CANDU™ HEAT TRANSPORT MAINTENANCE AND LIFE MANAGEMENT PROGRAM

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Abstract

AECL has developed an integrated Plant Life Management (PLiM) Program and is assisting several CANDU reactor owners in its implementation. The PLiM initiatives are supported by design, procurement, construction, commissioning, regulatory and operations feedback, as well as an R&D program that provides support with regard to plant aging mechanisms, surveillance methodologies, mitigation methods, and improved inspection technologies.

A specific example of the PLiM program effort is to ensure robust performance of the Heat Transport System (HTS). AECL has made efforts on several fronts to develop an integrated approach to monitoring, and maintaining the system performance. This includes efforts in system modelling, aging mechanism modelling, maintenance procedure development, and improved monitoring techniques.

The heat transport system of a CANDU nuclear power plant requires monitoring throughout the plant life for efficient operation of the station. Successful monitoring of a station can identify the timing of preventative maintenance and the proper assessment of safety parameters to cater for changes that have occurred during operation. One of the key components of successful monitoring is the development of a thermal hydraulic plant model of each component in the primary heat transport system. In response to this need, AECL has developed system models with appropriate methodologies to predict HTS performance with respect to time.

In conjunction with the development of predictive capabilities, AECL has identified several steam generator maintenance techniques to ensure long term performance. To quantify the impact of various maintenance activities, research has been conducted to establish deposit behaviour in steam generators and feeder pipes. This research enhances the ability to properly characterize the system conditions with time, making a significant contribution to overall maintenance management.

Part of understanding the system characteristics and being able to model them, is the ability to obtain direct measurements of degradation mechanisms. Of particular interest is the distribution of deposit loading on the primary side of steam generators. AECL has developed a capability to easily provide this characterization, using eddy current probe technology.

This paper discusses the overall approach developed at AECL to help understand and manage the maintenance requirements for the HTS. The discussion touches upon the basic modelling approach and the research being carried out to enhance the understanding of the key steam generator degradation mechanisms affecting HTS performance. Further, the paper will discuss the specific application of the primary side cleaning technology for application to CANDU plants.

The paper will also demonstrate the application of the approach by looking at the recent primary side mechanical cleaning at Gentilly-2 NGS where there was a restoration of ~5% of core flow and ~-3°C in reactor inlet header temperature (RIHT).

Finally, the eddy current method developed to measure steam generator tube primary side fouling will be discussed. The technique, combined with the HTS performance models, is able to assist operators, maintainers and technical staff in planning when steam generator cleaning should be carried out. Results from the Gentilly-2 primary side clean are presented to illustrate the effectiveness of this approach.

1. INTRODUCTION

Plant life management and performance improvement for CANDU Reactors starts with the design function, where allowances are built into the design requirements and specifications for key components, structures and systems. It continues into the operational period, with utilities and AECL undertaking comprehensive programs for performance attainment and improvements in inspection, surveillance and performance/safety analysis methodologies.

During the design of the original CANDU stations, potential mechanisms for aging of the plant were considered, and inspection and maintenance programs were provided. These programs were based on the best information available from the nuclear power industry at that time. Since then, AECL and CANDU utilities have been using the experience gained through the operation of these reactors, and throughout the industry in general, to develop a systematic and comprehensive Plant Life Management (PLiM) program to assure the future safe and economic operation of the reactors. This program is making use of the knowledge gained during the operation of CANDU stations both domestic and offshore, CANDU research and development programs, and other national and international sources.

The development of a comprehensive CANDU PLiM program began in earnest in 1994, with the identification of most of the critical systems structures and components (CSSCs), and a preliminary assessment of degradation mechanisms that could affect their fitness for service for their planned life. These assessments are complete, along with the work to define a CANDU PLiM strategy, including initial and some second pass detailed assessments of CSSCs, and a systems maintenance optimization program utilizing reliability centred maintenance (RCM) methods (Reference 1). The CANDU PLiM program is now reaching maturity, and an integrated program is being followed.

