STEAM GENERATOR AND PREHEATER TUBE ID FOULING AND THE IMPACT ON REACTOR INLET HEADER TEMPERATURE AND EDDY CURRENT INSPECTIONS

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Abstract

Materials selection is an important consideration in new build and refurbishment of Heavy Water Reactors (HWR). This paper will focus on the impacts of the deposit of magnetite on the tube ID of steam generators and preheater. Bruce Power OPEX is being shared to illustrate the importance of materials selection.

The deposit of magnetite on the tube ID of steam generators (SG) and preheater (PH) has two significant impacts that will be presented. Firstly, the degradation in SG and PH thermal performance causes a rise in the reactor inlet header temperature (RIHT). This rising trend continues unabated as long as deposits on the tube ID continues. If not managed this may result in loss of production due to the RIHT limits being reached. Mitigating actions such as tube ID cleaning is only a temporary solution as it does not stop the root cause which is feeder flow accelerated corrosion (FAC).

Secondly, deposit of magnetite on the tube ID of steam generators (SG) and preheater (PH) has an impact on tube inspections as required by CSA N285.4. There are two impacts on SG and PH inspections. ID deposits reduces the clearance for eddy current probes in the tubes and make it more difficult to acquire inspection data. Additionally, tube ID deposits can reduce the effectiveness to detect and size flaws in the SG and PH tubes. Both issues make eddy current inspection a challenge for the utilities.

These impacts affect the operation and inspection and maintenance of CANDU nuclear power plants at Bruce Power. Where possible these issues should be addressed in any future new build or refurbishment of HWR power plants.

1. Introduction

1.1 What are the issues?

Feeder pipe thinning by flow accelerated corrosion (FAC) has an impact beyond the structural integrity of these components. Although the issue of feeder life management is important, it is not the focus of this paper. FAC removes feeder piping material and deposits it on the steam generator and preheater tube ID as the coolant cools. This is governed the solubility of magnetite as a function of PHT coolant temperature. The end result is the degradation of the thermal performance and reduces the capabilities of the eddy current inspections.

The RIHT has risen more rapidly in the Bruce Units, and in CANDU Units in general, compared to the original aging predictions. RIHT is monitored with alarms to prevent operation outside the operating envelope as determined by the safety analysis. In order to maintain the RIHT below the high alarm limit, boiler secondary side pressures may be lowered or high pressure feedwater heater steam supplies can be isolated with a resulting loss of production.

RIHT continue to increase due mainly to the ongoing accumulation of deposits on the inside diameter (ID) and to a lesser extent on the outside diameter (OD) surface of the steam generator (SG) and preheater (PH) tubes. The increasing temperature trends are reviewed annually in order to determine the optimum timing for tube ID cleaning of the steam generators and preheaters or implementing alternatives methods to manage the impact on unit output.

Steam generator and preheater tube ID fouling also impacts on inspections that are required by CSA N285.4 standard and the life cycle management plans. Tube ID fouling with magnetite has two main effects on eddy current inspections. Tube ID magnetite reduces the detection and sizing capability of the eddy current inspection. The other impact of ID magnetite is the reduction in the clearance for the eddy current probes which results in more probe wear and increases the risk of getting the probes stuck in the tubes.

1.2 Primary Heat Transport System (PHT)

Bruce steam generators are tube-in-shell type heat exchangers. The primary heat transport pumps takes the coolant from the steam generator outlets and circulates it to the inlet headers (Figure 1). The reactor fuel channels are fed with coolant through individual feeder pipes from horizontal reactor inlet headers located at each end of the reactor. There are two reactor inlet headers per end because the reactor is divided into two cooling zones: the inner zone containing the highest power channels is supplied with lower-temperature coolant than the relatively lower power channels of the outer zone. This establishes relatively uniform channel outlet conditions for both zones. Figure 2 illustrates the zones and overall system.

The outer zone is fed directly from the four PHT circulating pumps, which draw water from the steam generator outlets (Figure 2). The inner zone channels are fed by coolant which passes from the pumps through preheaters which cool the D2O coolant flowing to inner zone channels and at the same time heats the feedwater flowing to the steam generators. Half of the inner zone coolant flow passes through the preheater the remaining half bypasses it. These two streams are mixed before entering the inner zone header (Figure 2).

