Two-Phase Flow Instability in Helical-Coiled Steam Generators of an Integral PWR: A Regulatory Gap Analysis for i-SMR Licensing

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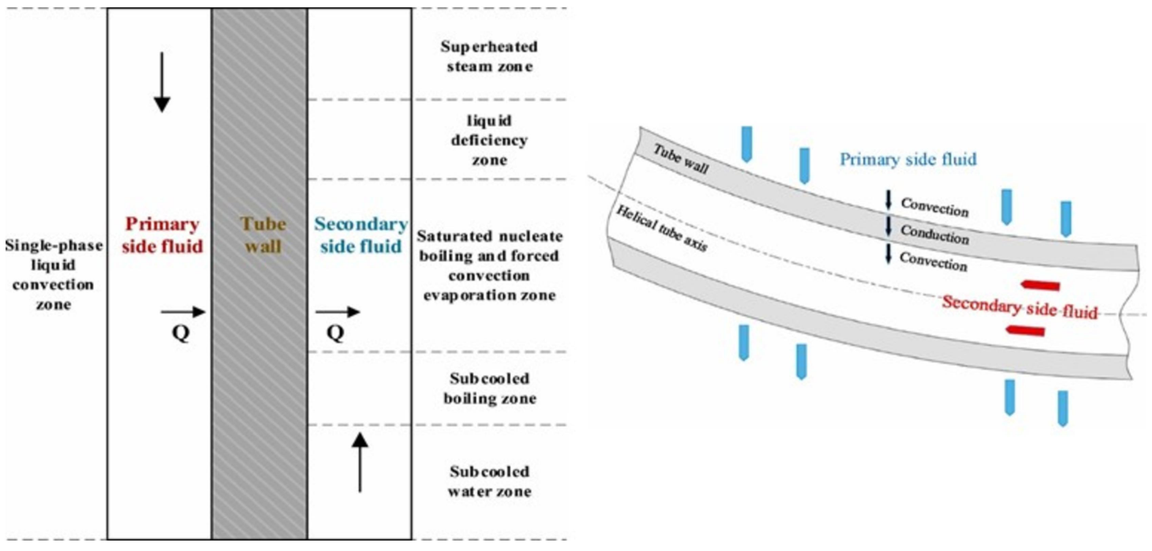
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I. Background

- ☑ The integrated Pressurized Water Reactor (iPWR) features a configuration in which the steam generator and pressurizer are located inside the reactor pressure vessel; it establishes design criteria that eliminate the risk of a loss-of-coolant accident (LOCA) caused by a large-scale rupture by eliminating large primary coolant piping.
- ☑ Korea's i-SMR is a reactor of this type: 170 MWe per module, sealless integrated coolant pumps for forced circulation, and a once-through helical-coil steam generator (HCSG).
- ☑ Secondary water enters at the coil bottom and leaves as superheated steam, so the entire liquid → two-phase → vapor transition occurs inside a small-bore, long, curved tube: conditions under which two-phase flow instability is likely.

Since the coils constitute part of the reactor coolant pressure boundary, the thermal and Hydrodynamic loads specified in GDC 4 and 31 are subjected to mandatory licensing.

II. Detailed HCSG Geometry



Outer Diameter	15.88 mm
Wall Thickness	1.27 mm
Inner Diameter	13.34 mm
Developed tube length	22.4-25.9 m

Boiling inside a Helical-Coiled tube & Main Parameter [1]

III. Two Screening Axes

☑ **Two separate screenings were carried out against different acceptance criteria → Must not be described as one:**

Axis A
Core & Protection
Can power oscillation violate fuel design limits?

Axis B
Coil structural integrity
Can the coils & welds withstand the loads?

☑ **Susceptibility ratio R (out-of-phase vs. in-phase Δp):**

$$R = \left(\Delta p_{inlet} + \Delta p_{1\varphi v}\right) / \left(\Delta p_{outlet} + \Delta p_{1\varphi l}\right)$$

The inlet flow restrictor (IFR) is the design countermeasure: it adds an in-phase single-phase loss, raising the denominator of R. Coil curvature adds a centrifugal field (high PIRT importance, only medium knowledge) that a 1-D system code cannot model explicitly. In TRACE it is represented by empirical Reynolds-dependent loss factors $k = a + b \cdot Re^c$ that fall to essentially zero at the low startup flow rates.

Exactly the range in which instability occurs!

