PROBABILISTIC MODELLING OF PITTING CORROSION IN STEAM GENERATORS

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ABSTRACT

Pitting corrosion is a serious form of degradation in steam generator tubing of some CANDU reactors. The initiation and propagation of the pitting process is fairly random, requiring inspection and cleaning activities to minimize the risk of tube leakage. This paper presents the analysis of pitting data collected over the years through the inspection of steam generators at the Pickering B Nuclear Generating Station. The paper describes the distributions of the number and size of pits generated over the service life of the station and correlates them with the history of outages and chemical cleaning and water lancing campaigns. The results of the data analysis can then be used to build a probabilistic model of pitting corrosion and to develop a risk-based model for steam generator life cycle management.

1. INTRODUCTION

Steam generator (SG) tube degradation is a complex process that depends on many factors, including material selection, impurities and chemical interactions, as well as operational and maintenance activities. Degradation modes such as circumferential cracking, intergranular attack (IGA), pitting, fretting, denting, erosion corrosion and thinning, and outer-diameter stress corrosion cracking (ODSCC) have been documented to affect a large number of steam generator tubes around the world (IAEA, 1997; Diercks et al., 1999; Tapping et al., 2000; EPRI, 2000; EPRI, 2003). This widespread degradation has been responded to with various mitigative actions, from simple tube plugging to repair and replacement activities, as well as other operational control strategies. Advanced in-service inspection technologies have also been developed in an attempt to quantify the extent of the degradation processes (e.g., Obtrutsky et al., 2002). Detailed understanding of all aspects of the relevant degradation modes, as well as methods for their assessment and mitigation are essential for maintaining the pressure boundary integrity and ensuring reliable steam generator operation.

The process of pitting (or under-deposit pitting) corrosion continues to be an active degradation mechanisms at the Pickering B Nuclear Generating Station (NGS). The main factor contributing to tube pitting is the combination of tube material and the presence of porous adherent deposits (Maruska, 2002). The earliest indication of under-deposit pitting corrosion was discovered in Pickering B Unit 5 in late 1991, resulting in extensive rehabilitative work at the station, including several inspections, water lancing and chemical cleaning campaigns, upgraded chemistry controls, and major modifications to the secondary side systems (Nickerson and Maruska, 1998).

The goal of steam generator life cycle management is to maximize value by balancing the cost of inspection and maintenance activities with the possible risk of not performing these activities, while ensuring the safe and reliable operation until the expected end-of-life (Maruska, 2002). Based on experience at Pickering B, there are uncertainties associated with the detection of pitting and the effectiveness of maintenance and operational measures used for mitigating the pitting process. These uncertainties complicate the life cycle management process and can potentially jeopardize the remaining economic life of the units. Accounting for these uncertainties through a risk-based approach is critical to the success of the life cycle management program.

The risks associated with steam generator tube degradation can be quantified through various probabilistic modelling techniques. Estimating the probability of leakage, e.g. from pitting corrosion, feeds into the risk-based LCM planning process, and helps to identify the most cost effective LCM strategy with the lowest overall risk.

1.1. Objectives

The goal of this study is to conduct an assessment of pitting corrosion at Pickering B NGS for augmenting the data required for developing a probabilistic model of the pitting process. This model would be necessary in the estimation of life-cycle costs and risks and in the quantification of the benefits of inspections and maintenance programs.

This paper presents an automated methodology to analyse all historically reported eddy current inspection data collected at Pickering B Unit 5 over the years. Using this methodology, the paper establishes the distributions of the number and size of pits generated over the service life and attempts to correlate them with the history of outages and maintenance activities at the station. The paper also investigates the relation of the extent of pitting with sludge deposits in the steam generators.

The results of the data analysis will be applicable to build a probabilistic model of pitting corrosion and to develop a risk-based model for steam generator life cycle management. The risk-based LCM model can be applied to evaluate the effectiveness of maintenance activities, i.e. water lancing and chemical cleaning, and to forecast the risk and cost over the remaining service life of the station.

This paper will focus on the analysis of Pickering B Unit 5, however, other Pickering B units are also being considered, and are presently being analyzed using the developed methodology. The methodology is based solely on the information contained in the eddy current database, and does not include any detailed analysis of the original (raw) probe signal data.

2. PITTING CORROSION IN PICKERING B NGS

Both Pickering A and B nuclear generating stations consist of four 540 MWe CANDU reactor units with twelve steam generators (SGs) per unit. All 48 steam generators used in Pickering B were manufactured by Babcock & Wilcox Canada using Monel 400 tube material. Each steam generator consists of 2573, 12.7 mm (0.5 inch) outside diameter tubes, which were mechanically rolled and seal welded into the tubesheet during construction. The tubesheet consists of a 311 mm thick by 1,854 mm diameter carbon steel forging, with a 4.75 mm layer of Inconel/Monel on the secondary side to reduce the potential for galvanic corrosion. The tubing was manufactured by three different companies to meet ASTM SB 163 specifications.

The steam generators at Pickering B are undergoing a variety of degradation modes. These include tube pitting (or under-deposit pitting corrosion), tube/support fretting, tube erosion corrosion, cold leg thinning, and tube failures due to debris (Maruska, 2002). These degradation mechanisms are active on the secondary side and impact the outside diameter (OD) of the steam generator tubes. However, the primary cause of steam generator tube degradation impacting all steam generators at Pickering B is pitting corrosion.

The steam generators in all four Pickering B reactor units have been impacted to varying degrees by under-deposit corrosion, with Unit 5 having the most extensive damage. All four units have experienced forced outages due to leaking steam generator tubes caused by through-wall pitting.

The process of steam generator tube pitting at Pickering NGS has been characterized to be occurring in two different and distinct ways (Maruska, 2002):

1. few "new" pits initiate and grow rapidly through-wall, causing forced outages due to tube leaks, and
2. few "old" pits propagate and grow slowly.

Some steam generators have large quantities of deposits but relatively few indications of pitting. Pits have been found predominantly at the tubesheet (within sludge) and to a lesser extent at fouled lower hot leg supports. Some pitting has also been identified at the tube freespan region.

2.1. Data Overview

The Pickering B eddy current (ET) inspection database contains over one-million data points, starting from the early 1990's to the present. Approximately 36 % of these records are associated with the inspection of Unit 5. While the majority of the data describes the inspection results for each tube, one-fifth of the records are related to sludge measurements. Because of inspection problems by the basic eddy current probe (CTR-1) near the top of the tubesheet (TTS) discovered in the late 1990's (Sullivan et al., 1999), as well as for other verification purposes, the original inspection database also contains a large number of review entries for various outages. The review entries are duplicates of the original records with revised parameters, e.g. pit depths, based on re-analysis of the original probe signal.

Figure 1 shows a summary of the database records for all twelve steam generators in Unit 5. As illustrated by Figure 1, most of the entries (56 %) are classified as NDD, or No Discernible Defect, with 4 % of the records related to pit-like indications. There are a total of twelve different inspection outages in the database consisting of the inspection of varying number of steam generators. Typically, one-half (or six) steam generators are inspected during each planned outage.

The database contains 19 fields which are used to characterize the eddy current signal. This includes fields such as voltage, channel, calibration group, probe type, extent of scan, axial location and elevation of indications, as well as the outage and type of indication and/or flaw. There are 70 different types of calls denoting various observations in the probe signal, including volumetric wall loss due to pitting corrosion.

