11th International Conference on Nuclear Engineering
Tokyo, Japan, April 20-23, 2003
ICONE11-36443

# FRETTING IN NUCLEAR STEAM GENERATORS – A NEW APPROACH

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Keywords: steam, generator, fretting, vibration, boiling

**Abstract**: Fretting has proven to be a chronic problem in nuclear steam generators for the past 50 years. It is caused by localized wear when vibrating boiler tubes rub against their structural supports. These supports are described and categorized. Prevalent thinking is that excessive clearance between the boiler tubes and the supports must be reduced to eliminate fretting, by reducing the momentum that is allowed to build up in the vibrating tube. Various approaches that have been tried are described.

The author puts forth a different explanation for the variation in the observed fretting. Based on his 35 years of steam generator design experience, and the observed history, he suggests that the intrinsic properties of boiling water at the saturation point may be used to remove vibration energy from the boiler tubes and cushion the tube-to-support impact. The properties of the saturated fluid, described by Mikic and Rohsenow in 1968, have not been properly modeled in fretting experiments. The physics behind the postulated mechanism is described. A new set of experiments is proposed to verify the cushioning mechanism and to provide design parameters.

Keywords: steam, generator, fretting, vibration, boiling

## 1. Introduction

Fretting – metal erosion by rubbing – has caused wear in nuclear steam generators since their inception. It continues to be a problem in some recent installations. Nuclear steam generators differ from fossil boilers in part because lower coolant temperature and the smaller temperatures rise (Δt) of the primary circuit require very large heating surfaces. The need to limit the hold-up volume of the radioactive primary coolant and the large heating surface required leads to the selection of smaller diameter tubing, to give the least hold-up volume per unit surface area. Smaller diameter tube is very flexible and high secondary coolant flow rates make vibration control through tube support systems more challenging.

Fretting occurs when the tubes vibrate in contact with their support structure, in both the U-bend region and in the tube bundle, when there is no lubrication. The energy that drives the vibration comes from coolant flow that is co-linear with the tubes except at the U-bend. Here the tubing briefly turns perpendicular to the flow, presenting both a different arrangement for initiating vibration (cross-flow) and for supporting the tubes. In the bundle the fundamental plane of vibration is like a guitar string, 360° around the axis. At the U-bend, vibration is at right angles to the plane of the 'U' with maximum amplitude at the curved portion and minimum at the legs (Figure 1). Higher harmonics are generally in the same plane. Therefore tube supports in the bundle must provide restraint for the full 360° while in the U-bend restraint is required primarily in the plane of the U.

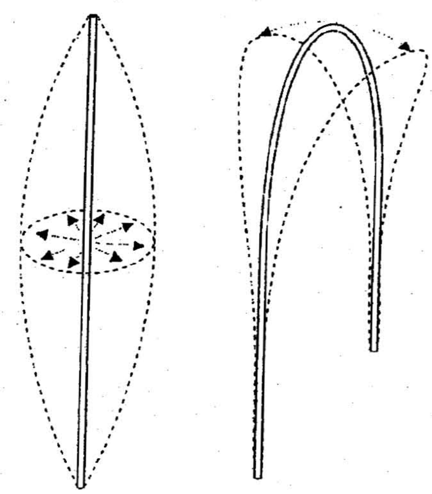

*Figure 1: Vibration Planes in Straight and U-Bend Tubes*

Fretting in single-phase fluids is generally well understood and documented, and tends to occur rapidly, as the forcing fluid is not compressible. For instance, in NPD-2[1], fretting failures in localized

[1] Nuclear Power Demonstration, Canada's first nuclear boiler.

single-phase flow took about six years to mature. In Darlington and rebuilt PWRs with two-phase flow, maturity is taking much longer. The secondary flow condition in PWR and HWR steam generators is two-phase, referred to as $T_{sat}$, where the coolant bulk temperature and pressure are at the saturation point. Additional heat input converts the liquid to steam, which appears as small bubbles on the surface of the tubes and which are swept away by the coolant flow. This liquid-bubble mixture is known as pool boiling. Local variations in pressure caused by turbulence can cause a phase change – bubbles to liquid or liquid to bubbles – with attendant release or absorption of the latent energy.

## 2. Fretting Control

The design approach to fretting control has been to restrain the tubes by support structures that dampen the amplitude of vibration. (Figure 2) The resulting support systems may be characterized as rigid or flexible. Rigid supports include drilled tube support plates (TSPs) with through holes for the tubes and interstitial holes for the $T_{sat}$ coolant; broached TSPs with trefoil or quad-shaped holes, which allow more $T_{sat}$ coolant contact with the tube at the support site, and solid bars of square, stiff cross-section. Another variant uses scalloped bars that clamp onto the tubes at the U-bends.

