DEVELOPMENT AND IMPLEMENTATION OF THE BRUCE B SECONDARY SIDE FLOW ACCELERATED CORROSION PROGRAM

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ABSTRACT

An inspection program for the detection of wall thinning due to erosion-corrosion (E-C), also known as flow accelerated corrosion (FAC), has been in place at Bruce B since 1987. The purpose of this program is to prevent injuries to personnel or losses in production by monitoring the integrity of secondary side system piping susceptible to this damage mechanism.

Bruce B is a four unit CANDU Station, each unit 860 Mw net output with in-service dates of March 1985, September 1984, April 1986 and May 1987 for Units 5, 6, 7 and 8 respectively.

To date two inspections have been completed in all units, with a third inspection performed in Units 5, 6 and 7. There have been few occurrences of significant wall thinning requiring the replacement of components or of system failures.

This is an evolving program, and as it has matured it has been modified to reflect improvements in the inspection methods and the processing of the inspection results.

THE EROSION-CORROSION PROCESS

Erosion-Corrosion (E-C), or Flow Accelerated Corrosion (FAC), is a material degradation phenomenon that affects ferritic materials which are normally resistant to corrosion processes due to the presence of a protective oxide film (typically magnetite) on the wetted surface. Under certain conditions, turbulent or fast flowing water or a water/steam mixture can remove the protective oxide coating, resulting in continuous dissolution of the underlying material.

FAC can occur in both single-phase and two-phase flow. The state of the fluid will determine the pattern of wear that is observed on the inside of the piping system. For single-phase flow, the appearance of the surface will be very smooth and uniform, often showing little or no obvious signs of wear.

For two-phase flow, two types of damage can occur. For two-phase flow along a straight length of pipe, or any other configuration with smooth and relatively undisturbed flow, the inside surface will have the appearance of "tiger striping". For regions where the flow is significantly disturbed by local geometrical discontinuities or by the piping configuration, the damage will have a more localized, and often show a more severely degraded appearance.

STRATEGY FOR PERFORMING FAC INSPECTIONS

The development of this program was prompted by a piping failure at Virginia Power's Surry-2 nuclear power plant and was established in 1987 to ensure that this type of failure would not occur in susceptible secondary side piping systems at Bruce B. The governing strategy for the FAC program has been evolutionary. Many developments have been introduced over the course of the inspection program based on station experience, changing conditions, and improvements in the performance of these inspections. The following sections sequentially describe the initial intent of the program, the changes that have been made and a summary of the current program direction.

Selection of Locations

Initial identification of the locations to be inspected was performed by the corporate Design Engineering group. The method of selecting the locations depended on the type of flow occurring in the pipe.

For single-phase flow applications, selection of the locations was based on a set of criteria developed by a U.S. utility consultant. These criteria are temperature, velocity and geometry. Additional factors such as the pH and the oxygen concentration were treated as second-order effects and were used only in a qualitative manner to make a choice between closely weighted locations. Trace element concentrations (such as chromium, molybdenum and copper) were not considered in the selection process since knowledge of these trace quantities was generally not available from the design documentation, especially in the case of carbon steel piping.

For locations experiencing two-phase flow, selection was based on a combination of experience in the industry and engineering judgment. Portions of all carbon steel lines carrying two-phase flow were considered for inclusion in the program.

Inspection Rationale

The FAC program was initially set up such that the inspection of all locations in the program would only be performed in one unit. This unit, termed the lead unit, would be the unit with the longest operating time. The assumption was made, that for all other conditions remaining constant, the lead unit would present the worst case for FAC damage in the station. Any locations in the lead unit that were observed to be affected significantly would then be inspected in the remaining units. For Bruce B, Unit 6 was the first unit in-service, and as a result was the lead unit. The program was initially divided into two "phases". Phase 1 covered all of the high-energy piping in the station for which failure would have an impact on personnel safety. Phase 2 extended the inspections to lower energy piping systems, for which failure would primarily be production loss.

Inspection Methodology

In order to obtain accurate values of the thickness of the pipe or component, the inspections were performed using ultrasonic techniques. Initial procedures required a scan of the entire surface of the component in order to determine the minimum thickness for the component. This was combined with measurements at specific points on the component, in order to provide some reference measurements that could be used to compare the progress of wall loss between successive inspections. The measurements for wall thickness are performed during planned unit outages due to the limitations of the measurement equipment with the piping at operating temperature, and from personnel safety concerns due to the close contact required when making measurements.

