DARLINGTON STEAM GENERATOR TUBE FRETTING FITNESS-FOR-SERVICE: OPERATING EXPERIENCE AND STRUCTURAL AND LEAK-RATE TESTS

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ABSTRACT

Ontario Power Generation (OPG) has developed and implemented a systematic managed process for steam generators at all of its facilities. One of the key requirements of this managed process is to have in place long range Steam Generator Life Cycle Management (SG LCM) plans for each of its reactor units. The primary goal of these plans is to maximize the value of the nuclear facility through safe and reliable steam generator operation over the expected life of the units. These SG LCM plans integrate and schedule all steam generator actions such as inspection, operation, maintenance, repairs, modifications, assessments, performance monitoring, research and development, and feedback.

This paper provides an overview of how structural and leak-rate testing, being conducted by OPG, is being used to support fitness-for-service assessments for fretting degradation in the U-bend region of the recirculating steam generators at the Darlington Nuclear Generating Station, in particular over the time period from 2002 to 2006.

BACKGROUND

Regulatory Environment

The Canadian Nuclear Safety Commission (CNSC) regulates activities involving nuclear energy or materials in Canada. The CNSC regulates nuclear power plants and nuclear materials through a comprehensive system that issues licences containing conditions that must be met by licensees. Regulatory control is also achieved by specifying standards that licensees must meet. Some of these standards are prepared within the CNSC, while in other cases, standards prepared by national standards writing bodies or other federal or provincial regulatory authorities are adopted. After a licence is issued, the CNSC carries out compliance inspections to ensure that its requirements are continually met. Reference [1] describes the CNSC's approach for regulation of steam generators.

The Canadian regulatory requirement governing fitness-for-service assessment for steam generator tubes is given in the Canadian Standards Association Standard CAN/CSA-N285.4, "*Periodic Inspection of CANDU Nuclear Power Plant Components*". This standard requires a disposition of detected indications that are predicted to exceed 40% of the nominal wall thickness before the next inspection. This standard does not specify the evaluation procedures for use in the fitness-for-service assessment of an indication, rather it is the responsibility of the licensee to obtain regulatory acceptance of all dispositions before restarting a nuclear power plant.

Life Cycle Management

A systematic managed process for steam generators has been implemented at OPG nuclear power plants. One of the key requirements of this managed process is to have in place long-term Steam Generator Life Cycle Management (SG LCM) plans for each plant. The primary goal of these plans is to maximize the value of the nuclear facility through safe and reliable steam generator operation, within the design and licensing basis, over the expected life of the plant, and where applicable, to preserve the option of life extension. The SG LCM plans integrate, prioritize, and schedule all steam generator actions such as inspection, operation, maintenance, repairs, modifications, assessments, performance monitoring, research and development, and feedback. The steam generators operated by OPG have experienced a variety of degradation modes; Reference [2] describes SG LCM experience at OPG nuclear power plants.

At OPG, a distinction is made between the terms Life Cycle Management (LCM) and Fitness-For-Service (FFS). The primary objective of both terms is the same, i.e., to assure the integrity of the steam generator tubes as a primary system pressure and containment boundary. The difference between the two terms is in the time span of application. SG LCM applies for the life of the plant, although practically it has a span of 5 to 10 years. FFS applies for the next operating cycle, i.e., until the next scheduled inspection. The current operating cycle for OPG plants are from two to three years. Figure 1 illustrates the distinction between the two terms with respect to the population of steam generator tube flaws in a plant. FFS manages the tail end of the evolving flaw distribution while LCM manages the bulk of the flaw population.

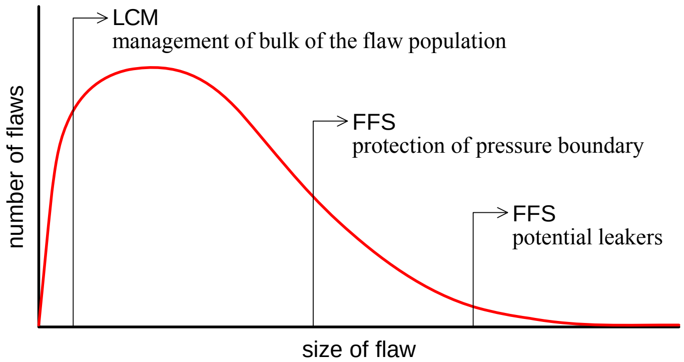

Figure 1: Life Cycle Management (LCM) versus Fitness-For-Service (FFS)

Fitness-for-Service Guidelines

To support its SG LCM plans, OPG developed Fitness-For-Service Guidelines (FFSG) for steam generator tubes, which are described in Reference [3]. These guidelines were submitted to the CNSC in 1999 for trial use, and in 2005, OPG revised the FFSG [4] to consider OPG experience over the intervening six years and suggestions received from the regulator. 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. The FFSG are intended to provide standard acceptance criteria and evaluation procedures for assessing the condition of steam generator tubes in terms of tube structural integrity, operational leak rate, and consequential leakage during an upset or accident event.

The FFSG provide an alternate method of satisfying the intent of CSA-N285.4 using inspection results in conjunction with representative, postulated distributions of flaws in the un-inspected tubes in the area(s) at risk in each steam generator to perform an assessment of the condition of all SG tubes. Assessments would typically be used to justify continued operation of steam generator tubes in a degraded condition, and/or as a means to justify the level of in-service inspection. The procedures would typically also be used in the determination of acceptable operating intervals. Guidelines for determining acceptability of repair procedures, including tube plugging, are provided. When tube degradation has been detected, a series of mandatory, consecutive periodic assessments of the steam generator tubes are required.

Acceptance criteria for degraded tubes in the FFSG are based on the concept of safety-related performance criteria that require tube structural integrity is maintained during the evaluation period, that operational leak rate is monitored and does not exceed the allowable limit, and that consequential leakage during upset or abnormal events is acceptable. The concept of performance criteria has been used to develop two sets of acceptance criteria.

Acceptance Criteria Prohibiting Leakage requires safety factors on load against through-wall penetration of the flaw for all loading events. Therefore, there will be no leakage when these acceptance criteria are satisfied.

Acceptance Criteria Permitting Leakage allows leakage during one or more loading events provided that safety factors on load against tube rupture are maintained, and that the consequential leakage is acceptable in terms of estimated accumulated dose versus applicable site dose limits.