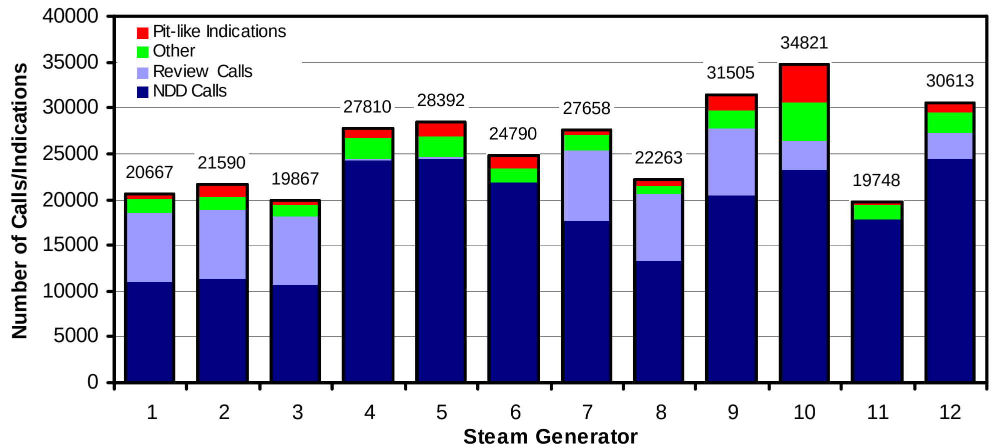

Figure 1*: Summary of database records for Unit 5 steam generators.*

There are only eleven different types of indications relevant to the analysis of pitting corrosion, which are shown in Table 1. The most important entries are the "blank" call types, which indicate a volumetric loss of wall material as a percentage of through-wall depth, along with location, elevation, and other relevant information. The type of flaw is indicated by a separate field, which can be used to determine whether the entry refers to pitting, or some other degradation mechanism.

Table 1*: Call types relevant to the analysis of pitting corrosion.*

Call Type	Definition	Description
(blank)		Volumetric wall loss of tube material
<		Volumetric wall loss of tube material less than the size indicated in the depth field. The size of the flaw is censored because the analyst is unable to discern the exact size.
FFO	For Future Observation	Discontinuity of interest, but not presently recordable. To be used only after the discontinuity has been rescanned. No rescans are required for FFO's, however, they should be scheduled for inspection in subsequent outages.
INF	Indication (Discontinuity) Not Found	Previous/current history confirmation. Call was made in previous/current inspection, discontinuity not found at this location. (Same probe type).
INR	Indication (Discontinuity) Not Reportable	Previous/current history confirmation. Call was made in previous/current inspection, discontinuity not reportable as per current criteria. (Same probe type or enhanced probe).
INV	Indication (Discontinuity) Not Verified	Enhanced Probe only: Bobbin call was made in previous/current inspection, discontinuity not detectable with an enhanced probe.
NDD	No Discernable Defects	No reportable discontinuities observed in data.
NDS	No Discernable Sludge	No sludge reportable.
RTB	Rerun Tube	Rescan required with the same probe type for confirmation. I.e. resize defect, tube identification.
SLG	Sludge	Deposits above the tubesheet.
TBR	Rerun Tube	Rerun tube. Early form of RTB calls.

4.

Another important call type is NDD, which indicates that the probe signal for the tube, or more specifically the extent of the tube that was scanned, contains no discernable defects. The NDD call is directly related to the probability-of-detection (POD) for the particular probe. Therefore, depending on the POD, there is a chance that defects may be present, even though the database indicated NDD.

Similar to the NDD call, the INF and INV calls are related to the probe POD and indicate that a previous or existing flaw cannot be detected at this time. Depending on the POD, there is a likelihood that the defect may in fact still be present, even though it was not detected. There is also a chance that the previous call was mislabelled (i.e. erroneous), and that no defect exists at that particular location and elevation.

The INR calls are used to confirm the presence of existing (prior) indications during a particular outage. These indications refer to indications that are detected (i.e. above the detection threshold), but are too small to be reported based on current reporting criteria (i.e. below the reporting threshold).

The calls FFO, RTB and TBR refer to the presence of a flaw indication, which require further inspection for verification. Although these calls, as well as the INR calls, do not contain size or depth information, they can be used to establish the time of initiation of a new pit, or confirm the detection of an existing pit.

The flaw type field is used to characterize the nature of the volumetric wall material loss. This field indicates not only whether the wall loss is occurring on the inside or outside diameter of the tube, but also if it is occurring at a tube support structure, or under sludge deposits. The process of flow induced erosion corrosion or “top hats” at the broach plate supports is also recorded in the flaw type field.

3. METHODOLOGY

The main objective of the data analysis is to construct a consistent and reliable dataset for Pickering B Unit 5 that can then be used for statistical analysis and probabilistic modelling of pitting corrosion. Construction of the dataset requires identifying and tracking all pit-like indications and their depths over time in all twelve steam generators. This information is used to establish the pit size distributions and pit initiation rates for the population of detected pits. The goal of the statistical analysis is then to fit probability distributions to the data. The issue of pit growth will also be addressed in light of the probability-of-detection (POD) issues and measurement errors associated with the inspection techniques.

Construction of the dataset for under-deposit pitting corrosion at Pickering B Unit 5 consists of the following three steps:

1. Update the original data with the reviewed values.
2. Make all values in the database consistent by correcting errors and omissions.
3. Identify all unique pit-like indications.

Each of these steps is described in greater detail in the following sections.

3.1. Review Data Update

The eddy current database for Pickering B Unit 5 contains a large number (over 50,000) of review entries based on the re-analysis of the original probe signal. It is reasonable to assume that all review entries provide not only equal, but a more accurate interpretation of the eddy current signal. Therefore, all original calls were replaced with their respective reviewed values, where applicable.

All review entries are duplicates of the original records with revised parameters values. Because the database contains no unique identifier between the two records, matching the original records with the revised values proved challenging. The only common element between the two sets of records is the calibration group field, which identifies a chronological series of tube tests between which the probe is checked for calibration. The calibration group applies to the entire probe signal within the extents of the inspection in the tube (denoted in the probe extent field) and may contain single or multiple indications depending on the degree and extent of the degradation process. For the purpose of the analysis, it was assumed that the data review applies to the entire probe signal in a tube, and hence the calibration group.

The other parameter that is assumed to be unchanged and common between the two sets of records is the flaw axial location. While the flaw elevation may change slightly as a result of the review, the flaw location, indicating the reference structure such as a tube support or top of tubesheet, is likely to remain unchanged. The original records and the reviewed values were therefore matched using both the calibration group and the flaw location fields.

The review of each flaw and calibration group was assumed to be comprehensive, therefore,

- If the number of reviews was *equal* to the number of original calls, all original calls were replaced with the reviewed values.
- If the number of reviews was *greater than* the number of original calls, all original calls were replaced and the excess reviews were added to the dataset.
- If the number of reviews was *less than* the number of original calls, all the matching records were replaced and the unmatched originals were deleted from the dataset.

3.2. Make Database Consistent

Due to the size of the database and the long period of record, many inconsistencies were present in the data. For example, the labelling of tube support structures and probe types has changed over the years, as well as the descriptions used for the various datasets. These changes affect the location, extent and probe type fields, which were updated for consistency. For example, old support labels, such as HLBP1 (hot leg broach plate 1) were replaced with new labels, i.e. H01.

Another major task was not only to determine which of the 70 different call types were relevant to pitting corrosion, but also to correct any anomalies associated with these calls. Other minor errors and omissions were also corrected, such as missing values and duplicate records.

