MECHANICAL CLEANING OF STEAM GENERATOR PRIMARY SIDE TUBE DEPOSITS: ASSESSMENT OF CLEANING EFFICIENCY BASED ON DEPOSIT CHARACTERISTICS

Aamir Husain, Vivian Chew,
Kinectrics Inc.

ABSTRACT

Mechanical cleaning of the primary side oxide in CANDU steam generators has been carried out at several stations since 1995. The most recent applications were the Sivablast™ campaign at Darlington Unit 1 in 2004 and the CANDU Clean™ campaign at Bruce Unit 5 in 2005. The Darlington campaign was characterized by a mixed outcome with the oxide removal efficiency achieved being significantly lower in two of the four steam generators (SGs) cleaned.

A study was undertaken focusing principally on differences between the characteristics of the primary side oxide in various CANDU SGs which possibly impact cleaning effectiveness. The oxide characteristics examined included:

- Overall steam generator oxide loadings and their variation with tube length,
- Composition and morphology,
- Chemical profile across the thickness of the oxide layer, and
- Porosity, surface roughness and thermal conductivity.

It was concluded that differences in bulk oxide characteristics of SG tubes at various stations are unlikely to significantly influence the outcome of mechanical cleaning. In general, the key factor limiting the oxide removal efficiency may be the abrasion behavior of the oxide adjacent to the metal interface. Such behavior may be influenced by both the major and minor constituents of the tube base metal. Up to approximately 80-85% of the oxide loading, consisting principally of the outer magnetite layer, appears to be amenable to removal by media blasting. Removal of the remaining oxide may not be beneficial as it is not expected to significantly reduce surface roughness further nor significantly improve the heat transfer characteristics of the SG tubes. Thus, additional improvements in reactor inlet header temperature and primary heat transport system flow rate would be unlikely to occur.

1.0 INTRODUCTION

Buildup of primary side deposits contribute to a loss in heat transfer efficiency of operating CANDU steam generators (SGs) and an associated increase in the reactor inlet header temperature (RIHT). The deposits also cause a reduction in the primary heat transport system (PHTS) flow as a result of increased roughness of the internal tube surfaces [Plante 2001]. Benefits of removing primary side deposits include restoration of the core flow and the RIHT, reduction in the feeder thinning rate resulting from a lower incidence in channel boiling [Plante 2001], reduction in radiation fields around the SG and increase in eddy current probe life as a result of wear reduction.

In recent years, there has been considerable interest in the development of mechanical processes for the primary side cleaning of SG tubes. Two processes, namely, Framatome ANP's Sivablast™ and AECL's CANDU Clean™ are now commercially available for this purpose; both rely on the use of media blasting to remove deposits.

Mechanical cleaning of the primary side oxide in CANDU SGs has been carried out at several stations since 1995. The most recent applications were at Darlington Unit 1 (DNGS U1) in 2004 and Bruce Unit 5 (BNGS U5) in 2005. With the exception of the Inconel-600 tubed SGs at BNGS, all the other SGs cleaned to date have been tubed with Incoloy 800. The DNGS campaign in 2004 was characterized by a mixed outcome with the oxide removal efficiency achieved being significantly lower in two of the four SGs cleaned Framatome ANP 2004].

A COG funded project was recently undertaken to shed light on the factors affecting performance of mechanical cleaning at various stations [Chew and Husain 2006]. Because both the Sivablast™ and CANDU Clean™ processes are proprietary technologies and hence process related information difficult to obtain, the study focused principally on differences in the characteristics of the primary side oxide between various CANDU SGs and which possibly impact cleaning effectiveness.

The oxide characteristics examined included:

- Overall steam generator oxide loadings and their variation with tube length,
- Composition and morphology,
- Chemical profile across the thickness of the oxide layer, and
- Porosity, surface roughness and thermal conductivity.

Unfortunately, no information was available on the abrasion behavior of the oxide. Before discussing the above, a brief description of the cleaning technologies is presented in Section 2.0 and the overall results from various cleaning campaigns are presented in Section 3.0.

2.0 GENERAL DESCRIPTION OF SIVABLAST AND CANDU CLEAN PROCESSES

The mechanical processes for cleaning primary side SG tube oxide rely on the use of abrasive blast media. Generally, steel beads are introduced under pressure into a tube at its cold-leg end and collected at the other end of the tube in the hot-leg. The reusable media and the removed oxide are gathered using a suction header that covers the entire hot leg tube sheet surface. An air ejector conveys the collected material, through a vacuum hose, to the reclaimer where the oxide is screened from the blast media with the latter returned for renewed service. The separated oxide is collected in shielded containers. The schematic for the process is shown in Figure 1 [Siemens 1999].