2. Discussion

2.1 Steam Generator and Preheater Tube ID Fouling impact on RIHT

The RIHT limits for the inner and outer zones are set based on what is assumed in the safety analysis. The RIHT is monitored by temperature sensors located on the reactor inlet headers. Alarms for both the inner and outer zones ensure that the RIHT stays within the limits during operation. Procedurally, the Operator has the ability to lower RIHT by two means. Firstly, if there is adequate margin, boiler secondary side pressure can be reduced thereby reducing the RIHT. Secondly, if there is no more margin to lower boiler pressure the reactor power is reduced to maintain compliance with RIHT limits. Therefore, raising RIHT will lead to eventual de-rating of the unit if it is not managed properly over the long term.

Past investigations into this issue have identified several causes of rising RIHT. The two major cause, in order of importance, are steam generator divider plate leakage and ID tube fouling [1]. Bruce Power has implemented measures to address both causes of rising RIHT. Between 2001 to 2003 all operating units at Bruce A and Bruce B had been modified by the installation of the divider plate skin fix. This modification greatly reduced the leakage which bypasses the SG tubes thereby reducing the heat transfer performance. Starting in 2005 a primary side cleaning system was implemented. Bruce Power employed the AECL CANDUclean system to remove the primary side tube ID deposits from the steam generators. This system is analogous to sand blasting the inside of the tubes. The CANDUclean system uses stainless steel shot as the abrasive material. The stainless steel shot is delivered into the tube with compressed air. As the shot and travels along the SG or PH tubes, the abrasion created on the tube walls removes the ID deposits. At the other end of the tubing the shot and magnetite deposits are collected. AECL CANDUclean system only gives temporary relief from rising RIHT trends. Typically, it provides approximately 5 to 6 years of margin when employed on Bruce steam generators.

2.1.1 Bruce on RIHT Trends

In order to manage the degradation of SG and PH thermal performance it is important to understand the rate of rise of RIHT for each unit. This information can be used to predict available RIHT margin and determine when mitigating actions are required to prevent a potential unit de-rate.

Bruce RIHT data comes from the Plant Information (PI) system database. The data was normalized to a specific reference operating condition to eliminate changes that are caused by known variations in reactor power, boiler secondary side pressure and feedwater temperature. Without normalization it is not possible to determine the rate of rise in RIHT (compare Figure 3 which is normalized & 4 which is not normalized). The reference conditions in Table 1 are used in the normalization formulas (1) to (4).

Station	**Reactor Power (RP) [%]**	**Boiler Pressure (BP) [kPag]**	**Feedwater Temp. (FWT) [°C]**
Bruce U3-4	@ 92.5	4350	176.5
Bruce U5-8	@ 93.0	4370	177.0

Table 1 Reference conditions for RIHT normalization

Bruce B normalization formulas:

$$T_{NIZ} = T_{MIZ} - 0.042*(93\text{-}RP) + 0.0106*(4370\text{-}BP) + 0.115*(177\text{-}FWT) \qquad (1)$$

$$T_{NOZ} = T_{MOZ} + 0.0613*(100\text{-}RP) + 0.0124*(4370\text{-}BP) \qquad (2)$$

Bruce A (Unit 3 and 4) normalization formulas:

$$T_{NIZ} = T_{MIZ} - 0.042*(92.5\text{-}RP) + 0.0106*(4350\text{-}BP) + 0.115*(176.5\text{-}FWT) \quad (3)$$

$$T_{NOZ} = T_{MOZ} + 0.0613*(100\text{-}RP) + 0.0124*(4350\text{-}BP) \quad (4)$$

T_{NIZ}	- Normalized inner zone temperature	BP	- Boiler Pressure [kPag]
T_{NOZ}	- Normalized outer zone temperature	FWT	- Feedwater Temperature [^{o}C]
T_{MIZ}	- Maximum inner zone temperature	RP	- Reactor Power [%]
T_{MOZ}	- Maximum outer zone temperature		

Figure 3 is an example of the normalized inner zone (IZ) RIHT graph for one of the Bruce B units. It include the following information:

- Normalized trend of the average IZ RIHT of the west and east IZ inlet headers
- Linear regression of the west and east IZ inlet headers

It should be noted that all RIHT trends, as well as Figure 3, includes all degradation mechanisms such as OD and ID fouling as well as tube plugging. The steam generator and preheater tube plugging rate are relatively small in the recent past and therefore not expected to significantly impact the RIHT rate of rise. OD fouling impact is expected to be small [1]. ID fouling is clearly a more significant degradation mechanism. This is illustrated by the fact that the rate of rise in RIHT is similar before and after SG ID cleaning. Figure 5 illustrates this.

After the trend in the rise of RIHT is determined it can then be used to make predictions into the future. The predictions are used to decide when mitigating actions should be implemented in planned outages.

2.2 Steam Generator and Preheater Tube ID Fouling impact on Inspections

Steam generator and preheater tube ID fouling also impacts on inspections that are required by CSA N285.4 standard and the life cycle management plans. Tube ID fouling with magnetite has two main effects on eddy current inspections. Tube ID magnetite reduces the detection and sizing capability of the eddy current inspection. The other impact of ID magnetite is the reduction in the clearance for the eddy current probes which results in more probe wear and increases the risk of getting the probes stuck in the tubes. Detail technical discussions on the reduction in detection and sizing of eddy current inspections if beyond the scope of this paper. For further details refer to the report in reference [5].

2.2.1 Eddy Current Detection and Sizing Capabilities

Although it is known that SG and PH tube ID deposits have a negative impact on the capability of eddy current inspections, current fitness for service methodology and inspections are adequate to ensure structural integrity of these components.

At the time of the Bruce B SG tube ID cleaning implementation, the quantification of the impact of deposits was not well known. Given this fact it was decided that the eddy current inspections should be performed before the start of tube ID cleaning. The rationale for planning the work in this manner is to ensure that tube ID cleaning does not result in erroneous growth rates in know flaws. In order to better understand the impact of ID deposits a small number of tubes where inspected before and after tube ID cleaning so that comparisons can be made. This data was eventually used for the study in reference [5].

2.2.2 Eddy Current Probe Wear and Tube ID Clearance

Tube ID magnetite deposit build up reduces the clearance for the eddy current probes. In addition to the reduced clearance, the increase in tube ID roughness from the deposits can also lead to increase wear of the probes. As the industry moves to more advanced probes, such as the X-probe, increased wear may lead to high probe cost for outage inspections.

Bruce Power in recent years have implemented changes to the eddy current inspection plans. Where possible full length scans are avoided, especially in the tight radius tubes. What is typically done is to inspect the hot leg (SG inlet) and all of the U-bend region. The cold leg straight tube lengths is then inspected from the cold leg side (SG outlet). This approach reduces the likelihood of probes becoming stuck in the tubes. Additionally, work is in progress to develop eddy current probes for restricted tube ID. Refer to [6] for further details of this development effort on small diameter eddy current probes.

3. Conclusion

Less than optimal selection of the original feeder material for Bruce A and B has resulted in higher than anticipated rate of FAC on outlet feeders. This has resulted in the deposition of the corrosion products from the feeders into the ID of the steam generator and preheater tubes. The cascading impacts have reduced RIHT margin and inspection capability. Additionally, the SG and PH tube ID depositions have contributed to increased dose to workers during inspection and maintenance outages.

The OPEX presented in this paper illustrates the importance of good materials selection for the planned life of the reactor. This OPEX is applicable to refurbishment and new build for heavy water reactors. Bruce A Unit 1 and 2 refurbishment projects have incorporated industry experience into the selection of replacement feeder materials.

Bruce Unit 1 and 2 refurbishment project have replaced the lower portion of all feeders with a material that contains a chrome content that is much higher than the original material. Only the lower portions of the feeders were replaced since this is the location where wall loss due to FAC is the most prevalent and hence, the life limiting area. Assessments were performed to demonstrate fitness for service, for the life of the plant, of the original portion of feeders which were not replaced.