The FFSG identifies a different acceptance standard for each of the two acceptance criteria:

Maximum Tolerable Flaw Size (MTFS) is the maximum size of the part-through-wall flaw that satisfies the acceptance criteria for flaw stability using the specified safety factors on load. The MTFS is the acceptance standard used with the *Acceptance Criteria Prohibiting Leakage.*

Flaw At Risk Of Leaking (FAROL) is the maximum size of the part-through-wall flaw that satisfies the acceptance criteria for flaw stability using a safety factor on load equal to 1.0. The FAROL is the acceptance standard used with the *Acceptance Criteria Permitting Leakage.*

Reference [5] is the technical basis for the minimum required safety factors specified in the FFSG as well as for the nonmandatory flaw models provided in the FFSG to establish these acceptance standards.

An additional requirement imposed on the use the Acceptance Criteria Permitting Leakage is that a safety assessment must be performed to demonstrate that the dose limits for the plant will be met for a postulated SG tube rupture during the most limiting upset or accident events.

DARLINGTON STEAM GENERATORS

The Darlington Nuclear Generating Station (DNGS) consists of four 880 MWe CANDU nuclear power plants (designated as Units 1-4), each unit is equipped with four vertical, recirculating, U-tube heat exchangers as illustrated in Figure 2. The design temperature and pressure for the inlet plenum are 315°C and 10.70 MPa (gauge), with a secondary side pressure of 5.07 MPa (gauge). Because of the lower pressure and temperatures, the recirculation ratios for CANDU steam generators are larger than those used in pressurized water reactors.

Each steam generator has 4,663 *Incoloy* Alloy 800 (I800) tubes with a nominal outside diameter of 15.9 mm (5/8") and a nominal wall thickness of 1.13 mm (0.044"). The tube support design utilizes drilled hole baffle plates in the preheater region, a lattice bar Anti-Vibration Bar (AVB) arrangement in the straight-leg regions outside of the preheater, and a fan bar AVB arrangement in the U-bend region. All of the secondary support structures are made of 410S stainless steel.

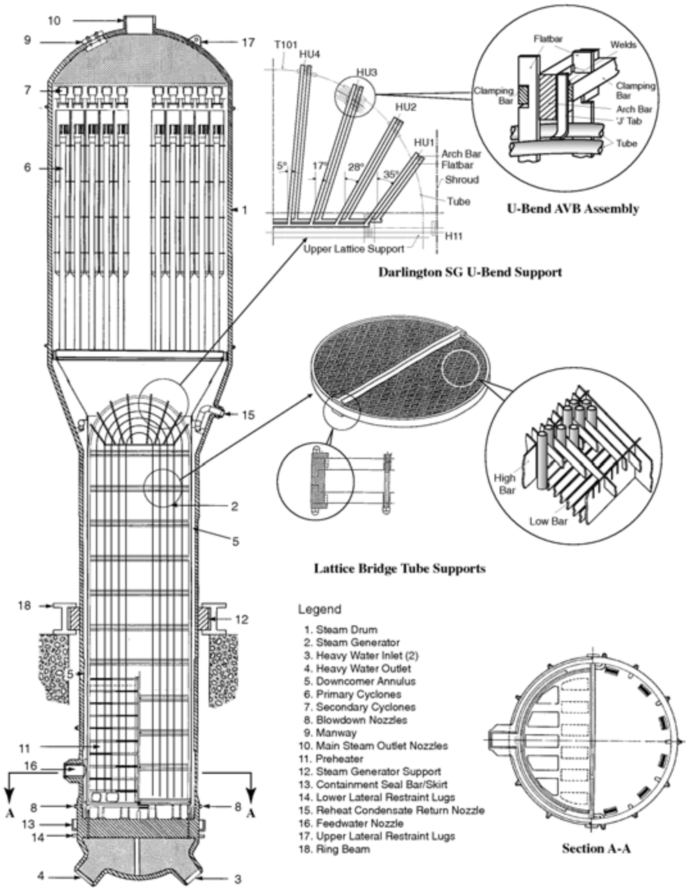

Figure 2: Darlington Steam Generators

Evaluation of eddy current (ECT) and ultrasonic (UT) inspections, in conjunction with engineering assessment of the steam generator design and construction, have determined that tube fretting in the U-bend region of the Darlington steam generators is an active mode of degradation. Reference [7] describes the understanding of the root cause for the observed fretting, which was supported by numerical simulations of Flow Induced Vibration (FIV) [8]. Reference [9] provides an overview of the systematic process, including the acceptance standards, being used to manage the tube fretting until a retrofit fix was installed. A similar process continues to be utilized in the retrofitted steam generators.

Tube Loads

For Darlington steam generators the limiting loading condition for normal and upset conditions (ASME Service Level A & B conditions) occurs during a short period during startup (or shutdown) when the primary side of the SG is pressurized and the secondary side of the SG is not pressurized. This limiting pressure differential (for normal and upset conditions) is 9.9 MPa. The maximum pressure differential during upset or faulted conditions (ASME Service Level C & D conditions) is 11.0 MPa.

In determining the Maximum Tolerable Flaw Size (MTFS), the FFSG specifies that a safety factor for primary membrane of 3.0, 2.7, 2.0, and 1.5 for ASME Service Level A, B, C, and D conditions, respectively. Therefore, the MTFS values for fret defects are calculated using a pressure differential of 29.7 MPa (i.e., 9.9×3). To determine the Flaw At Risk of Leaking (FAROL), the FFSG specifies that a safety factor of 1.0 be used. Therefore, the FAROL values for fret defects are calculated using a pressure differential of 11.0 MPa (i.e., 11.0×1).

The structural assessments are performed assuming a metal temperature of 288°C, which is representative of the temperature in the U-bend region of the DNGS steam generators during normal operation.

Characterization of Fret Scars

The length of the fret scar is an important parameter because the break-opening area (and therefore the consequential leak-rate) should a fret scar fail/leak, increases with the length of the fret scar. Therefore, for a given allowable primary-to-secondary consequential leakage, the number of fret scars that can be accommodated will decrease with the length of the fret scar.

The lower consequential leak-rate per fret scar means that shorter fret scars can be managed using the Acceptance Criteria Permitting Leakage of the FFSG. On the other hand, long fret scars must be managed using the Acceptance Criteria Prohibiting Leakage.

