FRETTING-WEAR DAMAGE: A SUMMARY OF RECENT FINDINGS

F.M. Guérout and N.J. Fisher

ABSTRACT

Flow-induced vibration of steam generator (SG) tubes may sometimes result in fretting-wear damage at the tube-to-support locations. Fretting-wear damage predictions are largely based on experimental data obtained at representative test conditions. Fretting-wear of steam generator materials has been studied at the Chalk River Laboratories for two decades. Tests are conducted in fretting-wear test machines that simulate steam generator environmental conditions and tube-to-support dynamic interactions.

A new high-temperature force and displacement measuring system was developed to monitor tube-to-support interaction (i.e., work-rate) at operating conditions. This improvement in experimental fretting-wear technology was used to perform a comprehensive study of the effect of various environment and design parameters on steam generator tube wear damage. This paper summarizes the results of tests performed over the past four years to study the effect of temperature, water chemistry, support geometry, and tube material on fretting-wear.

The results show a significant effect of temperature on tube wear damage. Therefore fretting-wear tests must be performed at operating temperatures in order to be relevant. No significant effect of the type of water treatment on tube wear damage was observed. For predominantly impacting motion, the wear of steam generator tubes in contact with 410 stainless steel is similar regardless of whether Alloy 690 or Alloy 800 is used as tubing material or whether lattice bars or broached hole supports are used.

Based on results presented in this paper, an average wear coefficient value is recommended that is used for the prediction of SG tube wear depth versus time.

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1. INTRODUCTION

Steam generator tubes are supported at intermediate points by supports in the straight-leg region and by anti-vibration bars in the U-bend region. Well-defined clearances, for thermal expansion and manufacturing considerations, are maintained between the tubes and the supports. Flow-induced vibration of steam generator (SG) tubes generates tube-to-support or tube-to-tube contacts that can result in SG tube damage and ultimately in SG tube leaks. According to a survey of steam generator tube performance during the 1992-1993 period, approximately 60 reactors reported fretting-related leaking, and a total of 500 to 600 tubes were plugged each year [1]. Therefore, SG tube fretting remains an important issue that requires that guidelines and design criteria be defined to establish acceptable limits of flow-induced vibration: the goal being to minimize fretting-wear and guarantee long-term SG tube integrity.

At Atomic Energy of Canada Limited (Chalk River Laboratories) fretting-wear tests are conducted in machines that simulate a steam generator environment (temperature, pressure, chemistry) and tube-to-support dynamic interactions. Earlier work focused on relating the tube damage to the tube/support interaction using a parameter called work-rate, which combines both contact force and sliding distance.

At the 1994 CANDU® Owners Group (COG) SG Conference, Fisher et al. showed that over small ranges of work-rate, a constant value, called the wear coefficient, can be used to relate the tube damage to the tube/support interaction [2]. The VIBIC code (VIbration of Beams with Intermittent Contact) compares tube-to-support interaction using analytical techniques and predicts fretting-wear using these experimentally-derived wear coefficients. Therefore, the SG tube life prediction capability is largely based on experimental data obtained at representative test conditions.

More recent work takes advantage of a new high-temperature force measuring system that was developed at CRL to allow for in-situ work-rate measurement at temperatures up to 350°C. Over the past four years, various test programs were initiated at CRL to study the effect of the environment on SG tube wear coefficients, as well as the effect of design parameters such as support geometry and tube material. The tube excitation level chosen was as close as possible to operating tube/support interaction levels while still generating measurable wear volumes within a 500-hour test duration. Work-rate usually ranged from 6 to 18 mW.

The first environmental parameter to be studied was temperature. The objective of these tests was not only to study the effect of temperature on fretting-wear, but also to evaluate the relevancy of tests performed at operating conditions as opposed to tests performed, for economic reasons, at lower temperatures. Another test series was performed to study the effect on

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fretting-wear of various types of SG chemistry controls (ammonia and hydrazine, morpholine only, morpholine and hydrazine, addition of phosphates or addition of boric acid). Test results reported in this paper also include a comparison of wear coefficients obtained for different types of support geometry (lattice bar, broached plates, scallop bars), tube material (Incoloy 800, Inconel 600, Inconel 690), and support material (410 SS, 321 SS).

2. FRETTING-WEAR TEST FACILITY AND EXPERTISE

Fretting-wear of SG materials has been studied experimentally at AECL for more than 20 years. The early test programs date back to SG tube failures that occurred at the Douglas Point prototype CANDU power station [3]. Since that date, several fretting-wear machines have been manufactured and commissioned at the Chalk River Laboratories. As of today, the test facility consists of eight machines for which temperature, pressure, and water chemistry can be independently controlled. Two of these machines and associated equipment are shown in Figure 1. The operating temperature and pressure limits are 320°C and 11.7 MPa. Each machine consists of an autoclave, excitation tube, instrumentation platform, vibration generator, and supporting structure. The machines are connected to a pressurized loop with an accumulator, a water storage tank, a make-up pump, and process instrumentation for temperature and pressure control. Interaction at the SG tube/support location is provided by the vibration generator via the excitation tube. This tube protrudes outside the autoclave through a flexible sleeve.