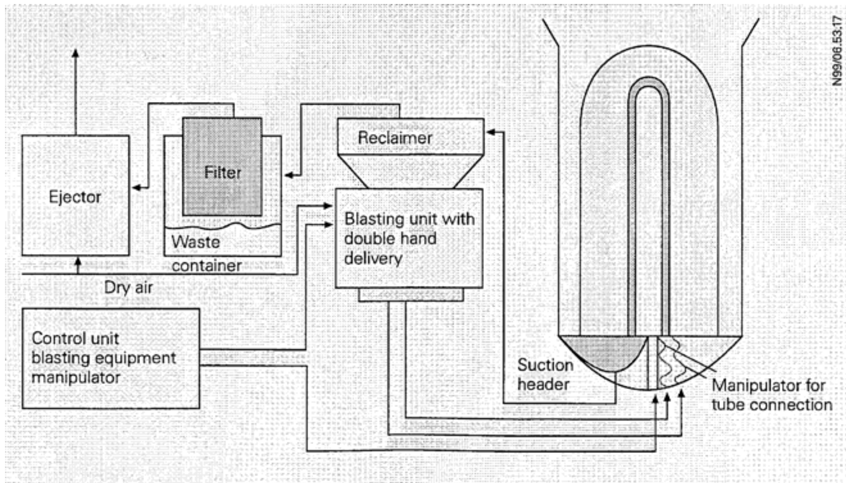

Figure 1 Schematic of the Sivablast™ Process

Depending on equipment layout and availability, two tubes can be cleaned simultaneously. The blast nozzles are connected by means of manipulators to the tubes being cleaned. The cleaning process is fully automated and controlled remotely [Bains 1999].

For increased effectiveness, SG tube surfaces must be dried prior to media blasting. Otherwise, the removed oxide adheres to the blast media and causes the reclaimer hopper to plug up, thus impeding the separation and recycling of the blast media.

Only dry waste is generated. Recycling of the blasting agent minimizes the volume of waste produced. Removed deposits are safely collected in a closed system under vacuum.

3.0 OVERALL EXPERIENCE IN MECHANICAL CLEANING OF CANDU SGS

Table 1 summarizes the overall results from the various mechanical cleaning campaigns conducted to date. Results for the first campaign conducted at Gentily-2 (G-2 NGS) in 1995 are not shown; this campaign was aborted because of higher than expected radiation fields and difficulties in sealing the primary head after only 10% of the tubes (i.e. 250 tubes) were cleaned.

The results in Table 1 are discussed below:

- Only 60% of the tubes were cleaned at both Pt. Lepreau (PLNGS) and DNGS because of schedule constraints and restricted accessibility to the tubes. At BNGS, only 4 of the 8 SGs (namely SG2, SG3, SG6 and SG7) were cleaned because of late set-up and equipment problems.

  Except at DNGS, blast media has generally been introduced at the cold leg tubesheet.

Table 1 CANDU Experience in Mechanical Cleaning of Primary Side SG Oxide

Station	Number of Tubes Cleaned	Total Oxide Removed, kg	Average Oxide Removed g per Tube*	Estimated Removal Efficiency**	Amount of Blast Media Used	RIHT Decrease (°C)
PLNGS (1995)	8,209 (60%)	789	96	~67%	1,925 kg 235 g/tube	-
G-2 NGS NGS (1999)	13,007 (92%)	3,045	234	-	475 kg 37 g/tube	-
Embalse (2000)	10,387	2,602	250	-	-	4.5
Wolsong 1 (2003)	13,261 (93%)	2,575	194	-	675 kg 51 g/tube	-
DNGS Unit 1 (2004)	11,248 (60%)	1,433	127	61-83%	606 kg 54 g/tube	0.5-0.9
BNGS Unit 5 (2005)	16,603 (98%)	1,430	86	~ 80%	1,182 kg 71 g/tube	0.8

* based on total oxide removed
**refers to the percent of the initial deposit removed during a clean

- In general, the average oxide removed per tube was estimated from the total mass of oxide removed. The amounts of oxide removed in G-2 NGS NGS, Embalse and Wolsong were roughly comparable (about 225 g/tube). In comparison, the amounts removed in PLNGS, DNGS and BNGS were significantly lower (about 100 g/tube). These differences are a reflection of both the oxide loading present initially and the oxide removal efficiency achieved during the clean.

- Data for oxide removal efficiency in Table 1 are shown only for PLNGS (1995), DNGS (2004) and BNGS (2005).

    - The initial PLNGS loading data are based on limited measurements made on removed tube sections.

    - The initial oxide loadings at DNGS were estimated using an eddy current technique (ECT). Previously measured Oxiprobe data were used to calibrate the ECT. The latter was applied in SG1 & SG2 prior to the clean and to non-cleaned tubes in SG3 & SG4 after the clean. The measured loadings, ranged from 140 to 171 g per tube [Framatome ANP 2004] with the loadings in SG1 and SG2 being higher than the values predicted from past Oxiprobe data. The accuracy of the oxide loading data, despite being based on extensive Oxiprobe/ ECT measurements, is somewhat uncertain.

      The oxide removal efficiencies achieved at DNGS were as follows: SG1 83%, SG2 69%, SG3 61% and SG4 81%; considering that only 60% of the tubes were cleaned, the average overall removal efficiency was only 44%. It is unclear why the removal efficiencies in SG2 and SG3 were significantly lower than those in SG1 and SG4. After the clean, examination of a hot-leg straight section removed from SG4 [Mayer and Zaluski 2005] indicated that in the area of Lattice Bar #3, 50% of the tube surface was still covered with an easily dislodged thick deposit. This may be due to inadequate pre-drying of the oxide - unlike at BNGS, drying at DNGS was not performed in a closed loop and the magnetite may still have been moist even though the reported dew point was low (comparable to that achieved at G-2 NGS NGS). In addition, the operating pressure at DNGS was also lower than at G-2 NGS NGS.

- o The estimate for the oxide removal efficiency at BNGS was based on limited Oxiprobe data measured several years prior to the recent clean. The estimate is, however, in good agreement with a value estimated from contact dose rate measurements taken around the SGs before and after the clean. This may be fortuitous because the dose rate measurements were taken only at one elevation above the tubesheet.