The requirement of having the unit shut down to perform the inspections fixed the minimum interval between inspections to that between major unit outages. This inspection interval may be increased or decreased as the results of inspections become known. However it is important to perform a minimum of two inspections at each location, since it is only after the results of more than one inspection that an FAC rate can be established.

Determination of Significant Thinning

Evaluation of the locations to determine which have thinned significantly is based on two factors. The first is the minimum thickness measured at the location. Significant thinning in a component is considered to occur when the minimum measured wall thickness (TMIN) falls below 87.5% of the nominal wall thickness (TNOM) at that location. This criterion is based on the allowable manufacturing tolerance in the production of seamless piping. Once a component has reached this value, the next important factor is TCODE, the minimum allowable thickness according to the governing design and construction code. The value of TCODE, in combination with the erosion-corrosion rate, can then be used to determine the remaining component life.

Calculation of the E-C Rate

Remaining component life is calculated in one of two ways. For those locations and units where two inspections have been performed, an erosion-corrosion rate can be calculated using the measured thickness values at the fixed measurement points. This rate can then be used to determine the amount of time required for a component to reach the TCODE value from its current value for TMIN. Until the second inspection, a FAC rate must be estimated, since the initial thickness of the components is unknown. However, the initial wall thickness can be approximated by measuring the thickness of new components and determining an average value based on a large number of measurements. The rates derived using these estimates for the thickness must be used with caution since they are based on only one factual measurement.

DEVELOPMENT AND CHANGES MADE TO THE INITIAL CONCEPT

Changes to the original program have been implemented based on experience gained. The following paragraphs describe these changes.

Lead Unit Concept

One of the fundamental assumptions of the initial concept was that FAC behaviour of all units would be the same provided that the operating conditions were identical. This led to the adoption of the lead unit concept. After the inspection of a number of the same locations in different units it became apparent that the lead unit concept could not be reliably used to evaluate the FAC behaviour of the entire plant. Significant differences in the extent of material loss was observed at the same location in all four units. This necessitated a change in the application of the inspection program. The program was reevaluated to determine which of the program locations should be inspected in all units, during every outage. These locations are presumed to be the most likely to suffer damage from FAC. A listing of 31 critical locations was prepared, and is used as the basis for the current program.

TCODE/TNOM Relationship

Calculations for TCODE have also revealed some unexpected values that have had an impact on the program. It was anticipated that the maximum value of TCODE would be in the vicinity of 60-70 %TNOM. However in one case, the value of TCODE was significantly increased by a large amount of thermal expansion combined with localized constraints. In this particular circumstance the result was that TCODE was over 80 %TNOM. The implication of this is that in some cases the determination of TCODE may be required before the thickness falls below 87.5 %TNOM.. This is to ensure that there is sufficient time to allow repairs to the system before code non-conformance can occur. A review is required of all of the locations in the inspection program to determine which are likely to require TCODE calculations in advance of the normal time.

Phase 1/Phase 2 Integration

The Phase 1 and Phase 2 designations for the inspection program have been dropped. The 31 critical locations in the inspection program combine high and low energy systems, largely based on our own experience and the experiences of other utilities.

Measurement Techniques/Material Loss Rate

A change has been made in the manner in which the inspections are performed. A 100% scan method was used at the onset of the program. In order to improve the speed and ease of performing the measurements, a new technique was adopted which relies on the use of a datalogger. In this technique the measurements are performed at discrete "grid" points along the length and circumference of the component. The size of the grid that is used is dependent on the nominal pipe size of the component being inspected. This is based on the industry standard.

The results of the inspections are automatically recorded by the datalogger. Additionally, the grid can be accurately reproduced at each inspection, and therefore the measurements can be repeated for the same location on the component. This has helped to provide a more accurate determination of the progress of thinning across the extent of the component. Finally, enhanced repeatability of the measurements means that more accurate data for the material loss rate calculations is now possible.