Key components of the program are as follows:

I. Systems Maintenance Optimization
II. Components and Structures Aging Management, to ensure degradation mechanisms are understood and steps taken to mitigate them.
III. Obsolescence Mitigation to identify or in some cases, to reverse-engineer replacement components and spare parts that meet the original design bases and qualification standards.
IV. Integrated Safety and Performance Assessment
V. Technology Watch, Research and Development, and Operational Experience Monitoring to anticipate new emerging issues as early as possible.

In addition to management of the physical plant, the CANDU PLiM program also recognizes the importance of managing the configuration control of the plant, it's management and personnel, and the business, regulatory, and public impact as the station ages.

The program elements reflect the dual nature of aging in the physical plant. The dual nature is that on one hand the individual aging components have a specific and unique impact on system performance. A steam generator transfers heat less efficiently, or a section of piping can be a source of concern for pressure boundary integrity. Both items can have both an economic and safety impact. On the other hand, these two components, when functioning together in a single system, can affect the system overall performance, and in fact the aging mechanisms can be linked. This reflects an integrated effect on the system, which can also impact both economics and safety of the operating system.

The Integrated System Safety and Performance Assessment element of the program has a specific focus on integrated effects. Until recently, this element of the program has been only informally part of the program. While R&D and system/component modelling support has occurred over the years, a consolidated attempt to present AECL's capabilities in the context of an integrated approach to aging has only been initiated over the past year. The focus of this effort is on Heat Transport System Aging Integration. This is the focus of this paper, which will look at the complex picture of HTS aging, efforts in the areas of prediction capability, aging mitigation, monitoring capabilities, and how each facet comes together to provide an integrated approach to HTS aging.

2. HTS AGING INTEGRATION

The primary components of the HTS are the piping, fuel channels, steam generators and pumps. Each of these components has aging concerns unique to the individual component. They are all subject to detailed assessments to ensure these components can meet their design life, and to understand the requirements to extend their life and consequently the life of the plant.

As described earlier, each of these components also interact within the system, resulting in an integrated impact on system performance, whether that be system efficiency or system safety. It is evaluation of the latter that has generally lead to the requirement to be able to simulate system conditions, particularly with respect to Regional Over Power Trip (ROPT) assessments.

When the "first generation" CANDU 6 stations were originally designed, AECL recognized the need for a detailed thermal hydraulic predictive modelling capability for the CANDU Heat Transport System (HTS). A number of aging mechanisms were anticipated and compensating margins related to the key components were provided to cater for the in-service aging degradation that would occur. Accurate predictions of HTS thermal and hydraulic parameters were recognized as an important capability. Hence predictive codes were not only developed but also extensively validated with both commissioning and operational data from the early CANDU 6 experience. This program of code development and refinement for prediction of HTS aging behaviour has continued throughout the operational period in cooperation with the utilities.

The focus on prediction capabilities has several implications on the R&D to support the capability. The plant model becomes a focal point that integrates R&D efforts as it relates to HTS aging. This becomes more obvious when considering the various programs associated with plant aging. Some examples are flow accelerated corrosion (FAC) and the associated magnetite transport R&D, steam generator fouling characterization, pressure tube creep research, and hydrogen ingress studies. Each of these topics is of interest for individual components, but they also have a combined effect that must be properly integrated when modelling the HTS.

Some of these aging phenomena have linked aging mechanisms, such as the FAC of the outlet feeders which acts as the source of magnetite while roughening the outlet feeders, which is then transported through the HTS and deposited as predicted by magnetite transport models. The deposition affects the primary side fouling of the steam generator and the roughness of the inlet feeders. The fouling affects both heat transfer and hydraulic resistance. Consequently, all of these effects are related outside of the modelling process..

However, the other aging parameters are linked only through the modelling process. The pressure tube creep profile is needed in order to simulate the impact of creep on critical heat flux and flow resistance. This resistance change is combined with that modelled for the steam generator and feeders. The overall steam generator performance requires understanding of the secondary side fouling, which in turn is dependent on secondary side chemistry. Only the combined set of information allows the prediction of HTS thermal hydraulic conditions.

