BRUCE A STEAM GENERATOR (BOILER) REPLACEMENT

Bob Burns,
Bruce Power
Jeff Millman,
Babcock & Wilcox Canada

ABSTRACT

Bruce A will be the first CANDU nuclear power plant to replace degraded steam generators. Fabrication is almost complete on the first set of Babcock and Wilcox Canada replacement steam generators. Several changes have been made in SG design in order to improve service life, inspection access and maintainability. The RSGs have been designed to interface with existing plant structures, simplifying installation. Upon completion, this project will improve SG reliability, outage durations and unit thermal performance.

The replacement steam generators for Bruce A have been designed based on a thorough assessment of the Bruce A degradation mechanisms and operating experience at other plants. The design features and material selection for the replacement steam generators are based on many years of successful operating experience in CANDU and PWR plants to ensure long-term reliable operation of the Bruce A replacement steam generators.

A rigorous inspection and maintenance plan is in place to ensure the integrity of the non-replaced Preheater and Steam Drum equipment.

1. Introduction

Steam Generators don't last forever. Since starting operation in the mid seventies, the existing Bruce A steam generators have degraded due to materials of construction, tube support design as well as historical secondary water-chemistry. Inspections of the existing SG Alloy 600 mill-annealed tubing have proven its susceptibility to stress corrosion cracking (SCC), pitting and intergranular attack (IGA) in various environments. Corrosion of the drilled carbon steel U-bend tube supports has resulted in deformation and stressing of the U-bend tubes, with associated SCC degradation in those regions. A lead contamination event in Unit 2 resulted in that unit's early demise and lay-up. High levels of feedwater impurities, including copper, have resulted in historically high levels of deposits in all SGs. Less than optimum layup practices at Units 3 and 4 further contributed to top of tubesheet (TTS) roll-transition region degradation.

TTS degradation in the Unit 4 SGs is currently the most life-limiting degradation in the operating Bruce A units. U-bend SCC, although a historical problem at Bruce A, is being monitored through inspection and is not presently limiting the inspection interval for the currently operational units.

Retrofit U-bend supports and operational chemistry improvements combined with thorough inspection campaigns at Units 3 and 4 have allowed these units to continue safe operation, albeit for reduced operating intervals between inspections. The life expectancy of the Unit 4 SGs is limited, as are the Unit 3 SGs to a lesser degree. The Units 1 and 2 SGs are unfit for operation and must be replaced prior to returning those units to power.

Improvements to water chemistry control and copper-bearing-alloy removal from the secondary plant have done a great deal to reduce the driving force for SG degradation, nonetheless, SG replacement is necessary for life extension.

2. Bruce A SG Configuration

The Bruce A reactors each have eight steam generator tube-bundles/cartridges connected to two common steam drums (four cartridges per drum – unique in the world) as shown in the plant cross-section in Figure 1. The primary head and part of the secondary shell of the SG cartridges penetrates primary containment and a bellows containment vessel provides the containment boundary between the secondary shell and the containment structure. The remainder of the secondary shells and the steam drum are located outside primary containment.

The Bruce A reactors each have four separate preheater vessels, located entirely within containment. The preheater vessels preheat the feedwater going into the steam drum (two preheaters per steam drum) by heat transfer from the reactor inlet flow to the inner-zone reactor fuel channels. The preheater flow diagram is shown in Figure 2.

While the common steam drum does pose some difficulties for plant operation (particularly during plant heat-up and cool-down), plant modifications, operating procedures and practices have been developed to effectively manage these difficulties. The most economical choice for refurbishment is to retain the existing common-steam-drum plant configuration in lieu of other options such as replacement with “light-bulb” style SGs similar to Bruce B. Only the lower SG tube-bundles/cartridges will be replaced and the existing steam drums with internals will be retained. Preheaters are not planned for replacement.

3. Life Extension of Non-Replaced Components

For life extension of the steam drums, the primary areas of interest are the remaining allowable number of transient cycles on the pressure boundary, the condition of the steam drum internals and the level of and nature of deposits in the steam drums. Fatigue assessments for significant historical stress cycles are being reviewed to determine the remaining number of significant cycles from the analytical predictions. In addition, the pressure shell periodic inspection program (PIP) has monitored and continues to monitor significant fatigue locations to ensure continued steam drum integrity. The principal structures in the steam drums are the flow ducts, primary and secondary moisture separators and feedwater distribution headers. Comprehensive steam drum internal inspections have been performed on some units and are in progress on others. Very minor restorative work on the steam drum internals is anticipated for life extension. Steam drum deposits have been visually inspected and chemically analyzed to determine the quantity and constituent of deposits in the drum in relation to replacement steam generator tubing integrity.