- Compared to the magnitude of the RIHT decrease realized at Embalse as a result of the SG clean, the RIHT decrease realized at DNGS and BNGS were significantly smaller. The anticipated RIHT reduction at DNGS, based on a target of 90% cleaned tubes, was 1.75-2.5°C. Similarly, the expected RIHT decrease at BNGS, based on all 8 SGs being cleaned (only 4 SGs were actually cleaned) was 3°C.

In the absence of sufficiently accurate metrics, it is difficult to comment on the relative outcomes of the various cleans. The oxide removal efficiencies at DNGS was comparable or better than the average value at PLNGS (in both cases only 60% of the tubes were cleaned). Similarly, the oxide removal efficiencies for SG1 & SG4 at DNGS are comparable to the average value for the 4 SGs cleaned at BNGS. The significantly lower oxide removal efficiencies realized in 2 of the 4 SGs cleaned at DNGS implies that process control was inconsistent during the clean. While post-examination of DNGS tubes has revealed the presence of significant levels of residual oxide, this may also have been the case at BNGS where no tubes were removed for post clean examinations.

4.0 CHARACTERISTICS OF STEAM GENERATOR PRIMARY SIDE OXIDE

The effectiveness of mechanical cleaning of SG primary side oxide is a function of both process related factors and the characteristics of the oxide. As discussed earlier, the focus here is on examining the known characteristics of SG oxide which may have contributed to differences in process effectiveness at the various stations. For this purpose, available information on the chemical and physical properties of SG primary side deposits was analysed in detail. The results of this analysis are presented in the following sections.

4.1 Overall Oxide Loading

Data for Pickering, BNGS and DNGS SGs obtained from Oxiprobe campaigns during the period 1993-2003 are summarized in Table 2 [Husain and Krasznai 2005]. Note the absence of Oxiprobe data for the unit cleaned at DNGS, i.e., Unit 1. Additional data obtained from a) examination of tube sections pulled from G-2 NGS NGS and BNGS, b) using ECT at DNGS Unit 1 and c) from single tube cleans at G-2 NGS and PLNGS are summarized in Table 3.

In general, oxide loadings vary significantly between the hot and the cold legs. This is further discussed in the next section. The oxide loadings in SGs at DNGS Unit 1 and BNGS Unit 5 appear to be comparable. The data for G-2 NGS [Miller et al 1994] and PLNGS [Allsop et al 1994] in Table 3 indicates an oxide growth rate of 21-24 $g/m^2/y$.

Table 2 Summary of Oxide Loading Data Measured Using Oxiprobe

Station	EFPY[a]	Total Oxide Loading	Magnetite Loading	Magnetite Loading per Tube (g)	Magnetite Loading per SG (kg)
PNGS-A U1 SG 8 ('93 Data)	14.5	21-147 g/m^2 7-47 mg/cm 8-58 µm	20-143 g/m^2	63±6[b]	164
PNGS-A U4 SG 5	16.4	-	16-205 g/m^2 5-65 mg/cm 42±18 µm	66±12	172±31
PNGS-A U1 SG 8 ('03 Data)	16.7	-	53-217 g/m^2 17-69 mg/cm 48±15 µm	74±6	192±16
BNGS-A U3 SG 2	11.8	7-217 g/m^2 3-68 mg/cm 1-84 µm	5-200 g/m^2 2-66 mg/cm	72[b]	302
PNGS-B U6 SG 7	13.9	-	98-389 g/m^2 31-123.6 mg/cm 65±26 µm (max.150 µm)	67-91 75±8	194±20
PNGS-B U8 SG 8	12.0	-	41-115 g/m^2 13-36 mg/cm 30±8 µm (max. 44 µm)	41±3	106±7
BNGS-B U5 SG 5	8.1	60-250 g/m^2 19-79 mg/cm 23-96 µm	38-209 g/m^2 17-76 mg/cm	79-85[b]	349
DNGS U3 SG2	5.0	-	6-153 g/m^2 2.6-65.6 mg/cm 2.4- 59 µm	56-72	279
DNGS U2 SG1	7.3	-	16-244 g/m^2 7-104 mg/cm 1.5-85 µm	83-102	422
DNGS U3 SG4	7.7	-	20-120 g/m^2 8.4-55.1 mg/cm 8- 50 µm	43-49	214

a EFPY denotes Effective Full Power Years
b Includes the contributions of other metals

4.2 Variation of Oxide Loadings with Tube Length

Oxiprobe oxide loading data measured as a function of tube length are shown in Figure 2.

- The oxide loadings in DNGS SGs appear to increase linearly before leveling out between tube lengths[1] of 10-20 m; this is followed by a sharp increase in the preheater region (≥ 20 m).

[1] Tube length was measured from the primary side, tube sheet face in the hot-leg.

- In Pickering SGs, the loadings generally increase, reach a peak value in the hot-leg and subsequently decrease with tube length until the preheater is reached whereupon a sharp increase is experienced.

- Data for BNGS SGs are much more limited; in the absence of an integral preheater at BNGS, the oxide loadings do not experience a sharp increase as at PNGS and DNGS.

