Steam Generator Life-Management, Reliability, Maintenance and Refurbishment

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My job as the first plenary speaker is to introduce the overall conference and then go into a bit more detail on the topic of the first session, namely issues associated with steam generators and heat exchangers.

SGCC 2012 is a different kind of a conference – it has its own focus and objectives, and it differs from its predecessors. CNS-sponsored steam generator conferences have a long and proud history, starting with the Steam Generator and Heat Exchanger Conference in 1990. This was a difficult time for steam generators – premature degradation of Alloy 600 tubes was rampant world-wide, and some CANDU® steam generators, which had previously seemed immune to the problems being experienced elsewhere, had started to experience significant fouling and corrosion issues. So it made sense to have a CNS conference dedicated exclusively to discussions of Steam Generator issues and possible solutions to those issues. The six previous steam generator conferences which have been held since 1990 have used a very similar format and a similar theme.

We are now in a different era in steam generators. The Alloy 600 tubing that was so problematic has been largely replaced by more robust materials. CANDU® steam generators have been brought under much more intense and effective life cycle management. And this focus on life cycle management has paid off as performance of steam generators has improved greatly. Indeed, steam generators are no longer considered at risk of limiting the life of the units. In fact, a sign of how much the situation in the steam generator world has improved is that most of the Incoloy 800 steam generators in CANDU® units are not being replaced during refurbishments as they are considered to be capable of operating reliably through the “second life” of the units. An exception to this is the Embalse unit, but for the most part Incoloy 800 SGs are not being replaced.

Given this improved environment in SGs, it seemed appropriate to expand the scope of the conference from one to three areas:

A. steam generators and heat exchangers as before, but also
B. controls, valves, pumps, and electrical systems
C. reactor components and refurbishment.

And these are the Programs A, B and C, respectively, at the conference.
The conference is specifically targeting to address the needs and interests of the operating utilities, and to ‘focus on what needs attention’. As a means of doing this, an ‘Issue-Identification & Definition’ process was started last winter. An Issue Identification Team, with COG President Bob Morrison as its Executive Lead, worked to identify issues which required attention in the three areas of interest. Of the many items identified by the Team and elaborated on by the Program Developers of this conference, four themes were recommended for special attention:

A. **Operate Clean – Build Clean – Plant Wide**: Despite its importance, system cleanliness has not always received the attention or understanding at the front lines that it deserves. The Operate Clean – Build Clean theme is addressed in a number of papers at this conference.

B. **Heat Exchangers, Valves and the Multitude of Other Off-Reactor Components during Refurbishment**: Refurbishment projects are usually dominated by the replacement of feeders and fuel channels. Notwithstanding the importance of these major components, the handling of these other components is also critical to a successful refurbishment. A number of papers at this conference address this topic.

C. **Effectively Engaging Service-Providers**: More work than ever is being done on behalf of the utilities by Vendors and Consultants. How we can effectively engage these service providers is critically important to us. This is the subject of the next plenary by Ron Oberth.

D. **The Fundamentals of Thermal Hydraulic Design and Functional Architecture**: This includes the details of fluid mechanics; detailed design characteristics, operating chemistry, etc. – getting the details right in these areas is critical to achieving technical success or a good project outcome.

The various Plenary Presentations in the next few days will lay these themes out more fully for the topics covered by each of the three sessions.

For the rest of this plenary I'm going to talk about steam generators. While my perspective is necessarily going to be that of the utility where I work, OPG, I think my comments will apply across much of the industry. As I said in the opening, we seem to be in a pretty good situation for the most part in steam generators. However, that's not to say that all our issues are fully resolved – far from it. While we don't consider that steam generator issues will limit the life of our units in the short term, we nonetheless spend a lot of money and outage time dealing with them. And the 50-60 year life that we will be looking for from the current machines is beyond our experience and knowledge base. So there are still several issues to pay attention to and I'm going to touch upon four which I believe are high priority issues.

1. Understanding the long term vulnerabilities of I800 and I690

The first issue has to do with the alloys that are expected to be in service long-term. Two alloys dominate steam generator tubing with the removal from service of Inconel 600. Incoloy 800 is used in much of the CANDU® fleet, the German PWRs, and some replacement PWR steam generators. Inconel 690 dominates the bulk of the replacement SGs in the PWR fleet. Both are excellent alloys, and a paper by Roger Staehle this morning will compare them in terms of inherent ability to resist degradation. However, our knowledge of the real-world, long term behavior of these materials is not complete. While Incoloy 800 has a longer service history than Inconel 690, it has also experienced some in-service degradation. OD-initiated intergranular cracking has been seen in a few German units and at the Almaraz plant in Spain. The root cause of the degradation has not yet been fully explained. With Inconel 690, the service history in commercial steam generators is not as extensive, and laboratory tests have shown that this material can be cracked under certain extreme conditions, such as lead contaminated environments. While a lot of good work has been carried out on Alloy 690 and on Alloy 800, there is nevertheless a need to develop a better understanding of their long term vulnerability under off-normal chemistry conditions. Utilities need this understanding to make business decisions about the likelihood of successful 50-60 operation (or even 80 year operation as some in the US are starting to look at). In addition, we may have some ability to fine-tune the chemistry regime that we operate our steam generators under, if we understand the environments that represent the greatest risks. We will need mechanistic information and "rate of progression" information for all the plausible degradation mechanisms to support fitness for service assessments and alternate plugging criteria, for use if and when degradation is discovered in the field.

