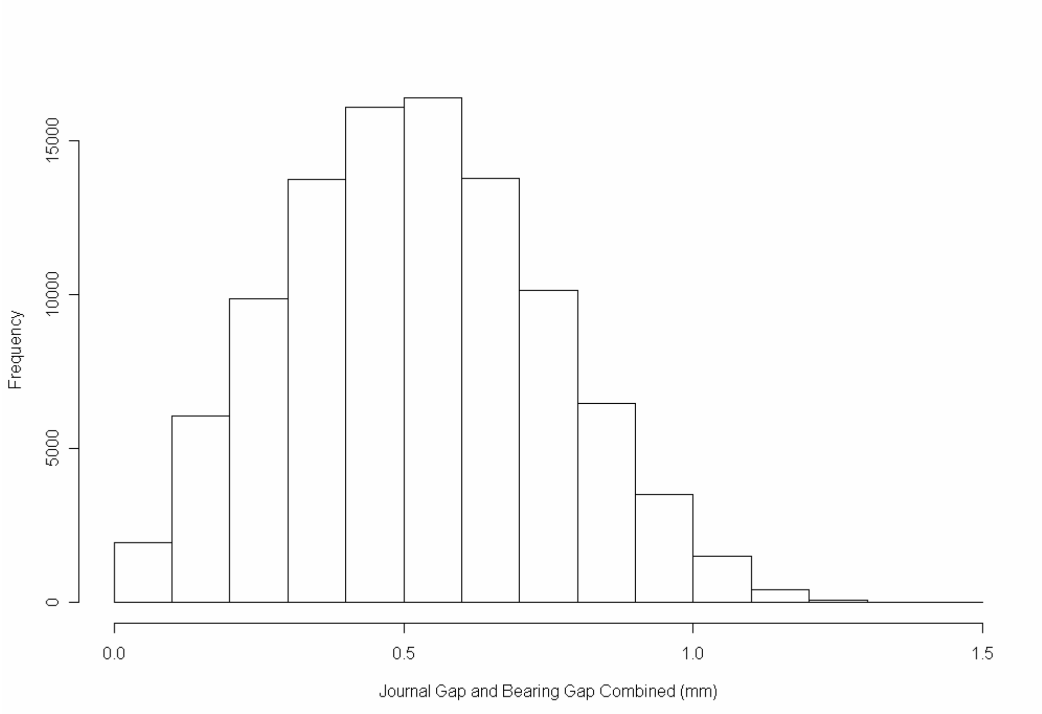

Figure 7: Histogram of the simulated journal and bearing gaps combined.