3.3. Identifying Unique Pits

The final, and most important step in the data analysis was developing the methodology for identifying all new and existing pit-like indications. A total of eleven call types in the database were determined to be relevant to pitting corrosion as shown in Table 1. The other important attribute, the flaw type field contained numerous inconsistencies, due to changes in recording practice over time. Because of these problems, it was assumed that all flaw indications would be considered to be corrosion pits, unless explicitly labelled as TH (top-hats) or ID (inner diameter) flaws. Furthermore, due to the presence of cold leg thinning in some steam generators, which is also reported as an OD wall loss in the eddy current database, the pitting analysis was limited to the hot leg side of the steam generator tubes.

Many different probe types have been used to inspect the Pickering B Unit 5 steam generator tubes for pitting corrosion. These include that basic eddy current bobbin probe, or CTR-1, the multicoil array probe CTR2-C4, and more recently the versatile X-Probe. Each probe is faced with challenges in detection and sizing due to the probe design limitations as well as environmental and operational factors. For the process of identification and sizing of pits, the following order of probe preference (or accuracy) was assumed, from best to worst:

1. X-Probe
2. CTR2-C4
3. CTR-1

This means that if a pit indication was scanned using multiple probes, the results of the most preferred probe would be used. The probe order plays a critical role in pit identification by dictating not only the most recent pit population, but also the entire historical record.

The main challenge facing the pit identification process involved resolving the issue of elevation referencing. The inspection probes travel at great speeds through the length of the tube starting from the end of the tubesheet. Because the use of an axial encoder is not standard procedure, there is no direct way to measure or track the exact axial location of the probe within the tube during the probe run. As a result, the axial location or elevation is computed based on the probe velocity. Although the location estimates can be improved by correlating the probe signal with known locations, such as tube supports, the resulting estimates are highly uncertain due to variations in probe velocity during each inspection run. The general approach to resolve this issue is to assume that all indications within approximately one inch (+/- 1.27 cm) from other (previously identified) indications to be the same. This concept is fairly arbitrary, however, and may result in mislabelling of indications (i.e. erroneous results).

The process of pit identification can be improved substantially by considering the information from each calibration group as a reference. While the elevation of flaw indications can vary a great deal between outages, the elevation of indications within each calibration group (i.e. individual tube signal or scan) is much more precise. That is, the axial distance (i.e. elevation difference) between multiple indications in the same calibration group is more accurate than the elevation differences between outages (i.e. between probe scans). In fact, it is possible to distinguish pits that are very close together (a few millimetres apart) in a particular probe signal. One of the key assumptions in the analysis is therefore that all indications within each calibration group are assumed to be unique, no matter how close they are to each other.

Figure 2 shows the inspection results for tube R28C56 in Pickering B Unit 5 SG-10. In addition to the sized indications, the INR calls, denoted by the hollow symbols, are also included in the figure. As illustrated by Figure 2, there is a great deal of variability in the elevation of the indications between outages. However, the distance between multiple indications in the same outage (and calibration group) is much more consistent, and can readily be used to identify both corresponding and unique pits between outages. As also illustrated by Figure 2, the elevation difference of corresponding pits between outages can be greater than the general +/- one inch margin.

The identification of new and existing pits is therefore accomplished by shifting all the new pits in a calibration group as a group to match the elevation of the existing pits. The optimal match is determined by minimizing the sum of the elevation differences between all the combinations of new and existing pits.

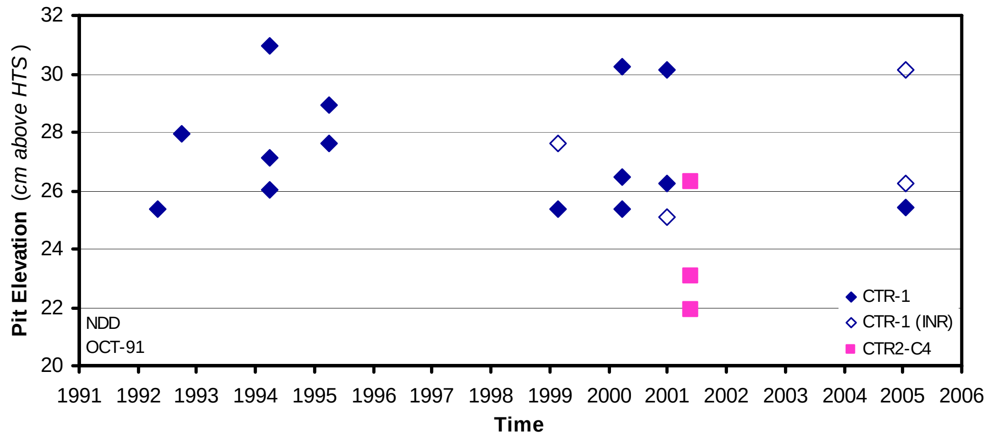

***Figure 2**: Eddy current inspection results for SG-10 tube R28C56.*

While this methodology significantly improves the matching of groups of pits, labelling single pit indications is still subject to uncertainty. To accommodate the larger elevation differences observed in the data, it was assumed that all single pits that are within 1.5 inches of existing (previously identified) indications would be considered to be the same.

The actual procedure for identifying the pits consists of a number of steps, with the probe order playing an important role. As stated above, only indications on the hot leg side of the tubes were considered in the analysis. The step by step listing of actions is as follows:

1. **Sort the Data**
   For each tube, sort the data from most recent to the oldest and also using the probe order. The idea is to consider the latest and most accurate information first.

2. **Process Non-Defect Calls**
   Remove all INF, INV and NDD calls for better probe only. The INF and INV calls are matched using location and elevation, while the NDD calls are matched using the scan extent. For example, an X-Probe NDD call from HTE to H06 in a tube in the most recent outage indicates that the tube has no pits between the hot leg end of the tube (HTE) and the sixth hot leg support (H06). Therefore, all prior indications of pitting within that span are assumed to be erroneous and can be ignored, unless they were also recorded using the same probe, i.e. X-Probe. Any prior indications above the sixth support plate must still be considered, however.

3. **Process Pit-Like Indications**
   For pit-like indications, also start with the latest and most accurate data, one calibration group at a time. For the calibration group, identify all pits as unique. Record the extent and type of probe coverage.

4. **Match Indications**
   Proceed to the next calibration group (previous outage and/or less accurate probe). Match pits by shifting all the new indications and minimizing the sum of the elevation differences. Flag results for detailed review whenever a single pit is shifted more than the 1.5 inch (3.81 cm) margin, or when the sum of the elevation differences is also greater than 1.5 inches. Consider unmatched indications (e.g. the case when the number

of new indications is greater than the number of existing ones) as unique pits only if the indications have the same or better probe than previously, or if the indications are outside the extent for all previous calls.

5. **Compute Averages**
   Compute average pit elevations and average shifted elevations. Single pits are compared to average pit elevations, while multiple pits are compared with the average shifted elevations. The average shifted elevations correspond to the average elevation differences within the group of pits.

6. **Repeat**
   Proceed to the next calibration group (previous outage and/or less accurate probe) and continue until the last (earliest) outage.

Figure 3 shows the results of the methodology for the tube R28C56 (shown above in Figure 2). As illustrated in Figure 3, a total of three unique pits are identified in the tube going back to the early 1990's. Figure 3 also shows the impact of probability of detection (POD) and reporting threshold on the results. The results from the FEB-05 outage using the CTR-1 probe identify a single pit, with the other two pits being unreportable. However, since the FEB-01 inspection using the more accurate CTR2-C4 probe identifies three pits, it is concluded that there must be total of three pits in the tube. The CTR-1 probe is not as sensitive as the CTR2-C4 probe and, aside from the APR-94 and APR-00 outages, generally reports fewer pits.

