A TECHNIQUE FOR ASSESSING THE ABRASION RESISTANCE OF STEAM GENERATOR INTERNAL TUBE OXIDE

Aamir Husain and Sriram Suryanarayan
Kinectrics Inc.,
800 Kipling Avenue, Toronto, ON, Canada M8Z 6C4

ABSTRACT

The outcomes of previous primary side mechanical cleanings of CANDU steam generators (SG) have varied significantly between different stations suggesting that differences in mechanical properties of the ID oxide may be partly responsible. To assess the root cause/reasons for such differences, a rotational wire brush tool to mechanically abrade oxide from the primary side of steam generator tubes was developed. Coupled with a collection system, the technique permits a layer by layer characterization of the oxide characteristics. The tool was applied to a Pickering Unit 2 SG cold leg and Unit 8 SG hot leg tube sections. The abrasion characteristics and the chemical and radiochemical profiles of the two oxides were found to be quite different. Additional samples from other CANDU stations will be studied in the next two years. The overall goal is to relate the mechanical and chemical characteristics of SG tube oxide to the future performance of mechanical cleaning.

1.0 INTRODUCTION

Mechanical cleaning (shot blasting) of the primary side oxide in steam generators (SG) using Areva's Sivablast^{TM} or AECL's CANDU Clean^{TM} has been carried out at several CANDU stations since 1995. Outcome of these cleans with respect to the extent of primary oxide removal and recovery of the reactor inlet header temperature has varied significantly from station to station. A detailed analysis of the role of oxide characteristics on efficacy of mechanical cleaning was presented by Chew and Husain [2006]. Oxide characteristics examined included:

- Overall loading of oxides in SGs,
- Variation of oxide loadings with tube length,
- Composition and morphology of the oxides,
- Chemical profile across the thickness of the oxide layer,
- Porosity of the oxides, and
- Surface roughness of the oxides.

No direct information was available on the abrasion resistance of SG tube oxide. Abrasion properties of the oxide may vary from unit to unit and from station to station, requiring site specific tuning of the mechanical cleaning process to achieve optimum results. A project with the objective of directly assessing the abrasion resistance of the primary side oxide was, therefore, undertaken.

This paper presents details of a wire brush technique developed to provide a layer by layer characterization of the SG tube oxide. Results from its application are also presented. The technique permits characterization of the SG tube oxide using relatively small lengths of tubing. This was an important consideration in selecting the technique because availability of tube artifacts is generally very limited.

2.0 TECHNIQUE DEVELOPMENT

The basic requirements for the abrasion technique were as follows:

- The technique should permit a layer by layer removal of the internal SG tube oxide because properties of the oxide vary across its thickness.

- The removed oxide should be collected to permit its characterization.

- Contamination of the removed oxide with any wear products should be minimal.

- The technique should allow valid inter-comparison of data for different sized tubes.

A concept based on the use of a rotating wire brush was judged to meet all of the above requirements. A set-up was designed and assembled from easily available components. Features of the set-up, shown in Figure 1, are as follows:

- A double spiral, double stem wire brush with stainless steel bristles (the double spiral brush has more bristles than a single spiral brush),

- A commercially available lathe to rotate the wire brush,

  The lathe, a Sherline Model 4500, includes a motor, an electronic speed controller, a 2.75" (70 mm) x 6.0" (152 mm) cross-slide and a 15" (381 mm) steel bed allowing a span of 8" (203 mm) between centers. The speed controller allows variable speed control from 70 to 2800 rpm without belt changes.

