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Embalse Steam Generator Replacement – Level Control

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ABSTRACT

This paper introduces the unique combination of new Steam Generator (SG) cartridges and the existing Embalse drums for the purpose of SG replacement. The new design presents clear advantages for extraction and re-introduction of new SGs but it also presents several design challenges. The issues are also augmented by the intent to increase the current 2015 MW^{th} thermal power output to 2064 MW^{th}. To achieve this, four larger SG cartridges will be installed to make the system power output nearly identical to other CANDU® 6 stations. Moreover, the feedwater system will be updated to supply the required water at the desired temperature to the secondary side of the SGs to maintain their desired levels during various modes of operation.

This paper also describes the challenges with respect to the Embalse SG Level Control (SGLC) to satisfy the operation and safety requirements. The new SGLC logic is designed using the Candu Energy sophisticated analytical simulator, C6SIM and the Canadian Algorithm for THErmohydraulic Network Analysis (CATHENA). The robustness and excellent performance of the new controller has been achieved at various power levels when reactor is operating at normal power and also following the events that requires sudden or gradual power reduction by the reactor control system.

1. INTRODUCTION

The Embalse Nuclear Generating Station is preparing for refurbishment planned for 2013/2014. One of the possible major events during the life of a nuclear plant is the steam generator replacement (SGR). Moreover, the current Embalse steam generator tube bundle is smaller than a standard CANDU® 6 steam generator tube bundle, which allows for enhancement of the plant output by selecting a standard CANDU® 6 steam generator tube bundle as the replacement design.

The life assessment of SGs evaluated the potential for SG life extension and a number of actions were completed towards meeting this objective (i.e.: primary divider plate replacement, additional U Bend support and inspection port installation) including further inspections [2]. The inspections identified degradation of the tube supports (carbon steel broached plate) and U-bend supports due to Flow Accelerated Corrosion (FAC). This issue, coupled with the plan to increase the plant power output during the life extension of the station, resulted in a strategic decision by NA-SA to replace the SGs. The review of the condition and replacement options available concluded that replacing the bottom portion of the SG, i.e. the shell, the tube bundle, the tube sheet, the primary head and its internals and the primary nozzles with a factory assembled cartridge (collectively called the “SG cartridge”) was the preferred solution.

The SGR issue, coupled with the plan to increase the plant power output, resulted in a strategic decision by NA-SA to replace the existing SGs with a unique combination of new SG cartridge and the existing drums [1]. The unique combination of new SG cartridge and an existing drum, while presenting some clear advantages for extraction and re-introduction of new SGs, also presents several design challenges.

The SG design needs to ensure that safety requirements are met and that level control has acceptable operating margin to avoid unnecessary reactor trip, turbine trip, or reactor power stepback by the reactor regulating system. The design process was streamlined to support this work.

Computer codes such as CATHENA and the analytical simulator, C6SIM, were used to simulate the steam generator level in order to verify the performance of the new SG design.
By linking the executable of the logic control to the thermalhydraulics model in CATHENA, the steam generator level at power manoeuvring, reactor stepback, reactor startup, and low power can be calculated at a much lower computational cost.

Furthermore, there are design details that must be addressed. For instance, to provide an optimal tubing arrangement for convenient design support in the refurbishment project, without having to implement excessive changes to NF supports, modifications to the Steam Generators were made.

2. REPLACEMENT OPTIONS and SELECTION

Several options were considered for SG replacement:

- In-situ replacement of the SG tube bundle, the original steam drum to be re-used.
- Removal and replacement of the entire SG (including the steam drum).
- Replacement of the bottom portion of the SG, i.e. the shell, the tube bundle, the tube sheet, the primary head and its internals and the primary nozzles with a factory assembled cartridge (collectively called the "SG cartridge"). In this option, the original steam drum would be retained for the extended life.

The final decision determined that replacing the bottom portion of the SG was the preferred solution. The Cartridge would be lifted out of the Boiler box and then manipulated through a series of steps leading to its lowering through the Hatchway on the Boiler Room floor and transported out of the Airlock. A new replacement cartridge would be brought in through the Airlock hoisted up the hatchway and reinstalled in the Boiler box.

