STATISTICAL METHODS FOR DARLINGTON STEAM GENERATOR TUBE FITNESS-FOR-SERVICE ASSESSMENTS

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ABSTRACT

OPG has developed Fitness-For-Service Guidelines (FFSG) for steam generator tubes. The main objectives of the FFSG are to provide reasonable assurance that tube structural integrity is maintained, and to provide reasonable assurance that there are adequate margins between estimated accumulated dose and applicable site dose limits for consequential leakage. When tube degradation is detected, a series of mandatory, consecutive periodic assessments of the steam generator tubes are required. The condition monitoring (CM) assessment provides a current and backward-looking assessment of the entire population of tubes, including validation and/or adjustment of predictive methods based on service experience and comparison with the previous operational assessment. A forward-looking operational assessment (OA) of fitness-for-service of the entire population of tubes in the reactor unit is performed to demonstrate that the acceptance criteria will be satisfied during the next evaluation period. The operational assessment considers the projected future condition of the tubes based on the inspection results and the predicted flaw growth rates.

The statistical methods used to obtain predictions for the tube fretting in the Darlington station will be presented. Initially, predictions were based only on the growth of the observed fret indications. Random growth based on the gamma distribution, with parameters estimated from the observed data, was assumed. Together with this model, a statistical test called the critical limit fret depth (CLFD) was developed to determine whether the prediction model was still appropriate, as part of the CM assessment. After several years of successful application of the model, a failure of the CLFD test was observed during the Darlington Unit 1 2004 outage. This prompted a review of the predictive methodology that resulted in a model for OA with the following components: (i) growth of existing fret indications; (ii) estimation of the number of new fret indications; (iii) estimation of the fret size of new fret indications; and (iv) integration of the different predictions. The growth model for existing fret indications is still based on the gamma distribution, but the population of frets was divided into several subpopulations based on contact size length and whether or not the frets are located in an area identified at greater risk of fretting. The model to estimate the number of new fret indications is based on a negative binomial distribution. The model to estimate the size of the new fret indications is also based on the gamma distribution, but with different parameters than those used to for growth of existing fret indications. The predictions from the different fret subpopulations are then integrated to determine the upper bound number of frets exceeding the applicable structural integrity limits. The predicted consequential leak rate for frets at risk of leaking is also estimated, using inputs from OPG’s Steam Generator Tube Test Project, for comparison against the maximum allowable consequential leakage rate.

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INTRODUCTION

OPG has developed Fitness-For-Service Guidelines (FFSG) for steam generator tubes [1,2,3]. The main objectives of the FFSG are to provide reasonable assurance that tube structural integrity is maintained, and to provide reasonable assurance that there are adequate margins between estimated accumulated dose and applicable site dose limits for consequential leakage. When tube degradation is detected, a series of mandatory, consecutive periodic assessments of the steam generator tubes are required. The condition monitoring (CM) assessment provides a current and backward-looking assessment of the entire population of tubes, including validation and/or adjustment of predictive methods based on service experience and comparison with the previous operational assessment.

For Darlington (D) steam generators (SG) an initial random growth model based on a gamma distribution with parameter $1/\lambda = 3.80$ %tw/yr was proposed [4]. This initial model was based on the available inspection data up to the year 2000, which consisted of the first inspection results for steam generators in all Darlington units. It was recognized that the use of only a single inspection for assessment of fret growth had limitations and hence increased uncertainty. This model was found to provide adequate bounds when comparing the predictions with observed data at the second inspection of the D2 SGs in 2001, the D3 SGs in 2002 and the D4 SGs in 2003. However, it was noted at these second inspections that some new frets appeared to be initiating between inspections and growing at a relatively larger rate, but these frets were not of sufficient number or size to invalidate the use of the model given in [4]. The prediction approach in [4] did not account for initiation of new frets between inspections, in particular the possibility of new deep frets initiating and exceeding the maximum tolerable fret size (MTFS) or the size of a fret at risk of leaking (FAROL) limits.

During the Spring 2004 inspection of D1, the observed number of frets exceeding MTFS and the observed number of frets exceeding FAROL in three SGs, were found to be greater than previously predicted. In total, seventeen frets were observed with depth exceeding MTFS, of which three had depth considered to exceed FAROL. All of these frets were located in tubes inside the defined area at risk (AAR)[1] and with effective fret contact length of ≤ 25 mm [5]. It was also found in [5] that in the AAR the number of frets exceeding the critical limit fret depth[2] (CLFD) limit was greater than predicted. Based on these observations it was clear that a revised approach for prediction of growth of existing frets and initiation of new frets was required. The rest of the paper describes the proposed new model that was developed in 2004 and applied for Darlington fretting.