- A customized sample jig to hold the tube sample,

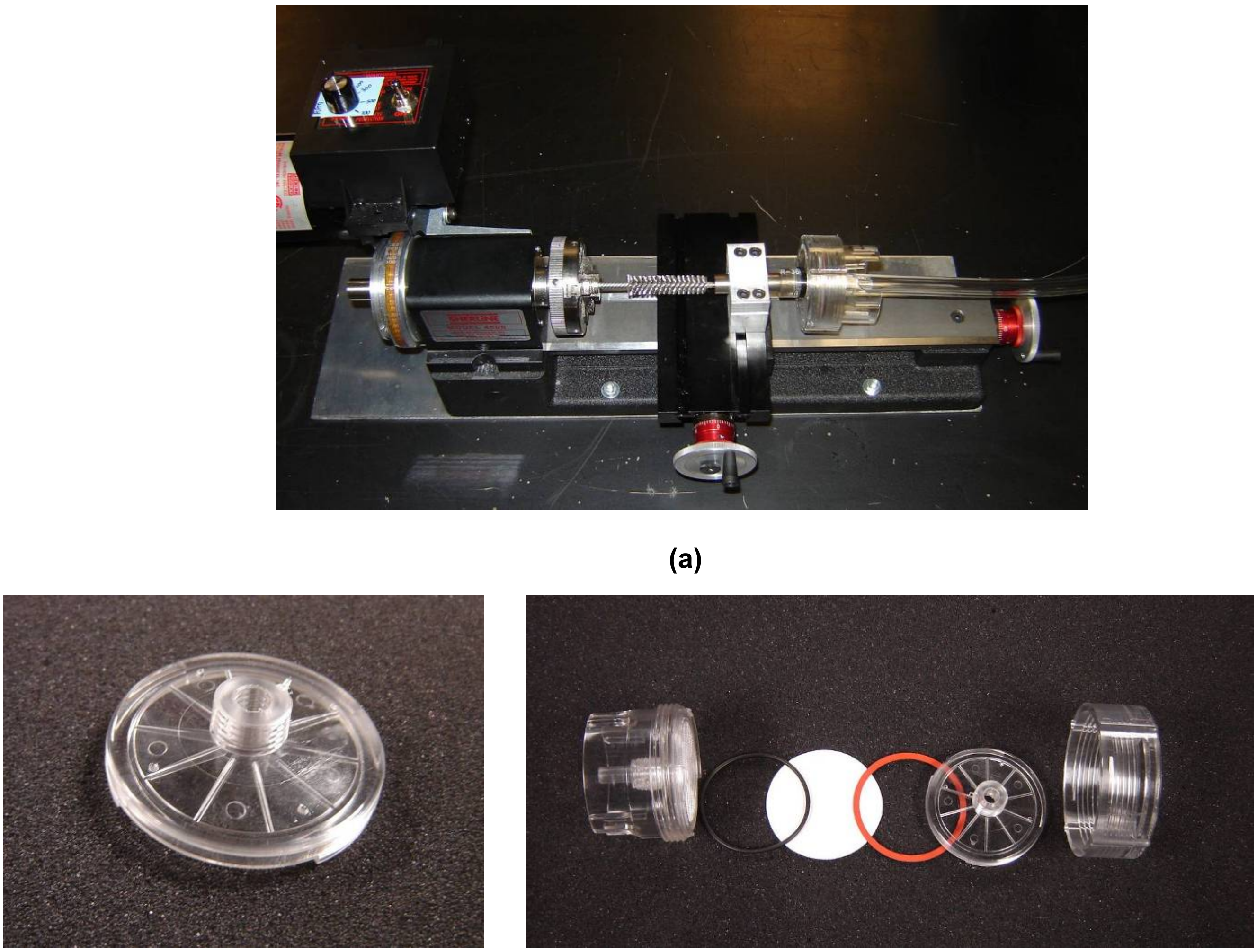
- A commercially available vacuum collection system (designed for use in forensic applications) with high air throughput and capable of trapping particles as small as 0.1 μm in size.

- A water trap to minimize the release of loose contamination in case the filter fails.

A preliminary assessment of the technique indicated that satisfactory outcomes could be obtained under the following conditions:

• Length of tube section	5 cm
• Speed of rotation	300-500 rpm
• Filter size	0.2 μm

Recovery of the abraded material, defined as the ratio of the filter housing (with filter) weight gain to the total weight loss experienced by the sample tube and the brush, exceeded 95%.