The existing steam drum would then be moved back to its original location and the replacement cartridge would be attached to the existing steam drum at the inner shroud and the shell through a closure weld of the pressure boundary.

The new design presents clear advantages for extraction and re-introduction of new SGs. The existing steam drum (with the steam separating equipment replaced) will be reused. The drum would be separated from the heat exchanger portion by machined cuts in the shroud and in the secondary shell of the vessel below the drum to shell cone section and stored in the Reactor Building on temporary structures located on the Boiler Box .

3. DESIGN AND MODIFICATIONS

Due to the replacement of SGs, changes need to be made to the steaming rate, inventory at various levels, downcomer effects, and the SGLC.

The Embalse drum is small and as a result two sets of level measurements are provided:

1. Narrow Range (NR): the pressure takeoffs for the high and low pressure connections of each transmitter are located on the drum.
2. Medium Range (MR): the pressure takeoffs for the high pressure connection of each transmitter are located below the zero level in the downcomer region. The take-off for the low pressure side of the transmitter has the same elevation as the low pressure side of NR transmitters.

As a requirement, triplicated MR measurements and their associated taps are added for both special safety systems (SDS1 and SDS2). This requires revising the level transmitters tubing runs. **Figure 1** illustrates the water level nozzles

To provide an optimal tubing arrangement for convenient design support in the refurbishment project without having to implement excessive changes to NF supports, and to avoid rework on the existing boiler level loop instruments, eight (8) new nozzles were added at elevation: 50' 4¾" (15 361) see Figure 2:

The design needed to integrate physical changes, safety, and process changes, together with a new SGLC to ensure stable operation. Section 4,5,and 6 will describe the other aspects related to Safety, Process and SGLC.

4. SAFETY EVALUATION

In CANDU® design, the SG must have enough inventory for stable heat removal from the heat transport system within the first 30 minutes due to loss of total feedwater. The 30 minute time frame will allow credit of operator action to start the emergency water supply system and re-establish a heat sink. This requires reducing the SG pressure, which is achieved by opening the main steam safety valves (MSSVs) of the SGs. The Canadian Algorithm for THErmohydraulic Network Analysis (CATHENA) code was used to simulate the performance of the system following a reactor trip based on low SG level. The Embalse CATHENA model includes the replacement cartridge of the steam generator tubes. The postulated event occurs with the reactor operating at an assumed power of 103% FP (with respect to the up-rated core thermal power of 2061.4 MW). An upper-bound decay power curve for post-reactor trip transient was used. With loss of feedwater, the SG level falls. In case the correction is not made, then reactor power will be reduced by the reactor regulating system (RRS) . The RRS sudden power reduction is called Stepback and it is a preventative act by the RRS to avoid spurious reactor trip by the SDS1/SDS2 systems. If the action of RRS is not credited, the reactor trips on low SGL, resulting in the primary and secondary circuit pressures and temperatures to decrease. A turbine rundown is initiated after reactor trip and the net steam flow from the SG decreases. Heat transfer to the secondary circuit continues after reactor trip. The primary circuit pressure and temperature increases very slowly as the SG temperature increases. The SG level falls as the pressure increases and SG riser boiling is reduced.

Failure of the feedwater system influences the heat sink for the heat transport system. The effect on fuel cooling is generally mitigated by the large amount of water normally contained in the SGs and by the thermal inertia of the primary circuit. Alternative heat sinks, which can be initiated by the operator if required for this event, have been provided in the plant design.

The design uses main pumps and an auxiliary pump to provide the required inventory at start-up and operation at different power levels. The auxiliary feedwater pumps are powered by diesel generators and would start on loss of the main pumps. Once this occurs, there is a continuous long-term heat sink for post-trip fuel heat generation. If the pump does not start, then the inventory in the SGs alone provides a continuous heat sink until the operator establishes an alternative heat sink, or preferably re-establishes feedwater by starting the pumps.