[1] The area at risk (AAR) is defined as tubes in Rows 70 to 101 and Columns 39 to 83 and contact points from HU2 to CU2. Tubes outside this region are consider to be in the not area at risk (NAR).

[2] A fret size used to test whether or not the predicted fret distribution bounds the tail of the distribution of the observed data.

DATA ANALYSIS

U-bend fretting inspection results from repeated inspections in D1, D2, D3 and D4 SGs up to the year 2004 were matched to determine whether a fret reported in a given inspection was new or existing.[3] Indications were matched by tube row, column, support (e.g. HU1, CU1, HU2, CU2, HU3, CU3, HU4, CU4) and location relative to the support: inboard (positive sign) or outboard (negative sign). This information also allowed determination of the effective contact length (mm) for each fret. The fret contact length is important as the structural limits (MTFS and FAROL) and allowable leakage depends upon the effective contact length (see [6]). Table 1 provides a summary of these sub-populations together with the MTFS, FAROL and number of frets allowed to exceed FAROL.[4]

Table 1: Fret Sub-Populations According to U-bend Flat Bar Contact Effective Length

Population	Effective Fret Length (mm)	MTFS (%tw)	FAROL (%tw)	Number of Allowable Frets Exceeding FAROL
P2a	≤ 25	58	80	6
P2b	(25, 30]	57	79	3
P2c	(30,32]	57	79	2
P2d	(32, 35]	57	79	1
P2e	(35, 38]	57	79	1
P2f	(38, 40]	56	79	1
P2g	(40, 50)	56	78	0
P1	≥ 50 mm	55	77	0

Note: Number of frets that could exceed FAROL and leak without exceeding the maximum allowable consequential leak rate of 10 kg/s [9].

A fret was considered as new if there was no prior inspection of the tube or no signal was observed at the first inspection during the eddy current (ET) signal-to-signal analysis. In some cases, the ET signal-to-signal analysis identified that a fret detected at the second inspection was in fact present but not reported at the first inspection. Typically these frets were shallow in depth and below the nominal 10%tw reporting criteria used for Darlington U-bend frets. In other cases, the ET signal-to-signal analysis identified frets where the locations had been incorrectly identified in the one of the inspections. After the appropriate corrections, the frets were matched and treated as existing frets.

U-bend Fret Growth Behaviour

Table 2 provides a summary of the fret growth behaviour for all 16 Darlington SGs between the two available inspections up to the year 2004. The Table provides for all SGs the summary of the number of indications and the mean growth rate of all, existing and new indications. It also

[3] Frets detected in the first inspection but removed from service by plugging were excluded from this process.
[4] The MTFS and FAROL limits are those used so far. These limits have been recently updated (see [6]).

indicates those cases where the observed mean growth rate was significantly larger than the 3.8 %tw/yr growth rate used in [4].

Table 2: Summary of Fret Growth Between Two Inspections in Darlington SGs

SG	Operating Period (yr)	All Indications		Existing Indications		New Indications	
		# Indications	Mean Growth Rate %tw/yr	# Indications	Mean Growth Rate %tw/yr	# Indications	Mean Growth Rate %tw/yr
D1-SG1	3.53	200	4.14	115	2.62	85	6.19*
D1-SG2	3.53	219	5.59*	82	3.42	137	6.89*
D1-SG3	3.53	140	4.28*	73	3.32	67	5.34*
D1-SG4	3.53	139	4.45*	79	3.31	60	5.96*
D2-SG1	1.38	99	3.8	86	2.82	13	10.26*
D2-SG2	1.38	143	3.82	110	2	33	9.86*
D2-SG3	1.38	257	2.8	210	1.59	47	8.19*
D2-SG4	2.97	105	3.84	63	2.83	42	5.36*
D3-SG1	2.83	163	3.93	81	2.5	82	5.34*
D3-SG2	2.83	343	3.58	167	2.37	176	4.73*
D3-SG3	2.83	130	3.99	68	2.49	62	5.64*
D3-SG4	2.83	49	3.09	29	1.71	20	5.11*
D4-SG1	3.66	85	3.27	41	2.27	44	4.2*
D4-SG2	3.66	71	3.61	20	1.71	51	4.36*
D4-SG3	3.66	29	4.1	9	2.52	20	4.81*
D4-SG4	3.66	124	3.7	55	2.33	69	4.78*

Notes for Table 2:
1. Growth Rate = Growth/Operating_Period with Growth = ($Depth_2 - Depth_1$), $Depth_i$ wall loss reported at inspection *i*.
2. Indications reported as 'not inspected' in the first inspection were considered as new in the second inspection. These include 3 indications in D1-SG2, 3 in D2-SG1, 11 in D2-SG2, 1 in D2-SG3, 1 in D2-SG4, 2 in D3-SG3, 2 in D4-SG1 and 2 in D4-SG2.
3. Growth calculated only for locations with repeated inspections and with negative values censored at zero (0).
4. A '*' indicates the observed mean growth was significantly larger than 3.8 %tw/yr at the 5% significance level.