The resulting model predictions act as another means of linking the programs as the predictions are used to provide information to assess specific effects such as hydrogen ingress and FAC amongst others. Consequently, all these mechanisms, and the development of understanding related to each aging parameter are to some degree interdependent. This is an important aspect of managing aging, as this interdependency implies that communication is required throughout the development process. Improvements in one area, can have implications for many other areas.

HTS aging integration, however, is more than integrating the combined aging effects of the individual components in a predictive model. It extends to the integration of monitoring techniques, mitigation techniques, maintenance histories, and developments in technology that allow for a comprehensive aging management program. The program begins with the initial design and accounts for the appropriate monitoring and mitigation techniques. The program must be implemented at the commissioning stage, where the system can be benchmarked for the life long monitoring that will be used to define the requirements for aging mitigation. Ultimately, a common set of tools is available and is used throughout the life of the system to maintain system performance and safety.

Such high level concepts are much easier to describe than to implement, and on systems with as many aging issues as the HTS, the integration of the aging efforts is a significant task. It is for this reason that AECL is currently focusing effort on HTS Aging Integration.

To illustrate HTS Aging Integration as it affects the operating station, the example of the primary side steam generator clean recently completed at Gentilly-2 is considered. The elements of this program included predictive capabilities along with the support activities to develop and support the aging models, a mitigation strategy in the form of mechanical steam generator cleaning along with the work to support this technology, and eddy current probe measurements to quantify the deposit loading and the effectiveness of the cleaning process. Each component is discussed in turn in the following sections.

2.1. HTS and Steam Generator Performance and Aging Predictive Capability

AECL has developed thermal hydraulic modelling methodology for the CANDU Heat Transport System (HTS) that uses two key codes; NUCIRC and THIRST. NUCIRC (Reference 2) is a 1-D steady state thermal hydraulic code, which has modules for predicting conditions in the overall HTS, as well as modules for predicting conditions in auxiliary systems and specific HTS components (e.g. steam generators and fuel channels). THIRST (Reference 3) is 3-D steady state thermal hydraulic code for the detailed assessment of steam generator secondary side conditions with particular focus on the secondary side flow velocity distributions, detailed primary-to-secondary side heat transfer and primary and secondary side deposition (i.e. fouling) behaviour.

The primary predictive tool for assessing the impact of aging mechanisms and of various maintenance related activities upon HTS operating conditions, such as steam generator cleaning, is NUCIRC. NUCIRC incorporates models of hydraulic and heat transfer aging mechanisms for all the HTS components such as fuel channels, steam generators, feeder pipes, and orifices. The methodology develops a comprehensive HTS model by adjusting the various HTS aging parameters so as to reproduce measured HTS operating conditions, e.g. inlet and outlet header pressures and temperatures, HT pump differential pressure, and core flows.

The methodology employs a NUCIRC-THIRST iterative process to ensure that NUCIRC's 1-D steam generator model captures the important THIRST 3-D effects on the overall steam generator primary side pressure drop, heat transfer, and secondary side temperature distribution. The iterative process is applied to each steam generator, with NUCIRC providing the primary side coolant boundary conditions to the steam generator and THIRST providing information on the detailed thermal hydraulic performance of the steam generator.

The NUCIRC steam generator models include segmented modelling of fouling (deposit behaviour) on the primary side of the steam generator tubing. This distribution is based upon experience of deposit behaviour in the HTS and in steam generators from both field measurements and mechanistic models of fouling behaviour. The steam generator model can then capture the bulk variations in both fouling and the change in the tube internal flow area resulting from deposits.

In addition, there are several other aging effects that are incorporated into the HTS model primarily in the modelling of the core and associated inlet and outlet feeders. These other aging effects addressed include:

- Pressure Tube (PT) Diametral Creep: Diametral expansion (creep) of the pressure tube occurs due to irradiation in service, leading to an increase in flow in the fuel channels for the same pressure drop.. Creep profiles are modelled based upon station measurements and current PT diametral creep models
- Crept Channel Hydraulics: NUCIRC has models to capture the impact of PT diametral creep on thermal hydraulics, which are based upon experimental results.