The effectiveness of the new design with respect to safety requirements will be analyzed by Candu Energy using CATHENA.

5. PROCESS

The design upgrades as described in Section 1, require higher feedwater and steam discharge flow rates. In light of the increased feedwater and steam flow rates, the capacity of feed water level control valves (LCV), the Main Steam Safety Valves (MSSVs), and the turbine bypass discharge valves or the Condenser Steam Discharge Valves (CSDVs) need to be re-assessed. The assessment of LCVs capacity and the SGLC performance have been carried out by extensive simulation.

In order to estimate the LCV capacity, CATHENA, which models the primary and secondary sides of the plant was employed. By performing the analysis at 100% and 110% reactor power of the uprated conditions the required valve flow coefficient Cv was estimated and the level control valves (LCVs) were sized. Once the capacity of the LCVs was determined, analysis was performed to demonstrate that the modified SGLC (Steam Generator Level Control) program is effective and produce robust performance at different power levels and in particular at low power when the transition of feedwater supply between the main LCV and the small LCV occurs.

6. STEAM GENERATOR LEVEL CONTROL

The SGLC (Steam Generator Level Control) program is designed to balance feedwater flow to steam flow while maintaining the SG level at the calculated setpoint. The SG level (SGL) needs to be controlled fairly tightly because:

- Too high a level will cause a turbine trip (danger of water carry-over, which could damage the turbine blades)
- Too low a level will cause a reactor trip (danger of losing the primary reactor heat sink).

The SGLC is challenging because level is very sensitive to reactor power, to steam pressure, and to feedwater temperature as each of these variables effects steam volume in the riser section of the boiler. The addition of cold feedwater can also have a detrimental effect. This is more noticeable at low power levels, where feedwater is relatively cool and where boiling conditions in the SG itself are not well established.

When feedwater flow is suddenly increased then the amount of boiling in the riser reduces, causing the drum level to go down instead of up. This so called non-minimum phase effect requires some caution in the design of the controller to ensure that the effect is not amplified unduly by controller action.

Likewise, if the feedwater flow is decreased (or steam flow is increased), the SGL initially begins to increase. The initial level rise upon increasing load is called "swell", while the initial drop in level upon a decreasing load is called "shrink.

Due to the strong swell effect, SGL is difficult to control. Experience has shown that control is much better if the control system does not "fight" this natural swell behaviour, i.e. if this swell curve, or something close to it, is defined as the desired setpoint.

In some older CANDU® 6 reactors like Embalse, the drum portion of the SG is relatively small and there is insufficient space to accommodate the swell/shrinkage over the full range of operating conditions. The newer CANDU® 6 reactors have a bigger drum (e.g. Qinshan, Cernavoda) which makes the SGLC easier. The Darlington SG drum is so large by design, which makes the level control much easier; no measurements are used in the downcomer (medium range, MR).
The MR measurements are quite inaccurate. The location of the lower tap in the downcomer subjects the measurement to a variety of disturbances, among them a Bernoulli effect due to the velocity of fluid passing the tap, and an "entry loss" effect due to the narrow gap at the top of the downcomer. These errors are bad for the control system, but even worse for the shutdown system. The errors are in the direction of making the level look too low, i.e. reactor trips on low level are actuated too soon and constitute an operational (not a safety) problem.

SGLC typically uses a three element controller, which means that the controller uses three feedback variables, drum level, feedwater flow and steam flow. In addition, the SGLC uses reactor power, feedwater temperature, and steam pressure signals as feedforward variables.

A small LCV is provided for low power operation. For reliability, two large LCVs per boiler are provided for high power operation. One of the challenges to level control is transferring from small to large control valves.

Figure 3 illustrates the schematic of the SGLG algorithm. The controller consists of a feedback term and several feedforward terms.

The outer loop applies a corrective signal to position the feedwater control valve in order to maintain the SGL at its setpoint. The inner loop is used to maintain the mass balance by correcting the difference between the steam flow out and feedwater flow into the SG. When the reactor power is below 20%FP, the mass balance term is not used.