Table 3 Summary of Additional Oxide Loading Data

Station	Oxide Loading	Comments
G-2 NGS [Miller et al 1994]	190 g/m^2 (average value for entire tube)	8.0 EFPY
G-2 NGS [Cheluget and Klimas 1997]	6.4 g/m^2 (average value in hot-leg) 271 g/m^2 (average value in cold-leg) 494 g/m^2 (cold leg region below 3rd baffle plate of preheater)	Prior to cleaning
G-2 NGS [Semmler et al 2002]	8.8 g/m^2 (hot leg); 61.3 (cold leg)	Less than 2 y after cleaning
PLNGS [Allsop et al 1994]	188 g/m^2 (average value for entire tube)	8.8 EFPY
BNGS U1& 2 [Miller and Burrill 1998]	200-250 g/m^2 (average value in U-bend)	-
BNGS U6 [Husain and McBride 2005]	190-340 g/m^2 (external preheater)	-
DNGS U1 [Framatome ANP 2004]	Because of growth between 2000 and 2004, actual loadings were estimated to be 40% higher i.e., 758 kg instead of 650 kg per SG or 157 g/m^2	Loadings data are based on ECT

Data in Table 3 suggests that the variation of oxide loadings with tube length in G-2 NGS SG tubes may also follow the trend observed in DNGS SG tubes. Similarly, recent characterization of BNGS Unit 6, SG4 preheater tubing indicated that the oxide thickness increased from 60 to 112 μm (190-340 g/m^2 magnetite) in the direction of flow over a tube length of approximately 2.2 m [Husain and McBride 2005].

Generally, the oxide loading increases with tube length as a result of the increasing degree of saturation of the heat transport fluid as it flows through a SG tube. At the entrance of the hot leg, where the primary coolant temperature is high and the heavy water is unsaturated in dissolved iron, the deposit loading is low. Thick magnetite deposits arise in the preheater because of the cooler temperature and the steeper temperature gradient in this region.

The magnitude of oxide loading within a tube would dictate the extent of ‘abrasive’ power required during a clean. Failure to fully account for the deposit loading within a tube and its distribution along the tube may lead to ineffective cleaning. This may have been a factor in all the cleans performed to date because of the general uncertainty in loading estimates.

As previously stated, blast media was introduced into the hot leg at DNGS and collected in the cold leg where the deposits are thickest. In contrast, the blast media was introduced into the cold leg in all other applications to date including G-2 NGS where the variation in oxide

