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# The Role of Two-Phase Coolant in Moderating Fretting in Nuclear Steam Generators

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## ABSTRACT

This paper expands the principal of coolant-cushioning in Nuclear Steam Generators whereby the two-phase coolant, especially the bubble film on the tube surface, moderates the vibration of coolant tubes against their supports. This thesis was advanced by the author in JSME ICONE-11 paper #36443 "Fretting in Nuclear Steam Generators – A New Approach". The current paper addresses tube bundle and AVB geometry issues; examines the tube bundle-coolant-AVB interfaces and examines implications for recirculation flow, AVB design and boiler size. The need for research to confirm empirical findings is reiterated.

## 1. INTRODUCTION

In the previous paper ("Fretting in Nuclear Steam Generators – A New Approach", ICONE-11 paper #36443) the author discussed the history of Nuclear Steam Generator (NSG) fretting which occurs commonly at the U-bend, between the tubing and the anti-vibration bars (AVBs). He described a mechanism whereby the two-phase coolant at saturation temperature ($T_{sat}$) provides a negative feedback mechanism to transfer vibration energy from the tubing and AVBs back to the coolant. Quoting from that document…

*"As a tube accelerates toward a flexible AVB, the local pressure between them rises as a result of the fluid's inertia and viscosity. Vapor bubbles on the tube's surface will be compressed; transferring some vibration energy to the bubbles, raising their pressure and providing a cushioning effect. As the local pressure rises and the bubble starts to revert to a liquid, latent heat is released which slows bubble collapse and resists the impact. The pressure should be highest just before impact and at this point many of the bubbles will have collapsed, providing a water film on the tube surface that will further cushion the impact.*

*The increased pressure is also applied to the AVB, tending to push it away slightly and transferring more vibrational energy from the tube back to the fluid. When the vibration accelerates the tube away from the AVB, local pressure is reduced and additional bubbles will be created, absorbing energy as latent heat as the bubble is formed, and as the AVB is pulled inward, transferring energy of vibration into the fluid."*

Since that paper was presented several questions have been raised and they are addressed in the following sections.

## 2. THE LOCATION OF $T_{SAT}$ FLUID IN THE NSG

Pool boiling, where the coolant is at saturation and is a foam of liquid and vapor phase water, occurs uniformly throughout the NSG. Exceptions are in the integral economizer where the fluid is a single phase liquid, and at the outlet end of the tubing, where there may be insufficient heat energy left in the primary fluid to maintain full $T_{sat}$ conditions.

Everywhere else in the bundle, from the innermost ring to the outermost, the heat flowing from the primary side generates vapor bubbles in a compact mass as described in the next section. In the critical U-bend area, $T_{sat}$ conditions are universal.

There are several reasons for this uniformity. First, on the primary side, most of the NSG pressure drop occurs at the inlet tube sheet. Since this pressure drop is high compared with the drop along the primary tubes and outlet header, inlet flow to the tubes is well distributed.

Secondly, the pressure drop inside each tube of the bundle is approximately equal. Although the individual tubes are of varying length, the shorter inner tubes have small-radii bends while the longer outer tubes have large-radii bends. Since the effects of length and radius on pressure drop are opposite, they tend to cancel and thereby equalize the pressure drop. The outlet flow is smooth and contributes little to the overall pressure drop.

Finally, on the secondary side, the recirculation (ratio is typically 6 in CANDU NSGs) means that the water circulates through the steam generator, ensuring good mixing. The higher coolant velocity attributed to high recirculation also aids in mixing.

Turbulence caused by the bundle supports; the AVBs and the cross-flow at the U-bends keeps remixing the secondary coolant as well.

## 3. PICKERING A

The four-reactor Pickering A station has seen over 20 years of service with no fretting. It has limber lattice bar AVBs or none at all (see previous paper for details). Although each boiler is smaller than modern units, (160 MW each versus 525 to 858 MW for CANDU 6 and Darlington respectively), they are nonetheless full scale power plant boilers, not laboratory test rigs. They have experienced full scale conditions of flows, water chemistry, temperatures & pressures, load ramps, start-up and shut-down cycles, for over 20 years, with no fretting.