The level setpoint, *LS*, is programmed as a function of power to ensure an adequate heat sink inventory is maintained over the entire operating range.

Figure 4 shows the SG operating setpoint that includes the transmitter error carry under effects.

The uprated conditions required modifications to the SGLC control parameters. The new controller was tested using C6SIM which was created specifically for control analysis. The performance of the controller was then validated by implementing the new control parameters with the qualified safety code, CATHENA.

7. CONCLUSION

Solutions were provided to ensure that level control for the unique combination of the new SG cartridge and an existing drum satisfies the design and safety requirements. This is achieved by providing large enough operating margins to avoid unnecessary reactor and turbine trips as well the spurious reactor power reduction by stepback function of reactor control system.

An approach that allows for the appropriate design and modifications, process and safety evaluation and SGLC was integrated, including changes that allow the increase of power output.

To provide an optimal tubing arrangement for convenient design support in the refurbishment project without having to implement excessive changes to NF supports, modifications to the Steam Generators were made. The design process was streamlined. By linking the executable of the logic control to the thermalhydraulic of the system in CATHENA, the steam generator level at power manoeuvring, reactor stepback, reactor startup, and low power can be calculated at a much lower computational cost.

The robustness and performance of the new controller was assessed by extensive simulation using Candu analytical simulator, C6SIM and the safety code CATHENA. The results show that the new controller is effective and well behaved at various power levels and under different operating conditions The final tuning of the controller will be done during the commissioning of the SGLC.

8. REFERENCES

[1] J. Parkitny, N. Subash - Replacement of Steam Generators for Embalse NGS - The steam generator cartridge design and manufacturing issues, localization and site assembly challenges, 6th International Steam generator Conference, Toronto, Canada, November 2009

[2] G.Diaz, R.Sainz,R.Gold, R.Dam- Embalse Refurbishment, Pre-Project Condition assessment, 28th CNS Conference, June 2007