4. References

[1] D.L. Beaton, "Bruce A & B Heat Transport System Reactor Inlet Header Temperature Trend Assessment", NK21-33100-975086-P-ESSD, November, 1988

[2] K. Chuong, "Bruce B Review of the RIHT (data up to November 2010)",

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[3] K. Chuong, "Bruce A Review of the RIHT (data up to November 2010)", NK21-33110-P-NSAS, December 2010

[4] S. Stancu, "Reactor Inlet Header Temperature Normalization Formula Adjustment", NK29-33110-P-NSAS, June 2006

[5] B.A.Lapine, L.Davey, J.Lei and J.Renaud "The Effects of ID Magnetite on Eddy Current Response to Flaws in Inconel 600 and Monel 400 Tubing", COG-08-4024, October, 2008

[6] J.Renaud and L.Davey, "Equivalency Demonstration of Eddy Current Probes for Restricted Tubing", COG-08-4022, March, 2010

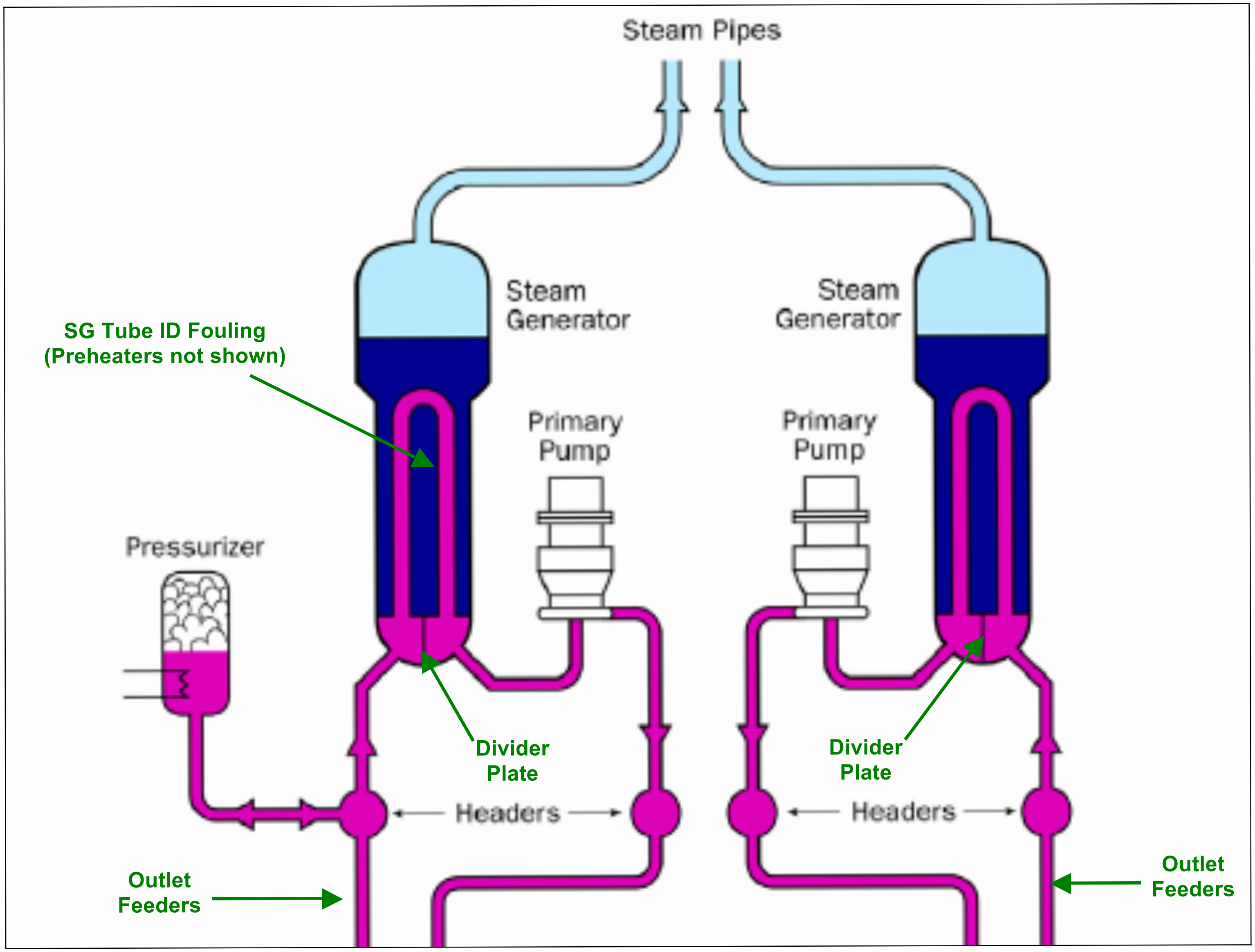

Figure 1 Simplified Bruce B Steam Generator (applicable to Bruce A except for steam drums)

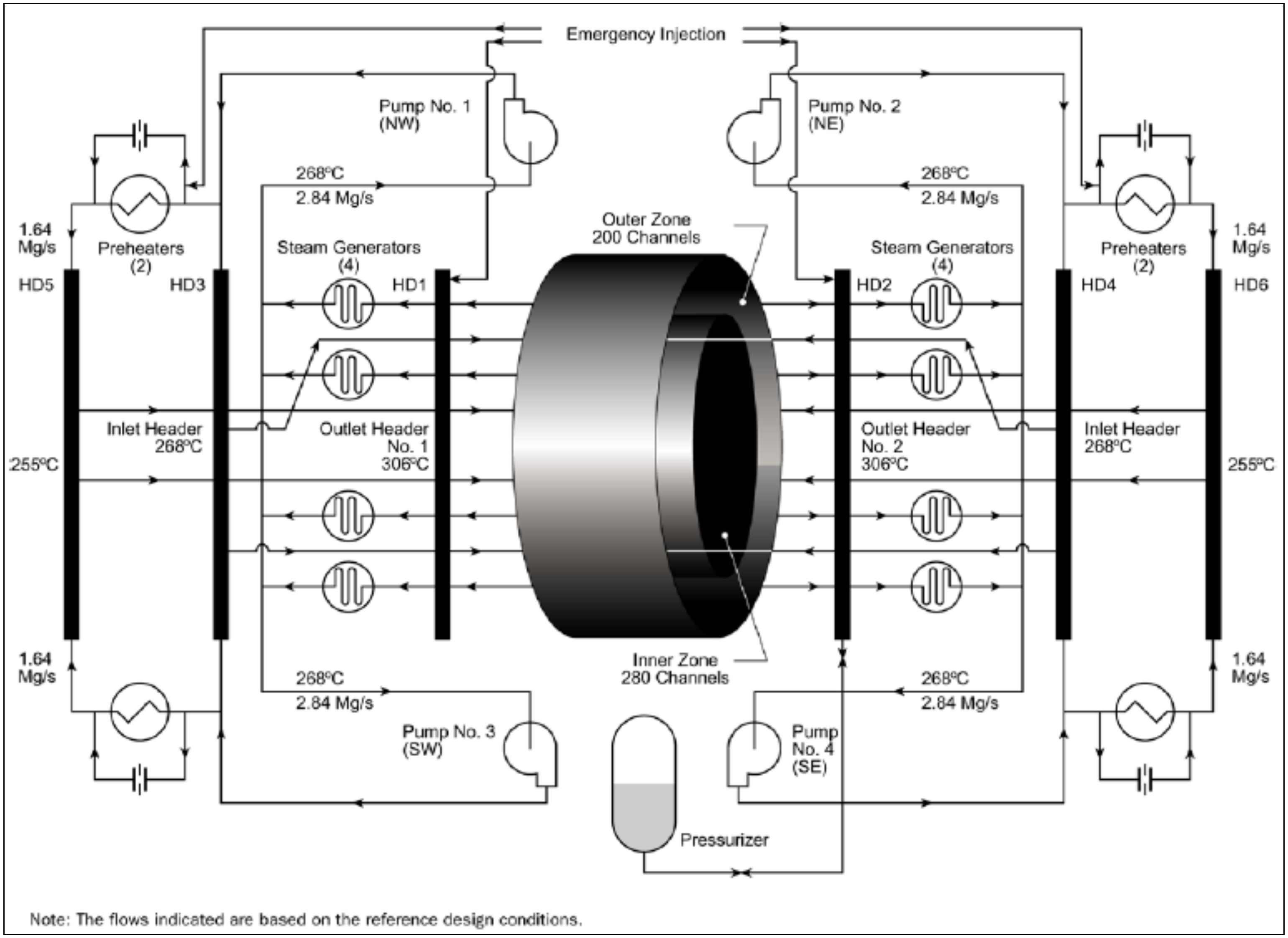

Figure 2 Simplified Bruce B Primary Heat Transport System (applicable to Bruce A except for operating conditions)