From Table 2, it is observed that in D1 SGs 2, 3 and 4 the observed mean growth rates for all indications are significantly larger than the 3.8% tw/yr assumed in the growth model given in [4]. The observed mean growth rates for existing frets in all SGs are not significantly larger than 3.8 %tw/yr. It is also observed that in all 16 SGs the mean growth rates for new indications are significantly larger than 3.8 %tw/yr. The highest mean growth rates for new fret indications are in D2 SG1, SG2 and SG3. However, the rates in these three SGs are considered to be an artifact of the short operating interval (1.38 yrs), the ET detection capability for fretting and the fact that the available signal-to-signal analysis [7] only reviewed frets with depth ≥ 15% tw in the second inspection. For example, an apparently new fret with depth 13%tw in the second inspection (just above the ET reporting threshold of 10%tw) would have an apparent growth of 9.42%tw/yr based on the 1.38 yr operating period. The observation that the large growth of new indications in D2 SG1, SG2 and SG3 could be considered an artifact is further supported by the growth rate for new frets in D2 SG4, with a longer operating interval of 2.97 yrs, which is quite consistent with the growth observed in other D1, D3 and D4 SGs.

New U-bend fret behaviour by contact fret length and AAR/NAR

Further analyses of the D1 2004 results given in [5] indicated (i) that new frets were occurring mainly in the area at risk (~95% of the total new frets); (ii) these frets had mainly a contact length ≤ 25 mm length; and (iii) the deep (>MTFS or FAROL) new frets were confined to the fret sub-population with effective length ≤ 25 mm. Therefore, it was of interest to further investigate in all D1, D2, D3 and D4 SGs the relationship between the numbers of new fret indications vs. the effective contact fret length.

Table 3 provides a summary of the number of new fret indications vs. effective fret length for all 16 Darlington SGs. The observations indicate that consistent with the results reported in [5], about 80% of the 1008 new fret indications have length ≤ 25 mm and <2% have contact length longer than 32 mm. The Table also indicates that the majority (91.7%) of the new indications are in the AAR and all observed indications with contact length larger than 32 mm (subpopulations, P2d, P2e, P2f, P2g and P1) are in the NAR.

Table 3: Summary of New Indications Observed in All Darlington SGs by Length

Subpopulation		# in Area Not At Risk	# in Area At Risk	Total # of Indications	%
P2a	**<= 25**	31	784	815	80.9
P2b	**(25,30]**	18	137	155	15.4
P2c	**(30,32]**	18	3	21	2.1
P2d	**(32,35]**	5	0	5	0.5
P2e	**(35,38]**	3	0	3	0.3
P2f	**(38,40]**	2	0	2	0.2
P2g	**(40,50)**	3	0	3	0.3
P1	**>= 50**	4	0	4	0.4
TOTAL		84	924	1008	100

Table 4 provides a summary of the average fret growth rate for new indications by fret contact length.

Table 4: New Fret Indication Growth (all Darlington SGs) Vs Fret Length

Population	Effective Length (mm)	n	Mean (%tw/yr)	Std (%tw/yr)	Min (%tw/yr)	Max (%tw/yr)
P2a	≤ 25	815	5.86	2.77	2.73	23.23
P2b	(25, 30]	155	5.23	2.26	2.73	16.67
P2c	(30,32]	21	5.18	2.26	3.28	10.87
P2d	(32, 35]	5	7.76	4.34	3.01	13.04
P2e	(35, 38]	3	6.11	3.54	3.53	10.14

P2f	(38, 40]	2	5.16	0.31	4.95	5.38
P2g	(40, 50)	3	4.08	0.66	3.53	4.82
P1	≥ 50 mm	4	9.21	3.15	4.95	11.59

Figure 1 provides a comparison of the growth rates for new fret indications in the different sub-populations using box-whisker plots. No clear trend of the growth of new indications with respect with contact size is observed from Figure 5. Some frets in sub-populations with length > 32 mm (P2d, P2e, P1) appear to have relatively high growth rates. However, further examination of the 17 indications with contact size larger than 32 mm indicated that all the indications with growth rate larger that 7.97 %tw/yr were observed in one of the D2 SGs with an operating period of 1.38 years. As was mentioned above, the apparent large growth in these D2 SGs is likely due to a combination of inspection detection capability and a short operating period.