- Core Component Roughness: The change in roughness of feeders, endfittings, and fuel channels is determined based upon station flow data and station header pressure measurements.
- Pump Model: The HTS pump performance can also change with time. Station data are used to ensure the NUCIRC HTS pump model accurately reflects the observed performance.
- Orifice degradation: Station data on the core flow distribution is used to determine the level of degradation in various orifice sizes.

From this description it becomes apparent that success in using NUCIRC to model the HTS is as much dependent on the methodology used to develop the model as it is the code itself. It is important to note that the detailed modelling approach need not be carried out in detail each and every time. Experience with the model has taught that once the model is set, the model can be extended into the future by aging the appropriate models. This makes the approach practical for monitoring in an on-going manner.

A byproduct of this approach, is that parameters such as steam generator fouling and feeder roughness, which are not directly measurable without invasive measurements, can be inferred from the station data. Over time, as these variables are updated to maintain the model, the time history can be developed providing a means of tracking the system behaviour beyond what is conventionally available. This approach has been used for the purpose of performing ROPT analysis for Gentilly-2, PLNGS, and Wolsong 1, and has proved to be an extremely useful means of monitoring the overall system performance.

2.2. HTS Aging Understanding

There are several HTS aging mechanisms to address in the predictive codes. Focusing on steam generator tube ID cleaning as an example, a good understanding of deposit behaviour in CANDU HTS conditions is needed for accurate predictions of this aging effect and its mitigation. This knowledge has come from the AECL R&D program on aging mechanisms, combined with utility data and reactor specimens provided for laboratory analysis. At our Chalk River Laboratories, tube specimens from several in-service steam generators were examined to gain in-depth knowledge of the HTS deposits on the ID surface of the tubes (Reference 7). Experiments were performed at CANDU HTS conditions to measure deposit thermal resistance. Additional hydraulic experiments and measurements were conducted to determine the effect of deposit roughness.

As discussed earlier, using NUCIRC to model the HTS condition the various aging parameters throughout the system can be established at different points in time. This approach provides insight into the system condition, and can be used to predict the impact of known changes such as cleaning the steam generator. What is not gained directly is an understanding of when the various aging parameters will need to be addressed. This limitation can be managed by monitoring the plant using NUCIRC throughout its life, from which reasonable time lines can be developed. In this case extrapolation of history can be used to anticipate future maintenance requirements.

An alternative approach to developing a predictive capability is to age the NUCIRC model accounting for the effects of time on the various aging parameters. This requires a mechanistic understanding of the aging phenomenon. Along these lines, the R&D efforts at AECL have developed some understanding of the complexities behind fouling deposits and creep models. Moreover, analysis of station data allows for confirmation of time based aging. These models are used in two ways. Firstly, they give an objective comparison for the NUCIRC inferred results. This acts as a mutual verification. The second approach is to provide a means of aging the NUCIRC models into the future. This gives the model a truly predictive capability, allowing the estimate of time before the cumulative aging effects must be dealt with.

The models for diametral creep and fouling have shown promise in achieving this goal. Further work is under way to understand the nature of magnetite transport, and its relationship to FAC. Further effort is also underway to understand FAC itself, which may help in determining the expected distribution of roughness in feeders and the rate of change over time. Similarly, the deposit of magnetite on the inlet feeders needs to be characterized to allow the expected distribution of roughness on the inlet feeders to be modelled. Deposit distribution in steam generators is reasonably well understood, with good prediction of deposit loading being made, which are in turn used in NUCIRC's segmented steam generator model. Over time more components are being analyzed, experiments are being completed, and understanding is improving.

At the present time, the most practical approach for predicting effects of aging into the future would appear to be a combination of both concepts. Currently, the ability to predict roughness trends from models is limited, and the uncertainty on predictive capabilities for creep and fouling, limit the extent to which one can extend the prediction without confirmation from site measurements. Therefore, the combination of the two approaches provides a reasonable method for evaluating the plant aging and what it is likely to do in the near future.