The preheater vessels have Alloy 600 MA tubing, however preheater and SG secondary side operating environments are very different from each other. There is normally no boiling in the preheaters, thus no concentration of potentially harmful contaminants from a change-in-state of the fluid. Based on limited historical tube inspections, there appears to be very low levels of degradation of the preheater tubing. On this basis, it was determined that the existing preheaters were suitable for life extension. Tube ID-cleaning will be performed to improve thermal performance of the preheaters and to improve ECT probe access and inspectability of the tubes. Confirmatory baseline ECT inspection and secondary side internal inspections will be performed to provide a good baseline for life extension of the preheaters. In addition, the plain carbon steel primary divider plates will be replaced with flow accelerated corrosion (FAC) resistant materials to provide good assurance of their integrity over the life extension. The location of the preheaters, fully within the primary containment vault, makes future replacement of these vessels challenging.

4. Replacement SG Design Overview

The replacement steam generator design and materials were selected based on a thorough assessment of the Bruce A SG degradation mechanisms and operating experience at other CANDU plants. Replacement steam generator materials and features are based on proven performance in newer generation CANDU plants and PWR plants with replacement SGs.

The significant degradation mechanisms in the original steam generator Alloy 600 MA tubing are summarized as follows;

- OD and ID SCC at the TTS roll-transition
- OD Pitting and IGA at TTS and top of sludge pile
- Denting and SCC at the U-bends tubes due to carbon steel U-bend support corrosion and bundle/shroud channel-guide lock-up. Significant operational stress is imposed on the tube bundle from the degraded carbon steel U-bend supports, further contributing to stress induced tube bundle degradation. The bundle/shroud channel-guide lock-up was relieved by in-situ modification.
- Excessive tube vibration due to loss of hot leg (HL) carbon steel U-bend support necessitating auxiliary antivibration bar (AVB) installation

The replacement steam generators, illustrated in Figure 3, incorporate proven features to substantially mitigate the above degradation mechanisms. The replacement steam generator (RSG) tube bundle is Alloy 800 material which has a long, proven track-record in CANDU and European PWR plants. The tube material is procured to enhanced specification requirements, which include limitations beyond minimum requirements for signal-to-noise ratio, surface finish, defect acceptance standards (volumetric and surface) and cleanliness.

The thermal performance of the replacement steam generators is designed to closely match the thermal performance of the original steam generators in the new-clean condition. The thermal conductivity of Alloy 800 material is less than Alloy 600 material, which is compensated by approximately 10% thinner tube wall and 15% more tubes. The overall height of the tube bundle is about the same. Thermal-hydraulic comparisons have confirmed that the minimum inventory requirements for safety evaluation are met.

The tube supports are all stainless steel which precludes corrosion denting observed from the original carbon steel supports. The straight-leg tube supports are low-pressure-drop/open-flow lattice grid supports which will provide much higher margins to fouling and blockage than the original higher-pressure-drop/restricted-flow broached plates. Blockage of the upper broached plates lead to SG level instability early in the life of Bruce A. While improvements in water chemistry control have reduced the deposit transport to the SGs significantly, the added benefit of tube supports that do not restrict the recirculating flow to the same degree is a benefit.

The U-bend supports are flat-bar type supports common in newer generation SG designs. These supports allow minimally obstructed flow through the U-bends, minimizing restricted flow areas that would otherwise preferentially accumulate deposits. Tight tolerances limit the tube-to-bar interface gap. The design allows distribution of U-bend support weight over a number of peripheral tube layers to minimize stress imposed on the tubes. The U-bend supports move with the tube bundle and do not restrict free thermal motions of the tube bundle, thus minimizing tube stress. Extensive analytical qualification (frequency-domain and time-domain) has been performed for tube vibration and wear resistance.

The tubes are full-depth hydraulic expanded in the tubesheet to minimize the depth of the secondary crevice and to achieve an improved residual-stress and cold-work state relative to the original steam generator (OSG) hard-roll expanded configuration.

Other improvements in material selection for the replacement steam generators include all-forged primary heads, chromium bearing carbon steels and stainless steel for internals components subject to significant potential FAC.