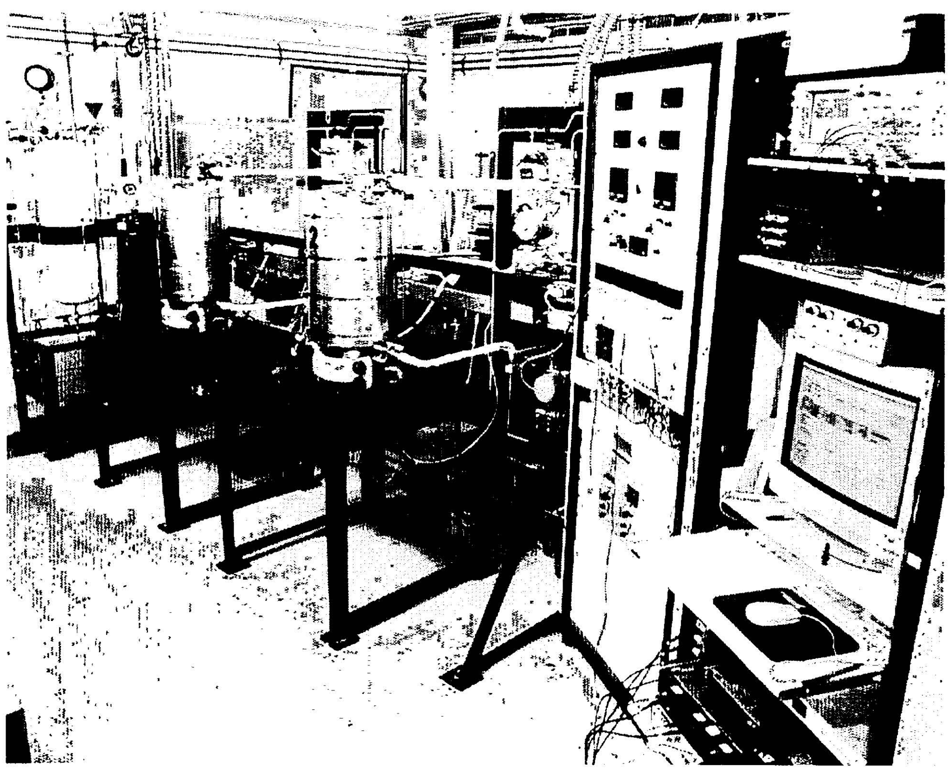

Figure 1: Two of the Eight High-Temperature Machines Used at AECL-CRL

The relative tube-to-support motion during operation is monitored using high-temperature eddy-current displacement probes. Substantive work was undertaken to improve the relevance of signals delivered by these displacement probes at high temperature. The transducer environment and the relative position of the transducer-to-transducer holder were shown to have a significant effect on probe sensitivities. A calibration cell was fabricated to simulate the presence of force transducers in the fretting-wear machine and allow for calibrations at temperatures up to 320°C. The change in sensitivity with temperature was in the order of 10 to 20% between 25 and 315°C.

In the past, tube-to-support interaction forces were measured at room temperature before and after tests. Forces could not be measured at temperatures above 150°C, due to difficulties in thermal compensation of the piezoelectric crystals used in miniature force transducers. To remedy this problem, high-temperature pressure transducers were modified for use as force transducers and in 1991, a new force measurement system capable of operation at temperatures up to 350°C was designed. In this system, the support specimen is held by four transducers arranged at 90° increments around its circumference. Signals from opposing transducers are electronically summed to yield the net impact force in perpendicular directions. Accurate calibrations of this high-temperature force measurement system were performed at temperatures up to 315°C. Temperature was shown to have a very small effect on transducer sensitivities (<5%) [4].

Displacement and force measurements are used to calculate the work-rate, which was shown to be an appropriate parameter for relating tube damage to the tube/support interaction [1]. Work-rate is a parameter introduced by Frick et al. [5] to quantify the rate of energy being dissipated at the contact. It is a quantity derived from normal force, F_n, sliding distance, s, and sample time, t, expressed as follows:

$$\dot{W} = \frac{1}{t}\int F_n . ds \tag{1}$$

The work-rate, as defined in Equation 1, is used to normalize the wear-rate. The wear-rate calculation is based on either weight losses of the SG tube specimen or on wear volumes measured by 3-D surface profilometry.

Equation 2 shows the relationship between wear rate $(\dot{V})$ and work-rate $(\dot{W})$, derived from the Archard's Law [6]. This relationship is used to define a dimensional wear coefficient, K, whose units are m^2/N or Pa^{-1}:

$$K = \frac{\dot{V}}{\dot{W}} \tag{2}$$

Work-rate measurement at high-temperature accounts for variations of tube/support interaction levels throughout a test. It also allows the work-rate to be controlled during a test and facilitates testing within a well-defined work-rate range.

During a typical 500-hour duration test, work-rate is measured daily using an AECL proprietary software package called WRAP (Work-Rate Analysis Program), based on the LabVIEW® data analysis package. The software is used to compute parameters such as normal, shear, and resultant forces, contact percentages, sliding distances and work-rates. Low-pass digital filters are usually applied with cutoffs at 1 kHz for displacements and 5 kHz for forces. A preset threshold value on force signal is used to define contact (usually 5 to 10% of the maximum peak force value). The characteristics of sample acquisition for a SG tube/support configuration is usually a sample time of up to 4 seconds at a sample rate of 16 kHz.

Testing of the effect of a specific parameter on fretting-wear or testing for a specific tube/support configuration is usually repeated at least twice to assess the dispersion of results.

3. EFFECT OF TEMPERATURE ON SG TUBE WEAR

3.1 Previous Studies on the Effect of Temperature on Wear

Early test results on the effect of temperature on fretting-wear were obtained by Ko in 1985 [7]. In this case, the depth of wear on tubing samples was given as a function of temperature for both Incoloy 800/304 stainless steel and Incoloy 800/carbon steel material combinations. This data was used to generate equivalent wear volume rates. The work-rate was approximated based on the level of tube interaction used for these tests. Temperature was shown to have a significant effect on wear coefficients. Wear coefficients at SG operating temperatures were shown to be 5 to 10 times higher than at 25°C.

A similar effect of the temperature on fretting-wear was shown for zirconium alloys for small amplitude impacting motion (work-rate of 1 to 5 mW) [8]. Maximum damage was observed in the 225 to 286°C temperature range (approximately 10 times more than at 25°C). Beyond these temperatures, at 300 and 315°C, less damage was observed (approximately seven times less).

Similar trends were observed in a study by Saito and Mino of two heat-resisting alloys [9]. As temperature increased, wear was shown to increase up to a temperature range of 200 to 300°C, beyond which it decreased rapidly.

3.2 Current Study on the Effect of Temperature on SG Tube Wear

In 1993, a test program was launched at CRL to study the effect of SG environment on SG tube fretting-wear. Tests were first performed to investigate the effect of temperature [3]. The objective was to assess the relevancy of tests performed at operating conditions as opposed to tests performed, for economic reasons, at lower temperature.