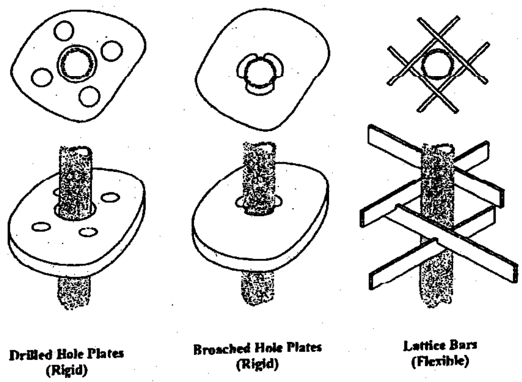


*Figure 2: TSPs and AVBs*

Flexible systems are those with solid bars of rectangular cross-section that have some flexibility in one plane. Presumably this flexibility cushions the impact when the lattice bar moves slightly upon tube impact and balances the gap on either side. Flexible systems may be used both as tube bundle supports and at the U-bends. Both the rigid and flexible systems that use a latticework of bars, rather than tube plates, to support the tubes, are referred to as AVBs (anti-vibration bars). Current USA designs use TSPs in the bundle and AVBs at the U-bends, while Canadian designs now use AVBs throughout.

Loss of chemistry control because of interruption to free coolant flow at the tube–support interface may cause chemical corrosion of the tube, or corrosion product buildup in the crevasses at the interface may cause denting.[1] The conflict between the need to restrain the tube by contact with a support structure and the need to keep coolant flow uninterrupted is the design challenge. The classic solution has been to keep the contact area between the tube and the support small, but not so small that contact pressure becomes extreme. The naturally narrow but long contact between a cylinder and plane surface seems ideal, especially when the contact line is co-linear with the flow, and is the reason for the preference for AVBs at the U-bend among most designers today.

A variety of tube support geometries have been used. At the U-bend bars may be arranged in fans or in various lattices, ranging from the simple single bar used in Pickering A to the much more complex lattice in Darlington A. (Figure 3) With flexible AVBs, the flat side of the AVB contacts the tube.

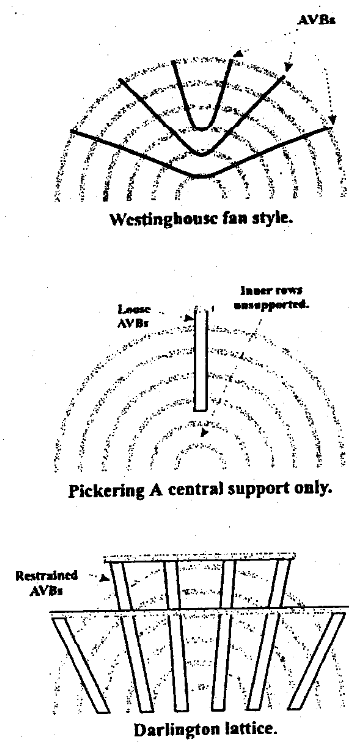


*Figure 3: Some Typical U-Bend AVB Layouts*

While it is desirable to lower flow to reduce fretting, velocities must be sufficient to maintain tube wetness. Flow velocity depends on the design recirculation ratio. Some PWR steam generator designers lowered the recirculation ratio to two, from the norm of four or more, presumably to lower the flow velocity and attendant fretting.

## 3. History of Fretting in CANDU Nuclear Steam Generators

The CANDU prototype, NPD-2, designed in the mid-1950s, had a steam generator patterned after US Navy submarine boilers. It had drilled TSPs and AVBs in the U-bends – their first application in Canada and one of the reasons for their subsequent use in Pickering A – with a U-shaped pressure shell lying horizontally and AVBs in the bend. It developed phosphate wastage and later fretting caused tube failures. These failures were associated with localized high velocity single-phase flow impinging on a tube next to a drilled TSP. The next CANDU station, Douglas Point, designed in the late 1950s, had steam generators similar to NPD-2's, except two vertical U-bent pressure shells. At the U-bends, the tubes crossed over one another as the tube pattern changed from tight in the economizer leg to wider spacing in the boiling leg. Mild fretting occurred at the crossovers where the tubes touched. There were no AVBs at the bend and TSPs were used in the tube bundles. Some fretting occurred at the TSP immediately below the bend.