The developed methodology for pit identification was implemented in the Visual Basic for Applications (VBA) programming environment in MS-Access. The analysis of all the tubes in each steam generator on a standard desktop PC took approximately two minutes of computing time. All pit-like indications on the hot leg side were assigned unique identifications, or discarded based on the best probe and elevation margin criteria. For Unit 5, several tubes were flagged for detailed review due to the exceedance of the 1.5 inch elevation margin. These tubes were processed manually and added to the final database of results.

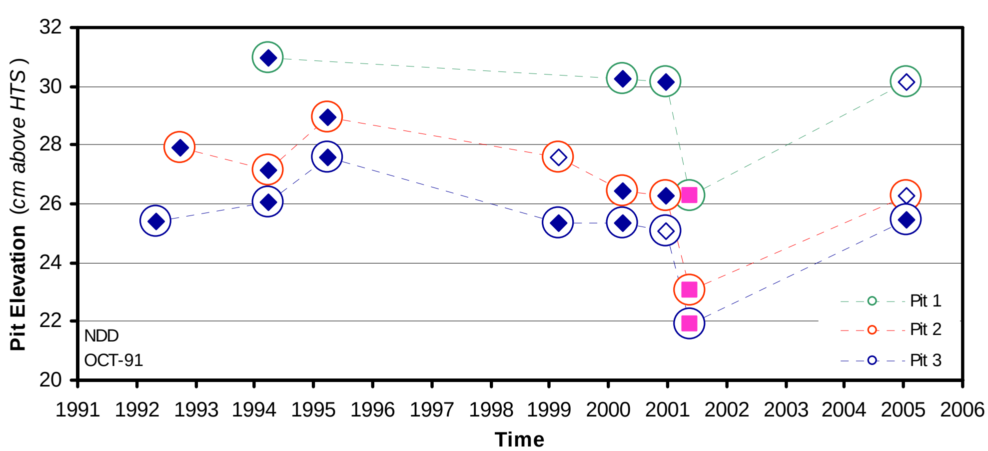

***Figure 3**: Eddy current inspection results for SG-10 tube R28C56.*

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4. RESULTS

The summary results of the data analysis of Pickering B Unit 5 are shown in Figure 4. It shows the total number of unique pits (identified on the hot leg side) in all twelve steam generators in Unit 5. As indicated in Figure 4, pitting corrosion is most extensive in SG-9 and SG-10, while SG-11 is the least impacted (i.e. in terms of the total number of unique pits). All other steam generators exhibit a similar degree of pitting corrosion.

As shown in Figure 4, SG-10 is by far the most impacted steam generator in Unit 5, therefore, the following detailed discussion will focus on the results of SG-10.

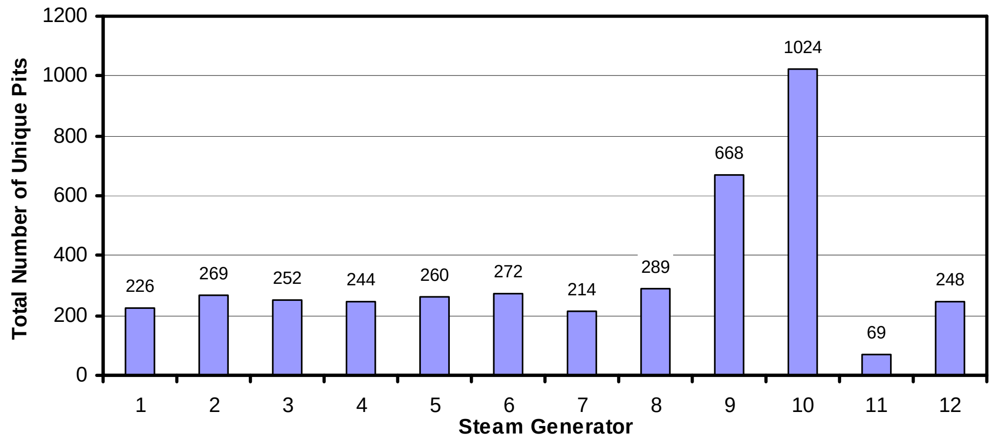

Figure 4*: Total number of unique hot leg pits in Unit 5 steam generators.*

4.1. SG-10 Results

Figure 5 shows the evolution of hot leg pitting over time in Pickering B Unit 5 SG-10. The dates for the two water lancing (WL) and chemical cleaning (CC) campaigns are also included in the figure. Following the initially high pitting rates before the OCT-92 water lancing and chemical cleaning campaign, the initiation of new pitting was reduced substantially for a long period until the late 1990's, when an increase in the pitting rate was observed. Based on Figure 5, FEB-01 WL/CC campaign has substantially reduced the rate of new pit initiation.

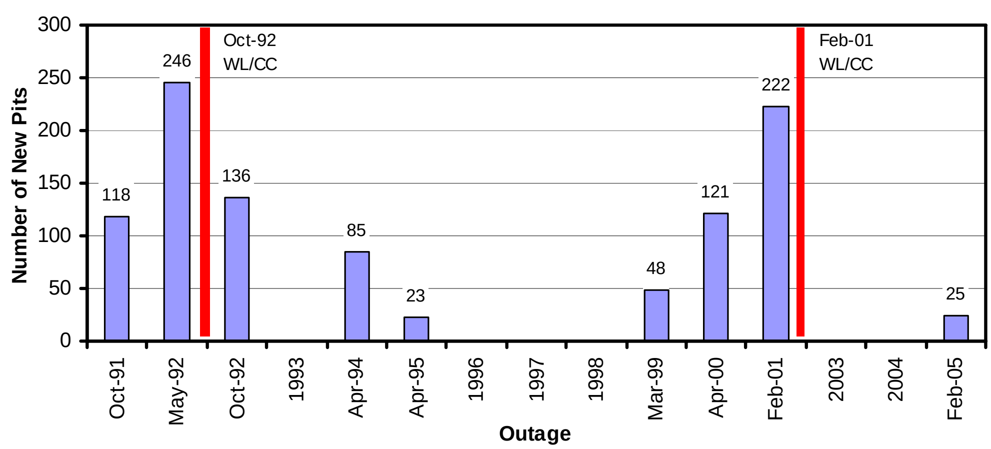

Figure 5*: Number of new hot leg pits for SG-10 in each inspection outage.*

The distributions of pit sizes for each of the outages for Pickering B Unit 5 SG-10 are shown in Figure 6. As illustrated in Figure 6, the size of new pits have decreased over time, with only a few new pits generated greater than 20 or 30 % through-wall depth (TWD) in the more recent outages. The increase in the number of new pits observed in SG-10 in APR-00 and FEB-01, therefore, consists exclusively of very small pits, characterized as being less than 20 or 30 % TWD.