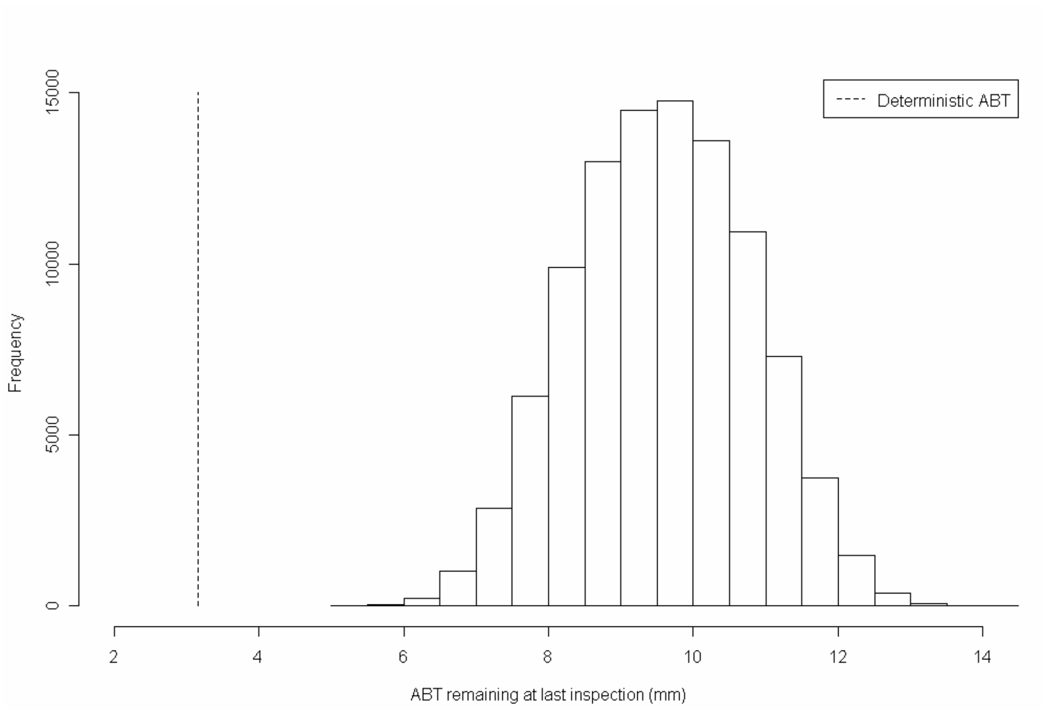

Figure 8: Histogram of the simulated ABT remaining at the last inspection for an example fuel channel. The deterministic value is also marked.

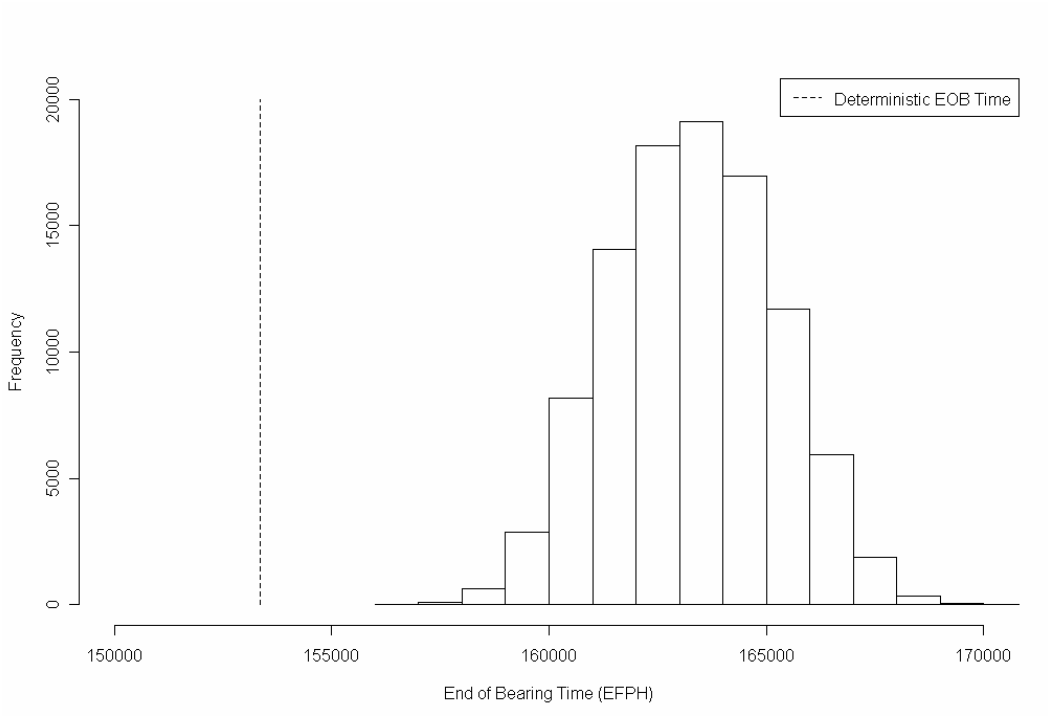

Figure 9: Histogram of the simulated EOB time for an example fuel channel. The deterministic value is also marked.