The first four Pickering A reactors designed in the early 1960s, learned from the original problems and used AVBs on both the tube bundles and U-bends – a first in North America. Only the outer tubes of the U-bend had AVBs, and only at a single position (see figure 3). All other steam generator suppliers in North America were using drilled or broached TSPs at that time with AVBs at the bend. Despite the size of the Pickering steam generators (over 500,000 meters of tubing per reactor) their performance was among the best in the world. No fretting failures have been reported.

The second four Pickering B reactors and all eight Bruce A&B reactors used broached TSPs with scalloped AVBs, which held the tubes tightly. They held the U-bends so tightly that at first they were deformed during heat treatment and were replaced. There have been numerous tube failures in these stations.

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John was involved in steam generator design for 35 years, from 1945 to 1980. He lead the design team for the Pickering A nuclear station in the mid 1960s. They were the first with internal economizer and integral steam drum. The 48 steam generators at this four-reactor station have had exemplary performance.

John obtained his B.A.Sc. in Mechanical Engineering from the University of Toronto in 1943 and joined the Royal Canadian Navy Volunteer Reserve as an Engineering Officer posted with the Royal Navy doing convoy duty in the Mediterranean. When he returned to Canada he worked at the Naval Research Establishment in Halifax developing anti-acoustic torpedo gear. Coincidentally these were parallel rods that vibrated in water streams.

After the war John did steam boiler engineering at several firms and became Chief Engineer of Dominion Bridge's new boiler department in 1958. Here he attended a special course on nuclear design and submitted bids for early nuclear steam generators and reheaters. In 1964 he joined Babcock and Wilcox Canada, first as a project engineer on fossil-fired boilers and then to head up the new nuclear steam generating section where they developed a new 500Mwe design for Pickering A.

He is a registered professional engineer with the province of Ontario. He has been honored by the American Society of Mechanical Engineering as a life member for outstanding lifetime achievement. The Canadian Nuclear Association also honored him with their Outstanding Contribution Award for designing the steam generators used in CANDU stations.

The four reactors at Darlington A were originally designed the same as Pickering B and Bruce – broached TSPs and scallop bars. Later the design was changed to AVBs throughout, with supplementary stiffeners at the U-bend. Fretting has been reported at this station.

A number of papers have reviewed this history and the attendant science[ii]. Experience in the USA[iii] and Europe has been similar. Westinghouse steam generators use drilled TSPs with AVBs at the U-bend while Combustion Engineering used AVBs. All designs have exhibited some fretting, being worse on a few early CE designs where round bars were used, thereby concentrating the contact pressure. Void spaces at the double bends were suspected of upsetting flow and increasing vibration. Later CE designs used square bars. Babcock and Wilcox USA designs were based upon the once-through concept with no U-bends.

The ubiquitous nature of fretting suggests that it may occur at any tube-support juncture if the vibration amplitude is high and contact area small. The literature contains a number of references to localized regions of high water velocity or to wider than normal clearances as the suspected culprits in fretting failures[iv]. The former excites higher vibration amplitudes and the latter presumably allows more vibrational acceleration before impact. U-bends tend to have more fretting because the excitation is higher in cross-flow. Since fretting failure matures slowly in two-phase flow and seems to occur only when excitation velocity or impact pressures are unusually high, one might conclude that a solution requires relatively minor changes.

Control of high water velocity at the design stage is straightforward but limited by performance requirements. While localized high-flow areas associated with water entry points can be designed out, only recirculation ratios control bulk flow. Cross-flow at the U-bends creates the greatest excitation and cannot easily be eliminated. The support structure must control any remaining vibration that cannot be designed out.

Ideally, it seems that the clearance between the support and the tube should be minimal so that the tube cannot build up momentum before it hits the support. Investigators have conjectured that excessive clearance causes increased fretting, but these conjectures are unsubstantiated. Manufacturing tolerances, ease-of-assembly needs and thermal expansion all limit the designer's ability to minimize clearance. The scalloped AVBs of Pickering B and Bruce A and B solved the first two concerns but opened the door for denting and increased chemical attack.

If water velocities are irreducibly low and clearances are as low as practical, and if fretting still occurs, what can be done? An attempt to 'weave' thin AVBs through the tube bundle or the use of offset AVBs as used in marine boilers (Turner, et al, *op. cit.*) to provide zero clearance, has not been attempted in nuclear steam generators. There is surprising little experimental data on flow-induced vibration and fretting in two-phase fluids as in nuclear steam generators. Design guidelines are empirical. Some researchers used wind tunnel vibration simulations (Weaver et al, *op. cit.*) and some (Hodge et al, *op. cit.*) used air-water mixtures to simulate pool boiling. Most experimental work is conducted at room temperature and pressure. These compromises may be misleading, as suggested later.