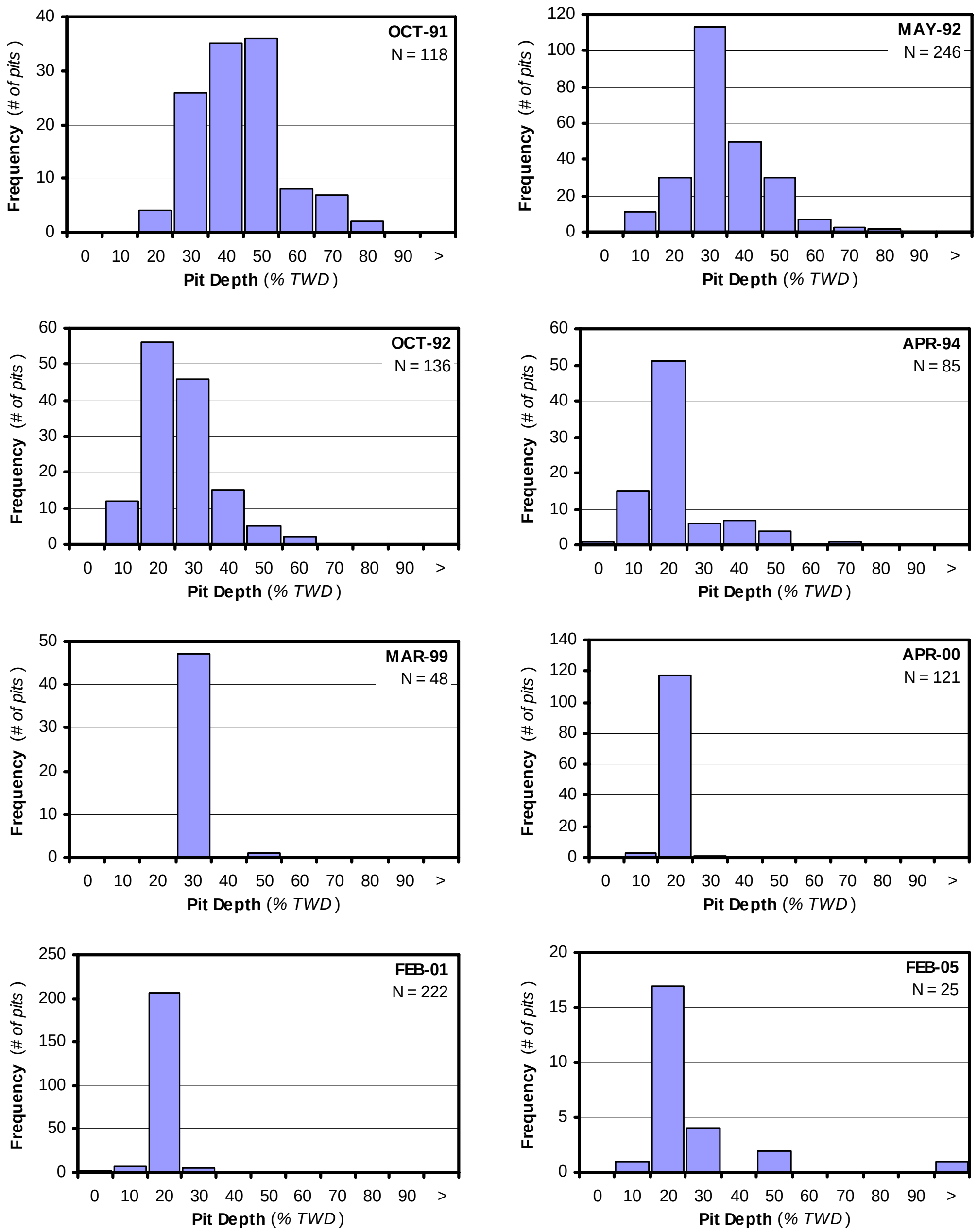

Figure 6: *The distribution of new pit sizes in each outage for SG-10 (excluding the APR-95 outage, which had only 496 tubes inspected).*

All inspection probes are subject to some uncertainty as reflected by their respective probability-of-detection (POD) curves. The POD curve reflects the reliability of the inspection technique by indicating the lower pit size bound that can be reliably detected. It is assumed that the likelihood of detection increases with the size of the pits.

The results of the performance demonstrations have shown that the CTR-1 probe has difficulty in accurately sizing smaller pits (Sullivan et al., 1999). That is, the error increases for pits less than 30 or 35 % through-wall depth. Unlike the basic bobbin probe CTR-1, the CTR2-C4 probe uses a multi-coil (array) transmit/receive design, which allows it detect corrosion pits with higher accuracy. For example, in SG-10 in the FEB-01 outage, a total of 86 % of the new pits in the FEB-01 outage were detected exclusively by the CTR2-C4 probe. The CTR-1 probe was unable to detect or report these smaller pits (i.e. NDD or not found). In fact, 81 % of the new pits detected during the FEB-01 outage were not reportable by CTR-1 probe during the subsequent FEB-05 outage. These results demonstrate how the POD issue complicates the analysis of pit initiation rates in each outage interval. The actual pit initiation time is masked by the instruments ability to detect it.

Figure 7 shows the number of hot leg pits initiated in SG-10 over time for different sizes. As illustrated in Figure 7, the increase in the number of new pits in APR-00 and FEB-01 is due almost entirely to pits ≤ 25 % TWD. For pits > 25% TWD, the initiation rate has been variable, though it shows a more stable trend in recent times.

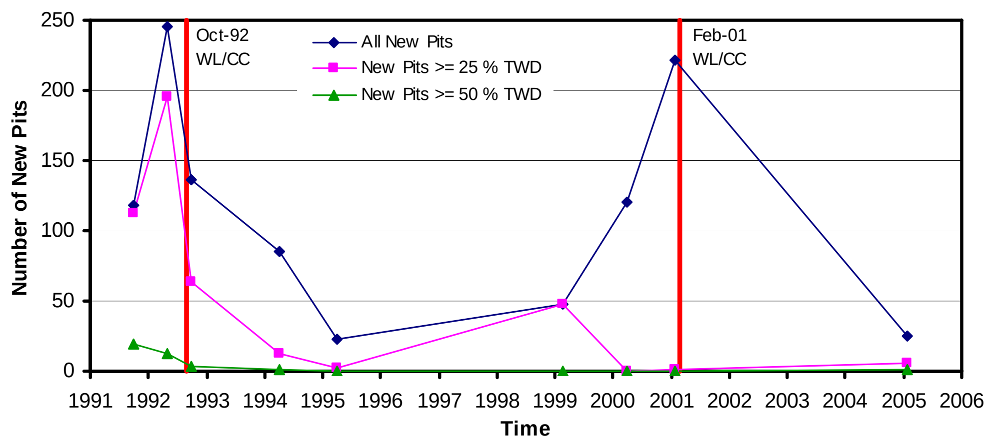

***Figure 7**: Number of new hot leg pits for SG-10 of various size.*

4.2. Unit 5 Results

The initiation of hot leg pits ≥ 25 % TWD in all Unit 5 steam generators is presented in Figure 8. As illustrated by the plots, the initiation rate in recent years has been lower than that in the early 1990's. The two possible factors contributing to this decrease may be the removal of the sludge deposits in the early 1990's by water lancing and chemical cleaning and subsequent improvements in the secondary side operational chemistry through the removal of copper bearing components and implementation of a high hydrazine chemistry regime. In general, chemistry control alone has a limited ability to influence the pitting corrosion process, however, combining it with effective sludge removal may be responsible for the observed reduction in the pit initiation rates.