(a)

(b)

(c)

Figure 1: Wire Brush Abrasion Tool (a) Overall View Showing Lathe with Sample Jig, Brush, Sample and Filter Housing (b) Overall View of Filter Housing (c) Disassembled View of the Filter Housing

3.0 APPLICATION OF WIRE BRUSH TECHNIQUE

3.1 Preliminary Investigations

Results from a preliminary run are shown in Table 1. The run was conducted in a step-wise manner with Step 1 involving the introduction of the rotating brush into a selected tube section. The filter housing along with the filter was replaced at the end of each step. While the tube sample and brush were only weighed initially and at the end of Step #5, the filter housing and filter used in each step were weighed before and after the step. Note the following:

- Tube weight loss was substantially higher than the brush weight loss (a factor of 12) indicating that the material collected on the filter housing was primarily tube oxide.

- The overall recovery was estimated to be 97%. The recovery on the individual filters was somewhat less (89%) because the abraded oxide also deposited on other filter housing surfaces.

Figure 2 shows the appearance of the various filters used; their appearance is consistent with the removal of decreasing amounts of oxide in the successive abrasion steps.

Table 1: Results from a Preliminary Run

Step #	Duration	Weight Change (g)				% Recovery
		Tube Sample	Brush*	Filter	Filter Housing	
1	after insertion of brush into tube section			0.0083	0.0104	
2	45 s	-0.0326	-0.0027	0.0089	0.0103	Filter 89% Housing 97%
3	45 s			0.0071	0.0068	
4	45 s			0.0044	0.0043	
5	45 s			0.0026	0.0026	

* Brush was rotated @ 300 rpm.

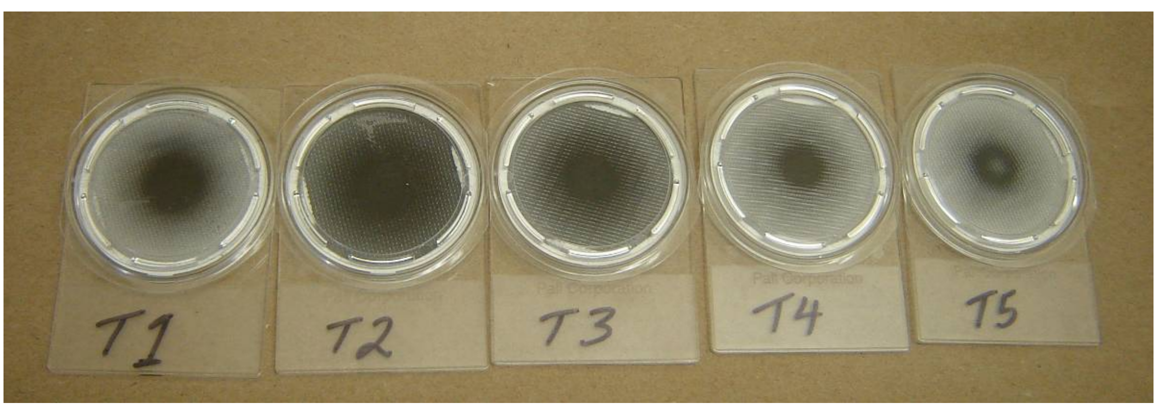


Figure 2: Appearance of Filters from a Preliminary Run

3.2 Detailed Investigations Using Pickering Steam Generator Tube Sections

Following successful preliminary investigations, comprehensive assessments were carried out using a Pickering Unit 2 SG 7 R42C73 cold leg and a Unit 8 SG7 R27C71 hot leg tube sections. Results are summarized in Tables 2 and 3. Figure 3 shows the cumulative amount of the abraded tube oxide material collected as a function of time.