Tests were performed for four temperatures: 25, 215, 265, and 315°C. Three high-temperature fretting-wear machines equipped with the new high-temperature force measurement system described in Section 2 were used simultaneously for this test program. Identical chemistry parameters such as pH, oxygen content, and hydrazine content were maintained for all tests performed. A pH of 9 was controlled by the addition of morpholine. The oxygen level was maintained below 5 ppb. Incoloy 800 tubing was used for the SG tube specimens. The typical outside diameter was 15.94 mm. The support material was 410 stainless steel. Two types of supports were tested: flat bar and broached hole. The support width was 25.4 mm for the flat bar supports and 27.2 mm for the broached hole supports. Tube-to-support diametral clearances were 420 and 360 μm, respectively. Impacting motion was dominant for all tests. Typical tube motion is shown in Figures 2a and 2b for both types of support. The Incoloy 800 tube/410 SS flat bar support configuration is typical of the U-bend region of Darlington and new CANDU steam generators. The Incoloy 800/410 SS broached hole support configuration is typical of the straight leg of earlier steam generators.

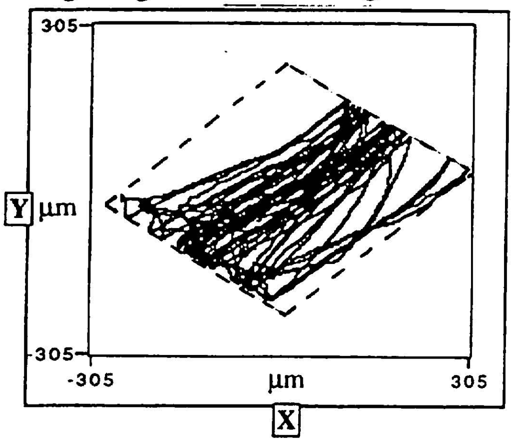

Figure 2a: Tube-To-Flat Bar Support Relative Motion.

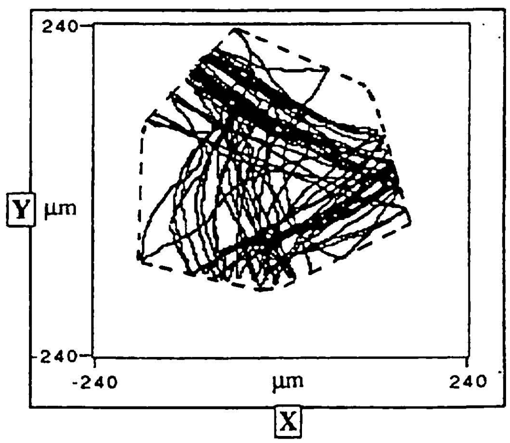

Figure 2b: Tube-To-Broach Hole Support Relative Motion.

Wear coefficients are plotted in Figure 3 for the flat bar support configuration (for work-rates ranging from 12 to 25 mW), and in Figure 4 for the broached hole support configuration (for work-rates ranging from 12 to 40 mW). For both types of support geometry, the wear coefficient increases between 25 and 215°C, and decreases between 215 and 315°C.

The results are consistent over a large range of work-rate values. For the tube/flat bar support configuration, and for work-rates in the order of 20 mW, the comparison of wear coefficients between elevated temperatures and room temperature is as follows: the wear coefficient is approximately 30 times higher at 215°C than at 25°C, 20 times higher at 265°C than at 25°C, and 2 times higher at 315°C than at 25°C. Therefore, temperature has a significant effect on fretting-wear and, in order to be relevant, tests must be performed at operating temperatures.

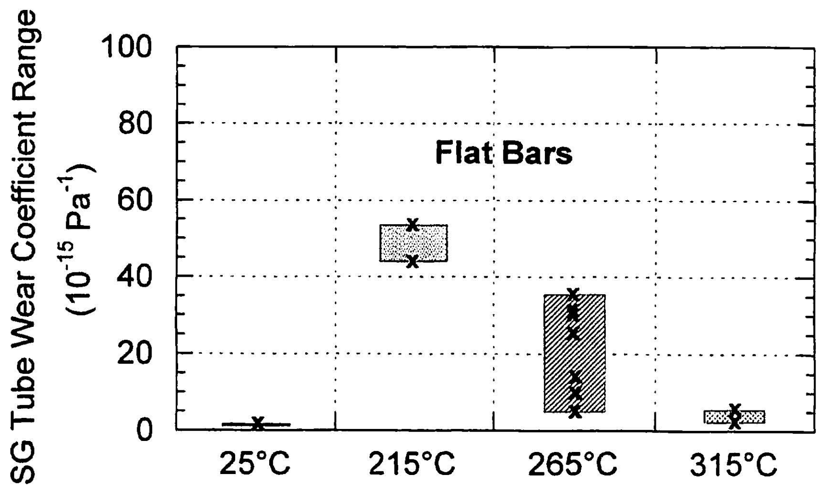

Figure 3: Fretting-Wear of Alloy 800 tubes/410 SS Flat Bar Supports: Effect of Temperature (12 mW < Work-Rate < 25 mW).

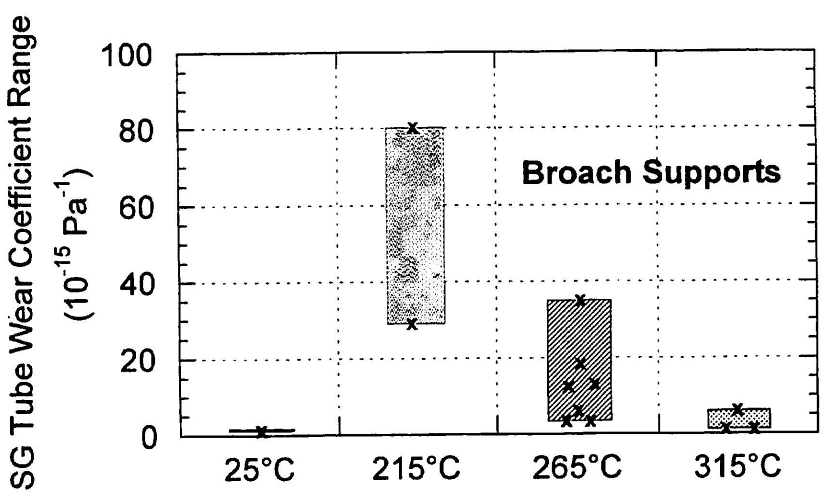

Figure 4: Fretting-Wear of Alloy 800 Tubes/410 SS Broached Supports: Effect of Temperature (12 mW < Work-Rate < 40 mW)