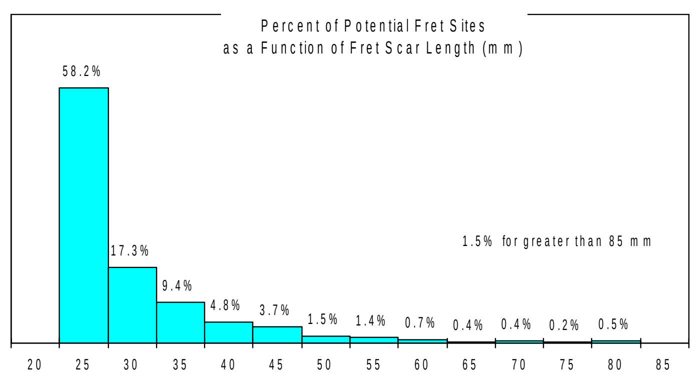

Figure 3: Distribution of Potential U-Bend Fret Scars

The number of *potential* U-bend fret scars is limited. The geometry of a fret scar can be approximated by the impression of the unfretted support structure on the tube. In the case of the DNGS steam generators there are a *potential* 54,208 flat-bar fret sites in the U-bend region. Figure 3 is a histogram of the percentage of potential fret sites versus the length of the flat-bar fret. More than 93% of the potential fret scars are 38-mm long, or less.

Figure 4 illustrates how the flat-bar fret scar have been characterized. Two parameters are used, the length and the depth of the fret scar. For flat-bar frets, this is a reasonable assumption that has been confirmed with the use of UT inspections as well as pulled tubes.

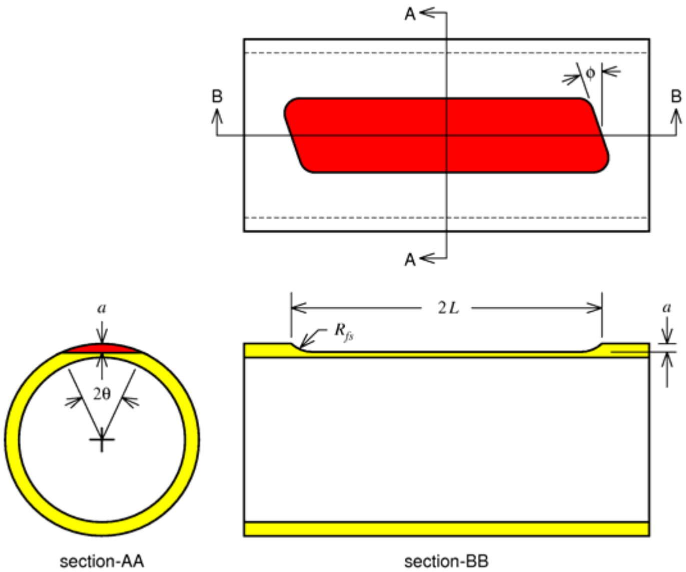

Figure 4: Characterization of DNGS Flat-Bar Fret Scar

Figure 5 is a photograph of a flat-bar fret scar that was removed for metallurgical examination from DNGS Unit 1 in 2004. The fret was 25-mm long and had a depth of 68½%tw (through-wall).

Figure 5: Removed DNGS Flat-Bar Fret Scar

STEAM GENERATOR TUBE TESTING PROJECT

To support its SG LCM, OPG has undertaken research and development in a number of areas, e.g., development and validation of Non-Destructive Examination (NDE) techniques and testing to validate both structural and consequential leak-rate models used in fitness-for-service assessments.

The Steam Generator Tube Testing Project (SGTTP) was initiated by OPG in 1999, in response to regulatory management actions related to the establishment of technical specifications for laboratory testing of steam generator tubes with flat-bar fret defects. The SGTTP is an ongoing multi-year project that is funded by OPG. The Project Execution Plans (PEP) identifies the team members, roles and responsibilities, scope of testing, deliverables, quality program, project controls, and available resources for the each year/phase of the SGTTP. The Project Manager function is performed by OPG who subcontracts the Test Contractor and Technical Advisor roles to Kinectrics and AECL, respectively. The SGTTP Technical Advisor prepares and issues a test specification for each series of tests. The PEP stipulates both minimum requirements and technical considerations that must be met by each technical specification.

The test specification identifies the geometry of each test specimen, the test procedure to be used, and provides a pre-test prediction of the test results. Once the test specification has been issued, the Test Contractor proceeds with having the specimen fabricated and measured. The testing is performed to an approved testing procedure. The test results are issued to the Technical Advisor and Project Manager in the form of a *Quick-Look Report*, digital pictures of the failed specimen, and spreadsheets containing the relevant test parameters recorded during the test. Upon completion of a series of tests, the Technical Advisor provides the Project Manager with a summary of the test results and an assessment of the potential impact of the test results on current fitness-for-service assessments.

To date, three distinct types of tests have been specified:

Burst-Pressure Tests, are structural tests. The principal test result is the internal pressure at which the remaining defect ligament fails. These tests have been performed in the Kinectrics' Burst-Test Facility. A typical burst-pressure test involves heating the specimen to 288°C and then monotonically increasing the internal pressure of the test specimen. Quasi-static loading rates are used. The test is over when the specimen fails.

Pressurized-Bend Tests, are structural tests. The principal test results are the internal pressure and bending moment at which the remaining defect ligament fails. These tests have been performed in the Kinectrics' Leak-Test Facility. A typical pressurized-bend test involves heating the specimen to 288°C, then pressurizing the specimen to 11 MPa, and then subjecting the specimen to a monotonically increasing lateral load in a 4-point bend or 3-pt bend support configuration. The test is over when the specimen fails.

Leak-Rate Tests, are used to establish the mode of failure and the consequential leak-rate for a specific flaw. The principal results of this test are the internal pressure at which the remaining defect ligament fails, the consequential leak-rate, and the Break-Opening Area (BOA). These tests have been performed in the Kinectrics' Leak-Test Facility. A typical leak-rate test involves heating the specimen to 288°C, loading the specimen until it fails, and then measuring the leak rate over an appropriate period. Both 3-point and 4-point bend support configurations have been used. Where possible, quasi-static loading rates are used. The design of these tests is complicated by the fact that it is necessary to have the specimens fail at a load that is representative of the maximum loads the tube would see in service. If the defect is too shallow, then it may not be possible to fail the specimen due to the pressure rating of the Leak-Test Facility, which is about 16 MPa. The Leak-Test Facility has been qualified for flow rates up to 2½ kg/s at 290°C and 4 kg/s at room temperature, and the total amount of leakage is limited to 200 litres.

Reference [6] describes the testing performed in the first three years of the SGTTP and how these test results are being used to validate the surface flaw models used for assessment of ligament failure in the nonmandatory appendices of the FFSG. At the end of 2005, the total number of tests conducted is 344 (274 burst-pressure, 52 leak-rate, and 18 pressurized-bend).

Material

The tubing material for DNGS steam generators was manufactured and tested in accordance with the ASME B&PV Code material specification SB-163 for Section III Class I components. The specific alloy for the tubing is Nickel-Chromium-Iron Alloy UNS N08800, which is also referred to as Incoloy 800 (I800). The four units of DNGS have sixteen steam generators, which contain a total of almost 75,000 tubes. A database of the 54 heats, 649 lots, of I800 tubing used to fabricate the DNGS steam generators was developed. Figure 6 plots the ultimate tensile strength versus the yield strength from the 649 lots of I800 tubing for DNGS steam generators.