Table 2: Results for Pickering Unit 2 SG7 R42C73 Cold Leg Section

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Abrasion time (s)	42	60	60	60	60	180
Filter weight gain (g)	0.0471	0.0204	0.0043	0.0035	0.0026	0.0071
Housing weight gain(g)	0.0615	0.0254	0.0051	0.0034	0.0023	0.0074
Tube weight loss (g)	-0.1019					
Brush weight loss (g)	-0.0067					
% Recovery - filter	78%					
% Recovery - filter housing	97%					

Table 3: Results for Pickering Unit 8 SG7 R27C71 Hot Leg Section

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Abrasion time (s)	41	45	45	45	45	120
Filter weight gain (g)	0.0096	0.0076	0.0072	0.0075	0.0075	0.0156
Housing weight gain(g)	0.0114	0.009	0.0083	0.0093	0.0094	0.0194
Tube weight loss (g)	-0.0655					
Brush weight loss (g)	-0.0026					
% Recovery - filter	81%					
% Recovery - filter housing	98%					

Note that in Tables 2 and 3, Step 1 involved the insertion of the rotating brush into the tube section followed by continued abrasion for a total duration of ~ 40 s. In the case of the cold leg section, over 60% of the oxide was removed during Step 1; thereafter, the abrasion rate decreased significantly, being slowest at the oxide-metal interface (see Figure 3(a)). In contrast, the abrasion rate of the hot leg oxide was essentially constant (see Figure 3(b)). These features possibly point to significant differences between the characteristics of the cold and hot leg oxides (this is also substantiated by the elemental profiles shown later) although differences in the operating chemistry regimes at Units 2 and 8 may also be a contributing factor. Differences in such plots for various tube oxides may be indicative of differences in their abrasion characteristics and hence in the ease of oxide removal using mechanical cleaning processes.

Specific gamma activity data as a function of oxide thickness are summarized in Table 4. Oxide thickness (corrected for brush wear) was calculated from the weight of oxide removed in each step, assuming a porosity of 50 % and a density of 5.15 g /cm^3 (corresponding to the density of magnetite). The Co-60 specific activity data are shown in Figure 4 as a function of cumulative oxide thickness (where the oxide thickness was considered to be zero at the oxide/water interface). While the Co-60 activity decreased with increase in oxide thickness, the Am-241 activity was essentially constant across the oxide layer with significantly higher values for the cold leg oxide than for the hot leg oxide.

Table 4: Specific Activity of Pickering SG Tube Oxide

Specific Activity (μCi/g) Unit 2 SG7 R42C73 Cold Leg Section			Specific Activity (μCi/g) Unit 8 SG7 R27C71 Hot Leg Section			
Oxide Thickness (μm)	**Co-60**	**Am-241**	**Oxide Thickness (μm)**	**Co-60**	**Am-241**	**Nb-94**
14	29	0.24	3	26	0.04	0.19
20	28	0.43	5	22	0.04	0.16
21	15	0.54	7	18	0.06	0.15
22	12	0.47	9	16	0.07	0.15
23	10	0.46	11	15	0.10	0.13
25	9	0.43	16	14	0.09	0.13
Overall	**24**	**0.30**	**Overall**	**17**	**0.07**	**0.14**

The oxide collected on the filters was analyzed using Induction Coupled Plasma – Mass Spectrometry (ICP-MS). Data for the principal elements Fe, Ni, Cu and Cr were interpreted based on the following considerations:

- Monel 400, the Pickering SG tube base metal is a Ni/Cu alloy[1] and contains negligible levels of Cr. The 304SS[2] brush material contains Fe, Cr & Ni but no Cu.

- Except at the water/oxide interface, the contributions of Ni, Cr and Cu deposited from the primary heat transport water (the metals originate in the water from corrosion of various system materials) was considered to be negligible compared with the contributions of Ni and Cu from the tube material and Cr from brush wear material.

- Thus, Cr present on filters from Steps 2 and higher was considered to originate exclusively from the brush wear product; the corresponding Ni was, therefore, estimated from the composition of 304 SS. Similarly, the tube Ni contribution was approximately estimated from the base metal composition and the measured Cu concentration[3]. The sum of Ni contributions from the brush and the base metal estimated thus agreed well with the measured Ni value thus validating the assumptions made.

Figure 5 shows the Fe, Ni and Cu concentrations in the oxide, after accounting for the brush wear contribution as described above. In both cases, the Ni/Cu ratio across the entire oxide layer is consistent with the composition of the Monel 400 tube base metal.