4. EFFECT OF WATER CHEMISTRY ON SG TUBE WEAR

In 1995/96, a fretting-wear test program was performed to study the effect of SG normal water chemistry on tube fretting-wear. The objectives were to compare the normal water chemistries in use at the various stations from a fretting-wear perspective (effect of using ammonia versus morpholine control, effect of hydrazine, effect of phosphates, effect of boric acid addition), and also to provide baseline wear coefficients prior to the study of the effect of more corrosive environments resulting from faulted water or ion concentration conditions. The test program was divided into five series of three identical tests, i.e., comparison of wear coefficients using the Darlington, Gentilly-2, Point Lepreau, Bruce A, and Bruce B SG chemistries.

The first three series were performed using the Darlington, Gentilly-2, and Point Lepreau normal SG chemistry. The Darlington plant uses ammonia and hydrazine (pH = 9.8, $O_2 < 5$ ppb). The Gentilly-2 plant uses morpholine only (pH = 9.3, $O_2 < 5$ ppb). The Point Lepreau plant is the only Canadian station operating with congruent phosphate treatment (morpholine, hydrazine, and phosphate with pH = 9.5 and $O_2 < 5$ ppb). Flat bar supports made of 410 SS stock bar were used for all tests of these three first series even though broached supports are used at the Gentilly-2 and Point Lepreau stations. This choice was deliberately made to prevent the effect of water treatment being masked by an effect of support geometry. Incoloy 800 SG tubing was used for the tube specimens. The test duration was 500 hours for each test and the work-rate was maintained in the 5 to 10 mW range. This was done to be as representative as possible of real steam generator tube excitation, while still generating measurable wear volumes at the end of a 500-hour test.

Even though low work-rates were used, the results showed relatively high wear-rate-to-corrosion-rate ratios. These ratios indicate the level of possible interaction of wear and corrosion. It is indicated in the literature that this interaction is likely to affect the wear results if the ratio is less than 10 to 1 [10]. For the current tests, work rates of 5 to 10 mW resulted in wear rate-to-corrosion-rate ratios in the order of 200 to 1 for the tube specimens and 50 to 1 for the supports. Even for realistic SG tube/support interaction levels of 1 to 5 mW, the ratios would still be higher than the limit ratio of 10 to 1, below which wear-corrosion interaction occurs.

The wear coefficients for the Darlington, Gentilly-2, and Point Lepreau SG chemistries are shown in Figure 5. Average wear coefficients of 28×10^{-15} Pa^{-1}, 20×10^{-15} Pa^{-1}, and 11×10^{-15} Pa^{-1} were derived for the Darlington, Gentilly-2 and Point Lepreau SG chemistries, respectively.

The wear coefficients obtained for each series confirm that, within the dispersion of results observed for each series (between ±30% and ±70%), the type of normal SG water treatment used has no significant effect on fretting-wear damage so long as the chemistry parameters are kept within normal specifications. The average wear coefficient obtained using the Point Lepreau chemistry is slightly lower than for the Darlington and Gentilly-2 chemistries, but additional testing would be required to confirm this trend.

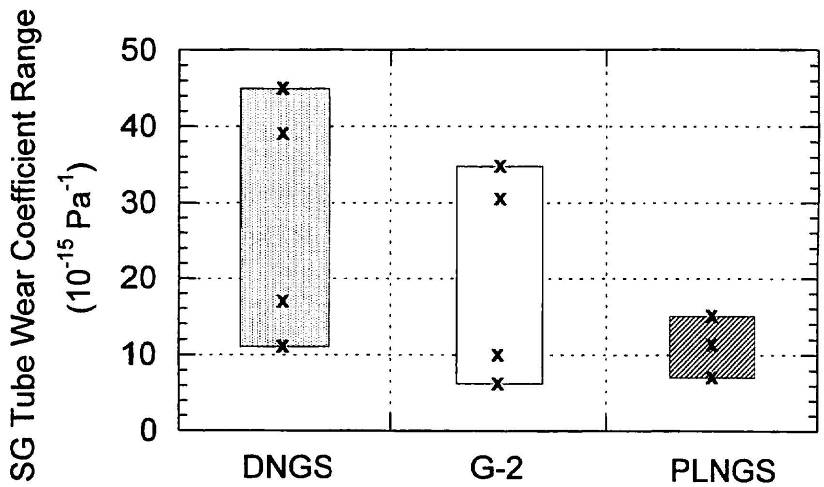

Figure 5: Fretting-Wear of Alloy 800 Tubes/410 SS Flat Bar Supports: Effect of the Type of SG Chemistry Control (6 mW < Work-Rate < 11 mW).

Two series of three 500-hour tests were performed to study the effect of adding boric acid to normal SG water chemistry. At the Bruce-B station, the SG water chemistry is controlled using morpholine and hydrazine (pH = 9.7, O_2 < 5 ppb). At the Bruce-A plant, boric acid is added to the SG normal water to mitigate corrosion of the carbon steel supports. The tube/support configuration used for all tubes of these two series was Inconel 600/A108-1018 carbon steel drilled hole. The drilled hole specimens were used to simulate the scallop bar geometry. Typical tube-to-support relative motion for this test series is shown in Figure 6. The wear coefficient results are shown in Figure 7 for both types of water chemistry. For the Bruce-B chemistry, wear coefficients ranged from 5×10^{-15} to 19×10^{-15} Pa^{-1}, averaging at 13×10^{-15} Pa^{-1}. For the Bruce-A chemistry (boric acid added), wear coefficients ranged from 14×10^{-15} to 26×10^{-15} Pa^{-1}, averaging at 19×10^{-15} Pa^{-1}. Considering the dispersion of results for each series, no significant effect of boric acid addition on SG tube wear coefficient was observed: the dispersion of results was 14×10^{-15} using the Bruce-B chemistry and 12×10^{-15} Pa^{-1} using the Bruce A chemistry. The difference in average coefficients using the two different types of chemistry was only 7×10^{-15} Pa^{-1}.