## 4. THE TUBE-TO-COOLANT INTERFACE

Figure 1 is a schematic view of the interface between a NSG tube and the secondary coolant.

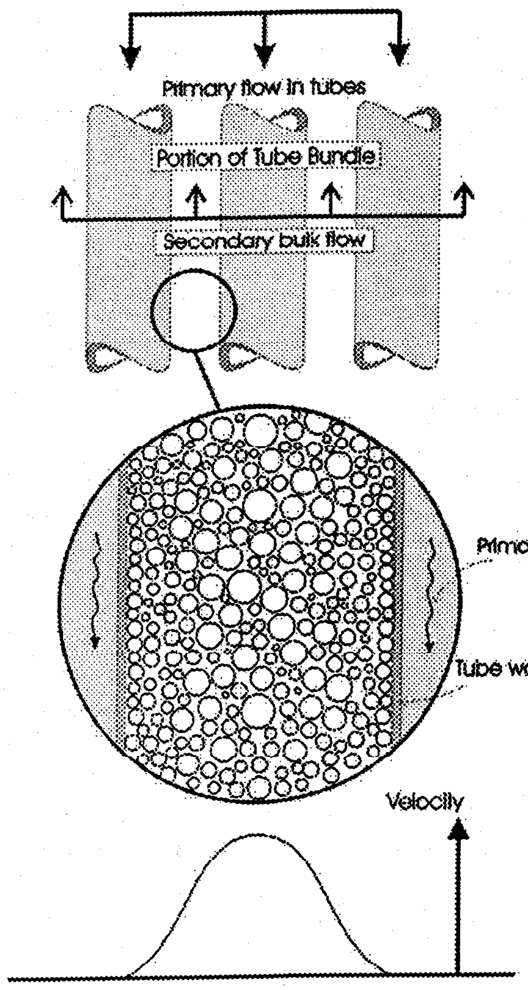

*Figure 1. Tube-Coolant Interface*

The surface of each tube is densely packed with various size bubbles growing with the heat input. The bulk coolant is a foamy mix. The coolant velocity is high in the middle and drops towards the tube surface.

Figure 2 shows schematically the dynamics of the interface.

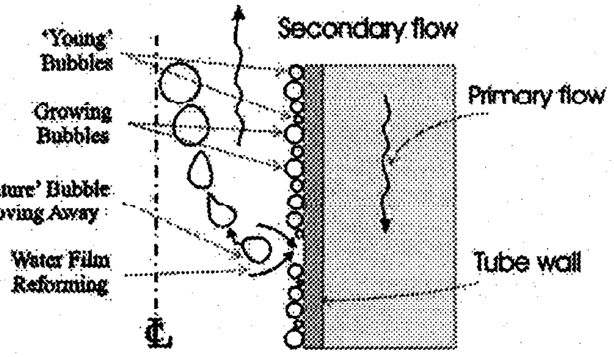

*Figure 2. Interface Dynamics*

Bubbles start in the water film on the tube surface and grow in size until they are large enough to be entrained by the coolant. As they move away from the surface they are constrained by adjacent bubbles to move perpendicular to the tube surface at first, then are then swept away. The water film reforms behind the departing bubbles and new bubbles start to form.

The key here is that the tube surface is covered with a dense, uniform bubble coating whose net velocity is perpendicular to the surface, near the surface.

In Figure 3 an AVB is inserted in the coolant channel.

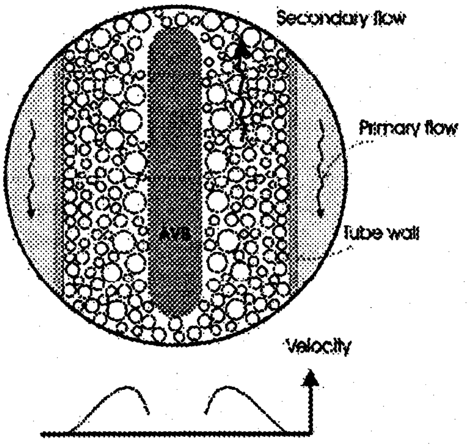

*Figure 3. In AVB Region*

Bernoulli's Principal requires that the coolant velocity increase

in the restricted area but surface drag produces a velocity profile show schematically below.
Figure 3 shows the AVB centered between the tubes. If it moves off-center, then the coolant velocity will rise and the pressure fall on the narrowing side, tending to further pull the AVB off-center. However, the momentum of the $T_{sat}$ fluid counteracts this tendency as does the compressive property of the fluid. (As the pressure drops, more bubbles form, resisting the movement.)