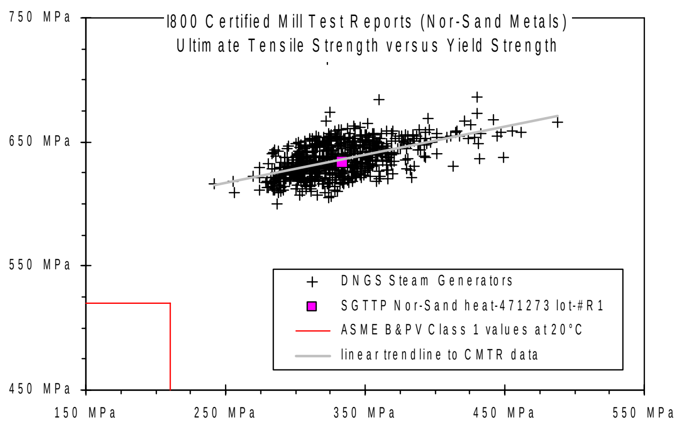

Figure 6: DNGS SG Tube CMTR Database

For the 649 data points, the mean value of yield strength is 331 MPa with a standard deviation of 33 MPa, and the mean value of ultimate tensile strength is 636 MPa with a standard deviation of 14 MPa. These mean values are significantly greater than the ASME B&PV Class 1 yield strength (210 MPa) and ultimate tensile strength (520 MPa) values specified for I800 tubing at room temperature.

The I800 tubing used in the SGTTP came from a heat of tubing that was not used in the fabrication of the DNGS steam generators. Therefore, it is necessary to ensure that the tubing used in the SGTTP is representative of the tubing used to fabricate the DNGS steam generators. In Figure 6 the lot of I800 tubing used in the SGTTP is also plotted. The values of the yield strength and ultimate tensile strength are 334 MPa and 633 MPa, respectively. The average of the yield and ultimate tensile strengths for the SGTTP material are the same as the average of the mean values for the DNGS material. Therefore, the results of tests on the SGTTP are applicable for DNGS steam generator tubes.

Test Specimens

The SGTTP has conducted tests on DNGS steam generator tubes with (and without) defects. The most relevant defects for the assessment of flat-bar fret scars are defect free specimens and flat-bar fret defects (see Figure 4). The flat-bar fret defects are fabricated using Electrical Discharge Machining (EDM), a skew angle (ϕ) of 0°, and radius (R_{fs}) of 2.4 mm.

STRUCTURAL TESTING

The SGTTP I800 flat-bar fret defect database used for structural assessments consists of 51 tests (33 burst-pressure and 18 leak-rate). All test specimens were at least 500-mm long and all tests were conducted at a nominal temperature of 288°C. Figure 7 plots the measured failure pressure against the defect depth for this database. The database covers a range of defect lengths of from 0 mm to 80 mm, and a range of defect depths from 0%tw to 92%tw. This figure includes lines equal to the pressure differentials applicable for the MTFS (29.7 MPa) and FAROL (11.0 MPa) acceptance standards.

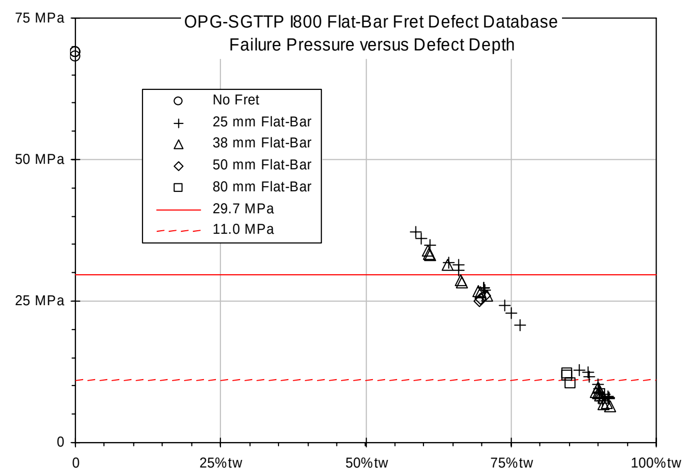

Figure 7: I800 Flat-Bar Fret Defect Test Results

Validation of the FFSG Axial Flaw Model

This experimental database was used to validate the axial flaw model provided in the nonmandatory appendices of the FFSG. As described in Reference [5], the FFSG axial flaw model was developed empirically using the results of the flat-bottom EDM axial slot, Inconel 600 tube tests conducted by the US-NRC in Phase 1 of the Steam Generator Tube Integrity

Program. This axial flaw model gives the failure pressure (P_{FFSG}) as a function of the tube parameters and flaw dimensions:

$$P_{FFSG} = \left[-0.743 + 1.825\sqrt{1-\frac{a}{t}} + 4.322\left(\frac{a}{t}\right)\left(\frac{a}{2L}\right)\right]\left(\frac{2t}{D}\sigma_f\right) \quad (1)$$

where: a is the depth of the flaw,
t is the wall thickness of the tube,
$2L$ is the length of the flaw,
D is the mean diameter of the tube, and
σ_f is the flow strength of the tube material.

The flow strength is defined in terms of the ASME specified yield strength (S_y) and ultimate tensile strength (S_u):

$$\sigma_f = 1.15\left(\frac{S_y + S_u}{2}\right) \quad (2)$$

Figure 8 plots the predicted FFSG failure pressure against the measure failure pressure for the I800 flat-bar fret defect database.

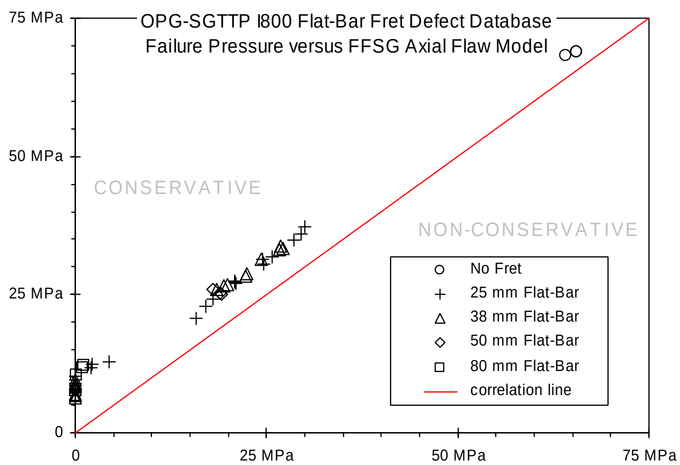

Figure 8: Validation of FFSG Axial Flaw Model

It can be seen that for all of the tests, the failure pressure is conservatively predicted by the FFSG axial flaw model. The margin of conservatism is greatest for the largest defects, i.e., the ones with the lowest failure pressure. From the figure, it is seen that there is a shift, relative to the correlation line, in the plotted data. This is due to the FFSG specified value for flow strength. At 288°C, the value of the FFSG specified flow strength is 392 MPa for the DNGS steam generator tubes. For the three defect free specimens, the average failure pressure (P_f) is 68.7 MPa, which corresponds to a flow strength of 448 MPa. The flow strength of the SGTTP material is about 15% greater than the FFSG specified value and this would explain the conservative bias of the test results.