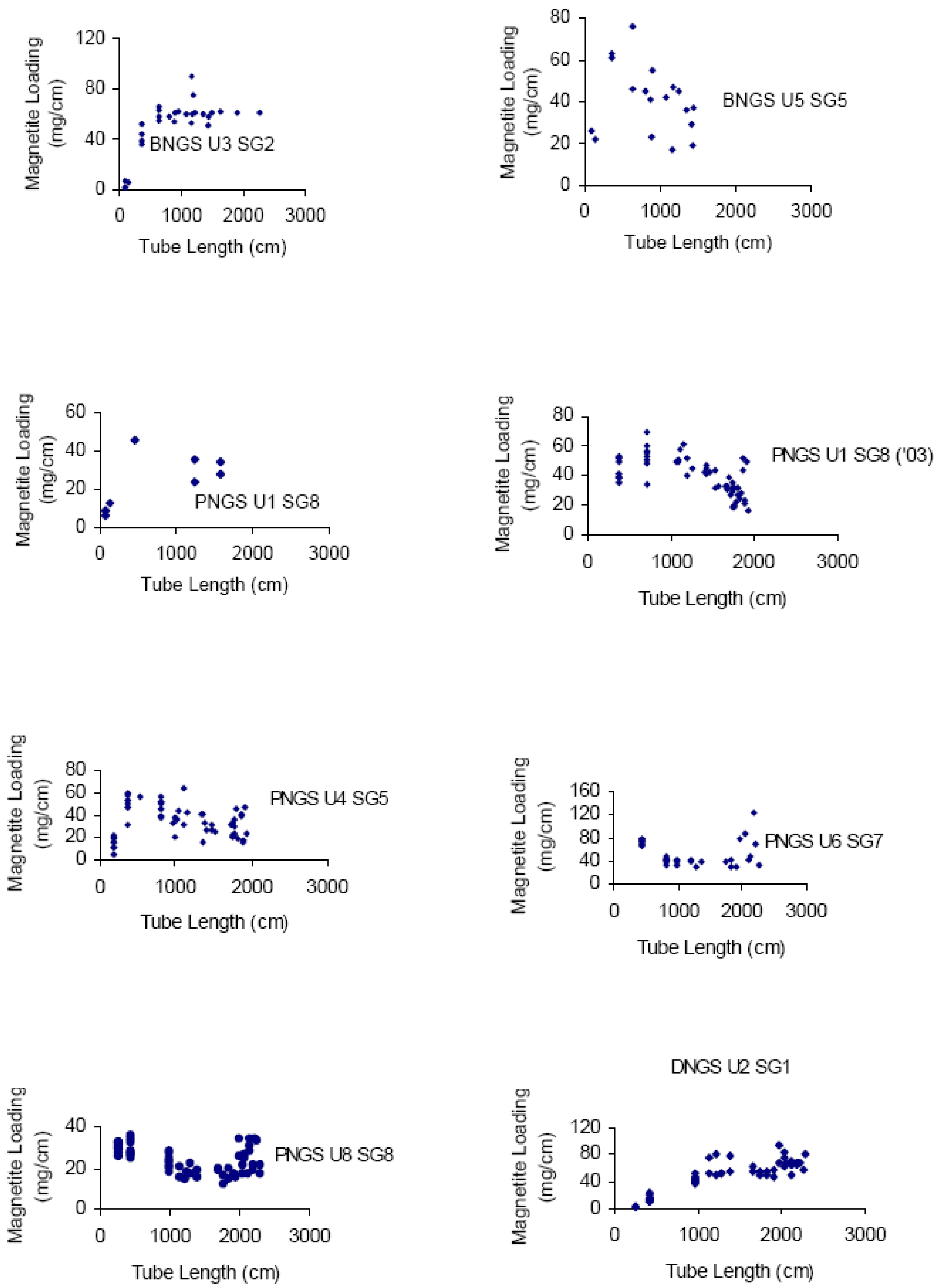

Figure 2 Oxide Loadings Measured Using Oxiprobe

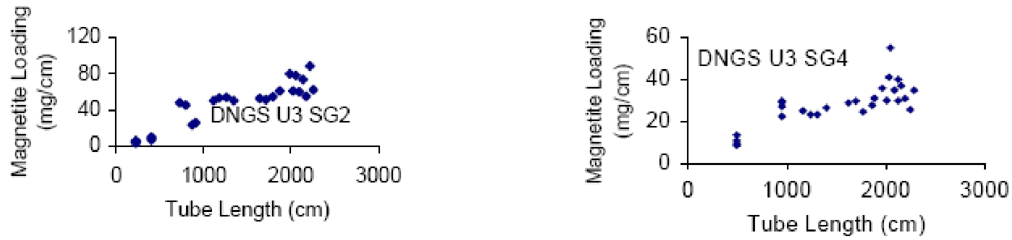

Figure 3 Oxide Loadings Measured Using Oxiprobe (cont'd)

loading with tube length may be similar to that at DNGS. Consequently, in the DNGS application, the oxide loadings continually increased with tube length even as the energy of the blast media was being dissipated along the tube.

4.3 Composition & Morphology of Oxide

In general, deposits on SG primary side surfaces consist of transition metal (Fe, Ni and Cr) oxides. The oxides can be considered to be of two types: a) grown-on protective indigenous oxides which are strongly adherent to the base metal, and b) oxide deposited from solution which overlies the grown-on oxide. The grown-on indigenous oxides are formed by corrosion of the base metal accompanied by incorporation of solution deposited material into the oxide structure. The deposited oxide may arise as a result of precipitation from solution or from particulate deposition. Generally, the grown-on oxides tend to have a spinel structure with a chemical form represented by $Ni_xFe_{3-x-y}Cr_yO_4$ where x and y are variable.

In CANDUs, such as those at Pickering, which are characterized by carbon steel piping, Monel boiler tubes and the absence of in-core boiling, the chemistry conditions are reducing and the stable form of Fe is Fe_3O_4. Consequently a black protective layer is formed on system surfaces. Stainless steel surfaces such as those of the end-fittings are, however, characterized by a chromium ferrite[2] layer at the metal interface. Generally, some Ni ferrite and Cu deposits may also be present. In the more advanced BNGS, DNGS and CANDU 6 designs, which feature carbon steel piping, Inconel/Incoloy boiler tubes[3] and the presence of in-core boiling, bulk chemistry conditions are still reducing but the dissolved O_2 levels (especially at the core outlet) are slightly higher. In addition to magnetite, chromium ferrite and nickel ferrite, some hematite may also be present.

Morphologically, the deposited oxide consists of octahedral crystals of magnetite. Their size depends on the coolant temperature and dissolved iron concentration; sizes up to 10 µm have been observed [Miller and Burill 1998; Maroto et al 1998].

4.4 Chemical Profile

The distribution of elemental constituents across the thickness of an oxide layer may influence its resistance to mechanical abrasion. Figure 3(a) shows the variation of Cr and Ni across the 60 µm oxide layer on an Inconel 600 cold leg straight tube section removed from a BNGS Unit 6 preheater in 2004 [Husain and McBride 2005]. The profiles indicate the following:

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[2] Under reducing conditions, Cr exists as Cr^{+3} (not very soluble) and readily enters the spinel structure as $FeOCr_2O_3$.
[3] The bulk composition of Inconel 600 is as follows: Fe 6-10%, 14-17 % Cr and 72 (min) % Ni; in comparison, that of Incoloy 800 is as follows: 39.5 (min) % Fe, 19-23 % Cr and 30-35% Ni.

- The concentration of Cr and Ni were essentially constant across the oxide layer (~2.5E-03 and ~1.1E-02 g/g magnetite, respectively) but increased sharply as the base metal was approached. Thus, increased formation of ferrites occurs as the interface is approached.

- The ratio Cr/Ni ratio was constant across the oxide layer; its value of 0.21 was identical to the corresponding ratio in the base metal suggesting that the Inconel 600 base metal was the primary source of Cr and Ni in the oxide layer.

For comparison, the Cr and Ni profiles across a similar (i.e. 60 µm) thickness of oxide on an Incoloy 800 DNGS Unit 3 SG3 tube section (hot leg U-bend) removed in 2002 [Husain and Cervoni 2003] are shown in Figure 3(b).

- The Cr and Ni profiles are similar to those shown in Figure 3(a) except that the increase near the metal interface is not as sharp. The average concentration of Cr in the bulk oxide (2.0E-03 g/g magnetite) was also similar to that found on the BNGS tube section although the Ni concentration (2.4E-03 g/g magnetite) was significantly lower. The latter is consistent with the much lower Ni content of Incoloy 800 relative to Inconel 600.

- As with the BNGS tube, the Cr/Ni ratio in the bulk oxide was essentially constant; its value of approximately 0.91 was, however, significantly higher than the value of 0.55 at the oxide-base metal interface.