And, of course, we will need to maintain robust inspection programs to validate the findings of the R&D, and to provide us early warning of in-the-field degradation. We do not want to be overwhelmed by an advanced state degradation the first time we discover it. As such, we need to continue to develop faster, better and, yes, cheaper inspection technologies to allow efficient steam generator inspections in the shorter outages which we anticipate post-refurbishment.
But it all needs to start with a better, in-depth understanding of the long-term vulnerabilities of Incolloy 800 and Inconel 690, so that's the first need area of need.

2. The importance of keeping foreign material out

The second issue has to do with the importance of keeping foreign material out of the steam generators. This issue may seem self-evident, but it has enough aspects to make it complex and difficult. Foreign material comes in many forms and from many sources.

First of all, manufacturing. We have had ample demonstration in the industry of the importance of keeping foreign objects out of the SGs during manufacture. That's the "build clean" bullet above. There have been many instances of welding rods, bolts and other construction debris and even small tools such as a tape measure at Pickering, being found in the tube bundle during operation. When we are fortunate, we find these foreign objects during our inspections and can retrieve them or preventively plug the affected tubes. When we are unfortunate, we find them when they produce a through-wall flaw, a leak and a plant shut-down, as happened with the Pickering tape measure. Either way, manufacturing debris represents a long term burden on utilities. This can be through the need for additional time and effort to retrieve debris and plug tubes, and, perhaps more importantly, through the reputational damage that results when SG leaks cause releases to the environment. Foreign material exclusion standards for new steam generators need to keep getting tighter and tighter to minimize the future burden on the utilities.

During operation, there are also many opportunities to introduce foreign material to the boilers, for example:

- During inspection or maintenance activities in the boilers, parts taken in can be inadvertently left behind. The most extreme example of this is surely the lead blanket left behind in the U-bend of a Bruce unit 2 steam generator which produced massive lead-induced cracking and was the main cause of the early retirement of the unit in 1995.
- Loose parts can also be generated by catastrophic failure of tools taken into the steam generators, such as high pressure water lances or inspection equipment. Complex systems

fail in unpredictable ways, and the added complexity of modern inspection and maintenance tools may cause this risk to increase.
- Loose parts from feedtrain can be carried into the steam generator with the feedwater and threaten the tubing

Over the years, we have reduced the risk through enhanced maintenance practices in the area of Foreign Material Exclusion, and rigorous Failure Modes and Effects Analyses for any tool introduced into the boiler. But I think that more efforts are required, as we do not appear to be close to a "zero events" situation yet.

If we include deposits in this broad definition of foreign material, (and I propose that we should because sludge is definitely not part of the design, so by definition it must be foreign material), if we include deposits, then Foreign Material Exclusion becomes a matter of survival for the boilers. Modern steam generator designs go out of their way to eliminate crevices and occluded locations, for example with full depth expansion in the tube sheet, and open lattice grids and flat bar u-bend supports that provide for line contact between supports and tubes. Then we undo all that by letting deposits enter the steam generators and create crevices where contaminants can accumulate and create aggressive conditions. Inconel 690 and Incoloy 800 are excellent, resilient alloys. But they are not "impervium", that imaginary material that can withstand anything. If we treat these alloys badly enough, they will degrade. We need to improve the methods to prevent deposits from accumulating in our steam generators. This is generally considered a "chemistry problem", as optimized chemistry control can reduce steady state corrosion product transport. However, total transport to the boilers is also greatly influenced by how many start-up transients our units are subjected to – this is definitely not a chemistry issue. And some "low-tech" maintenance activities, for example, shoveling sludge out of the condenser hotwell during outages, can reduce the amount available for later transport – again, not a chemistry issue.

I think that if we expect our SGs to last 50 or 60 years, we need to collectively become obsessive about keeping sludge out of them. We in CANDU® need to develop a greater sense of urgency around adopting the dispersant injection technology developed at EPRI in the last several years. It will take a concerted, collaborative effort between the chemists, the equipment engineers and the environment groups to allow us to use it in our plants. But this is such a promising technology for new or relatively clean SGs such as those at Darlington that we just need to get on with it.