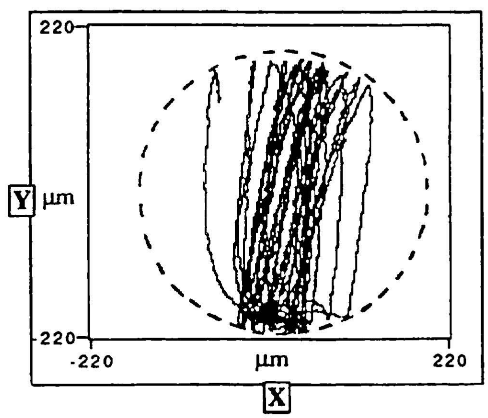

Figure 6: Tube-to-Drilled Hole Support Relative Motion

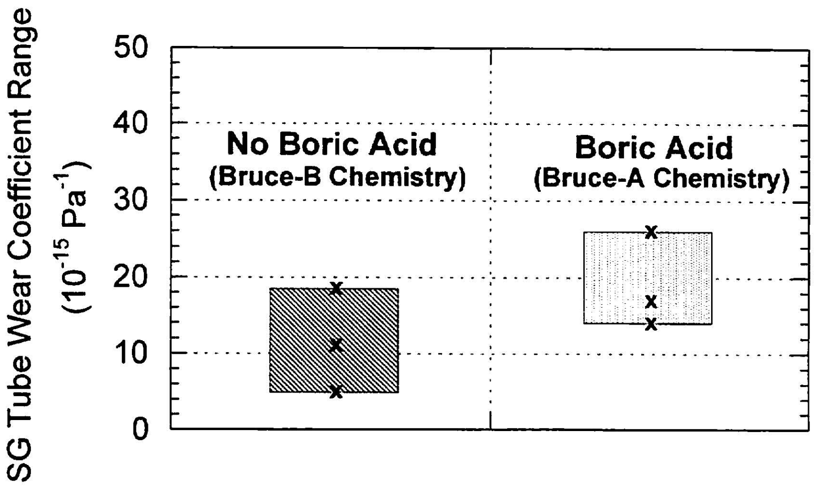

Figure 7: Fretting-Wear of Alloy 600 Tubes/A108-1018 Scallop Bars: Effect of Boric Acid Addition (6 mW < Work-Rate < 10 mW)

5. EFFECT OF SUPPORT GEOMETRY ON SG TUBE WEAR COEFFICIENT

Wear coefficient results were compared for ten 500-hour tests performed at 265°C for the Incoloy 800/410 SS support configuration: five tests using a flat bar support and five tests using a broached hole support. Typical tube/support relative motions for both types of supports are shown in Figures 2a and 2b. The work-rate range investigated was 8 to 27 mW. The wear coefficient results are shown in Figure 8. For the flat bar supports, the SG tube wear coefficients ranged from 6×10^{-15} to 35×10^{-15} Pa^{-1}. For the broached hole supports, the range was 3×10^{-15} Pa^{-1} to 35×10^{-15} Pa^{-1}.

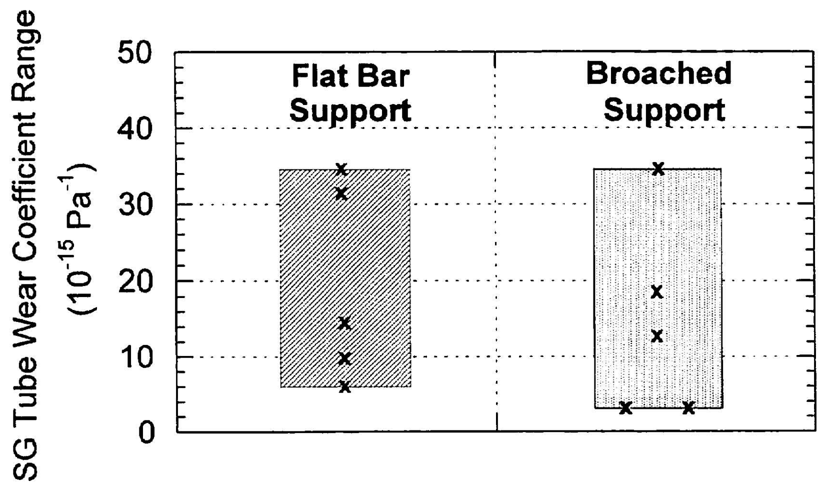

Figure 8: Fretting-Wear of Alloy 800 Tubes/ 410 SS Supports: Effect of Support Geometry (8 mW < Work-Rate < 27 mW).

Within the observed dispersion, average wear coefficients for I800 tubing in contact with both types of support are similar.

6. COMPARISON OF FRETTING-WEAR COEFFICIENT FOR ALLOY 690 AND ALLOY 800 SG TUBES

Alloy 690 is now used as replacement material for Alloy 600 in most Pressurized Water Reactor (PWR) steam generators because of its better resistance to stress corrosion cracking (SCC). In CANDU reactors, the need for a replacement is not crucial since Alloy 800 tubes have been shown to be less prone to SCC than Alloy 600 tubes. Nevertheless, CANDU customers may prefer Alloy 690 to Alloy 800 for their steam generators. Therefore, fretting-wear testing of Alloy 690 tubing was requested to compare its performance to that of Alloy 800 tubing under identical test conditions. Six tests were performed at 265°C for Alloy 690 tubing against a 410 SS flat bar support with work-rates ranging from 10 to 26 mW. The test duration was 500 hours. The typical tube/support relative motion used for these tests is shown in Figure 2a. The results were compared to several tests using Alloy 800 that were performed earlier in 1993/94 and 1995 under identical test conditions (see Sections 3.2 and 4).