In unpublished work the author used a model of the U-bends with air excitation to study vibration modes. Unsupported U-bends vibrated synchronously together with moderate amplitude and two vibration modes. However, rigidly supporting one tube caused its neighbor's vibration to increase. Both the synchronicity and the vibration increase suggest that the vibration mechanism is highly coupled among the tubes.

**4. An Alternative**

The author's experience[2] in this field and his experiments conducted after retirement suggest another approach to reducing the impact energy below the damage threshold. The vibration energy can be reduced dramatically by using the inherent properties of a $T_{sat}$ solution in pool boiling. In addition to the vibration damping that comes from fluid viscosity and lack of vortex shedding, $T_{sat}$ solutions can dampen vibration by phase change and by mechanical cushioning.

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.

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[2] see sidebar

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.

This negative feedback mechanism similarly eliminates vortex shedding and the Bernoulli effect, primary modes of excitation of the tube. Given enough linear contact area, these mechanisms can absorb sufficient vibrational energy to bring the impact well below the critical point The combination of bubbles and liquid in the gap act as a lubricant to prevent metal-to-metal contact, as in a journal bearing. A journal bearing which has lost its lubrication will gall as the two parts come in contact. The mechanism will also operate to balance conditions on either side of a flexible AVB and keep it centered in the gap.

For the bubble cushioning mechanism to operate, there must be sufficient flow in the gap to sweep away the bubbles as they form to maintain heat transfer and prevent dry out in the gap. "Sufficient" clearance is likely greater than one bubble diameter. Smaller clearances allow an individual bubble to span the gap, removing the water film and allowing metal-to-metal contact. The AVBs themselves must not introduce abrupt discontinuities in flow or the cushioning will be upset locally and fretting will occur. Attempts to unduly restrain the tube may, in addition to altering the local chemistry, enhance fretting by removing the cushioning mechanism. Indeed, the conjectures that increasing the clearance accelerates fretting, mentioned in the previous section, will hold true until the clearance is large enough to establish $T_{sat}$ conditions. There must be sufficient flow in the gap to sweep away the bubbles as they are formed, to prevent dryout. Lowering the bulk water velocity by decreasing the recirculation ratio may indeed contribute to the fretting mechanism in certain sized gaps by permitting dryout. Dryout, in addition to allowing metal-to-metal contact, may deposit chemicals from the liquid that could act as an abrasive during tube-to-AVB contact. If the tube is restrained but the vibrational excitation energy not absorbed, then adjacent tubes or unrestrained sections may increase their vibration and exacerbate fretting there.

Without a proper $T_{sat}$ solution, laboratory tests of fretting will not reflect this damping mechanism. Few, if any, of the reported tests used a $T_{sat}$ solution, opting for a two-phase system of water and a gas such as air or freon. Even steam injection into water will not produce a $T_{sat}$ solution.

The author suggests that experiments may be conducted (with $T_{sat}$ fluids) to determine the following:

- Verify that the mechanism operates as described.
- Determine the sensitivity to gap size and optimum gap.
- Determine variability with length of AVB contact area.
- Establish design guidelines.

## 5. Pickering A

The proposed mechanism of tube damping in a $T_{sat}$ solution by increased clearances is, the author believes, consistent with reported experience in a wide variety of steam generator designs. Of particular interest is the performance of the 48 Pickering A steam generators designed in the mid-sixties. They used flexible (1.5mm thick) AVBs at the apex of the U-bend. About half of the inner tubes had no support, as shown in Figure 3. The AVBs were not only thin, they were unfastened at either end, allowing them to move inside a restraining channel. This flexibility prevents the tube-to-support gap from being large on one side of the support any narrow on the other, as may happen with more rigid supports. A flexible AVB will find its own central equilibrium. Figure 4 shows the geometry.

On one diagonal (those sloping down to the left in the diagram) there is a row of AVBs in the center. On alternate sides of that row are AVBs on the other diagonal. This interweaving captures the center row without fastening. Restraining bars at the top and bottom (not shown) prevent any AVBs from slipping out of the channel. The arrangement is therefore loose and flexible, allowing the proposed mechanism to operate. No fretting or corrosion build-up has been reported.