2.3. Mitigation Techniques - Steam Generator Mechanical Clean

The understanding of aging phenomenon and the availability of tools that allow the application of this understanding, are an important part of managing aging. However, this only provides the means of identifying and tracking aging effects. The integrated plant management program uses this information to identify strategic maintenance activities, which can include anything from simply monitoring to complete replacement of components.

Given the importance of this aspect of PLiM, AECL has also undertaken efforts to identify mitigation technologies, and in some cases provide R&D support to apply these technologies to CANDU plants. One such example is the mechanical cleaning process for the primary side of steam generators.

The mechanical cleaning process was originally tested on a small sample of Gentilly-2 tubes, and subsequently, PLNGS applied the full process to their steam generators. PLNGS also lanced and chemically cleaned the secondary side and replaced the divider plates during the same 1995 outage. These other activities masked the overall effectiveness of the mechanical clean of the primary side at that time as the individual contributions were difficult to discern. The cleaning removed approximately 790 kg from the four steam generators (Reference 4). In this application, only 57% of the tubes were accessed. As will be shown later, the current understanding is that the success of the clean was limited.

Hydro Quebec decided to apply the mechanical cleaning process at their Gentilly-2 facility, but AECL was requested to perform some additional qualification work. Sections of tubing from the pre-heater region of a Gentilly-2 steam generator were used in this qualification testing. The results of this work were used to implement some design enhancements to improve the efficiency of the process. A key improvement in the process was the use of a suction header affixed to the hot-leg tubesheet. Improving the vacuum increases "draw" of the magnetite and steel shot into the separator. In this way, the velocity of the material is maintained along the length of the steam generator tube.

As will be shown later, the resulting clean was very successful Over 3000 kg of magnetite was removed from the 4 steam generators. Approximately 92% of all tubes were accessed. From lab measurements it is known that the mechanical cleaning process leaves ~10 um deposit after cleaning, which leaves approximately 575 kg in the steam generators. This implies a cleaning efficiency of 80 to 90 %.

2.4. Monitoring Capability

In addition to these experimental studies, recent advances have been made in AECL's eddy current testing (ECT) capability to enable the steam generator tube ID deposits to be characterized in-situ when the tubes are being inspected. This development has been applied in the field at several plants and is providing valuable field data on deposit behaviour. The information on deposit thickness and distribution within the steam generators is being fed back to both the deposit predictive models and also to the HTS thermal hydraulic models mentioned above.

In support of this application, a program is being conducted to develop eddy current probes and procedures for quantifying internal and external magnetite deposits on steam generator tube surfaces.

An eddy current technique to measure internal magnetite, using the industry standard bobbin probe, has been developed and validated on four Darlington 3 steam generator tubes. First Oxiprobe (Reference 6) measurements of magnetite loading were taken and then the eddy current bobbin probe inspection was performed. These tests provided an opportunity to determine the magnetic permeability of primary side magnetite deposits and to develop equations to predict the deposit thickness and loading.

Figure 1 show a typical eddy current absolute bobbin probe signal from one Darlington 3 steam generator tube, after it was sampled with the Oxiprobe at seven locations along the tube length. The localized areas cleaned with the Oxiprobe are clearly evident on the figure. From the eddy current data it appears that the Oxiprobe was effective in removing most of the magnetite at six locations, but did not do as well at the thermal plate location. From the measured voltage computer modelling was used to estimate the magnetic permeability. This, in effect, calibrates the bobbin probe to provide quantitative results matching those of the Oxiprobe.

This demonstrates that primary side fouling can be assessed using currently available eddy current inspection technology. To illustrate the usefulness of this technology, Figures 2 through 4 show measurements taken at different stations. It is noted that the relative change in deposit thickness can be clearly seen due to the cleaning processes applied both at Pt. Lepreau and Gentilly-2. It is also apparent that the Gentilly-2 clean was significantly more successful. This result means the technique is a valuable tool to provide information on the level of deposits in the steam generators, which can be used to support monitoring the deposits periodically, or to provide direct feedback on the effectiveness of cleaning processes.