Alternative Flat-Bar Fret Defect Flaw Model

This database can be used to develop a defect specific, axial flaw model. Using the same form of expression as Equation (1), a regression analysis gives the following expression for the best-fit failure pressure (P_{BF}):

$$P_{BF} = \left[-0.3668 + 1.334\sqrt{1-\frac{a}{t}} + 2.277\left(\frac{a}{t}\right)\left(\frac{a}{2L}\right)\right]P_f \quad (3)$$

where P_f is the average failure pressure for the three defect free specimens, P_f = 68.7 MPa. The statistics from the regression analysis are a correlation coefficient of 0.994, an F-statistic of 3763, and a standard error of 0.0185P_f (1.27 MPa). These statistics indicate that Equation (3) provides a good interpolation model for the I800 flat-bar fret defect database.

Figure 9 plots the measured failure pressure against the best-fit model, Equation (3). Four of the 51 data points are below the 90% lower-bound, which is about 8% of the database.

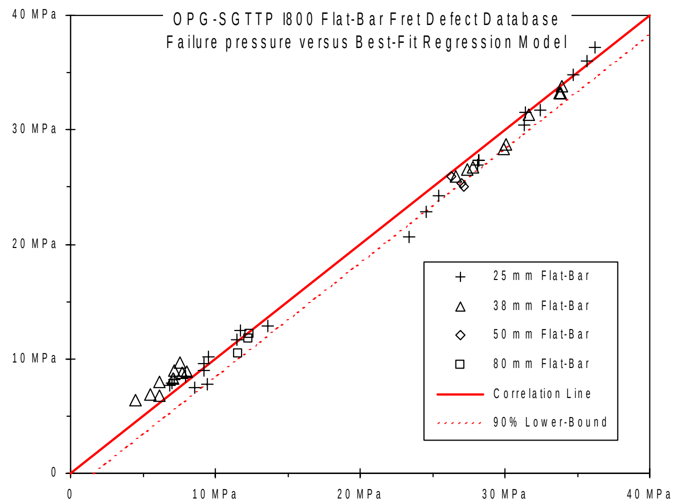

Figure 9: I800 Flat-Bar Fret Defect Best-Fit Model

From Figure 9 it is also concluded that the 90% lower-bound (i.e., Equation (3) minus 1.28 standard errors) would be an appropriate flaw model for flat-bar fret defects in Darlington steam generator tubes. This 90% lower-bound regression model (P_{LB}) is:

$$P_{LB} = \left[-0.3905 + 1.334\sqrt{1-\frac{a}{t}} + 2.277\left(\frac{a}{t}\right)\left(\frac{a}{2L}\right)\right]P_f \quad (4)$$

In developing a defect-specific flaw model, it is also necessary to account for variability in the material properties of the in-service tubing. As discussed previously (see Figure 6) a database of the DNGS steam generator tube CMTRs was compiled. From this database, the mean value of the room temperature flow strength (defined as 1.15 times the average of the yield and ultimate tensile strengths) is 556 MPa with a standard deviation of 25 MPa, which is 4.42% of the mean. The 90% lower-bound flow strength would be 94.3% (i.e., 100% -1.28×4.42%) of the mean value. This lower-bound material property is introduced by scaling Equation (4) by a factor of 0.943, which gives the DNGS flat-bar fret defect flaw model (P_{FBFD}):

$$P_{FBFD} = \left[-0.368 + 1.26\sqrt{1-\frac{a}{t}} + 2.15\left(\frac{a}{t}\right)\left(\frac{a}{2L}\right) \right] P_f \qquad (5)$$

where P_f is the average failure pressure for the three defect free specimens, i.e., $P_f = 68.7$ MPa.

For a given length of fret scar, this flaw model can be used (iteratively) to calculate the depth of the fret scar corresponding to the desired pressure differential. Using the pressure differentials applicable for the MTFS (27.7 MPa) and the FAROL (11.0 MPa), the appropriate acceptance standards can be evaluated. Table 1 summaries the acceptance standards calculated using the DNGS flat-bar fret defect flaw model.

Table 1: DNGS Flat-Bar Fret Scar Acceptance Standards

flaw length	MTFS	FAROL
12 mm	69%tw	90%tw (1)
25 mm	63%tw	87%tw
30 mm	63%tw	86%tw
32 mm	63%tw	86%tw
35 mm	62%tw	86%tw
38 mm	62%tw	85%tw
40 mm	62%tw	85%tw
50 mm	61%tw	85%tw
80 mm	61%tw	84%tw
200 mm	60%tw	83%tw

notes: (1) This value is limited by the upper-limit for acceptance standards specified in the FFSG.

LEAK-RATE TESTING

The SGTTP I800 flat-bar fret defect database includes 18 leak-rate test. All test specimens were at least 500-mm long and all tests were conducted at a nominal temperature of 288°C. The failure pressures for these tests are included in Figure 7, where the leak-rate tests are the group of tests with greatest defects depths, between 90%tw and 92%tw.

As indicated previously, the break-opening area (and therefore the consequential leak-rate) will increase with the length of the fret scar. The depth of the defect will also affect the break-opening area, because shallower defects will fail at higher pressures. The higher pressure in turn will result in larger break-opening area because of the greater enthalpy of the water used to pressurize the test specimens. For this reason, SGTTP leak-rate tests are conducted on specimens with deep defects, which are designed to fail at loads that are representative of design basis accident events.

Effect of Specimen Bending

Due to the enthalpy of the water used to pressurize the test specimens, the blowdown associated with the defect failure is significant. The actual secondary support structures are considered when specifying a support configuration for testing. Figure 10 and Figure 11 illustrate the effect that specimen support configuration can have on the break-opening area in nominally identical test specimens with flat-bar fret defects.