To summarize, in a $T_{sat}$ fluid, the tube surface is uniformly coated with growing bubbles whose momentum is perpendicular to the surface at first, then they are swept away by the bulk flow. The combination of this momentum, the phase change and the water film remaining on the surface, counteract the vibration energy of the tube-AVB system, reducing the likelihood of metal-to-metal contact and consequent fretting.

## 5. OTHER EFFECTS OF $T_{SAT}$ FLOW ON FRETTING.

The author believes that the AVB-tube interface should have sufficient clearance to allow the foregoing effects to operate. This clearance has other benefits. With adequate flow between the AVB and tube, there will be no local dryout and therefore less crud deposition. Crud buildup will remove the cushioning benefit and act as an abrasive to enhance fretting, at least until such time as it fills the gap, locks the tube and starts denting damage.

In Section 4 of his previous paper the author makes passing reference to *"...lack of vortex shedding."* The negative feedback mechanism of $T_{sat}$ coolant conditions acts on vortex shedding excitation in the same way as it does on vibration. As the coolant splits to flow around a tube and accelerates, pressure drops and the flow rejoins its counterpart at the rear of the tube, initiating a vortex. The $T_{sat}$ solution, however, responds to the pressure drop by converting more fluid to the vapor phase, robbing it of some of the vortex energy. Large vortices are converted to smaller, more diffuse ones, lessening excitation. A similar principal is used to decrease wind excitation of tall smokestacks by adding spoilers which shed many small vortices rather than allowing large ones to form.

## 6. IMPLICATIONS FOR RECIRCULATION RATIO

Designer response to fretting damage has in part been to reduce the recirculation ratio. This reduction in turn reduces the secondary coolant velocity and, it was thought, reduces vibration by reducing the excitation energy. Lower bulk coolant velocity, however, enhances crud deposition especially at the support structures. Because the fluid momentum is lowered, less coolant can penetrate the narrow AVB-tube spaces and the cushioning effect is lowered. In consequence, both denting and fretting are enhanced, rather than ameliorated.

## 7. IMPLICATIONS FOR AVB DESIGN

To maximize the benefit of the cushioning effect, the following design inputs are needed:

- the AVB-tube interface should have sufficient clearance for the $T_{sat}$ solution to operate
- the AVB should be wide—wide enough to generate the necessary cushioning force
- the AVB should be thin—thin enough to be flexible and absorb some of the transferred vibration energy

Designers around the world have reacted to fretting damage by lowering flow rates; increasing the number of AVBs; tightening structural tolerances to reduce the AVB-tube gap, and by designing AVBs which grip the tubes snuggly, either by clamping or wedging. But fretting and denting continue. Simple experiments showed that, in an array of vibrating tube bends, if one bend was tightly held in position, bends in adjacent positions increased their vibration. Clamping did not eliminate vibration energy, but transferred it. The author believes this effect is the reason current designs fret. Vibration energy must be transferred out of the U-bends.

## 8. CONCLUSIONS

The author believes that a major paradigm shift is required. Fretting and crud deposition at the AVB-tube interface can be reduced or eliminated by reducing the number of AVBs, increasing clearances and making the AVBs limber. He further believes that fretting history in NSGs bears out this thesis (see ICONE-11 paper).

The concept of coolant cushioning is not new. As Howard Rae said in a review of these problems...

*"Damping of the vibration by liquid films between the tube and support structure are also important in [the assessment of tube vibration]."* [1]

However, the full mechanism of this damping in pool boiling has not been fully appreciated and in consequence has not been suitably investigated. Most investigations have been conducted in fluids other than saturated water/steam mixes. The mechanism must be verified and quantified if it is to be a proper design tool.

## ACKNOWLEDGMENTS

Thanks to Wayne Joslin who helped me get these thoughts on paper.

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[1] Rae H.K., Chapter 14, Heat Transport System, "Canada Enters The Nuclear Age" (1997)