Wear coefficients are compared in Figure 9 for work-rate varying from 8 to 21 mW. For Alloy 690, wear coefficients ranged from 9 x 10^{-15} to 49 x 10^{-15} Pa^{-1}, with the average at 24 x 10^{-15} Pa^{-1}. For Alloy 800, wear coefficients ranged from 6 x 10^{-15} to 35 x 10^{-15} Pa^{-1} with the average at 25 x 10^{-15} Pa^{-1}. Therefore, for predominantly impacting motion, the fretting-wear behaviour of SG tubes against 410 SS flat bar supports is similar regardless of whether Alloy 690 or Alloy 800 is used as tubing material.

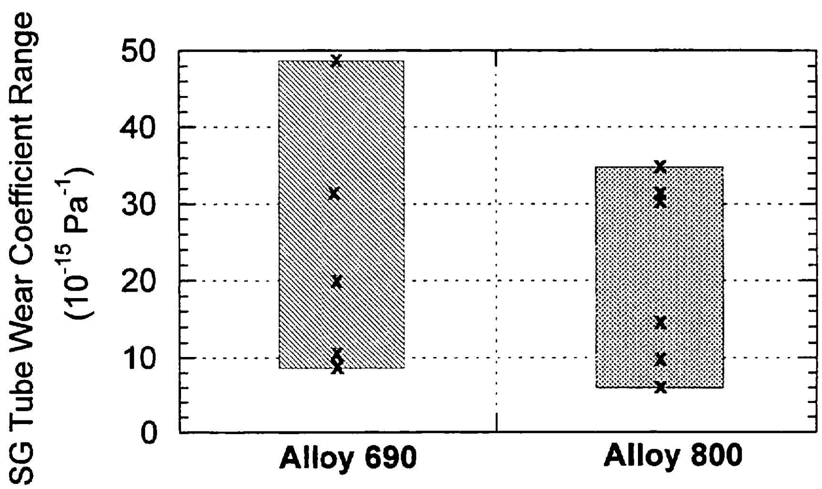

Figure 9: Fretting-Wear of SG Tubes/410 SS Flat Bar Supports: Effect of Tube Material (8 mW < Work-Rate < 21 mW).

7. DISCUSSION

The test results summarized in Sections 3 to 6 show that SG tube wear coefficients do not vary significantly (within the scatter of results), whether a normal SG chemistry is controlled with ammonia or morpholine, whether phosphates or boric acid are added, whether a flat bar support or a broached support is used, or whether Alloy 800 or Alloy 690 is used for SG tubing. At 265°C, for work-rates ranging from 6 to 18 mW, wear coefficients range from 5 x 10^{-15} Pa^{-1} to 45 x 10^{-15} Pa^{-1} for the various types of test condition described above. The test results are shown in terms of wear rate versus work-rate in Figure 10. The average SG tube wear coefficient value in the 6 to 18 mW work-rate range is 20 x 10^{-15} Pa^{-1}. The conservative value for design purpose is 40 x 10^{-15} Pa^{-1}.

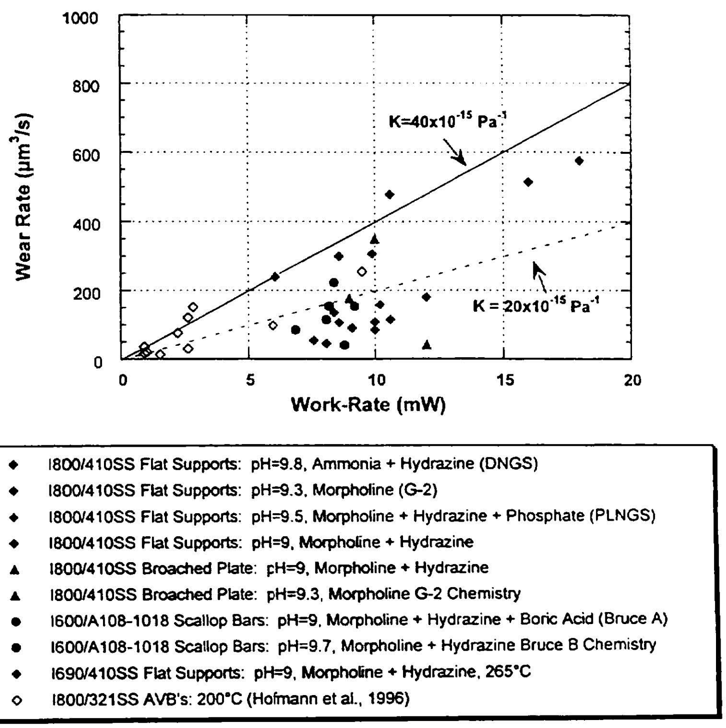

Figure 10: Fretting-Wear Results Obtained at High Temperature for Various Types of Normal SG Chemistry, Support Geometry, Tube Material and Support Material.

For identical test conditions, the scatter in the data was slightly greater when tests were performed at lower excitation levels (6 to 10 mW). This raises the question of which SG tube wear coefficient values to use for realistic SG tube excitation levels (i.e., 1 to 2 mW). The results presented in Sections 3 to 6 are considered short-term test results in view of the long-term wear process taking place in a steam generator. Most tests were performed for slightly higher excitation levels (5 to 20 mW) in order to generate measurable wear within a 500-hour test duration. The use of a large number of short-term tests is required whenever the effect of various parameters on the wear process needs to be understood within a reasonable amount of time. These effects are now better understood and the wear coefficient average values for work-rates of 6 to 18 mW are well defined.

At this stage, there is a need to perform a limited number of long-term tests (5000 to 10,000 hours) for tube/support interaction levels of 1 to 2 mW and to derive the corresponding wear coefficients. However, there are already some indications in the literature that the SG tube wear coefficients will not vary significantly. Results published by Hofmann et al. are shown in Figures 10 and 11 for impacting motion of Alloy 800 SG tubing against 321 SS anti-vibration bars [11].