Figure 10 shows the large amount of bending in a 4-point bend configuration versus the small amount of bending in a 3-point bend configuration where the blowdown force was reacted by the middle support that was located opposite the defect.

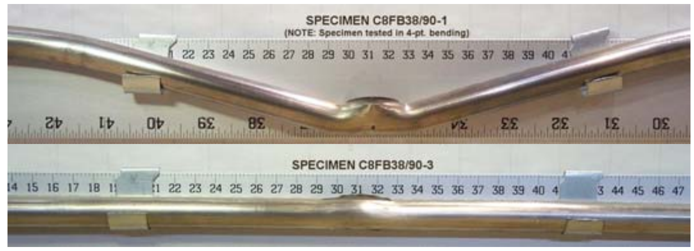

Figure 10: Effect of Specimen Bending 4-point (top) versus 3-point (bottom)

Figure 11 shows that the large amount of bending, can result in significantly larger break-opening.

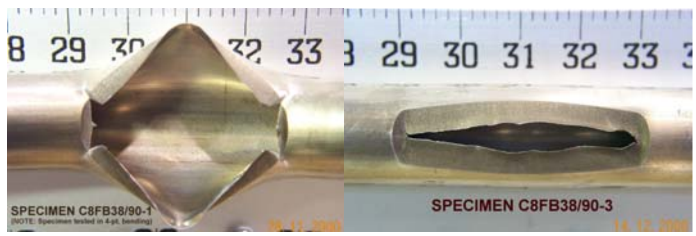

Figure 11: Effect of Break-Opening 4-point (left) versus 3-point (right)

Effect of Secondary Support Structures

In addition to this support effect, the proximity of secondary support structures can have an effect on the break-opening and the consequential leak-rate. For DNGS U-bend fretting, the secondary support structures are 410S stainless steel flat-bars. A series of leak-rate effects tests were conducted to investigate the effect that these secondary support structures would have on the consequential leak-rate of flat-bar fret scar defects. In these tests, the support configuration illustrated in Figure 12 was used. The secondary support structures were rigidly fixed and equal to the length of the fret scar defect being tested. The gap between the tube and the "top flat-bar support" was controlled at 1½ mm, and the offset of 12½ mm was used. In some tests the "bottom flat-bar support" was present while in other tests the bottom support was *not* present.

The Figure 13 compares the break-opening for two tests with 25-mm long flat-bar fret scar defects. The test *without* the bottom support (F8FB25/91-2) had a defect that was 90.0%tw, failed at 10.2 MPa, had a leak rate of 1.7 kg/s, and break-opening area that was about 50% of the flow-area of the tube. The test *with* the bottom support (F8FB25/91-6) had a defect that was 90.2%tw, failed at 9.5 MPa, had a leak rate of 0.8 kg/s, and break-opening area that was about 50% of the flow-area of the tube. When the lower support was present, it affected the shape of the break-opening and resulted in a reduction in the leak rate.

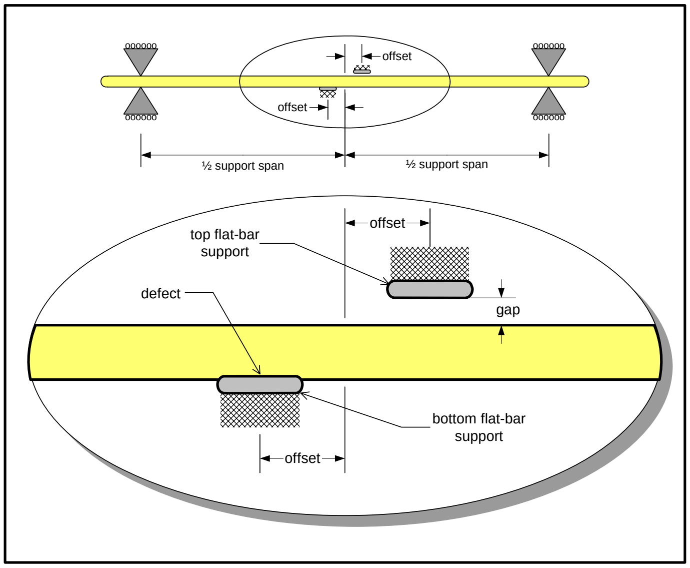

Figure 12: Leak-Rate Effects Tests Support Configuration

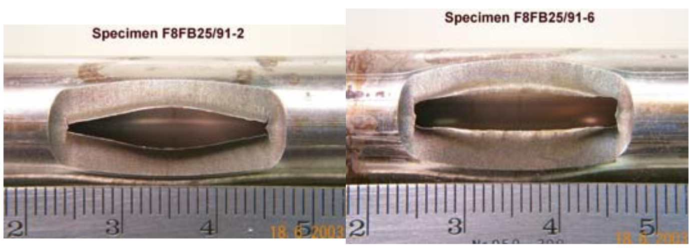

Figure 13: Proximity of Bottom Support Without Support (left) versus With Support (right)

Figure 14 and Figure 15 plot the primary test parameters for these two tests as a function of the test time, where zero time corresponds to the time at which the defect failed. In the plots, the test parameters have been normalized, by dividing the test parameter by the reported maximum value. For these leak-rate tests, the test parameters plotted are:

- The reaction load in the top flat-bar support.
- The temperature and pressure of the water in the supply vessel.
- The mass loss (water loss) from the supply vessel, which is then integrated to give the instantaneous mass loss (leak rate).
- The temperature of the water in the centre of the test specimen and the fluid pressure measure upstream and down stream of the test specimen.

The noise (oscillations) in the vessel mass loss test parameter is due to the sensitivity of the cantilevered support system used to measure the change in mass of the supply vessel. The actual leak rate for a test is averaged over the time period indicated by the vertical lines. This integration of the mass loss signal eliminates the noise in the signal. Subsequently, an electrical filter and a small mechanical damper have been added to the Kinectrics Leak-Rate Facility to eliminate this noise in the vessel mass loss signal.