Figure 1
Water level nozzles

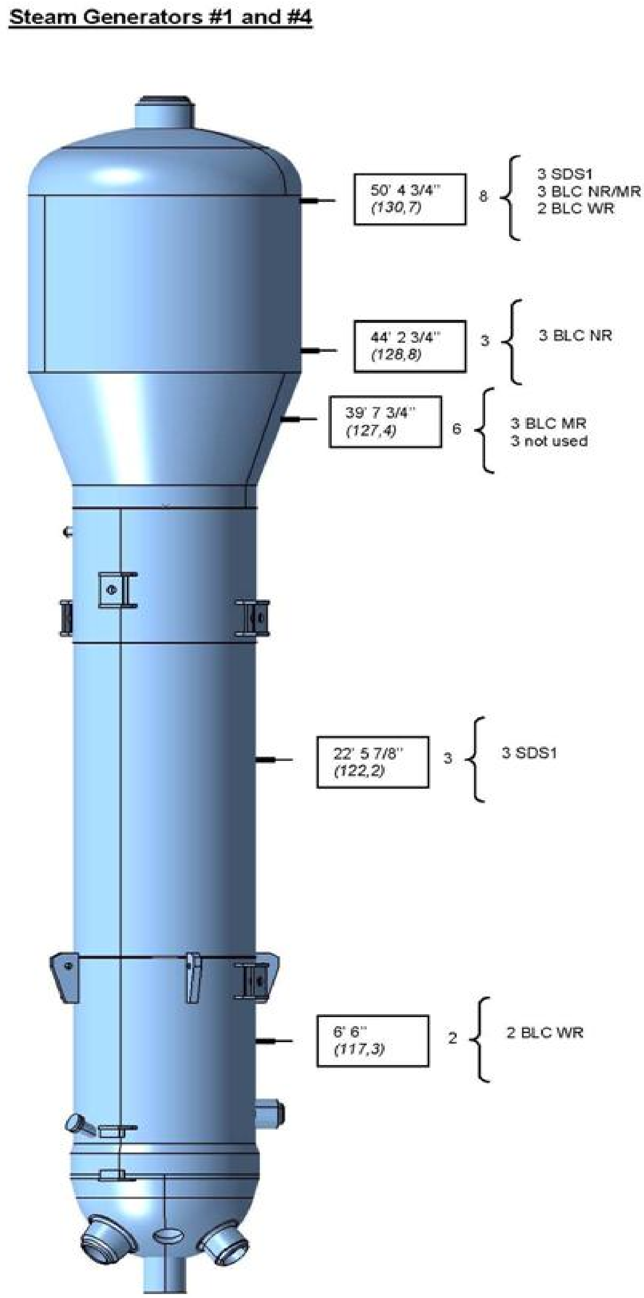

Figure 2
New nozzles added

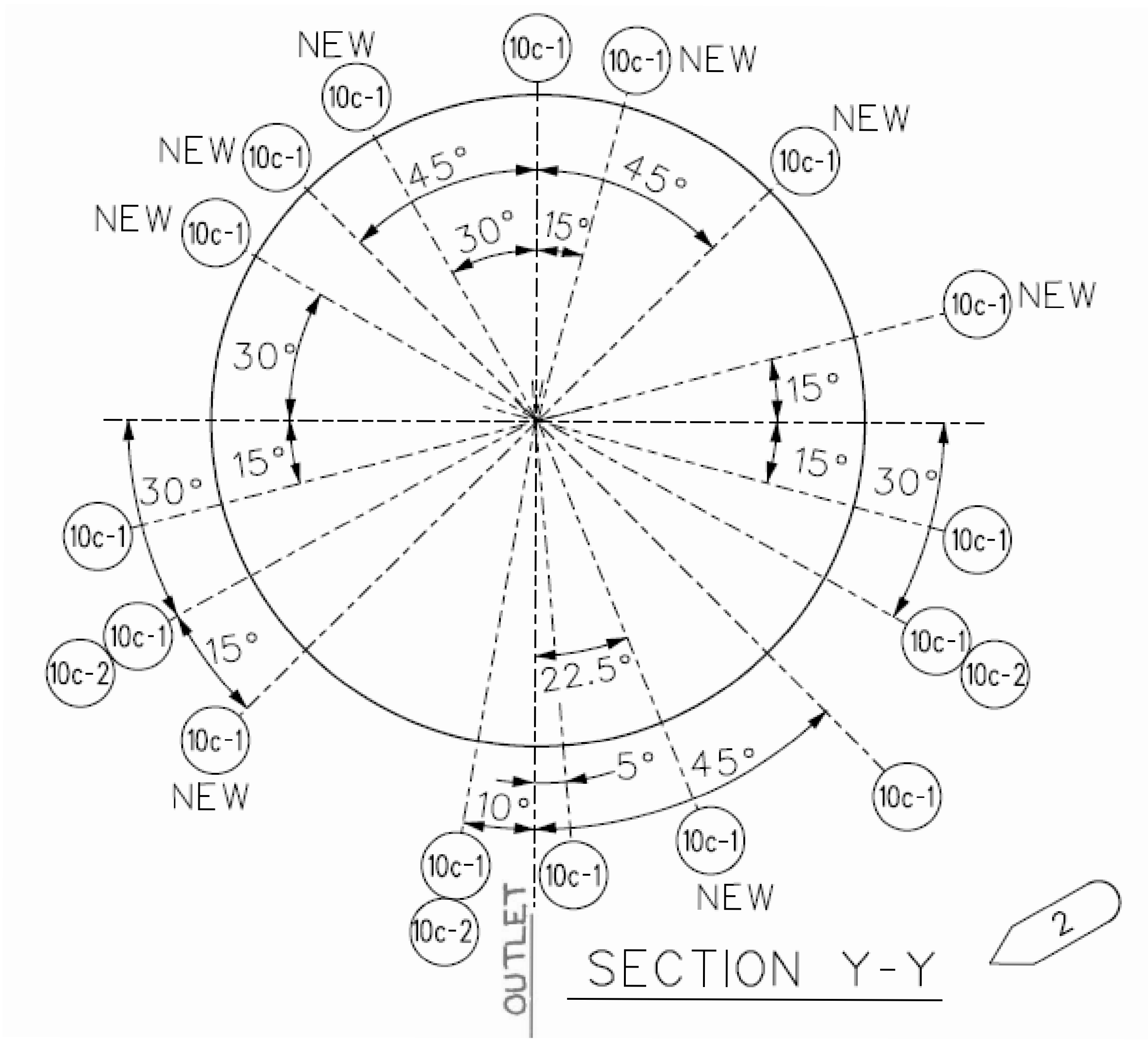