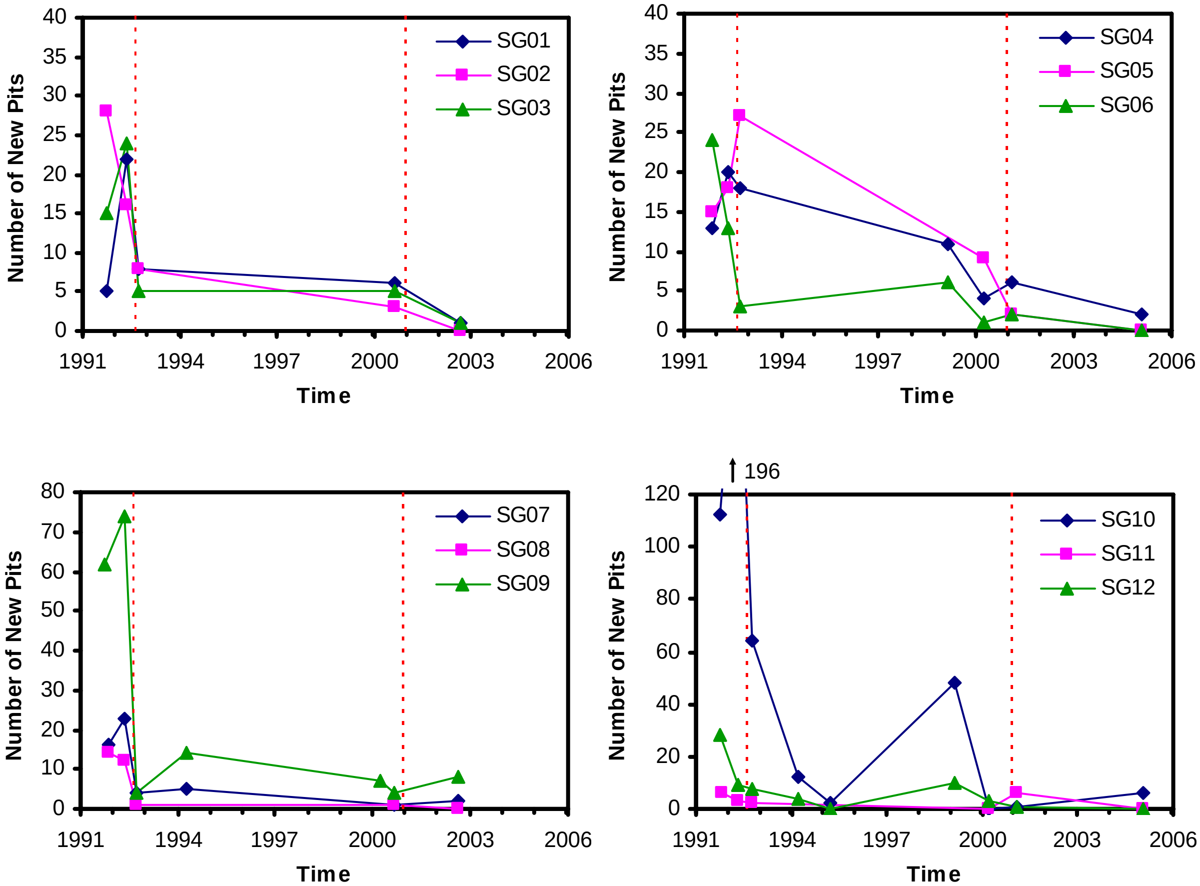

***Figure 8**: Number of new hot leg pits >= 25 % TWD in all Unit 5 steam generators.*

Based on Figure 8, it appears that the FEB-01 WL/CC campaign has contributed to a reduction in the pit initiation rates in several steam generators. Statistical analysis and probabilistic modelling work is underway to investigate this issue quantitatively.

4.3. Assessing Pit Growth

Based on previous assessments of pitting corrosion at Pickering B NGS, it was determined that only a few of the existing or "old" pits propagate and grow slowly (Maruska, 2002). Figure 9 shows the results for common hot leg pits observed during selected outages for SG-10. The red line indicates the area of increased uncertainty at less than or equal to 35 % TWD.

As shown by Figure 9, there is considerable scatter in the measured pit depths between the outages. The scatter in the data is relatively evenly balanced indicating both growth and "negative" growth. It is unlikely for a pit to fix itself once it has been established, therefore, the scatter can be attributed to the measurement error associated with the inspection probes. It is possible that some growth may be taking place, however, it is very difficult to observe due to the large measurement errors (up to 13 % for CTR-1) associated with the probes.

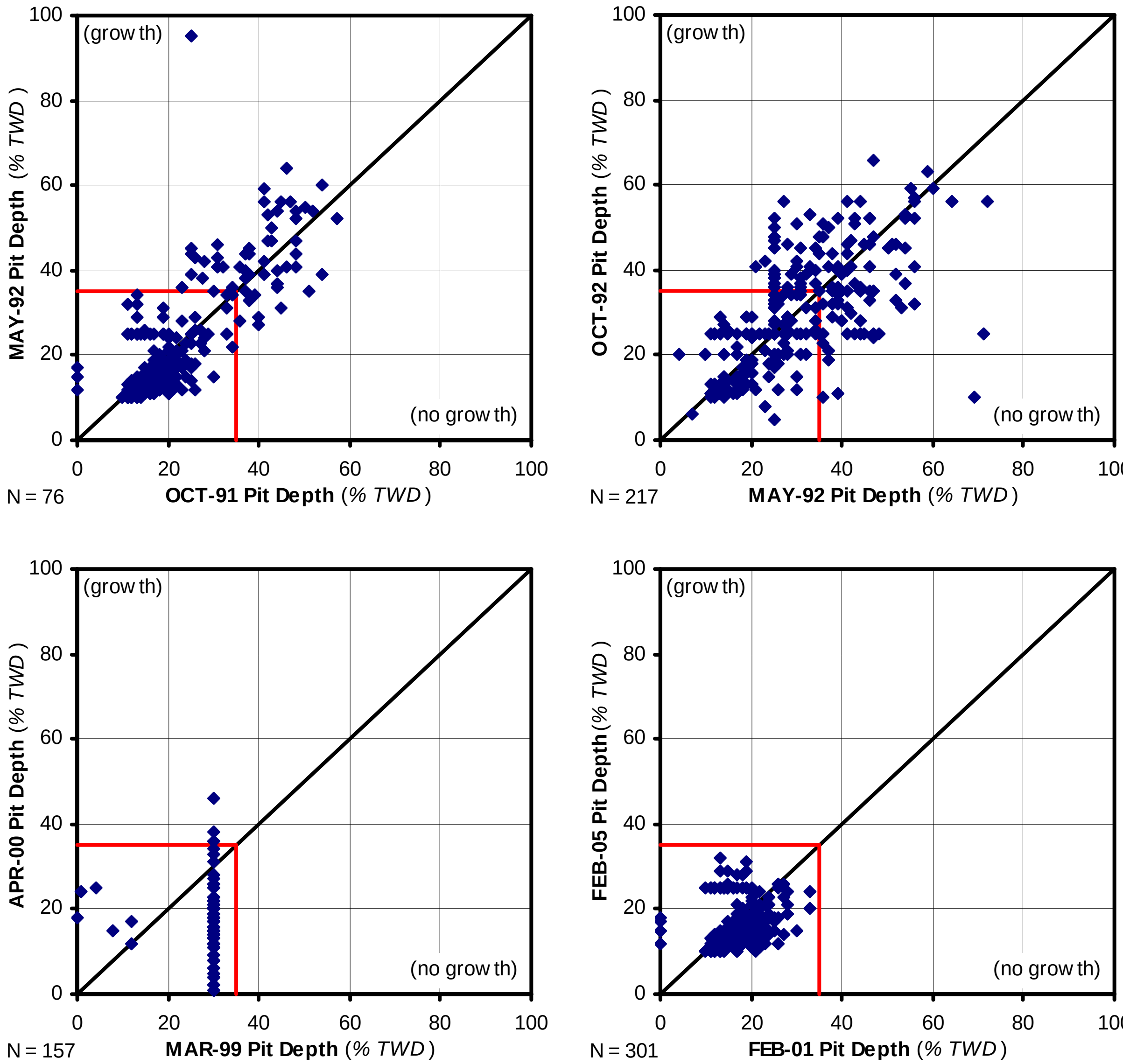

***Figure 9**: Depths of common hot leg pits observed between two selected outages for SG-10.*

The common pits measured during the MAR-99 and APR-00 outages demonstrate the impact of censoring on the results. During the MAR-99 inspection campaign, most of the pit sizes were censored and recorded as being less than 30 % TWD. Due to limitations in the examination technique, pits below the 30 % TWD lower limit were reported as simply < 30 % TWD. During the APR-00 outage, however, the technique was changed and the pits were assigned a specific depth. These results were not based on the use of a different probe, but were due to changes in the inspection practices, based on past measurements of the actual pit sizes with ultrasonics. This furthermore highlights the spectrum of uncertainties associated with the smaller pits.