## 6. Conclusion

The intrinsic properties of a $T_{sat}$ solution provide a damping mechanism that will transfer vibrational energy from the steam generator tubes and will lubricate the tube-support interface. If fluid velocities are properly managed in the design and if the U-bends are allowed a modest amount of freedom, fretting will not occur. In fact, some preliminary

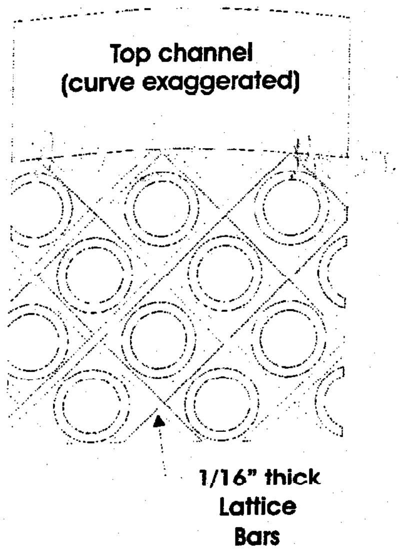



*Figure 4: Pickering A AVBs*

experiments suggest that unrestrained U-bends may have fewer tendencies to fail than overly restrained ones. Fatigue failure at the rigid TSP adjacent to the U-bends is mentioned as a concern in the literature but no failures have been documented. Given the widespread nature of fretting in nuclear steam generators, some realistic mockup tests are needed to move from black art to engineering.

The author concludes that the ideal tube support system consists of a minimum number of flexible AVBs, or none at all in some cases. Consideration must also be given to ensure that the support structure does not upset $T_{sat}$ flow. Clearances between AVBs and tubes should be large enough to maintain $T_{sat}$ fluid conditions. Dampened vibration itself does not appear to be harmful to the tubes and the cushioning effect of the $T_{sat}$ fluid will prevent the metal-to-metal contact that is the basis of fretting.

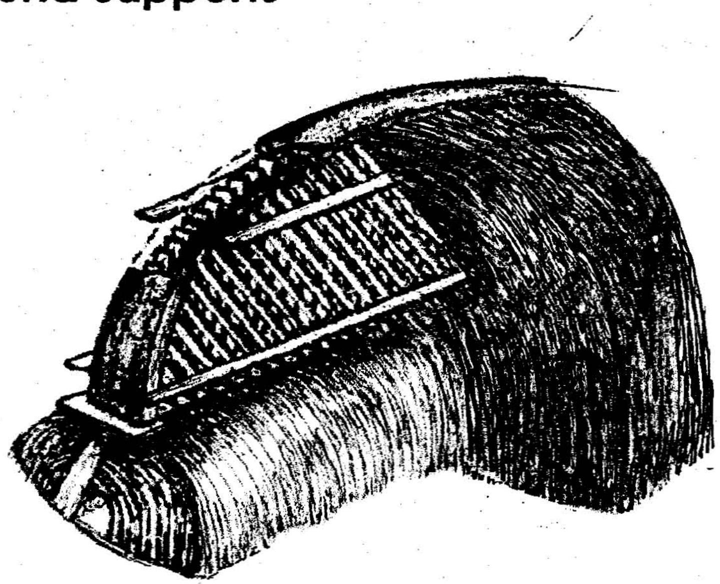
**Acknowledgements:**
Thanks to Wayne Joslin who helped me get these thoughts on paper.

[i] EPRI Steam Generator Reference Book
[ii] R. I .Hodge, J. E. LeSurf and J. W. Hilborn, "Steam Generator Reliability, The Canadian Approach. XIX Nuclear Conference of Rome (1974) (AECL-4771)
D. J. Stelliga, J. M. Dyke, "Nuclear Heated Steam Generators", Canadian Electrical Association, (1970)
[iii] B. B. Mikic, W. M. Rohsenow, "A New Correlation of Pool Boiling Data", American Society of Mechanical Engineers (1968)
A. P. L. Turner, J. P. N. Paine, "Tube Corrosion and Wear: U-Bend Supports (AVBs) and TSP Intersections", Electric Power Research Institute Steam Generator Reference Book. (1994)
[iv] W. Schneider, R. Klarner and J. Smith, "Replacement Steam Generators", Nuclear Engineering International, 1 Jan 2002.

# Pickering A Nuclear Steam Generator

## U-Bend Supports

Outer tubes had one central support of loose AVBs designed to allow tubes to vibrate freely.



Inner tubes had no supports