It was also instructive to examine the elemental profiles for tube sections with significantly lower oxide thickness. This is shown in Figure 3(c) for a straight section from the hot leg of DNGS Unit 3 SG4. The following should be noted:

- The Cr and Ni profiles are similar to those measured for the U-bend section (Figure 3(b)) with the oxide-metal interface also being rather diffuse.

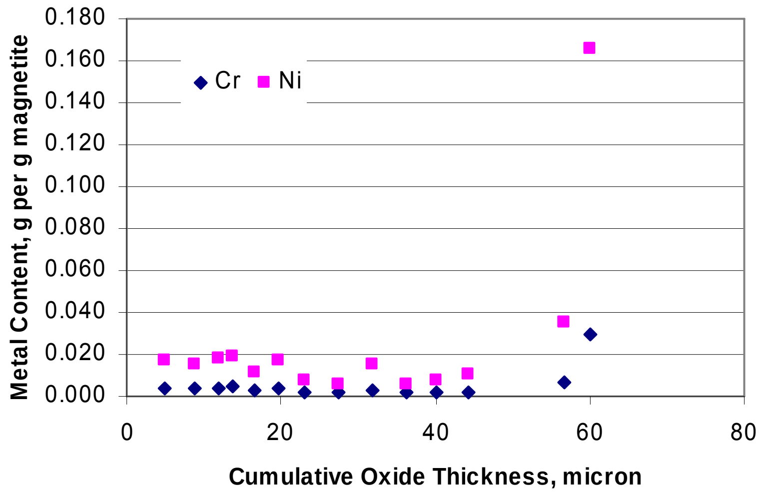
- At comparable values of the oxide thickness, the concentrations of Cr and Ni in the bulk oxide were higher than in the U-bend tube section.

- The Cr/Ni ratio decreased from 0.69 in the bulk oxide to approximately 0.50 (a value representative of the base metal) adjacent to the oxide-metal interface.

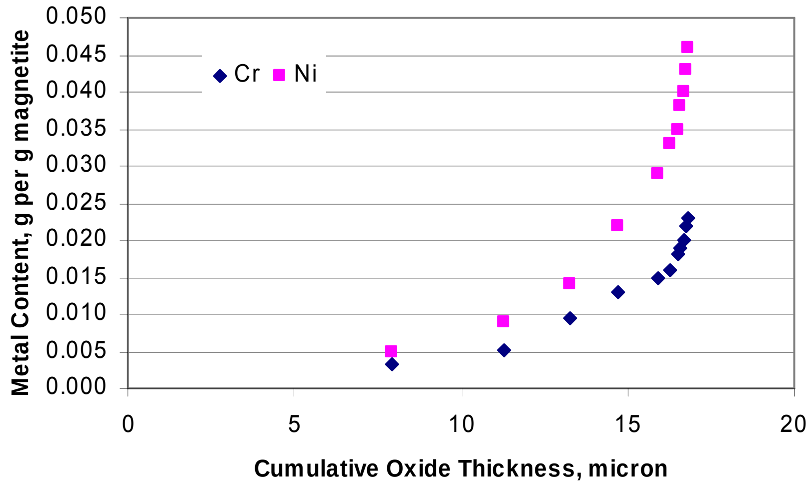
Based on the above discussion, an overall picture of the chemical characteristics of CANDU SG oxides emerges as it relates to media blasting:

- Fe is the dominant element in the SG oxide arising principally from deposition from solution. Chromium and nickel are present at a much lower extent and arise by diffusion from the base metal. As a result, the concentrations of these minor elements in the bulk oxide and in the grown-on oxides depend on the composition of the base metal. The Inconel 600 oxide-metal interface appears to be more sharply defined than the corresponding Incoloy 800 interface.

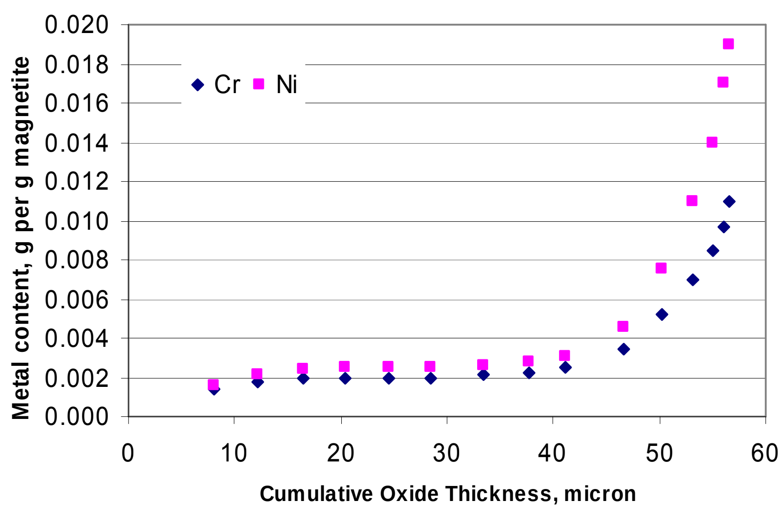
- Generally, the presence of chromium and nickel ferrites above a specified threshold leads to a reduced dissolution rate. While the observed dissolution rate decreased as the metal interface was approached, the rates were similar for both the BNGS Inconel 600 and the DNGS Incoloy 800 oxides. The comparable ease of dissolution in both cases does not



(a)



(c)



(b)

Figure 3 Distributions of Cr And Ni Across the Oxide Layer of a) Bruce Unit 6 Preheater Tube Cold Leg Section b) DNGS Unit 3 SG3 Hot Leg U-Bend Section c) DNGS Unit 3 SG4 Hot Leg Section

necessarily imply a similar resistance to abrasion or mechanical cleaning. However, the success with media blasting at BNGS (Inconel 600 tubed SGs) and several CANDU 6s (Incoloy 800 tubed SGs) suggest that differences in the characteristics of Inconel and Incoloy oxides do not significantly impact on the efficacy of media blasting.