Figure 10 shows the results for all common hot leg pits observed between any two outages (not necessarily consecutive) from all the Unit 5 steam generators. That is, a pit that is observed during, for example, four outages, would appear on the plot six times (all combinations of observed depths between all four outages).

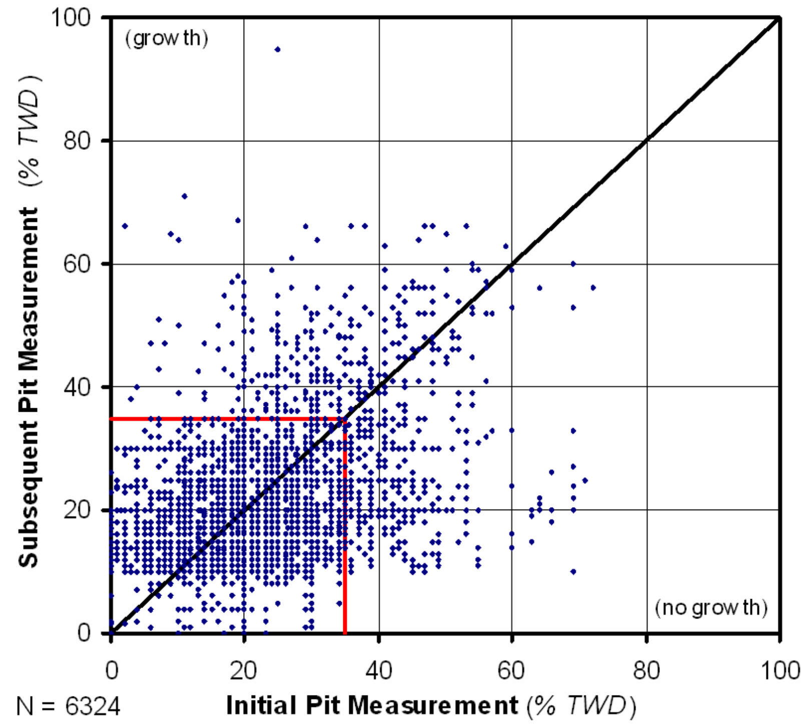

***Figure 10**: Depths of all common hot leg pits observed between any two outages for all Unit 5 steam generators.*

As shown by Figure 10, there is considerable scatter in the data, making it difficult to discern any systematic and significant growth. However, since this plot contains all the observations from all Unit 5 steam generators, any growth should be clearly evident as a clustering of points above the 1:1 diagonal line. The results of Figure 10 therefore concur with the conclusions of the previous assessments, that only a very few pits seem to exhibit any measurable growth. Of course, the analysis results are slightly biased by the fact that any tubes having pits greater than 50 % TWD are generally removed from service by plugging, thereby limiting the assessment of pit growth to pits that are less than the 50 % TWD plugging criteria.

4.4. Impact of Sludge on Pitting

One of the key factors in pitting corrosion is the presence of porous adherent deposits. The deposits of scale, crud, and sludge consist of various hostile ions (e.g. chloride, sulphate species, and copper) which facilitate the process of metal dissolution and pit formation. By definition, therefore, under-deposit pitting corrosion occurs within and/or near the sludge deposits.

As discussed previously, the eddy current database for Pickering B NGS contains estimates of sludge height as recorded during the inspections. The adherent sludge deposits, and especially the large sludge pile present at the top of tubesheet (TTS), are visible in the eddy current probe signal, and are therefore also recorded in the database. The estimates of sludge height are subject to uncertainty, with the data from the early 1990’s being less reliable than the results from the more recent outages.

In many instances, multiple sludge heights for a single tube during the same outage were reported in the database. This issue was resolved by computing the average value of sludge height for the tube, whenever the values were sufficiently close to each other. For cases with significant variability in the recorded elevations, the values were compared to the elevations in the nearest surrounding tubes and then selecting the closest match.

Figure 11 shows the sludge profiles measured for SG-10 during the MAY-92 and FEB-05 outages. As stated above, the sludge measurements from the MAY-92 outage are subject to higher uncertainty than the results from the FEB-05 outage. The sludge surfaces were interpolated using the method of kriging. Kriging is a geostatistical method for interpolating and contouring spatial data.

As shown in Figure 11, a considerable amount of sludge was present at the top of the hot leg tubesheet in SG-10 in the early 1990's. Following the water lancing and chemical cleaning campaigns, the sludge pile was reduced significantly with only a small pile remaining on the tubesheet in the FEB-05 outage. The small amount of remaining sludge is likely to be comprised of severely consolidated and hardened deposits which are nearly impossible to remove completely using existing methods.

The results for the APR-00 outage for SG-10 are illustrated in Figure 12. It shows the interpolated sludge pile profile as well as all new pits detected during the outage at the top of the hot leg tubesheet (HTS) (some new pits were also found at the support locations). The pit elevations are indicated by the height of the bars while their relative size is denoted by the colour contouring.

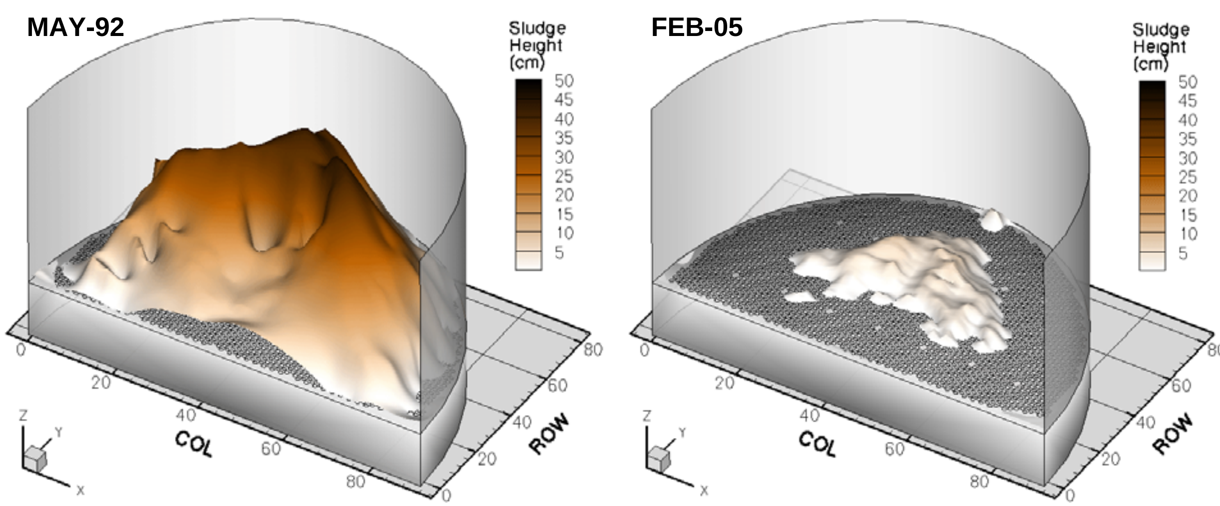

Figure 11: *Interpolated sludge profiles in SG-10 during the MAY-92 and FEB-05 outages (note: vertical axis is exaggerated for effect).*