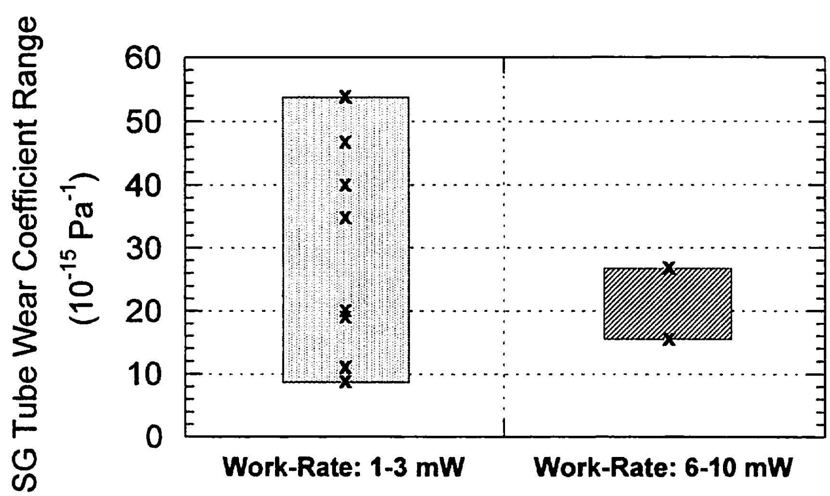

Figure 11: Fretting-Wear of Incoloy 800 SG Tubes/321 SS AVBs at 200°C (Hofmann et al.): Wear Coefficients for Low Tube/Support Interaction Levels.

Ten tests were performed at 200°C for tube/support interaction levels ranging from 1 to 10 mW. The wear coefficient ranged from 9 x 10^{-15} to 54 x 10^{-15} Pa^{-1}, and the average was 28 x 10^{-15} Pa^{-1}. This range of wear coefficients derived for work-rates between 1 and 3 mW is in very good agreement with that found for higher levels of interaction. Therefore, until the results of long-term tests are available, it is recommended that, for the prediction of SG tube damage resulting from impacting motion, a conservative value of 40 x 10^{-15} Pa^{-1} for the SG tube wear coefficient be used. The recommended value for an average wear coefficient is 20 x 10^{-15} Pa^{-1}.

8. TUBE WEAR PREDICTION

The wear coefficients presented above can be utilized to predict the progression of fretting-wear damage in a SG tube. In addition to the wear coefficient, the tube-to-support dynamic interaction (work-rate) and the geometrical relationship between wear volume and wear depth must be known.

Work-rates can be computed for a SG tube interacting with its supports due to flow-induced vibration using a non-linear finite element code such as VIBIC (VIbration of Beams with Intermittent Contact). Examples of such calculations can be found in the literature [12, 13]. A reasonable estimate for the work-rate in the U-bend region of a well-designed SG is 1 mW.

The geometrical relationship between wear volume and wear depth for a SG tube in contact with a U-bend flat bar restraint (FUR) is shown in Figure 11. Assuming that the tube and flat bar are perfectly aligned, the volume of removed material , V, is simply the area of intersection of a straight line and a circle (tube) of radius, R, multiplied by the flat bar width, L:

$$V = \frac{R^2 L}{2}(2\alpha - \sin(2\alpha)) \tag{3}$$

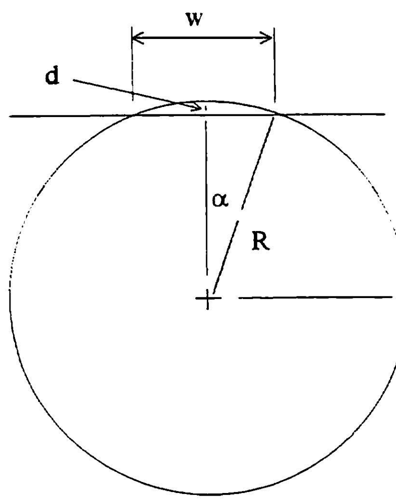

Figure 11: Contact Between a SG Tube and Flat Bar Restraint

The contact angle, α, is related to the tube radius and scar width, w,

$$\alpha = \sin^{-1}\left(\frac{w}{2R}\right) \tag{4}$$

and the wear depth, d, is related to the contact angle,

$$d = R(1 - \cos\alpha) \tag{5}$$

These relationships assume that the tube wear remains macroscopically flat (i.e., that the support wear is small in relationship to the tube wear). This assumption has been shown to be reasonable for the shallow frets generated in the fretting-wear tests described above.

However, the support has been observed to wear in these tests: generally at between 20 to 50% of the tube wear. Therefore, it is more realistic to assume that the tube-to-support contact becomes more conformal as the wear depth increases, distributing the wear volume over a larger area of the tube surface. In other words, as the wear depth increases, the tube wear no longer remains macroscopically flat, and the true wear depth is less than that predicted by Equation 5.

Equations 1 and 3 can be used to predict the progression of wear through a SG tube for a given value of work-rate, wear coefficient and tube-to-support geometry. Figure 12 shows such predictions for the following representative values:

Work-Rate, $\dot{W}$:	1 mW
Wear Coefficient, K:	20×10^{-15} Pa^{-1}
Tube Radius, R:	7.95 mm
Flat Bar Width, L:	28 mm