3. AN EXAMPLE OF HTS AGING INTEGRATION: HTS PERFORMANCE IMPROVEMENT USING STEAM GENERATOR PRIMARY SIDE CLEANING

The foregoing discussion provides insight into the integrated HTS aging management program that AECL has implemented. The NUCIRC code, supported by R&D, and combined with the mitigation tools such as primary side mechanical cleaning and monitoring tools such as the eddy current technology, provides a solid approach to dealing with HTS aging. As discussed earlier, Hydro Quebec applied the AECL-recommended steam generator primary side cleaning process to all four steam generators at their Gentilly-2 plant in their 1999 outage. Prior to the outage, AECL was asked to predict the change in HTS conditions to be expected following the cleaning.

Using the above methodology, a NUCIRC model based upon 1995 system conditions was aged using the understanding gained to date on HTS aging parameters at Gentilly-2 to account for the four years leading up to the 1999 outage. The analysis predicted HTS flow recovery due to steam generator primary side cleaning of approximately +5% and a Reactor Inlet Header Temperature (RIHT) decrease of 3.6°C. Gentilly-2 station measurements of HTS performance after the steam generator primary side cleaning show an actual flow recovery of 4 to 6% (Figure 5), and the RIHT decrease to be approximately 3°C (Figure 6) (Reference 5). These field results compare very well with the code predictions and provide confidence in the ability to predict the expected HTS performance improvement from activities such as steam generator primary side clean. The results also confirm the effectiveness of the primary side cleaning process itself.

A further validation of the effectiveness of the process is seen from the application of the advanced ECT capability described above. Figure 4 shows the measured tube internal diameter deposit distribution along a tube, both before and after the steam generator primary side clean application. The effectiveness of the clean process in removing a large fraction of the deposits is clearly illustrated.

It is noted that the Gentilly-2 result is specific to that plant, and therefore the same results can not be assumed for another plant. Each steam generator is somewhat unique, as is the current condition of the individual HTS of a given plant. As such, the recommended approach is to use the NUCIRC methodology to assess the overall system condition, and then use the model to assess the potential benefit of a primary side clean. This emphasizes the integrated approach to making decisions regarding mitigation activities.

4. SUMMARY

AECL has developed a comprehensive and integrated Plant Life Management (PLiM) program and is helping CANDU reactor owners to achieve the goals of providing safe, economic, and reliable life attainment and for preserving the option for extended operation. AECL also continues to develop an enhanced capability for plant performance improvements, and has focused on providing an integrated HTS aging management program. This program makes use of tools such as NUCIRC, supported by significant advances in the understanding HTS aging, in combination with effective mitigation technology, and improved ECT inspection techniques to measure cleaning effectiveness. The example of Steam Generator primary side cleaning applied recently at one CANDU site has demonstrated both the predictive capability of the HTS performance codes and the effectiveness of this remedial technique for HTS Aging. Hence, both the process itself and the HTS performance predictions are important and proven tools for managing HTS aging.