Calculation of the FAC rate has also undergone some changes over the course of the inspection program. With the adoption of the grid method for performing the inspections, and with the availability of the data in electronic form, calculation of the rate and so remaining life was transferred to an automated means using a spreadsheet software application. At first, the results of successive inspections for a component were compared on a point-to-point basis to determine the maximum change in thickness for the component. This maximum change in thickness was then used to calculate a single value of the FAC rate for the component. This meant that this rate represented the worst case for the entire component. Calculations of the remaining life for some components using this method yielded very low values, resulting in the need to perform additional inspections to confirm these values of the life and prepare for replacement of the components as required. The repeat measurements indicated that the progress of FAC was not as severe as predicted, indicating a need to revise the method for calculating the rate.

In view of this, a review of industry practices was conducted and it was determined that the rate was best calculated on a band basis. A band refers to a set of inspection points that lie along a circumferential line on the component. The maximum change in thickness for each band of a component can then be determined, and this value of the change in thickness used to calculate the FAC rate.

This is the rate that is then applicable to that band. This local value of the rate can then be used to calculate the remaining life for all of the points in the inspection set for a component, and the minimum value of the remaining life for all these points becomes the remaining life for the component. It is anticipated that this method of calculating the rate and the remaining life will provide more realistic values for these two quantities.

The Adoption of Templates for Measurement

Following a CANDU Owners Group, (COG), sponsored FAC conference where the use of this technique was first highlighted by Pt. Lepreau, Bruce B procured a number of inspection templates. These were used for the inspections during the next outage and immediately showed their worth in a number of respects.

The accuracy and repeatability of the inspection process has been greatly improved since the template grid openings are placed exactly at the required grid points and are sized to suit the probe tip being used. Also, the wrong grid cannot be used. In addition by permanently marking the locations the same template will be returned to exactly the same place, again enhancing repeatability.

Carrying out the inspections is very much speedier and requires less concentrated effort trying to ensure the probe is in exactly the right location. The likelihood of mistakes being made is thus significantly lessened.

Additionally there is no requirement to touch-up or to redraw the measurement grid.

Additional Consideration With Respect to Significant Thinning

In addition to the 87.5 %TNOM criterion for significant thinning, the material loss rate must also be considered. This is because it is possible for a component with a relatively large thickness of usable wall also having a sufficiently high rate so that it could thin to less than TCODE before the next outage. Based on the average amount of time between inspections, it was decided that significant thinning would be when the erosion-corrosion rate is 5 %TNOM/year or greater. This value was chosen since it represents the approximate rate that would be required for the wall thickness of a component to decrease from 100 %TNOM to 87.5 %TNOM in the interval between two inspections assuming these are carried out during successive planned outages.

Selection of Most Susceptible E-C Locations in Parallel Lines

For some of the inspections performed, there have been some instances where the location is one of a pair or series of parallel lines.

Initially for identical parallel piping systems, one of the lines was picked at random and examined for FAC damage. In the future, for selected locations which have identical parallel piping, the inspections will be expanded to include all of the parallel lines. For the remaining locations which have parallel lines, if significant wall losses are detected in the line which is included in the inspection program, the inspections will subsequently be increased to include all of the parallel lines.This will ensure that all possible wall thinning is detected. Subsequently only the line showing the maximum degradation rate may be used as the indicator for that series of lines.

Separate LIE/CE Program

The structure of the erosion-corrosion program is geared specifically to the detection of the usually slow and uniform process of flow-accelerated-corrosion. The interval between inspections is acceptable only if the wall losses are primarily due to this failure mechanism.

For certain locations in the program, there is a possibility that the material loss may be the result of mechanisms other than FAC. Specifically, some locations can be identified as being susceptible to wall loss due to liquid impingement erosion or cavitation erosion. An example of this is several locations in the Boiler Blowdown system for which wall loss leading to failure has been the result of either cavitation erosion of liquid impingement erosion. The possibility of this type of damage leading to system failures has resulted in the development and implementation of a separate program, aimed at detecting the occurrence of this type of damage.

In this program, the detection method and frequency of inspections are different than that used in the FAC program. Due to the localized nature of the damage, the grid system is not the best method for detecting damage. In addition, the inspections need to be performed more frequently, since the damage is likely to progress much more rapidly than in the case of FAC. As a result, the inspections are performed using radiography as the primary detection technique, with the unit operating and the insulation in place.

This presents a limitation in the size of the piping that can be inspected, and the amount and type of system fluid present in the piping, but is a more practicable inspection procedure than U/T, which would require the unit to be shut down to perform these inspections safely and effectively. If radiography reveals a problem then it will be confirmed by another technique, likely U/T at the next available outage.