- In DNGS SGs, the oxide loading consistently increases with tube length as shown in Figure 2. On the other hand, the relative content of ferrites in the oxide would be expected to decrease with tube length. The latter follows because the wall temperature decreases along the tube length and hence would lead to decreased diffusion rates for base metal constituents. Thus, the type of oxide encountered as the blast media coursed through the DNGS SG tubes (from hot to cold leg) would have differed from that encountered in the other applications where the blast media was introduced in the cold leg. It is, however, not known whether such differences contributed to the outcome at DNGS.

- In addition to Cr and Ni, several other base metal constituents such as Co and Ti are also present to varying extents in the oxide. Their effect was, however not investigated here.

4.5 Porosity of Oxide

Porosity of the primary side oxide varies across its thickness and would be expected to influence its removal by mechanical or chemical means. Several investigations attest to the variability of porosity in SG oxides:

- The average porosity of the outer (close to the coolant) and inner (close to the metal) layers on a 150 μm thick G-2 NGS cold-leg tube deposit was calculated to be 50% and 5%, respectively [Klimas et al 1998].

  After two successive 1 and 59 s mechanical cleaning steps, porosity of the remaining oxide ranged between 3 and 8% compared with an initial porosity of 38-43 %. After the cleaning, the deposit was of uniform thickness and appeared to be well consolidated. The cleaning process may itself have contributed to the compaction of the deposit.

- The porosity of the overall oxide on G-2 NGS cold leg pre-heater tube sections was estimated to be 40 %. The porosities of the remaining oxide on two tubes after the first clean step (69% of oxide removed) were 3.8 and 8.0 %, respectively. The corresponding values after the second clean step (total of 90% of oxide removed) were 5.6 and 2.9 % [Semmler et al 1998].

- Based on the dissolution behaviour of primary side DNGS SG tube oxide in concentrated HCl [Husain and Cervoni 2003], the dissolution rate for SG oxides exceeding a thickness of approximately 16 μm could be characterized as follows:

  - The outer 7-8 μm layer dissolved very rapidly,
  - The dissolution rate over an oxide thickness of 7-8 μm adjacent to the oxide-metal interface decreased as the interface was approached,
  - In the intervening layer, the dissolution rate was uniform.

  The above behavior may be attributed to variations in porosity and to the increasing ferrite levels as the metal interface is approached. Reduced porosity adjacent to the metal interface may arise from incorporation of base metal constituents with time.

4.6 Surface Roughness

The surface roughness on the primary side of SG tube surfaces has a significant impact on the core flow rate. The average surface roughness (defined by the parameter R_a[4]) for SG tubes removed from the cold leg pre-heater region of G-2 NGS in 1996 was found to decrease from 3.3 μm to 1.8 μm after 69% of the oxide was mechanically removed and further to 1.2 μm after removal of 90% of the oxide. The latter value was only 10-30% greater than that of new G-2 NGS SG tubes. Additionally, the R_a value for G-2 NGS SG tubes obtained after 1 minute blasting were in excellent agreement with the corresponding value of 1.0 μm for BNGS Unit 4 cold-leg SG tubes [Semmler et al 1998].

Table 4 provides a comparison of the 1996 data with subsequent data obtained in 2001 [Semmler et al 2002]. Clearly, the R_a value for cold-leg tube sections was higher than the value for hot-leg tube sections with the latter being somewhat higher than the value for new SG tubes.

Table 4 Surface Roughness of SG Tubes Removed from G-2 NGS

	R_a, μm
Cold leg SG tube removed in 1996	3.3
Cold leg SG tube removed in 2001	1.8
Hot leg SG tube removed in 2001	1.2
New Incoloy 800 tube	0.85

The roughness results lead to conclusions which are consistent with those reached earlier:

- Based on similar R_a values for media blasted G-2 NGS and BNGS Unit 4 tubes, the morphological characteristics of the Incoloy 800 and Inconel 600 tube oxides are considered to be similar.
- The surface roughness is a function of tube length: it is high in the cold leg, where the oxide is thick and low in the hot leg, where the oxide is thin.
- As expected media blasting results in a reduction of surface roughness.

5.0 DISCUSSION

In general, the effectiveness of the mechanical cleaning process is a complex function of

- process parameters such as blast time, pressure and flow rate of the blast media, direction of flow in the tubes and the extent of pre-drying (this was discussed earlier) of the internal SG surfaces.

  Compared to other applications, a significant difference at DNGS was the introduction of blast media into the hot leg (collected in the cold leg). The available literature does not

[4] R_a (average surface roughness) is defined as the arithmetic average of the distances of all profiles from a mean line over a distance of 300μm.

provide a rationale for this choice. Based on pressure drop considerations, flow of the blast media from the cold leg to the hot leg would appear to be more advantageous because the deposits in the cold leg are generally more copious and have a higher surface roughness than deposits in the hot leg. When the blast media are introduced in the cold leg, the abraded oxide will be transported with the blast media into the hot leg. This would be beneficial if the removed oxide enhances the abrasive power of the blast media (oxide along the flow path would be increasingly difficult to abrade because of its lower porosity and relatively higher ferrite content). When the blast media are introduced in the hot leg, any beneficial abrasive effect of the removed oxide would be largely felt in the cold leg where the oxide is already more friable (higher ratio of deposited to indigenous grown-in oxide) and more porous.