---

[1] Composition of Monel-400: 63 % Ni, 31 % Cu and 2.5 % Fe
[2] Composition of SS-304: 72 % Fe, 18.8 % Cr and 9.5 % Ni
[3] Differences in Cu and Ni diffusivities will cause the Cu/Ni ratio in the oxide to increasingly depart with time from the corresponding ratio in the tube base metal

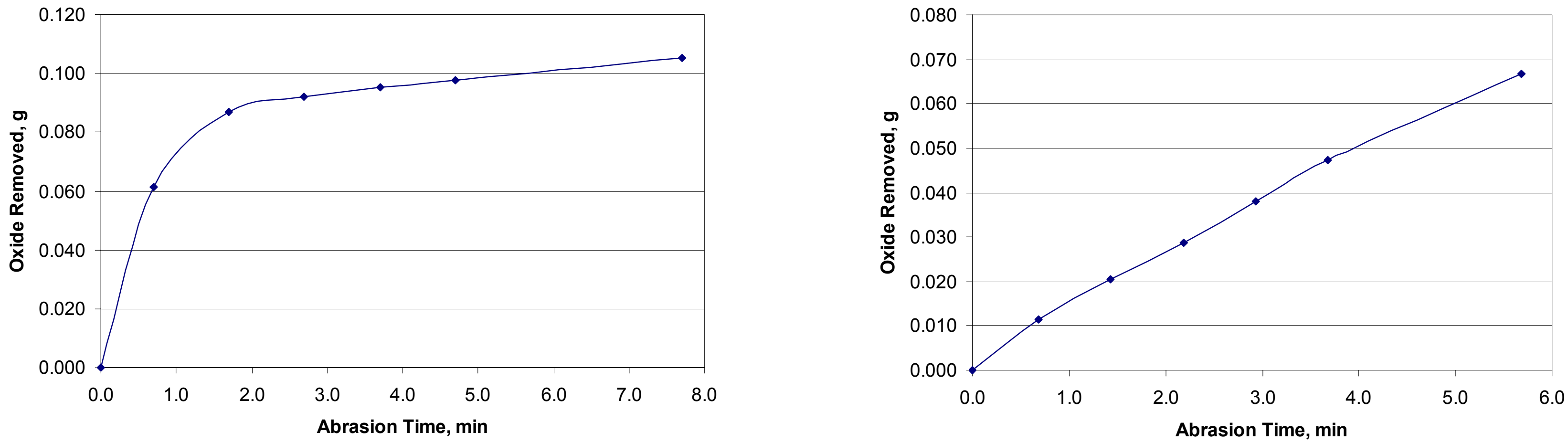


Figure 3: Cumulative Oxide Removed (a) Pickering 2 SG7 Cold Leg (b) Pickering 8 SG7 Hot Leg