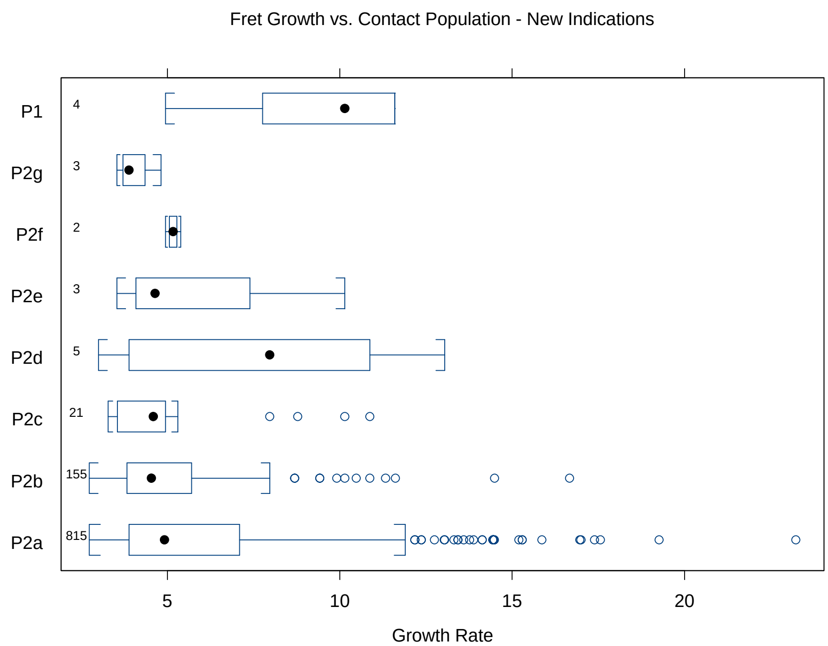

Figure 1- Fret Growth vs Contact Population-New Indications

An ANCOVA model was used to test the association between the growth rate of new fret indications and the contact size length. The model used the growth rate as the response, Unit (1,2,3,4) and Area at Risk (AR: AAR, NAR) as factors and contact size as covariate. These results confirmed that for the new indications there is no significant contact size effect (p-value = 0.86). The results also indicated that for new indications there is no significant area at risk effect (p-value=0.54), but that there is a significant unit effect (p-value=0).

Existing U-bend Frets- Growth Analysis by contact length and AAR/NAR

Two other important observations can be made from the D1 2004 results given in [5]: (i) existing U-bend frets that grew to exceed the MTFS and FAROL limits were found only in the AAR; and (ii) these indications occur only in the fret sub-population with contact size length ≤ 25mm. Therefore additional analyzes were performed to investigate these observations in more detail. Table 5 and Figure 2 provide a summary of the fret growth by contact size subpopulation for existing frets. It can be observed from Table 5 and Figure 2 that for existing indications there is a clear reduction of the growth rate with respect to the contact size.

A similar ANCOVA model to that describe above was used to test for association between the growth rate and the contact size for existing frets. The results indicated that there is a significant Unit effect (p-value < 0.001) and there is a significant contact size effect (p-value < 0.001). In addition, the results indicated that there was not a significant area at risk effect (p-value=0.69). A close look at the number of indications in Table 5 indicates that all indications with contact length size > 30 mm occur in the NAR and therefore, the effect of NAR can be confounded with the effect of the contact size. Furthermore, the maximum growth rate on these 21 existing frets with length >30 mm (populations P2c-P2g, P1) was only 1.77 %tw/yr suggesting that the growth in the NAR can be slower than the growth in the AR.

Table 5: Summary of Fret Growth of Existing Indications by Contact Size Population

Population	Effective Length (mm)	NAR	AR	Total	Mean (%tw/yr)	Std (%tw/yr)	Min (%tw/yr)	Max (%tw/yr)
P2a	≤ 25	18	1052	1070	2.71	2.85	0.00	23.19
P2b	(25, 30]	9	188	197	1.21	1.46	0.00	8.70
P2c	(30,32]	9	0	9	0.87	0.62	0.00	1.77
P2d	(32, 35]	9	0	9	0.59	0.44	0.00	1.45
P2e	(35, 38]	2	0	2	0.14	0.20	0.00	0.28
P2f	(38, 40]	0	0	0				
P2g	(40, 50)	1	0	1	0.00		0.00	0.00
P1	≥ 50 mm	0	0	0				