Other improvements incorporated in the replacement steam generators, some of which are discussed in more detail in the following section, include:

- Multiple tubesheet and tube support handholes installed during fabrication
- Fully welded integral primary divider plate incorporated
- Elliptical primary manway opening allows removal of the inner cover for maintenance and potential refurbishment of the inner cover
- No tubesheet obstructions, such as; surface blowdown headers; tie-rods; shroud feet to obstruct lancing and inspection access
- Improved internal blowdown piping arrangement to better facilitate draining of the tubesheet surface during outages. Tubesheet drain nozzle incorporated for future potential connection to a drain/blowdown system within primary containment.
- Features to allow direct downcomer flow measurement incorporated

5. Improvements in Replacement SG Maintenance Features

The original steam generators had no external access available to the U-bend region and between tube support plates. Difficult entry through the steam drum and field installation of inspection nozzles on the secondary shell were required to inspect, repair or clean the OSGs. Access to the secondary tubesheet face for waterlancing and inspection was also inadequate, requiring addition of nozzles and removal of some blowdown internals. The RSGs have a large handhole at either end of the no tube lane (NTL) to access the tubesheet and one inspection port at every second lattice grid elevation. In that way, at least one side of all tube supports can be accessed for inspection and maintenance activities. A large U-bend access port has been incorporated to facilitate inspections of the U-bend region of the SGs.

The OSG primary manway openings are circular, which means that the inner covers cannot be removed for repair or maintenance. Installation of round gaskets on the inner cover is challenging and the inner cover can constrain inspection and maintenance activities within the bowl. The RSG has elliptical manway openings to facilitate inner cover removal for inspection and maintenance and simplified gasket replacement. Manway cover manipulators will be similar to those used at Bruce B but with further enhancements.

The OSG primary side divider plate is a segmented/bolted configuration which was designed to be removed to facilitate inspections. Removal of Bruce A divider plates has never been required but the design has contributed to several problems. These carbon steel segmented divider plates have contributed to thermal performance loss from FAC degradation and associated flow bypass, necessitating challenging in-situ sealing modifications. A loose-parts concern exists because of their numerous small plates and bolts. Maintenance required inside the primary head has been hampered by hot particles retained in the crevices of the existing divider plates. Also, the OSG divider plates are not sufficiently robust to resist a large loss of coolant accident (LOCA) and their failure behaviour must be incorporated in the reactor safety analysis for LOCA.

The RSGs have integral all-welded primary divider plates, with smooth surfaces and blended/profiled transitions to the primary head and tubesheet with no sites for hot particle hide-out, no loose parts potential and are sufficiently robust to resist a large LOCA.

Previous attempts to measure downcomer flow rates to confirm detailed SG hydraulic predictions have met with limited success due to the presence of steam in the downcomer. Steam carry-under from the primary separators is known to occur and limits the ability to perform non-invasive downcomer flow measurements. The RSGs incorporate features in the upper inspection port cover to facilitate direct downcomer flow measurement.

The SG containment bellows, which is attached to the SG secondary shell approximately 1/3 of the way up from the tubesheet, creates challenges with tubesheet blowdown design and the ability to effectively drain the tubesheet during maintenance outages. The internal blowdown piping arrangement that elevates the tubesheet blowdown flow above the elevation of the bellows has been enhanced relative to the OSG with the addition of a peripheral "ditch" to better facilitate draining of the tubesheet. For the RSGs, a contingency tubesheet drain/blowdown nozzle has been incorporated for future potential use, however it is supplied capped for operation since a new piping system inside primary containment would be required to activate it.

6. RSG Interface with Plant Structures

The RSGs are designed to interface with the existing plant with minimal modification of the existing plant structures. The major pressure boundary attachment points are the shell riser and the primary heat transport (PHT) inlet and outlet nozzles. These interfaces have been designed with extra material (ID, OD and length) to facilitate custom machining at site to facilitate optimum fitup with the steam drum and PHT piping. The RSG incorporates a ring, or landing bar on the secondary shell for attachment of the existing primary containment bellows. The base support beam, shock-supression snubbers and tubesheet lateral support bumper interfaces are duplicated.

The RSGs incorporate integral, permanent lifting trunnions to facilitate rigging and handling during installation. The blowdown nozzle terminal points are duplicated, with the exception of the NTL nozzles which have not been incorporated in the replacement SG design to eliminate interference for tubesheet lancing and inspection. Two additional wide-range level taps have been added, which provide the same function as field-installed nozzles on some of the OSGs.

The two-phase riser region of the SG incorporates a shroud closure feature to attach the RSG cartridge riser to the steam drum ducting, after completion of the pressure boundary closure weld.

7. Seismic Margin Assessment

Bruce A is seismically qualified through a seismic walk-down process. Changes to the plant are reviewed using a Seismic Margin Assessment (SMA) process that evaluates the differences between the system changes and the original qualified arrangement. The RSG weight, stiffness and C of G are sufficiently similar to the corresponding OSG parameters that the SMA is confirmed for the configuration with the RSGs in place.