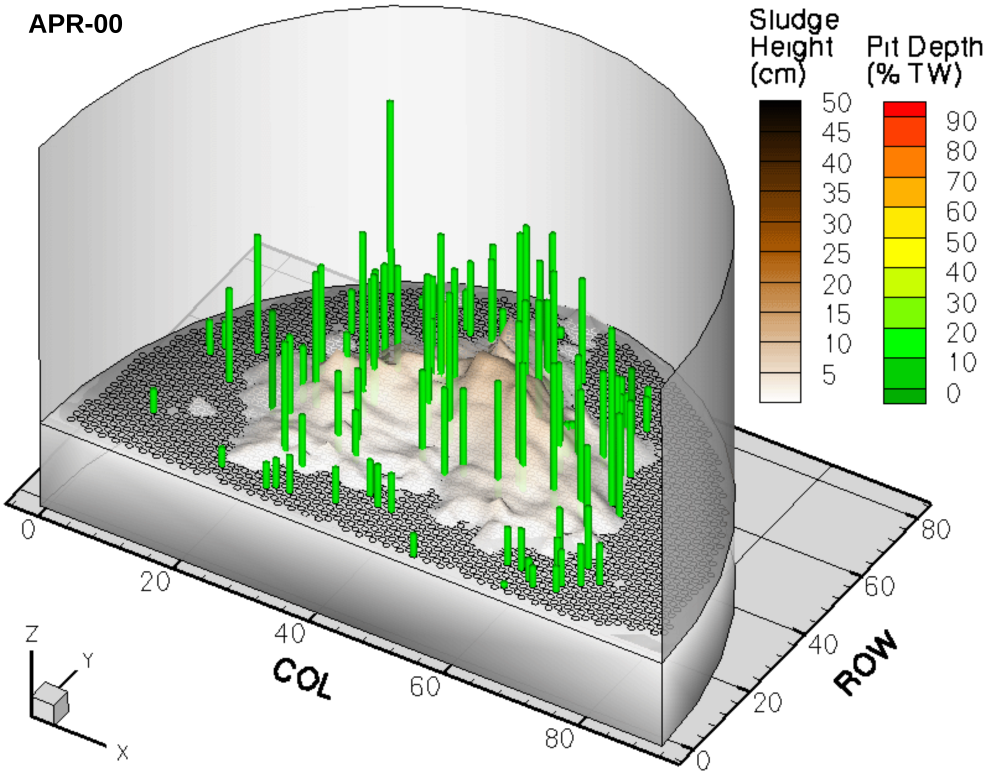

***Figure 12**: Interpolated sludge profile and new pits found during the APR-00 outage in SG-10.*

As shown in Figure 12, majority of the new pits are found in the freespan region above the top of the interpolated sludge pile profile. However, all of the new pits are small (see also Figure 6), less than or equal to 20 % TWD. Actual time of initiation of these pits is difficult to ascertain due to the POD issue.

Based on the results of the methodology, a total of 19 pits of significant depth (>= 50 % TWD) have emerged among all the Unit 5 steam generators since the first WL/CC campaign in 1992. These very few extreme pits pose the greatest threat to the operation of the stations, resulting in lost revenue and generation capacity through forced outages. Quantifying and predicting the likelihood of these extreme pits is very challenging, but also imperative for successful steam generator life cycle management.

Figure 13 shows the elevation of all new pits found at and above the top of the hot leg tubesheet (HTS) in all Unit 5 steam generators since the first WL/CC campaign in 1992. As illustrated in Figure 13, most of the deeper pits (>= 35 % TWD) are found very close to the top of the tubesheet. Based on preliminary analyses, majority of these larger pits are observed within the small sludge piles that remain following the WL/CC campaigns (see Figure 11).

Sludge, therefore, continues to play a critical role in the formation of pitting in Pickering B Unit 5 steam generator tubing. Work is continuing and will also involve the analysis of pitting corrosion in the remaining Pickering B units.

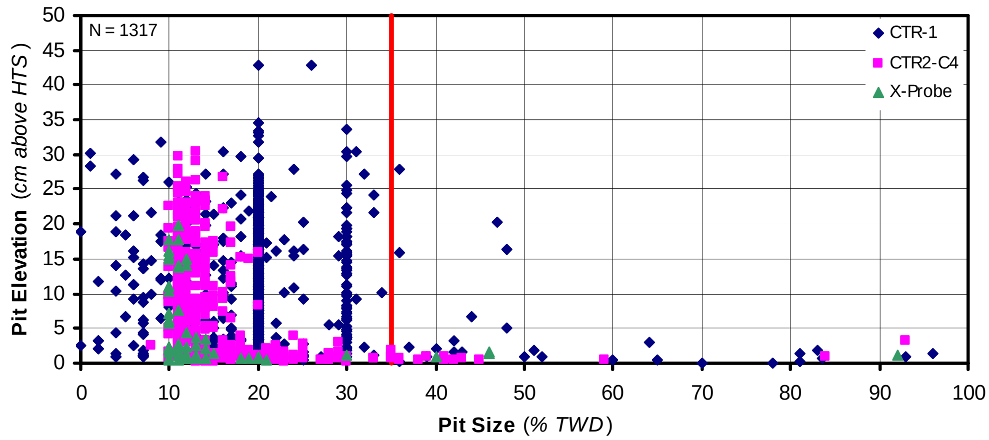

Figure 13*: The elevation and size of all new HTS pits after 1992 in Unit 5 steam generators.*

5. CONCLUSIONS

The eddy current inspection and maintenance campaigns have been useful in mitigating the impact of pitting corrosion of steam generator tubes. The inspection records about the size, number and location of pits and other defects are contained in large databases. For example, the Pickering B eddy current (ET) inspection database contains over one-million data entries, starting from the early 1990's to the present.

The paper presents an automated and efficient methodology for identifying and tracking all pit-like indications in all tubes over the service life of a steam generator. The developed software generates graphical displays of the analysis results. With this methodology, the unit and station wide database can be analyzed in an extremely efficient manner.

This method has been applied to analyze the pitting corrosion data collected over the years at Pickering B Unit 5. The analysis was based solely on the information contained in the eddy current database, and did not include any detailed analysis of the original (raw) probe signal data.

The results of the study concurred with earlier assessments in that all "new" pits were observed to initiate and grow rapidly to a given size and then remain unchanged, while only a very few "old" pits were found to propagate and grow slowly over time. A detailed analysis of Unit 5 SG-10 revealed that it is difficult to ascertain the time of initiation and the number new pits generated in a time interval due to variable nature of uncertainties associated with different inspection probes. The distribution of size of small pits is not easy to establish as large amount of data are censored and affected by measurement error. The distribution of pit size and rate of initiation are required for predicting the occurrence of extreme pits in the steam generators. It is therefore necessary to develop a probabilistic model that accounts for detection and measurement uncertainties for an effective life-cycle management of steam generators.

ACKNOWLEDGEMENTS

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