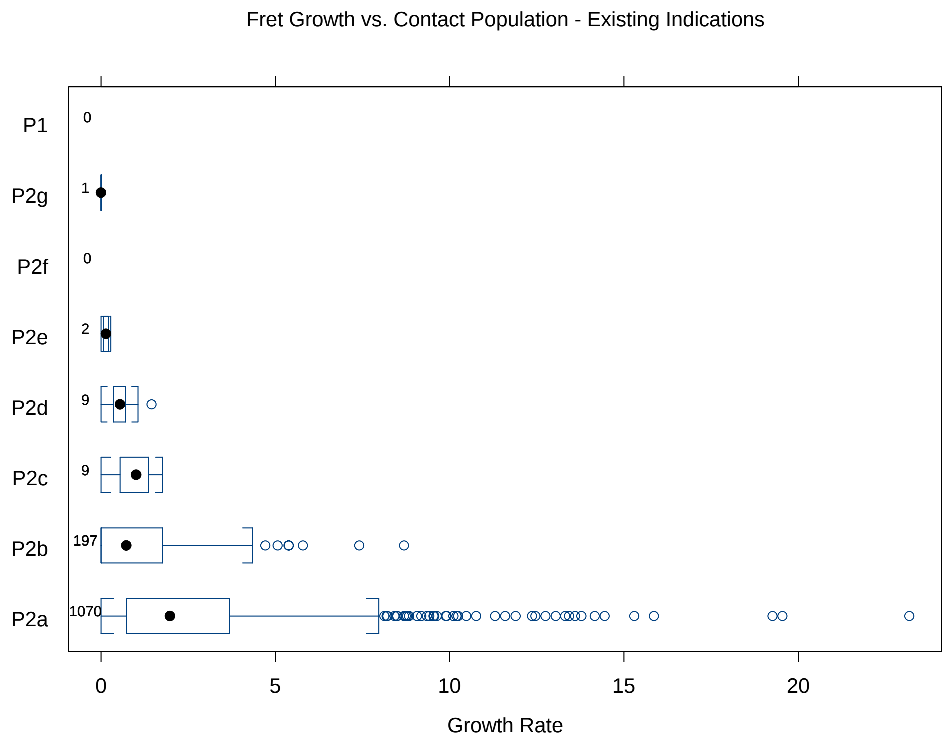

Figure 2-Fret Growth vs Contact Population-Existing Indications

To further analyze whether the growth in the NAR is indeed slower than in the AAR, a model similar to that described above, but removing the variable associated with the contact area was fitted to the data. The results indicated a significant area at risk effect (p-value < 0.001), confirming the large confounding between area at risk and contact size length and a difference in the growth in the AAR and the NAR.

MODELING AND PREDICTIVE APPROACHES

Fret Growth Model and CLFD Test

The mathematical concepts to model fret growth are based on the following observations. Suppose that the sizes of frets in a steam generator have a distribution at time *t*, say $F_t(s)$; the frets grow in a random fashion but follow a probabilistic distribution, say $G(r)$ between t and $t+\Delta t$. Then, at time $t+\Delta t$, the fret size distribution, denoted by $F_{t+\Delta t}(s)$, is given by

$$F_{t+\Delta t}(s) = \int_0^s F_t(s-g)\,dG(g) \qquad (1)$$

So, if we know the fret size distributions $F_t(s)$ and fret growth distribution $G(g)$, then we can determine the fret size distribution, $F_{t+\Delta t}(s)$, at time $t+\Delta t$.

The distribution $F_t(s)$ can be approximated by the empirical distribution, which is defined as follows:

Let $x_1, x_2, x_3, \ldots, x_n$ be the observed fret sizes at the last inspection. Define

$$F_n(s) = \frac{\#\,\text{of}\ x_i \le s}{n+1} \tag{2}$$

for each given fret size s.

The growth is assumed to have a gamma distribution with parameters λ and k where 1/λ equals the mean growth per year and k equals the operating time in years. This distribution is given by

$$\gamma(g) = \frac{\lambda^k}{\Gamma(\kappa)} \int_0^g x^{\kappa-1} e^{-\lambda x} dx \tag{3}$$

This is the growth distribution needed to predict the extent of fret growth at the next inspection. Substituting F_n and γ for F_t and G respectively in Equation (1), we can compute the distribution of fret sizes at the next inspection.

For a given fret size s_o, (such as the MTFS or FAROL %tw limits) the expected number of frets that will exceed s_o at the next inspection, denoted by m_s, is given by

$$m_s = n \int_s^\infty F_n(s-g)\, d\gamma(g) \tag{4}$$

The 95% upper confidence limit M_s for the predicted number m_s is given by

$$M_s = \min_M \left\{ M \mid \sum_{i=0}^{M} \binom{n}{i} p^i (1-p)^{n-i} \ge 0.95 \right\} \tag{5}$$

where $p = \int_s^\infty F_n(s-g)\, d\gamma(g)$.

The 95% upper confidence limit predictions are calculated for the eight fret sub-populations (assuming sufficient populations are present) in each of the AAR and NAR to predict the number of existing frets that will exceed MTFS and FAROL.