- Differences in SG design at various stations are illustrated in Table 5. Although the SG tube diameter at DNGS, G-2 NGS, PLNGS and Embalse is identical, the surface area in DNGS SGs is significantly greater. Based on values for the surface area and tube diameter, the average tube length at DNGS was estimated to be 3 m longer than that at G-2 NGS/PLNGS and 5 m longer than that at Embalse. Hence, otherwise identical conditions, mechanical cleaning of the DNGS SG tubes would pose a significantly greater challenge.

Table 5 Design Differences Between Various CANDU SGs

	Pickering A	**Pickering B**	**BNGS B**	**DNGS**	**G-2 NGS/PLNGS**	**Embalse**
SG per unit	12	12	8	4	4	4
Tubes per SG	2600	2573	4200	4663	3550	3542
Tube material	Monel 400	Monel 400	Inconel 600	Incoloy 800	Incoloy 800	Incoloy 800
Tube OD, mm	12.7	12.7	12.7	15.9	15.9	15.9
Surface area per SG, m^2	1858	1843	2400	4830	3200	2750
Average tube length, m	18	18	14	21	18	16

- In general, SG tube oxides have the following chemical characteristics:
  - The oxide consists of an outer layer of deposited oxide and an inner layer of grown-on oxide. The outer oxide is much more porous and has a higher surface roughness than the inner oxide.
  - The outer oxide is much easier to abrade than the inner oxide. This behavior (although no linkage is necessarily implied) is also consistent with the dissolution characteristics of the oxide, the inner oxide being much more difficult to dissolve than the outer oxide.
  - The outer oxide is largely magnetite while the composition of the inner oxide depends on the constituents of the base metal. Diffusion of base metal constituents (Cr, Ni and other elements) leads to a diffuse oxide-metal interface in DNGS Incoloy 800 tube deposits; the interface in BNGS Inconel 600 tube deposits

is, however, relatively sharp. It would appear from the incomplete oxide removal (efficiency of about 85% or less) experienced in all field applications to date that the oxide adjacent to the base metal is relatively resistant to abrasion. If only the outer oxide is principally abraded, the removal efficiency, considering other factors to be similar, should be comparable for SGs tubed either with Incoloy 800 or Inconel 600 (a somewhat higher oxide removal efficiency can possibly be achieved in Inconel tubed SGs because of the sharper oxide-metal interface relative to Incoloy 800 tubed SGs where the interface is more diffuse). This appears to be borne out by the outcomes of the mechanical cleans at various stations and of tests on removed tube sections.

6.0 CONCLUSIONS AND RECOMMENDATIONS

In the absence of sufficiently accurate metrics, it is difficult to assess the relative outcomes of various mechanical cleans performed to date. For instance, BNGS estimated the oxide removal efficiency for its SG clean to be 80% based on outdated Oxiprobe data and assuming the initial oxide loading to be the same in all cleaned SGs (this assumption is not supported by Oxiprobe data for SG2 and SG4 in DNGS Unit 3). Regardless of the inconsistency between the methodologies used for reporting the outcomes from various cleans, it is clear from the post-examination of cleaned DNGS tubes that significant levels of oxide still remained in the SG tubes after the clean. Process factors such as the low operating pressure and insufficient drying may have been responsible.

The results from all SG clean applications to date appear to suggest that, in general, the key factor limiting the oxide removal efficiency may be the abrasion resistance of the oxide adjacent to the metal interface. Up to approximately 85% of the oxide loading consisting principally of the outer magnetite layer appears to be amenable to removal by abrasion. The need to further optimize the blasting process in order to achieve the removal of the oxide at the base metal interface must be rationalized considering the diminishing benefits of such removal. The additional oxide removal may not lead to a further reduction in the surface roughness or a further improvement in the heat transfer characteristics[5] of the SG tubes. Thus, additional improvements in RIHT and PHT flow rate are unlikely to occur.

It is desirable to develop improved metrics for assessing the outcome of SG mechanical cleans. The following recommendations are proposed:

- Techniques should be developed for quantifying the oxide removal efficiency. This requires a measure of the oxide loading before and after the clean. Two alternate techniques may be employed, one based on eddy current and the second based on dose rate measurements.

  The SGSCAN technique represents a specific variation of the dose rate approach. It employs a miniature gamma scanning detector inserted through the tubesheet to record the Co-60 response from numerous surrounding tubes as a function of tube length. Because the Co-60 response is a measure of the oxide loading, performing the measurements before and after the clean provides data on the oxide removal efficiency.

[5]Work by Kilmas [1998] indicated that while the 90 to 150 μm thick internal deposits on a G-2 NGS SG primary side cold-leg tube section posed a significant resistance to heat transfer, the 10 to 30 μm thick dense layers remaining after a cleaning step (media blasting or chemical decontamination employing CAN-DEREM Plus) had no measurable effect on heat transfer.

The Co-60 response can also be further interpreted to obtain oxide loading data and hence an estimate of the amount of waste that would be generated during a clean.

- Planning for SG cleans should include examination of tube sections before and after a clean to provide direct visual assessment of the outcome. Profiling the oxide layer chemically and radiochemically would provide further insight on the achievable oxide removal efficiency.

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