8. Conclusions

The replacement steam generators for Bruce A have been designed based on a thorough assessment of the Bruce A degradation mechanisms and operating experience at other plants. The design features and material selection for the replacement steam generators are based on many years of successful operating experience in CANDU and PWR plants to ensure long-term reliable operation of the Bruce A replacement steam generators.

Thermal performance of the replacement steam generators will meet the thermal performance of the original equipment in the new-clean condition with high confidence. The RSGs have been designed to interface with existing plant structures, simplifying installation.

Enhancements to improve maintenance and inspection access have been incorporated. A rigorous inspection and maintenance plan is in place to ensure the integrity of the non-replaced steam generating equipment.

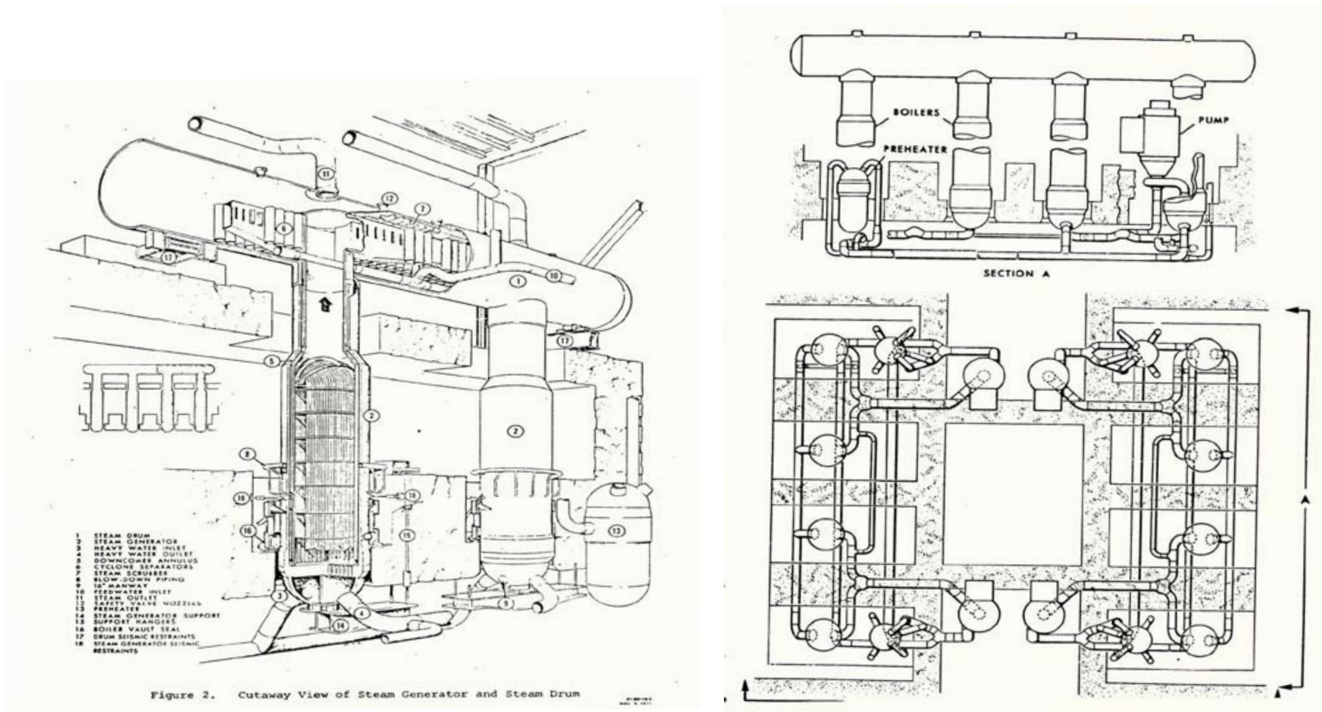

Figure 1: Steam Generator Arrangement

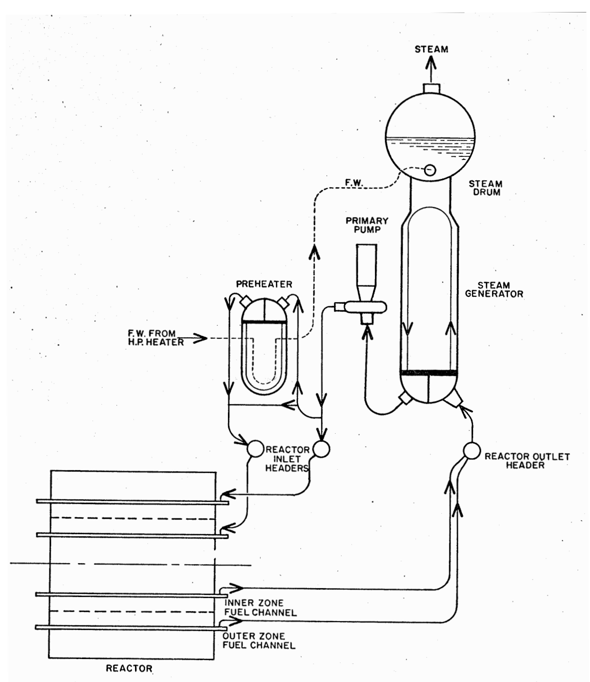

Figure 2: Preheater Flow Diagram

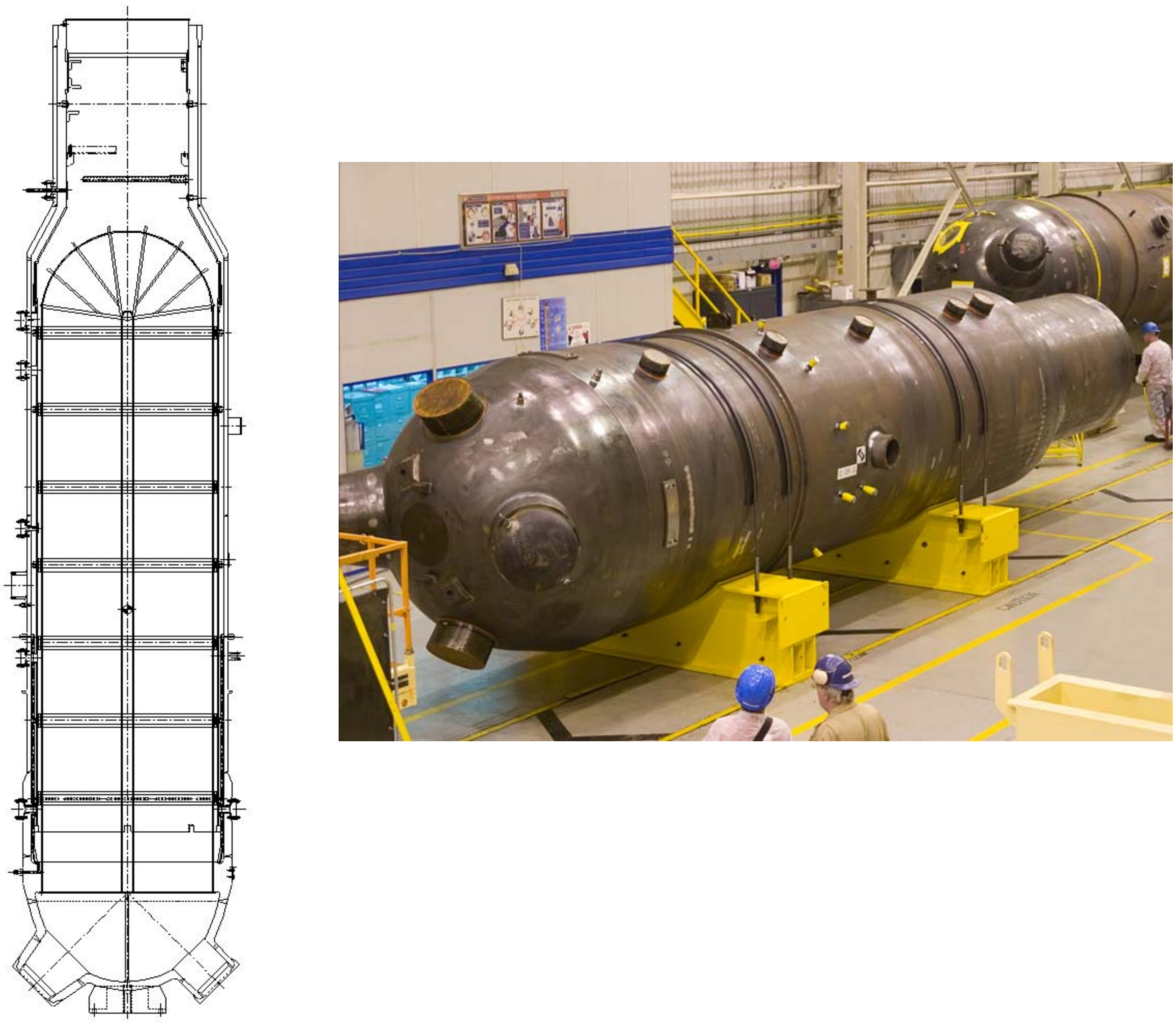

Figure 3: Replacement Steam Generator Arrangement