Tramp Chrome Analysis of Components

An addition to the scope of the program was the removal of small samples from the components in order to perform analysis to determine the chrome content of the pipe or component. This was especially important in the case of carbon steel piping, where chrome is a tramp element and is generally controlled only in the maximum amount that is allowed. It was hoped that it would be possible to correlate the results of the tramp chrome content to the observed material loss rates. Analysis of the results of the chrome sampling indicated that there was a general trend towards decreased FAC rates with increasing chromium content, but the scatter in the data prevented the development of any analytical correlation with the inspection results. The results of the chromium sampling could therefore not be used as a predictive tool for establishing FAC behaviour. Since two units were sampled in this manner with little resulting benefit, it was decided to discontinue chromium sampling.

Long Term Planning

As mentioned, the interval for the inspections is governed by the time between major outages on the units. As a result, long term planning of the FAC program is governed by the station 10 year outage plan. The length of each outage also has a direct impact on the number of locations that can be inspected in any given outage. This therefore requires that the scope of the inspection program be reviewed before each inspection to determine how many locations can be examined, and to determine which locations are the most important. At every revision of the ten year outage plan, the FAC program is reviewed to ensure that no gaps will exist in the inspection of the units.

CURRENT STRUCTURE OF THE EROSION-CORROSION PROGRAM

Based on the strategy described in the sub-section 'Selection of Locations', eighty-three locations have been designated as being susceptible. Due to limitations imposed by time and resources, not all of the locations can be examined in every inspection. The list of locations that are examined during any given inspection is based on two main selection criteria:

- The first is a list of 31 locations that have been identified as being critical to all units. These locations must be examined during each inspection on every unit.
- The second is a quantitative review of any locations, not included in the list of 31, that have been inspected previously. This analysis relies on calculations of the expected wall thickness for each component at a given location. The expected wall thickness is determined both for the inspection under consideration and for the following inspection. If the minimum wall thickness is expected to be low (i.e., near to or less than TCODE) for either of the two inspections, then that location is added to the current inspection. A pool of locations is maintained and appended to this list of locations as outage scope will permit.

To date this has resulted in an average of 45 to 50 locations being visited during each FAC inspection campaign with an average of two components at each location.

The program requires that it be responsive to changing conditions. In part this requires that it remain flexible and adaptable as experience is accumulated. In addition, the continued review of similar programs at other locations both within and outside of Ontario Hydro is necessary. This ensures that conditions relating to FAC that arise, and which have implications for the safety and productivity of Bruce B, are considered. Efforts to improve the efficiency of the generation, storage and usage of information from the inspections will continue. The scope will also continue to be revised with respect to the resources available and the importance of the locations being inspected.

Based on this philosophy, the following summarizes the current direction of the program:

- 31 locations must be examined during every inspection on every unit. These locations have been identified as being high risk, and potentially subject to significant thinning.
- TCODE calculations are performed whenever the wall thickness of any of the components at a particular location decreases to less than 87.5% TNOM. If, however, a review of the location indicates that temperature or load effects might result in an unusually high value of TCODE, the request for the calculation may be made earlier than usual.
- Inspections are performed on a grid system using automatic data recording.
- We will continue to use templates to the maximum extent possible to make most efficient use of the inspection resources available during any outage.
- We will continue to require that the inspections be complete by the mid point of the outage to allow sufficient time for any component repair or replacement. We will continue to work with inspection personnel to meet this standard.
- Removal of samples of the wall material for chrome sampling has been discontinued. This is the result of an inability to establish any useful correlation between the observed FAC behaviour and the trace chromium present.
- In cases where repeat inspections indicate that little or no wall thinning is occurring, the inspection

interval may be doubled. Alternatively, the location may be considered for removal from the program.

- A comprehensive review of the entire erosion-corrosion program will be conducted after ten years of inspections have been performed.
- Reporting of inspection results will continue to be by:
- the status/strategy report being updated on an bi-annual basis and containing all results up to and including the last outage. Also included will be any changes or developments introduced into the program since the previous revision.
- continued reporting of the results by means of direct communication with the System Engineers, as well as the preparation of in-service reports detailing the extent and results of each inspection. These in-service reports are prepared as soon after the inspection as practicable.