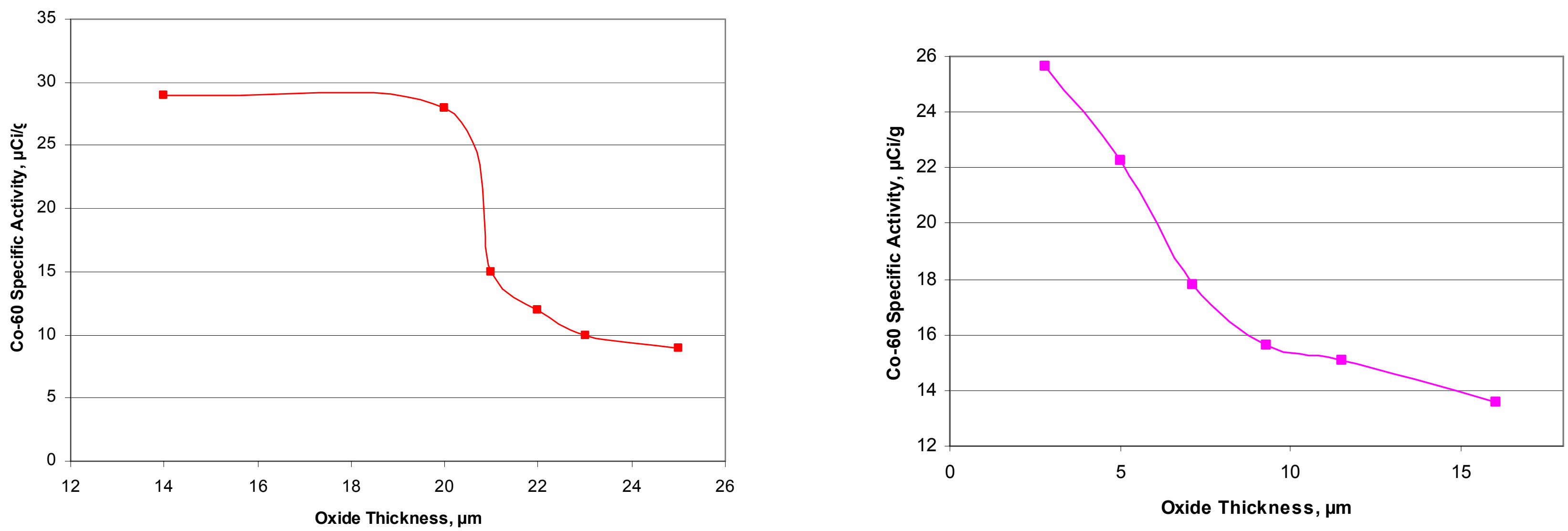


Figure 4: Variation of Co-60 Activity with Oxide Thickness (a) Pickering 2 SG7 Cold Leg (b) Pickering 8 SG7 Hot Leg

The plots indicate a significantly greater variation in Ni & Cu across the thicker cold leg oxide layer than across the thinner hot leg oxide layer. Figure 5(b) shows an unexpected dip in the Fe concentration; the cause for this is not clear.

3.3 Comparison of Measured Tube Oxide Characteristics with Data based on Oxiprobe Campaigns

A comparison between the present data for Pickering Unit 8 SG 7 with previous data for Pickering Unit 8 SG 7 measured using the Oxiprobe technique is shown in Table 5. The Oxiprobe measurements [Krasznai 2002], which were performed in Dec 2001, preceded the removal of the SG 7 hot leg tube section used in the present study by approximately 2 years. As shown in Table 5, agreement between the present and the previous Oxiprobe data is very good and provides a measure of validation for the present data.

Table 5: Comparison between Present and Mean Oxiprobe Hot Leg Data

	Pickering 8 SG 8	**Pickering 8 SG 7**
	Oxiprobe Data	**Present Data**
Co-60 (μCi/g)	19	17
Am-241(μCi/g)	0.08	0.07
Nb-94 (μCi/g)	0.06	0.14
Ni concentration*	5.4	4.8
Cu concentration*	2.1	1.5
Cr concentration*	0.030	-