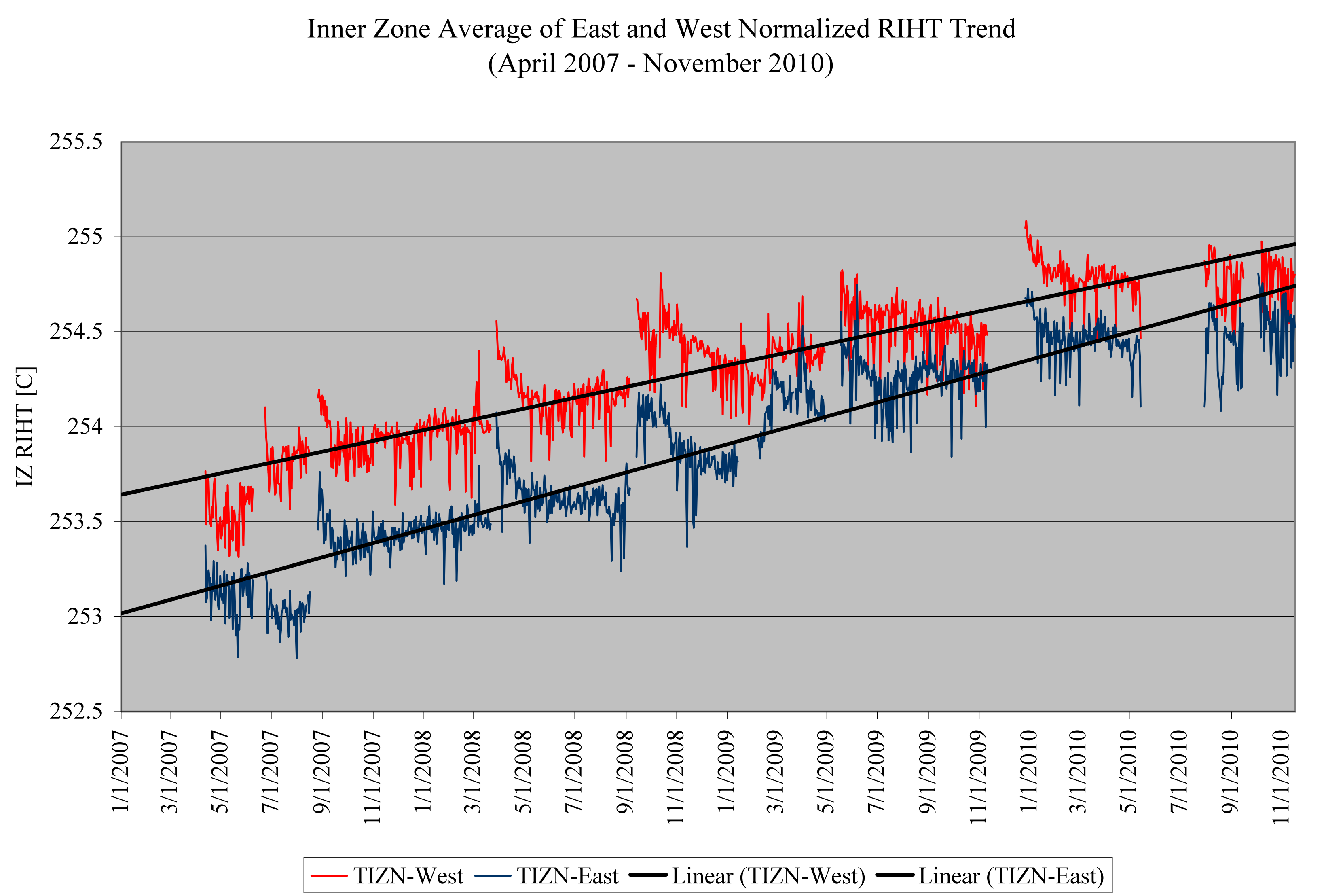

Figure 3 Example of a normalized trend for inner zone RIHT