Figure 3
Schematic of the SGLC logic

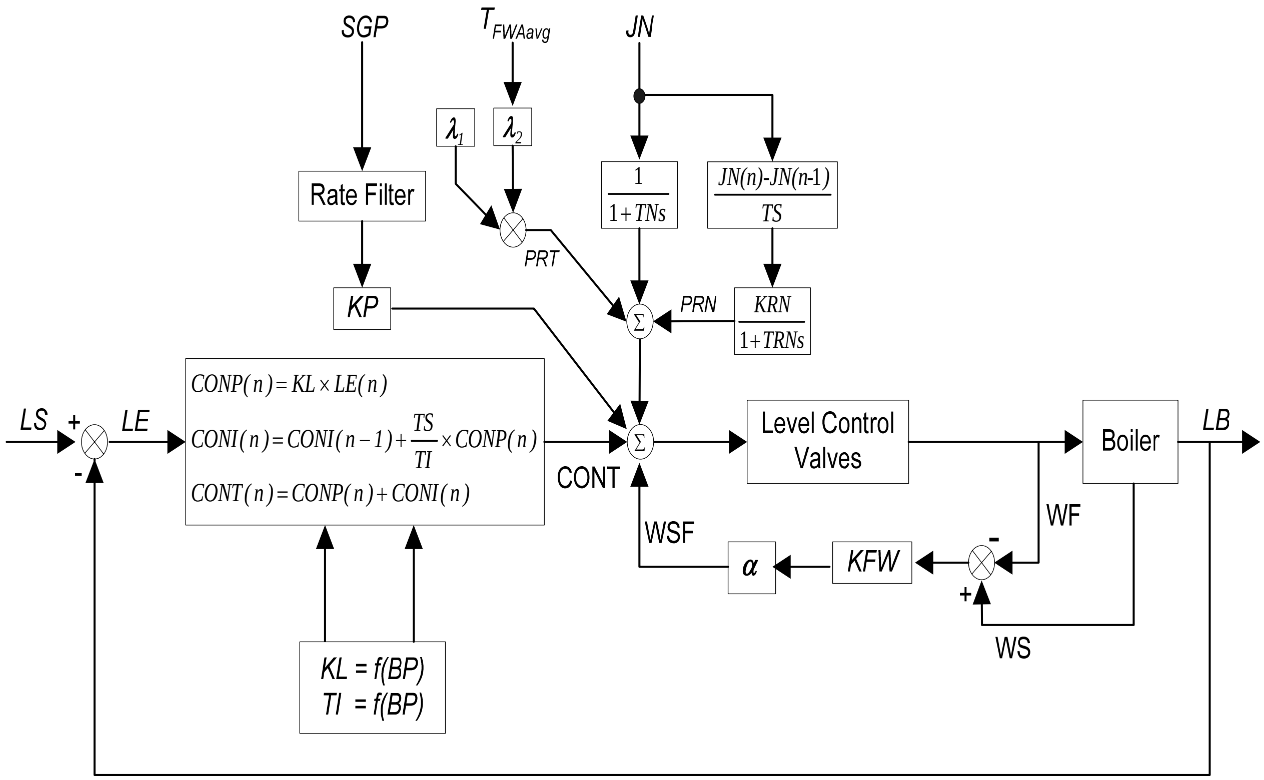

Figure 4
The Current Steam Generator Operating Setpoint