For CM one would like to determine whether or not the proposed model provides an adequate bound to model fret growth. For this purpose a test based on the critical limit fret depth (CLFD) was developed [4]. The idea of the test is to find a fret size, C, (the CLFD) that is in the tail of the predicted distribution and that can be used to test if the predicted distribution bounds the tail of the observed distribution. The test consists in comparing the predicted and observed number of fret indications in the future inspection exceeding the CLFD value. If the number of actual fret indications exceeds the predicted number, one would conclude that the predicted model does not bound the growth rate. In the proposed test the CLFD *C* is defined as the fret depth for which five (5) predicted indications are expected to exceed such value. This value is given by:

$$C = \min_{c} \left\{ c \mid \int_{c}^{\infty} F_n(c-g)\, d\gamma(g) \geq \frac{n-5}{n} \right\} \qquad (6)$$

The critical number of indications that can be observed exceeding the CLFD, S_o is given by the predicted 95% upper bound for the number of indications that can exceed *C*. This is calculated using Equations (4) and (5) with $s = C$.

Predictions for Fret Growth in Partially Inspected Steam Generators

Suppose that N_i out of *N* tubes in a SG are inspected and *n* fret indications are observed. Denote by *q* the number of indications in the plugged tubes. Let $F^1_{n,t}(x)$ denote the observed empirical distribution (calculated with Equation 2) based on the *n* observed indications and let $F^2_{n-q,t}(x)$ the empirical distribution based on the *n-q* indications left in service. The after plugging empirical distribution at time *t* for the SG is given by

$$F_{n,t}(x) = \left(\frac{N - N_i}{N} \right) \cdot F^1_{n,t}(x) + \left(\frac{N_i}{N} \right) \cdot F^2_{n-q,t}(x)\,. \qquad (7)$$

The predicted distribution for the time $t+\Delta t$ is obtained by applying Equation 1 to the distribution given in (7).

Model for Existing U-bend Frets

Based on the analysis of the data, separate growth models were suggested for the indications in the AAR, and for the indications in the NAR.

For existing frets in the AAR, the growth model was based on the deterministic plugging criteria used in the D1 2004 outage [5]. To achieve this, the parameter of the growth rate gamma distribution was set to $1/\lambda = 5.87$ %tw/yr to ensure that no more than 5% of the indications grow on average more than 13 %tw per year during a 2.5 year operating period (e.g., no more than 5% of the indications have growth more than 32.5%tw in the operating 2.5 years)[5]. This parameter was found to be very close to the value required to provide adequate coverage to the upper tail of the 2004 observed D1 SG2 fret distribution ($1/\lambda = 5.75$ %tw/yr).

[5] Note: the corresponding 95% percentile point of the gamma distribution with $1/\lambda$=5.87% tw/yr for the growth during one year is 17.6 %tw.

For existing frets in the NAR, the growth model was based on a gamma distribution with parameter $1/\lambda$ =3.80 %tw/yr. This was the parameter used in [4] and although the growth rate observed in the existing NAR fret indications was smaller, it was decided to leave this value for the NAR indications for conservatism in the predictions.

Model for New U-bend frets

Number of New Indications

A negative binomial distribution[6] was proposed to estimate the number of new indications that could be present in a steam generator. The negative binomial distribution with parameters *k* and *p* can be expressed as

$$\text{Prob}(N = x) = \binom{x-1}{k-1} p^k (1-p)^{x-k}$$

The parameters of the negative binomial were estimated based on the data observed on the 16 SGs and given in Table 2. The estimates were calculated using the method of moments[7] [8] with the parameter *k* rounded off to the closest integer. The estimated values were $k = 2$ and p = 0.0308. With these parameters the expected number of new fret indications per SG is 63 with a standard deviation of 45.25.

One drawback of using the negative binomial distribution is that the calculation of the number of new fret indications is not directly dependent upon operating time. However, this distribution was fitted to the number of new frets that were observed in the D1-D4 SGs over operating periods ranging from 1.38 to 3.66 operating years. Therefore, the number of frets obtained from this distribution should be appropriate for operating periods within the range of data. However, this methodology should be applied with some caution if used for operating periods much beyond the maximum observed period of 3.66 yrs. The time dependency of new fret initiation is not known and is difficult to establish with typical plant inspection approaches.

For an assessment of future fretting, the number of new indications in a given SG can be simulated from the negative binomial described above. Once the total number of new fret indications per SG is determined, it is split into sub-populations according to the contact length size. Due to the small amount of data, it was necessary to combine frets with lengths >32 mm (sub-populations P2d thru P2g, P1) into one sub-population (P3). Based on the observed data (see Table 3) it is recommended to split the total number of new frets into the four

[6] An attempt was made to fit the observed data using a Poisson distribution (used at Pickering B in predictions of new pits). However, the variability observed in the data was larger than the expected from a Poisson distribution and fitted better with a negative binomial distribution.