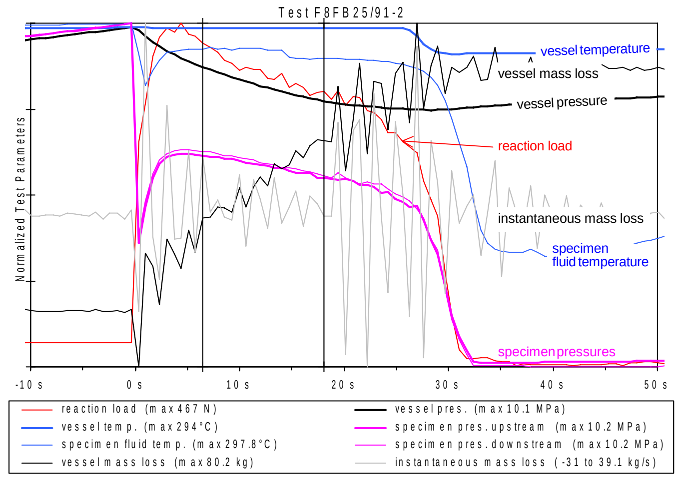

Figure 14: Test Parameters for F8FB25/91-2

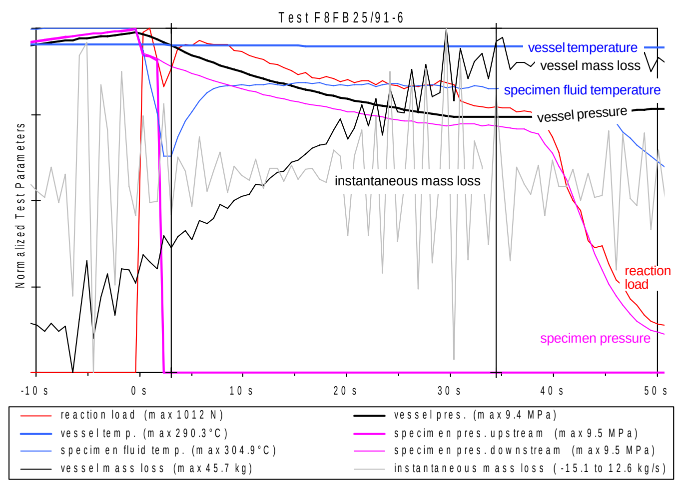

Figure 15: Test Parameters for F8FB25/91-6

The Figures illustrate that when the lower support is present that the value of the reaction load is higher. It is currently felt that this is a result of higher backpressure associated with the restricted blowdown.

In Figure 15, the specimen upstream pressure transducer signal was lost after the failure of specimen F8FB25/91-6. This was attributed to a short circuit due to the blowdown being redirected by the bottom support used in this test.

Break-Opening Area Model

In the case of longer flat-bar fret scars, the break-opening areas can be so large that the measured leak-rate is limited by pressure drop in the Kinectrics Leak-Rate Facility. Qualification testing of the facility has established limits on the unrestricted leak-rates for the facility of 2½ kg/s at 290°C and 4 kg/s at room temperature. This limitation was over come by using the Break-Opening Area (BOA) to quantify the consequential leak rate. The BOA is expressed in terms of the Flow Area (FA) of the tube (i.e., the inside cross-sectional area). Breaks where the BOA is equal to, or greater than, two times the tube flow area are equated to a tube rupture, i.e., equivalent to double-ended guillotine rupture of the tube.

The consequential leak-rate for a given BOA can is established by prorating the consequential leak-rate for a tube rupture, which for the U-bend region of DNGS SGs is 10 kg/s (reference thermal hydraulic conditions of 5.4 MPa and 100°C).

As discussed previously, the close proximity of secondary support structures affect both the break-opening and consequential leakage. Until this effect is better understood, the break-opening model is based on only those leak-rate tests performed without the “lower flat-bar support” (see Figure 12). This SGTTP I800 flat-bar fret defect, leak-rate database consists of 12 tests. Figure 16 plots this flat-bar fret defect database.

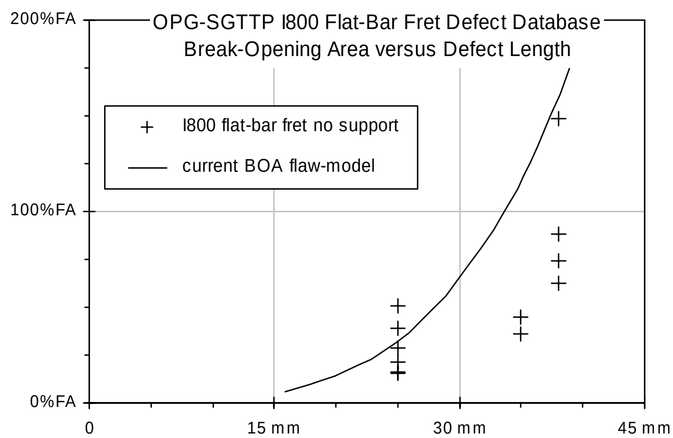

Figure 16: BOA for Long Flat-Bar Fret Scars

As can be seen from this figure, the break-opening areas from the leak-rate tests exhibit a large amount of scatter. The reason for the scatter is not well understood and so additional leak-rate tests are being performed to try and gain insight into this phenomenon.

Figure 16 shows the BOA flaw-model being used to estimate the consequential leak-rate of DNGS SG tubes with flat-bar fret defects. This model predicts that for flat-bar fret scars 40-mm or longer in DNGS SG tubes with fail with a leak-rate equivalent to a tube rupture (i.e., double-ended guillotine break). Therefore, the *Acceptance Criteria Prohibiting Leakage* must be applied for these longer frets.

RECENT DNGS OPERATING EXPERIENCE AND APPLICATION OF SGTTP RESULTS

The acceptance standards (MTFS and FAROL) developed from the burst-pressure test results have been used in establishing the scope and plugging criteria for SG inspection campaigns at Darlington. For example, in 2000, alternative acceptance standards were developed using available test data, a subset of the I800 flat-bar fret defect database presented in this paper. In particular, the larger values of the MTFS were sufficient to avoid the plugging of hundreds of Darlington steam generator tubes while a retrofit fix was being designed and installed.

The results of the SGTTP leak-rate tests were used to develop a model for predicting the consequential leak-rate from flat-bar fret scars in DNGS SG tubes. The results from this model are used in conjunction with the safety assessment of consequential tube failures during limiting design basis accident scenarios to establish limits on the number of flat-bar fret scars that could fail during an accident event. These assessments are then used with statistical predictions of future fret scar populations for the operational assessments of planned operating periods.

During the Darlington Unit 1 (D1) Spring 2004 outage, worse than expected fretting degradation at the U-bend AVB supports was observed. The previous inspection of the D1 SGs was in 2000. The D1 2004 observations found both new frets (that had initiated after the previous inspection in 2000) and existing frets exceeding the MTFS and FAROL limits. It was also observed that the growth model used for the statistical predictions was no longer bounding. In all four D1 SGs, 17 frets were observed with depths greater than the MTFS limit and three frets were observed with depths of greater than the FAROL limit (per the current Table 1 values, only two frets would be greater than FAROL). All of these deep frets were in the known area at risk (AAR) of degradation and had fret scar lengths of ≤25 mm. Therefore, the Acceptance Criteria Permitting Leakage were applied.