So in summary for this issue, we need to reduce the challenges to the tubes whether from objects that can fret through them or deposits that can create conditions that degrade them. The challenge can be simply stated as:

"If it isn't supposed to be there, keep it out"

with an "after the fact" corollary:

"If it isn't supposed to be there, get it out"

3. Getting the thermalhydraulics right

The third priority area deals with the need for steam generator designers to get the thermalhydraulics right. The basic thermalhydraulic properties of a steam generator are established by the original design. I recognize that some instances of thermalhydraulic problems are due to in-service changes. For example, deposition in broached holes in support plates has caused flow oscillations, and deposition on tubes has produced heat transfer problems, manifested as Reactor Inlet Header Temperature increases in CANDU® units or steam pressure decreases in PWRs. However, these effects can often be reversed by eliminating the cause of the change, for example, deposit removal and chemistry changes to prevent recurrence. But unlike chemistry regimes which can be adjusted throughout the operating life of the unit, the designed-in thermalhydraulic properties of the steam generator is something the utility is basically “stuck with”.

There have been many instances in CANDU® and PWR steam generators of inadequacies in the original design. Severe U-bend fretting was observed at Bruce 5-8 and at Darlington, as well as in several PWR steam generator designs, because of the inadequacy of the flow induced vibration characteristics of the original design. At Darlington, there appears to be an active hydrodynamic process, such as cavitation erosion, causing damage to some preheater tubes - again, a function of the design. Even a design change to solve another issue can do it to us. At our Pickering plant, divider plate leakage was a problem, and the leakage was mitigated by installing a skin over the hot leg side. The skin was held in place by bolts, whose loosening was prevented by locking tabs. Unfortunately, the thermalhydraulic characteristics of the flow in the primary heads was not adequately taken into account in the design, and the locking tabs have suffered from fatigue resulting in breakage. Because breakage of cold leg tabs is highly safety significant because of the possibility of blockage of flow through a feeder, all the locking tabs need to be replaced before the predicted failure date of the cold leg tabs. This is a high cost, high dose, outage-time consuming job, which would have been avoidable had the thermalhydraulics of the situation been assessed correctly in the first place.

Some of the examples I have cited are related to designs done long ago when our understanding was incomplete and computational tools were more limited than today. However, that can’t be the whole answer. I am sure that the owners of the San Onofre plant in Southern California had not expected that the brand new replacement steam generators they installed in their plant would suffer from severe tube-to-tube and tube-to-support fretting, and that their plant would be idled for many months with no clear path forward in sight. These were replacement steam generators designed with all the most modern tools available. And it seems that it was still wrong.
There is a clear need for SG designers to pay excruciating attention to understanding the thermalhydraulic characteristics of their designs and to avoid straying into unknown territory. Because the problems that can result when the thermalhydraulics are not right can be extremely difficult and expensive to remedy.

4. Protecting the steam generators during outages and lay-up

The final priority I want to mention is the protection of steam generators during outages and periods of extended lay-up, for example during refurbishments. Chemistry control during operation has gotten vastly better during the last few decades. Plants spend relatively little time outside the recommended secondary chemistry specifications and most operating time is spent near “desired levels” within the specifications. Operating chemistry has high visibility with plant senior management, and response to out-of-normal chemistry results is generally swift and effective. This has been a success story for plant operations. There is a need to develop the same level of intensity over the importance of outage chemistry to protect the long term health of the boilers. My sense is that there is a significantly lower level of awareness of the in-spec performance of our boilers during outages compared to during operation. We do not always use nitrogen blanketing of the boilers during outages, even though this is an industry best practice. We have experienced rapid, unexplained decomposition of hydrazine during extended outages at Pickering that made it impossible to maintain hydrazine levels to original specification. There seems to be a sense that because the temperature is relatively low during outages and that there is no active boiling going on, that the risk must be low. But the technical basis for this conclusion is weak, especially when steam generators are drained for maintenance operations such as water lancing or tube removal. For long-term protection of the steam generators, we need to raise the level of awareness of the potential for damage under outage conditions. This will be particularly important during refurbishment outages, during which steam generators will be in lay-up for a number of years and our experience base is very limited. We need to act very conservatively here to compensate for our lack of experience with extended lay-ups. There is also a need to develop better performance indicators for use during outages and lay-ups, and to generate the same level of management focus on outage chemistry performance as currently exists on in-service chemistry performance.

So there are four areas where I think significant effort and focus are required to sustain long term positive performance of our steam generators. There are many papers in the program for the next few days that will address several aspects of these issues - I’ve only mentioned a few of them. I would encourage you to discuss and debate the merits of these ideas during the conference and take the best ideas back with you to apply in your organizations.