[7] The method of moments given in [8] provides estimates for $P = S^2/Mn - 1$ (=28.0497) and $K = Mn/P$ (=2.246), where S^2 and Mn are the variance and the mean of the data. The estimates reported are for the rounded value of *k* and $p = 1/(1+P1)$ where $P1 = Mn/k$.

subpopulations as follows: P2a (<=25 mm), 80.9% of total; P2b (<25-≤30), 15.4%; P2c (>30-≤32mm) 2.1%; and P3 (>32mm)1.6%.

Growth of New Indications

The new fret indications are grown according to a gamma distribution with parameter $1/\lambda$=6.888 ± 0.278 %tw/yr and parameter κ = the applicable operating period in years. This parameter is based on the most limiting growth rate observed in the new indications of the Darlington SGs (see Table 2). It is assumed that growth in new frets starts right after restart of the reactor following an outage.

A simulation approach was used to estimate the number and growth of new fret indications exceeding MTFS and FAROL using the approaches described above. The predicted values may correspond to the mean or median of the simulation results over a reasonable number of simulations.

Aggregation of Results

Predictions for existing fret indications are calculated separately for indications in the Area at Risk (AAR) and for indications in the Area not at Risk (NAR). For each of these two cases, the predictions are further separated into eight different contact size subpopulations. In addition, the predictions for new indications are calculated separately for four contact size subpopulations. The aggregation of all these predictions is done as follows. The results are presented for the MTFS case with the aggregation of the predictions for FAROL being similar.

Expected number of indications

The aggregation of the expected number of fret indications is simply the sum of the individual expected numbers. So the expected total number of fret indications exceeding MTFS in the unit or a SG is calculated as:

$$\begin{aligned} E(MTFS) = \; & E_{MTFS\text{-}AAR\text{-}P2a} + E_{MTFS\text{-}AAR\text{-}P2b} + \ldots + E_{MTFS\text{-}AAR\text{-}P2g} + E_{MTFS\text{-}AAR\text{-}P1} + \\ & E_{MTFS\text{-}NAR\text{-}P2a} + E_{MTFS\text{-}NAR\text{-}P2b} + \ldots + E_{MTFS\text{-}NAR\text{-}P2g} + E_{MTFS\text{-}NAR\text{-}P1} + \\ & E_{MTFS\text{-}New\text{-}P2a} + E_{MTFS\text{-}New\text{-}P2b} + E_{MTFS\text{-}New\text{-}P2c} + E_{MTFS\text{-}New\text{-}P3} \qquad (8) \end{aligned}$$

where $E_{MTFS\text{-}\mathit{Area}\text{-}\mathit{Pop}}$ represent the expected number of indications exceeding MTFS in the *Area* = AAR, NAR, new and subpopulation *Pop* = P2a, P2b, …, P2g, P1 (P2a, P2b, P2c and P3 for new indications).

95% upper bound for number of indications

The aggregation of the 95% upper bounds for the number of indications exceeding MTFS uses the following expressions

$$\begin{aligned} E95(MTFS) = \; & E(MTFS) + \\ & sqrt((E_{MTFS\text{-}AAR\text{-}P2a} - E95_{MTFS\text{-}AAR\text{-}P2a})^2 + \ldots + (E_{MTFS\text{-}AAR\text{-}P1} - E95_{MTFS\text{-}AAR\text{-}P1})^2 + \\ & (E_{MTFS\text{-}NAR\text{-}P2a} - E95_{MTFS\text{-}NAR\text{-}P2a})^2 + \ldots + (E_{MTFS\text{-}NAR\text{-}P1} - E95_{MTFS\text{-}NAR\text{-}P1})^2 + \end{aligned}$$

$$(E_{MTFS\text{-}New\text{-}P2a} - E95_{MTFS\text{-}New\text{-}P2a})^2 + \ \ldots + (E_{MTFS\text{-}New\text{-}P3} - E95_{MTFS\text{-}New\text{-}P3})^2) \quad (9)$$

where $E95_{MTFS\text{-}Area\text{-}Pop}$ represents the 95% upper bounds for the number of indications exceeding MTFS in the *Area* = AAR, NAR, New and subpopulation *Pop* = P2a, P2b, …, P2g, P1 (P2a, P2b, P2c and P3 for new indications).

Equations similar to Equation (8) and (9) could also be used to aggregate subpopulations, e.g., only the AR, the NAR or New indications or aggregate existing indications in P2d, P2e, P2f, P2g and P1 into a P3 subpopulation.