5. ACKNOWLEDGEMENT

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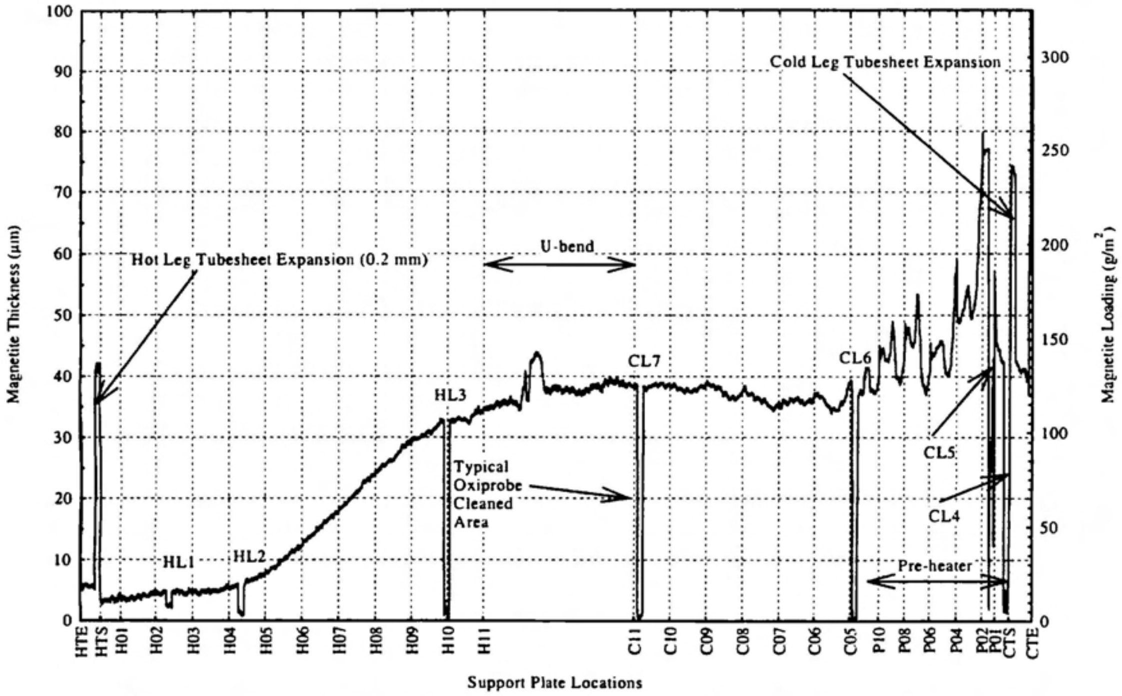

Figure 1 Magnetite Thickness and Loading Values from Darlington 3, SG 2, Tube R89 C75, 1999 Jan., after Localized Oxiprobe Sampling.

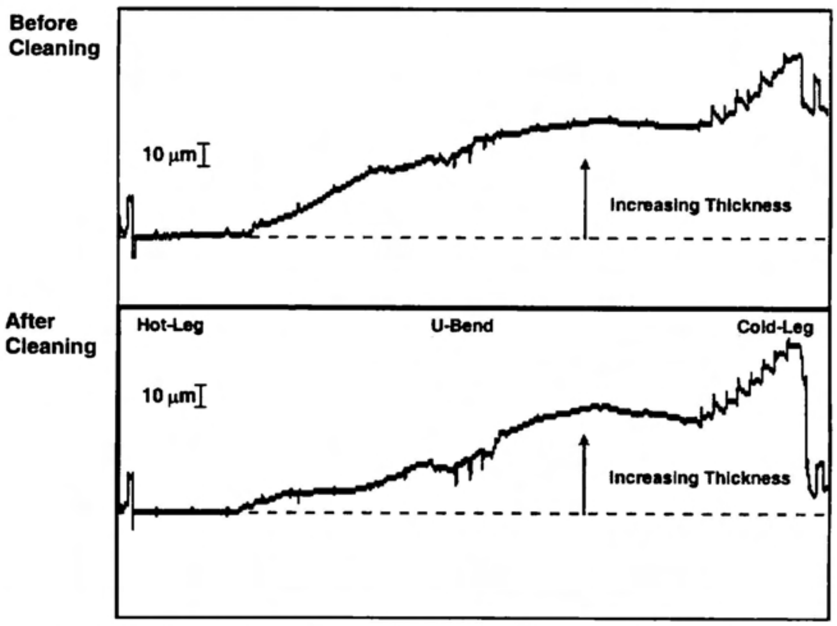

Figure 2 Magnetite Thickness and Loading Values from Point Lepreau Before and After Cleaning.