* Relative to 100 units for Fe

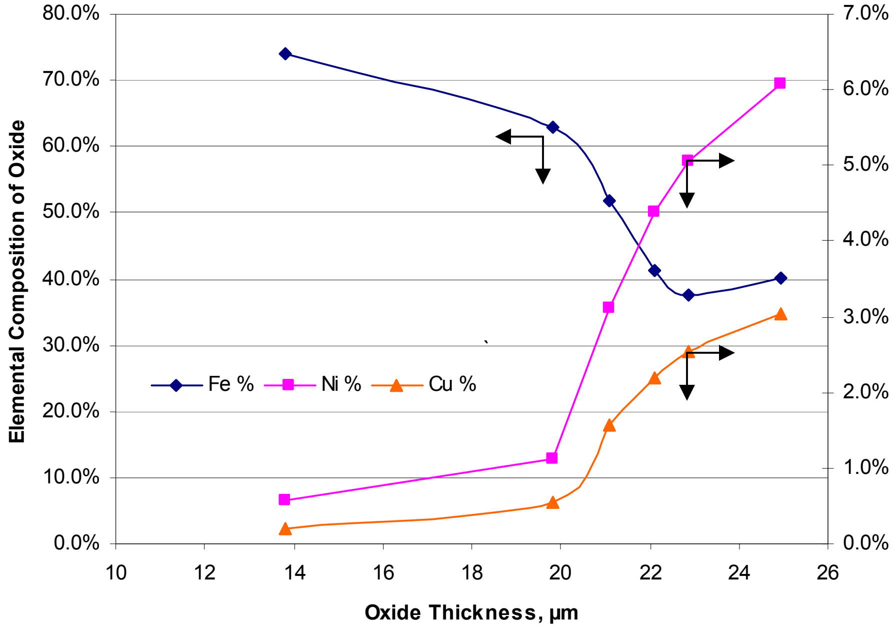
4.0 CLOSING REMARKS

Limited assessment has indicated that the wire brush abrasion technique permits quantitative, layer by layer, recovery of abraded tube oxide with relatively minor contamination from the brush wear products. Variation in oxide abrasion rates for various tube oxides may possibly be indicative of the ease of oxide removal using mechanical cleaning processes. Results from the analysis of the abraded oxide confirm that the technique yields valid activity and compositional profiles.

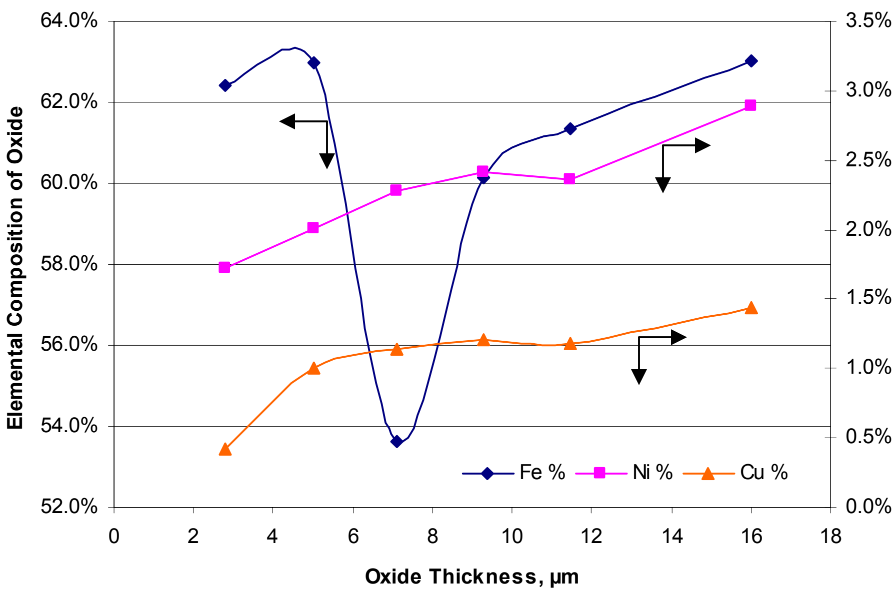
The technique is currently being applied to SG tubes from other stations besides Pickering. Measured abrasion characteristics of Darlington, Gentilly-2 and Pt. Lepreau tube oxides can be directly compared with each other because of their similar tube diameter (a different brush design is required because their tube diameter is larger). In general, however, inter-comparison of abrasion data for SG tubes with different diameters would require the effect of applied torque to be taken into account - for the same brush rpm, the applied torque would be greater for a tube with larger inside diameter.

ACKNOWLEDGEMENTS

The authors are grateful to COG for permission to publish this work.



(a)



(b)

Figure 5: Variation in Elemental Concentrations with Cumulative Oxide Thickness
(a) Pickering 2 SG7 Cold Leg Oxide
(b) Pickering 8 SG7 Hot Leg Oxide

REFERENCES

Chew, V. and A. Husain. 2006. Mechanical Cleaning of Steam Generator Primary Side Tube Deposits: Assessment of Cleaning Efficiency Based on Deposit Characteristics, COG-05-4067.

Chew, V., C. Morton and A. Husain. 2008. Development of a Technique for Assessing the Abrasion Resistance of Steam Generator Internal Tube Oxide, COG Technical Note TN-07-4080.

Krasznai J.P. 2002 Oxiprobe Measurements at Pickering Unit 8 Steam Generator 8 Primary Side Tube Deposit Loadings and Activity Determinations, Kinectrics Report 9349-030-2002-RA-0001-R00.