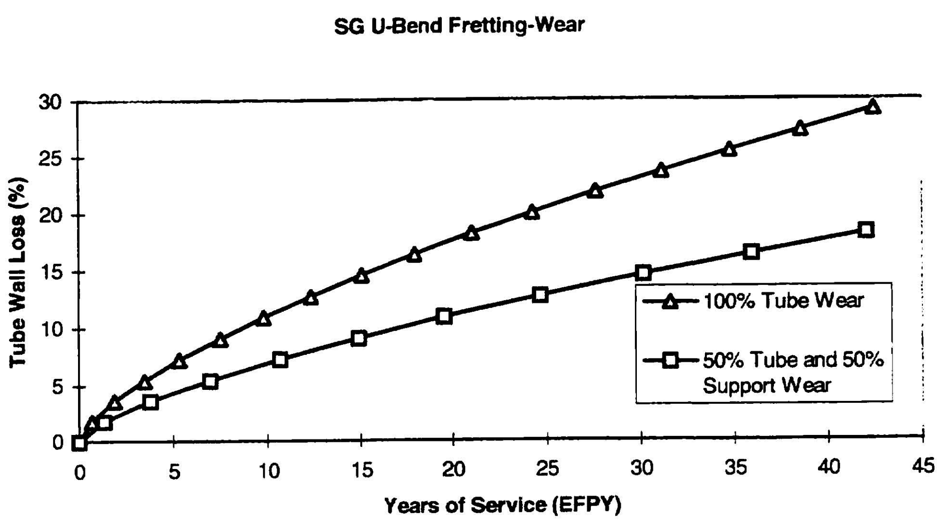

Figure 12: Predicted Wear Depth versus Time

Two curves are shown in Figure 12. The top curve (100% Tube Wear) is based on the assumption that the wear scar remains macroscopically flat. The lower curve (50% Tube and 50% Support Wear) assumes that the tube and support wear equally. These curves bound the prediction. Realistically, tube wear would be somewhere between these bounds.
For simplicity, work-rate was assumed to be constant in generating Figure 12. Similar, but more complicated curves could be derived for assumptions of changing work-rate with time.

The rate of tube wear depth decreases with time as the wear volume is distributed over a larger circumferential area of the tube surface. Tube wall losses of 5% are predicted within the first 5 years of service, but due to the decreasing rate of penetration, losses of 15 to 30% are predicted after 40 years.

8. CONCLUSIONS

Extensive fretting-wear tests were performed at CRL over the past four years to study the effect of SG environmental and design parameters on SG tube wear coefficient.

Tests were first performed to assess the effect of temperature using a force and displacement measurement system that allowed for monitoring of tube/support interaction level (i.e., work-rate) at operating conditions.

The results showed a significant effect of temperature on SG tube wear damage. For equivalent tube/support interaction levels, the wear coefficient at the SG operating temperature of 265°C was found to be 20 times higher than at 25°C. Therefore fretting-wear tests must be performed at component operating temperatures in order to be relevant.

On the effect of SG water chemistry control, no significant difference in SG tube wear coefficient was shown within the scatter of results, regardless of whether ammonia or morpholine was used to control SG water pH, whether phosphates were added, or whether boric acid was added.

It was also shown that, for predominantly impacting motion, the SG tube wear coefficient is similar for both Alloy 690 or Alloy 800 tubing materials, both flat bar or broached hole supports, and both 410 SS or 321 SS support materials.

Results obtained at CRL in the past four years combined with recent SG tube wear data published by Hofmann et al.[10] show that, for work-rates ranging from 1 to 18 mW, a conservative tube wear coefficient of 40×10^{-15} Pa^{-1}, and an average tube wear coefficient of 20×10^{-15} Pa^{-1} can be used for various types of SG normal water chemistry, support geometry, tube material, and support material.

9. ACKNOWLEDGEMENTS

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DISCUSSION

Authors: F.M. Guérout, N.J. Fisher, AECL

Paper: Fretting-Wear Damage: A Summary of Recent Findings

Questioner: R. Garg

Question/Comment:

(a) What assumptions are made with regards to thermalhydraulic conditions in the SG? Where do you get the thermalhydraulic loadings from?
(b) Is the fretting affected by "support elevation" or is it same for bottom to top-most support plate?

Response:

(a) The fretting-wear tests performed to study the effect of various parameters on wear coefficients are accelerated tests. The work-rate range of 6 to 12 mW chosen to perform most tests is based on using the lowest interaction level possible and still generating measurable wear within 500 hours. The average interaction level expected in a steam generator is in the order of 1 mW. The work-rate is predicted using the VIBIC, PIPO and THIRST codes developed at AECL. The thermalhydraulic loads are predicted using the THIRST code.

(b) The wear rates will be affected by support elevation if work-rate at the various support locations varies from one support plate to another. The wear coefficient is expected to remain unchanged.

Questioner: J. Gorman

Question/Comment:

What effects do pH_T and ECP have on fretting, considering their strong effects on oxide films? Do you intend to systematically study ECP and pH effects?

Response:

It is correct that pH_T and ECP have a large effect on oxide film formation. Therefore, pH_T and ECP could have an effect on fretting-wear of the fretting-wear and corrosion phenomena interact. It was shown that, for conditions leading to wear rates that are 10 times (or more) greater than corrosion rates, no interaction of the phenomena is expected. So far, we have not systematically studied the specific effect of pH_T or ECP in the case of the existence of a strong synergism between the corrosion and the wear processes (corrosion rates and wear rates in the same order of magnitude or wear rates lower than corrosion rates). Normal SG water chemistries seem to result in local corrosion rates that are much lower than the wear rates.

Questioner: J. Daret, CEA

Question/Comment:

Do you have an explanation or hypothesis for the effect of temperature on the tube wear damage, and what do you anticipate in terms of severity of damage depending on the location within the SG?

Response:

The strong effect of temperature on fretting-wear has been shown for other material combinations (Fisher et al. 1996), Suito et al. (1995), Jiang et al. (1995)). The change in wear coefficients with temperature could be attributed to changes in corrosion rates. However, relatively high excitation levels were maintained in these tests in order to generate measurable wear and, as a result, wear rates were much higher than corrosion rates. Therefore, minimal interaction of the corrosion and mechanical damage process is expected. Jiang et al. suggested that the increased production of debris at high-temperature could contribute to the formation of compacted protective layers on the surfaces. This effect was not clearly identified in these tests. The only difference observed was in the appearance of the worn surfaces: at 25°C, the worn surface appears "flat-hammered"; at 215°C, the removal of thin but large sheets of material is observed; at 265°C, the surface exhibits a scale-like tongues structure of superimposed laps that wear on the edge by removal of small plastically deformed; at 315°C, the scales are much smaller than at 265°C. Therefore, different wear mechanisms are observed at the different temperatures. We do not anticipate that this effect of temperature will change the severity of tube damage based on the location in the steam generator.