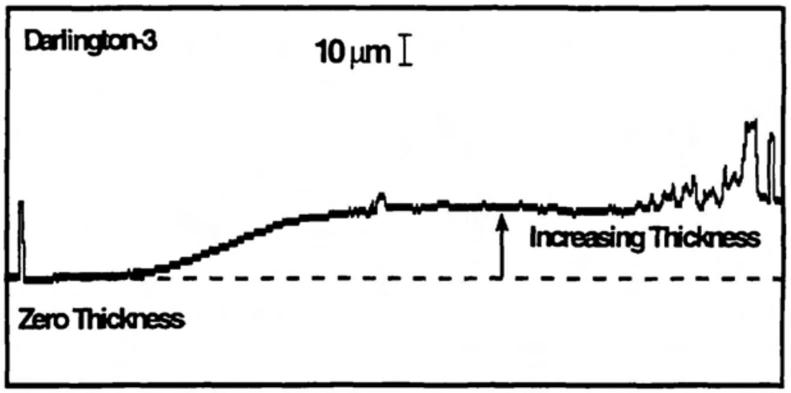

Figure 3 Magnetite Thickness and Loading Values from Darlington 3

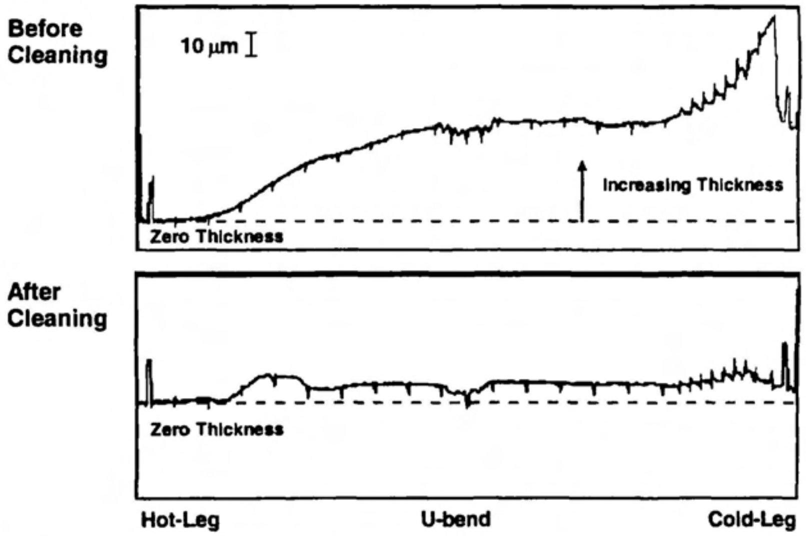

Figure 4: Magnetite Thickness Before and After Cleaning at Gentilly-2

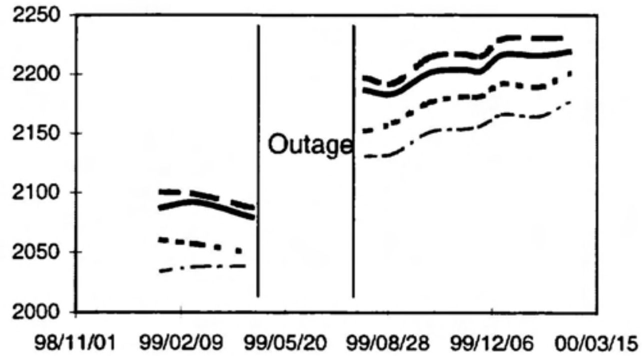

Figure 5: G2 Heat Balance Flows for Each of the 4 Core Passes Showing Flow Recovery From Primary Side SG Cleaning

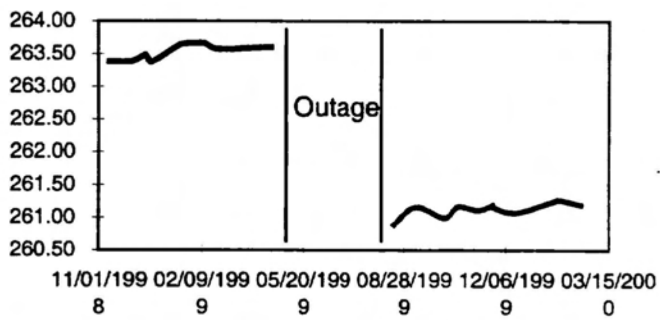

Figure 6: G2 Average RIH Temperature Showing Temperature Decrease Resulting From Primary Side Clean of the SG