Equivalent Leak Rate

An estimate of the mean and upper bound leak rate associated with fret indications exceeding FAROL in the unit can also be calculated. This leak rate can be expressed as a percentage of the allowable leak rate calculated from the consequential leak assessment (CLA), e.g., as a factor of 10 kg/s [9] and using the number of allowable frets from Table 1. This "Equivalent to CLA Rate" is calculated based on all subpopulations as:

$$\begin{aligned}\text{Eq CLA Rate} &= TP2a/6 + TP2b/3 + TP2c/2 + TP2d + TP2e + TP2f + TP2g + TP1. \\ &= TP2a/6 + TP2b/3 + TP2c/2 + TP3\end{aligned}$$

where T*pop* represents the number of indications exceeding FAROL in the unit. The 95% upper bound estimate is calculated as

$$\begin{aligned}\text{E95 CLA Rate} = \text{Eq\_CLA\_Rate} + \\ \text{sqrt}\ \{&[(TP2a - T95P2a)/6]^2 + [(TP2b - T95P2b)/3]^2 + \\ &[(TP2c - T95P2c)/2]^2 + [(TP2d - T95P2d)/1]^2 + \\ &[(TP2e - T95P2e)/1]^2 + [(TP2f - T95P2f)/1]^2 + \\ &[(TP2g - T95P2g)/1]^2 + [(TP1 - T95P1)/1]^2\ )\end{aligned}$$

SUMMARY

This paper describes the statistical model used to obtain predictions for the U-bend tube fretting in the Darlington station. This model is the result of a model review prompted by the 2004 D1 SG inspection results. The parameters of the model are based on all Darlington fret inspection data available up to and including the 2004 D1 SG inspections. The model is similar to that previously employed with the main changes being: (1) the breakout of the fret indications into eight subpopulations according to the contact size; (2) the use of two different gamma distributions for growth of existing frets in the AAR and the NAR; and (3) the use of a new model for the prediction of the number and growth of new fret indications.

In the new approach, the predictions to be used in the CM assessment are calculated for each subpopulation. These predictions are then aggregated to obtain overall results by SG and for the Unit to determine the upper bound number of frets exceeding the applicable structural integrity limits. The critical limit fret depth (CLFD) used to test whether the predictions bound the observed data is calculated separately for the population of frets in the AAR and for the population of frets in the NAR. The predicted consequential leak rate for frets-at-risk-of-leaking is also estimated, using inputs from OPG's Steam Generator Tube Test Project, for comparison against the maximum allowable consequential leakage rate. The applicability of the revised model is continuously monitored and confirmed by comparing the U-bend fretting predictions with the observations at future inspections of the Darlington steam generators.

NOMENCLATURE

Acronyms

FFSG	Fitness-For-Service Guidelines
CM	Condition Monitoring
ET	Eddy current
CLFD	Critical limit fret depth
SG	Steam Generator
D1	Darlington Unit 1
D2	Darlington Unit 2
D3	Darlington Unit 3
D4	Darlington Unit 4
tw	Through wall
%tw	Percent through wall
yr	Year
MTFS	Maximum tolerable flaw size
FAROL	Flaw at risk of leaking
AAR	Area at Risk
NAR	Not Area at Risk
P1	Subpopulation of frets with contact length ≥ 50 mm
P2a, …, P2g	Subpopulations of frets with contact length < 50 mm
P3	Subpopulation of frets with contact length ≥ 32 mm
mm	Millimetres
CLA	Consequential leak assessment
Eq CLA Rate	Equivalent CLA rate
E95 CLA Rate	95% upper bound CLA rate
T*pop*	Number of indications exceeding FAROL in population *pop* = P2a, P2b, …, P2g, P1 (P2a, P2b, P2c and P3 for new indications)

Symbols

λ	Parameter of the gamma distribution for growth rate
p-value	Significance level of a statistical test
$F_t(,)$	Cumulative probability distribution function for fret depth size at time t
$F_n(,)$	Empirical cumulative distribution function for fret size obtained with n observations
$G(.)$	Cumulative probability distribution function for fret growth rate
s	Fret size possible realization
g	Growth rate possible realization
t	Time
$\Delta\tau$	Time increment

x	Fret size observation
n	Number of observed indications
κ	Parameter of the gamma distribution
$\gamma(g)$	Gamma distribution for growth rate
$\Gamma(.)$	Gamma function
m_s	Expected number of indications exceeding the fret size *s*
M_s	95% confidence bound for number of fret indications exceeding *s*
p	Probability value
min	Minimum value
C	Critical limit fret depth
E()	Expectation value
$E_{MTFS\text{-}Area\text{-}Pop}$	Expected number of indications exceeding MTFS in the *Area* = AAR, NAR, new and subpopulation *Pop* = P2a, P2b, …, P2g, P1 (P2a, P2b, P2c and P3 for new indications)
E95(.)	Expected 95% upper bound
$E95_{MTFS\text{-}Area\text{-}Pop}$	95% upper bounds for the number of indications exceeding MTFS in the *Area* = AAR, NAR, New and subpopulation *Pop* = P2a, P2b, …, P2g, P1 (P2a, P2b, P2c and P3 for new indications)

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