The SGTTP I800 flat-bar fret defect database was used to demonstrate that the required safety factors against tube rupture were maintained in the D1 SGs (see Figure 7). The BOA model (Figure 16) was used to demonstrate that six frets with length 25 mm could fail without exceeding the allowable consequential leakage limit of 10 kg/s. Therefore, margin existed between the estimated leakage from the three frets exceeding FAROL and the allowable leakage limit, and the overall condition monitoring assessment was shown to be acceptable. A total of 135 tubes were plugged in the D1 SGs due to fretting at U-bend/AVB supports during the Spring 2004 outage. Revised statistical approaches were developed to take into account the higher fret growth rates and fret initiation (see related presentation in this conference). The retrofit auxiliary AVB fix, described later in this paper, was also installed in the D1 SGs during the Spring 2004 outage (the same fix as had been installed in the D4 SGs in 2003), but no beneficial effects of this fix were credited in the plugging criteria or growth models used to perform the Operational Assessment.

Following the D1 2004 observations, previous results from the most recent inspections from the D2 SGs in 2001, the D3 SGs in 2002 and the D4 SGs in 2003 were reviewed. Although there had been no observations of deep frets and no failures of the statistical prediction models at these second inspections of the D2, D3 and D4 SGs, it was noted that some new frets also appeared to be initiating between inspections. Therefore, the new statistical models developed after the D1 2004 results were also applied to D2, D3 and D4 SGs and revised dispositions were submitted for each unit. A decision was made to perform a limited inspection of the U-bend fretting AAR in the D3 SGs during the Fall 2004 outage to compare against the D1 SGs and the revised disposition. The retrofit auxiliary AVB fix was also installed during the D3 Fall 2004 outage. About six months later, a similar inspection and auxiliary AVB installation was completed in the D2 SGs in Spring 2005. In both the D3 2004 and D2 2005 inspections, no deep frets were observed in any SGs. All D2 and D3 results were well bounded by the revised fret models and rates of fret initiation and growth were lower than in the D1 SGs.

Over the period of 2003 to 2005 a retrofit fix was installed in all sixteen Darlington steam generators. The fix consisted of auxiliary AVB supports installed in between the existing arch-bar supports to complement the existing U-bend anti-vibration system. The design had to optimize the coverage to the areas of known or more severe degradation. This requirement set the penetration depth of the auxiliary AVBs and the number of column lanes across the tube bundle that the bars were installed in. Six column lanes under the inner tie-tube were excluded from the design as it was considered non-cost-effective, which left four tube columns in the affected area without contact to the auxiliary AVBs. Based on where the fretting was seen along the tubes, four auxiliary AVB supports were placed in between the arch-bar supports from the second U-bend support on the cold side of the bundle (i.e., CU2) to the third U-bend support on the hot side of the bundle (i.e., HU3), with a weighting more towards the cold-leg side. The new supports in between CU2/CU3 and CU4/HU4 were centered and angled to bisect the angle between adjacent supports, while the other two, CU3/CU4 and HU4/HU3, were positioned closer, respectively, towards the CU4 and HU4 supports, to avoid the cross tie-tube obstructions. Based on the fretting inspection data, coverage exceeds 90% of the U-bend fretted tubes.

In Spring 2006, the first re-inspection of a Darlington unit after installation of the auxiliary AVB fix was performed in D3. The operating interval was only about 1.3 years since installation in 2004 and so it was difficult to quantify any benefits, however no significant growth or initiation of original U-bend AVB frets was observed. Some new shallow frets (25 in 23 tubes) with maximum depth 16%tw were detected at the auxiliary AVBs. This observation may reduce the expected relief on extent of inspection and plugging anticipated from auxiliary AVB mitigation of the original AVB U-bend fretting. The upcoming re-inspection of the D1 SGs during the Fall 2006 outage will provide a good opportunity for further assessment.

SUMMARY

Structural and leak-rate testing has provided a robust and cost-effective technical basis to support the disposition of the U-bend fretting observed in the Darlington steam generators. The results of these tests helped to minimize the number of tubes removed from service due to plugging, to demonstrate adequate margins in fitness-for-service assessments and to provide sufficient time to design and implement a retrofit fix.

NOMENCLATURE

The following is a list of acronyms/initialisms and a list of symbols used in this paper.

%tw	percent through-wall, normalized depth of a flaw.
AAR	area at risk.
AECL	Atomic Energy of Canada Limited.
ASME	American Society of Mechanical Engineers.
AVB	Anti-Vibration Bar.
B&PV	Boiler and Pressure Vessel.
BOA	Break-Opening Area.
CANDU	CANadian Deuterium Uranium. CANDU is registered trademark of AECL.
CMTR	Certified Mill Test Report.
CNSC	Canadian Nuclear Safety Commission.
CSA	Canadian Standards Association.
CU#	U-bend support (# = 1 to 4) on the *cold* side of the bundle, see Figure 2.
DNGS	Darlington Nuclear Generating Station.
ECT	Eddy Current Testing.
EDM	Electrical Discharge Machining.
FA	Flow Area.
FAROL	Flaw At Risk Of Leaking.
FFS	Fitness-For-Service.
FFSG	Fitness-For-Service Guidelines.
FIV	Flow Induced Vibration.
HU#	U-bend support (# = 1 to 4) on the *hot* side of the bundle, see Figure 2.
I800	Incoloy, Alloy 800.
SG	Steam Generator.
LCM	Life Cycle Management.
MTFS	Maximum Tolerable Flaw Size.
NDE	Non-Destructive Examination.
OPG	Ontario Power Generation.
PEP	Project Execution Plan.
SGTTP	Steam Generator Tube Testing Project.
US-NRC	United States Nuclear Regulatory Commission.
UT	Ultrasonic Testing.

a	depth of the fret scar, see Figure 4.
D	mean diameter of the tube.
$2L$	physical length of the fret scar, see Figure 4.
P_{BF}	failure pressure, Best-Fit regression model.
P_f	failure pressure of a defect-free tube.
P_{FBFD}	failure pressure, Flat-Bar Fret Defect axial flaw model.
P_{FFSG}	failure pressure, FFSG axial flaw model.
P_{LB}	failure pressure, Lower-Bound regression model.
R_{fs}	radius of fret scar, see Figure 4.
S_u	ultimate tensile strength of tube material given in Table U of Section II of the ASME B&PV Code.
S_y	yield strength of tube material given in Table Y-1 of Section II of the ASME B&PV Code.
t	wall thickness of the tube.
ϕ	skew angle of fret scar, see Figure 4.
2θ	enclosed angle of fret scar, see Figure 4.
σ_f	flow strength of the tube material.

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