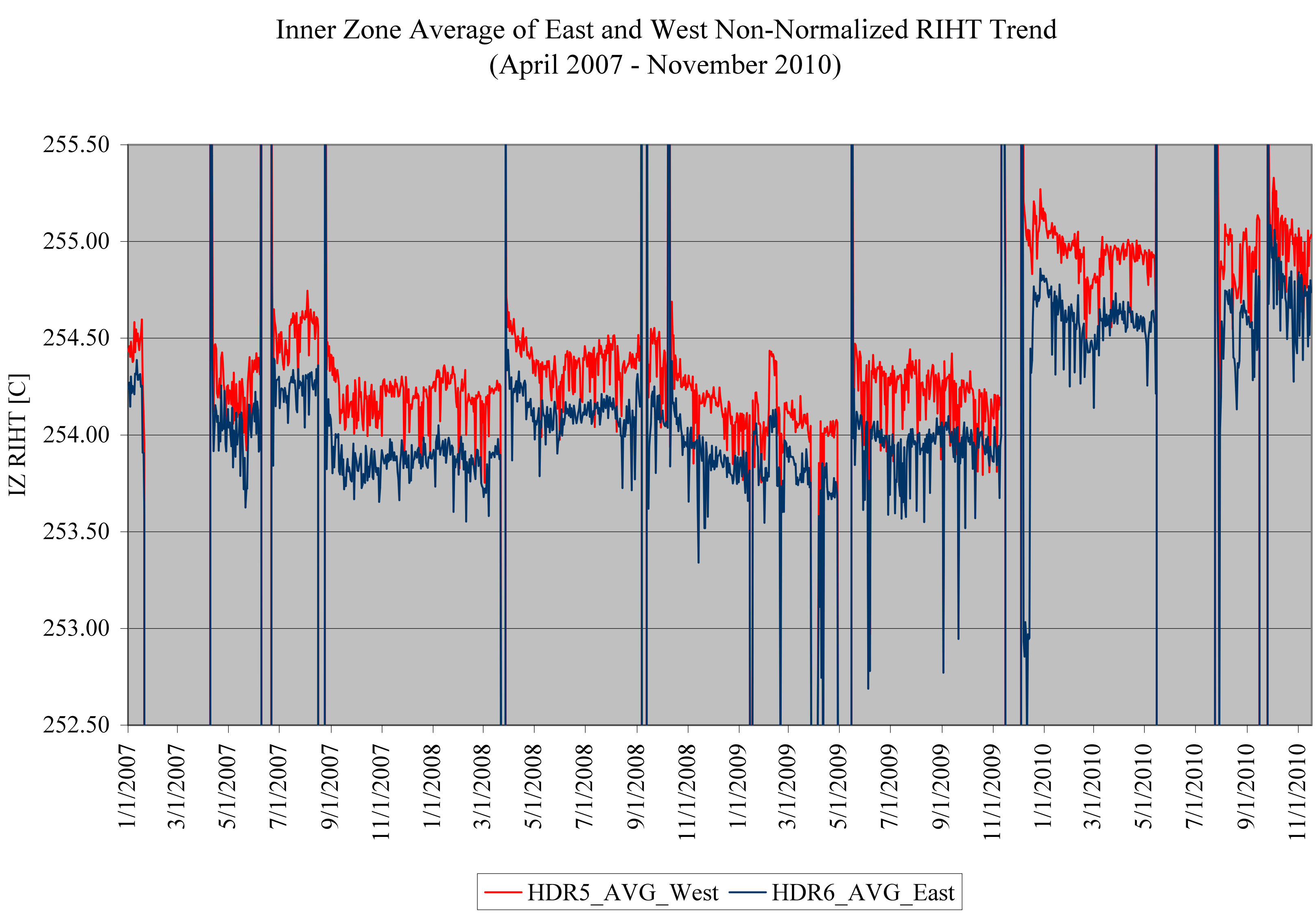

Figure 4 Example of a non-normalized trend for inner zone RIHT

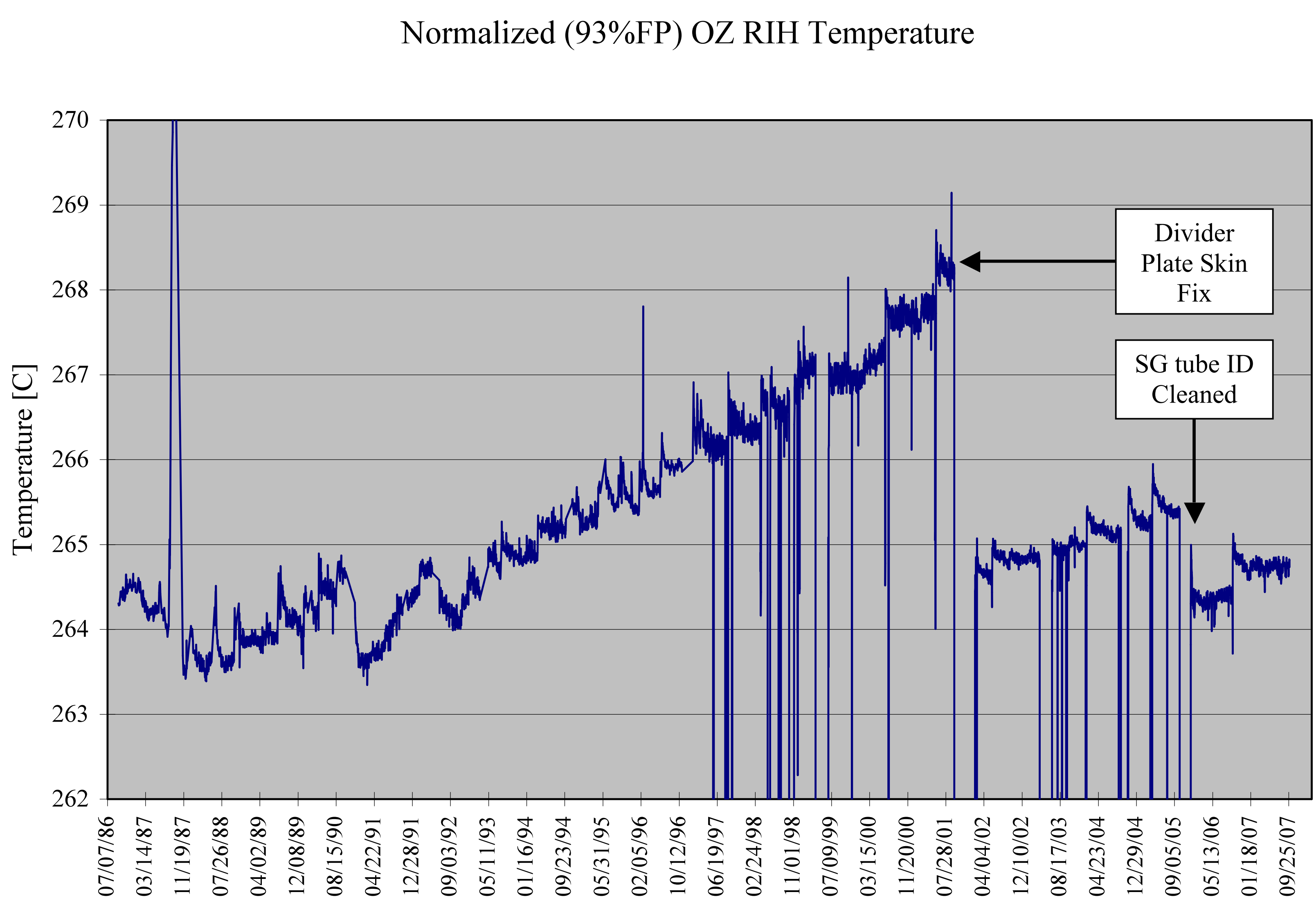

Figure 5 Illustration of the similar rate of rise in RIHT before and after SG tube ID cleaning in late 2005