IV. Instability Mode Screening

Mode	Disposition	Relevance to coil integrity
Ledinegg (Flow excursion)	Screened out (single valued Δp flow), but seen superimposed on DWO in SIET coil tests	High in DWO PIRT: CHF exceedance & wall damage
Static modes (boiling crisis, flashing, geysering..)	Excluded by CHF limit or need low-P / high-quality regimes the design lacks	Not applicable, or aggravating only
Natural-circulation (riser) instability	Governing mode for the natural circulation reference design	N/A to pump driven i-SMR its removal also drops the basis for reusing the secondary result
Secondary-side DWO	Self-cancelling on Axis A Governing mode on Axis B	Alternating thermal stress & fatigue at the tube-to-tubesheet weld
Parallel-channel (incoherent) coil oscillation	Out of phase coil flows keep total HCSG flow & Δp~constant	Detectability problem: no system indication → no measurable LCO
Condensation-Induced water hammer	Needs two-phase reverse flow at coil inlet NOT obtained in any case	Impulse 4 – 44.5 kN if credited

Disposition of candidate flow instability modes and their relevance to coil integrity[2]

V. Density Wave Oscillation (DWO)

1. Inlet-flow perturbation
↓
2. Density wave travels along the coil
↓
3. Delayed pressure-drop response
↓
4. Positive feedback sustains the oscillation

☑ **No L-shaped boundary: Curvature suppresses the low-subcooling instability predicted by Ishii's vertical channel theory, so the vertical stability map cannot be applied to coils.**

☑ **Better parameter: relative single-phase liquid length – most coils unstable below ≈ 0.125, stable above.**

☑ **IFR dominate: Reducing form-loss K by 22% drove a coil from ±3 % to ≈ -150 % flow deviation; raising K by 44% cut a -200 % excursion to -50 %.**

VI. Thermal Fatigue & Basis

40.9 K
Wall centerline Temperature swing

72.4 MPa
Alternating stress vs 93.8 MPa limit

23 %
Fatigue margin (Surrogate data)

☑ **Illustrative: Uses a published SS304 strain coefficient and Alloy 690 modulus; the actual coil's strain-gauge correlation is withheld as proprietary.**

☑ **Welding: Likely crack initiation is the tube-to-tubesheet weld. 316L butt-weld tests gave 148.7 MPa at 10^7 cycles.**

☑ **Cycle count unaccounted: No DWO transient in the design table. At 8~10 s periods, ≈ 2.5~3.2 x 10^5 cycles accrue over 60 years - controlling only if actual properties push stress above 93.8 MPa.**

VII. Regulatory gaps for i-SMR

☑ **Forced circulation removes riser instability but changes the shell-side boundary condition on which the secondary result depends (±20 % HTC reversed several coils' classification). The DWO boundary must be recalculated, not inherited.**

Gap	Recommended action	Review section
No domestic acceptance criterion for HCSG T-H stability	Add one covering both fuel limits & coil integrity	**DSRS 15.9.A**
Eval-model qualification range undefined (0–20 %)	State the power range the model must cover	**DSRS 15.9.A**
No DWO entry in the design-transient table	Require an explicit DWO transient + 60-yr cycle Budget	**SRP 3.9.1**
Uncertainty via one-at-a-time studies	Require statistical tolerance limits	**DSRS 15.9.A**
No component fatigue data for the weld	Require S–N data (actual material, environment, frequency)	**SRP 3.9.3 / DSRS 5.4.2**
No in-service inspection for IFR wear	Add IFR-wear inspection tied to stability sensitivity to K	**ASME XI / KEPIC MI**
Tube-plugging limit not tied to stability	Tie plugging limit to a stability criterion	**Tech Specs**
Proprietary design information withheld	Establish an access procedure before review	**Review procedure**

Regulatory gaps requiring new/revised review guidance for the i-SMR HCSG[2-4]

VIII. Domestic Basis Underway

☑ **The NSSC has issued a regulation on the acceptance of alternative technical standards and an i-SMR safety-review guideline. Its SMR regulatory roadmap calls for a detailed restructuring in 2027, sequential amendment of statutes and standards from 2028, and a complete licensing framework by 2030.**

The question is not whether a domestic framework exists, but whether it contains an acceptance criterion equivalent to DSRS 15.9.A — and whether that criterion covers the structural integrity of the secondary-side coils as well as the core thermal limits.

IX. References

[1] Palash K. Bhowmik, Dabasish Chowdhury, Hossam H. Abdellatif, Scott Wahlquist, Sunil Kumar, Subash Sharma, Amir Ali, Fulvio Mascari, Piyush Sabharwall (2025), Flow instabilities in helical-coil steam generators for small modular reactors: A review, *Nuclear Engineering and Design*, 433, 113846.

[2] P. Yarsky, J. Thompson, M. Bernard, J. Valverde (2025), Methodology and confirmatory analysis for density wave oscillation in NuScale US460 helical coil steam generators, *Nuclear Engineering and Design*, 445, 114442.

[3] NuScale Power, LLC. (2023). Methodology for the Determination of the Onset of Density Wave Oscillations (DWO). Licensing Topical Report, TR-131981-NP, Revision 1, Docket No. 52-050.

[4] NuScale Power, LLC. (2020). Evaluation Methodology for the Stability of the NuScale Power Module. Licensing Topical Report, TR-0516-49417-NP-A, Revision 1, ADAMS ML20086Q664.

Conclusions

- **Two axes: On the core axis the governing mode was riser instability and secondary DWO was self-cancelling. On the integrity axis, that same cancellation makes incoherent DWO undetectable — the mode that must be evaluated under GDC 4 & 31.**
- **Recalculate for i-SMR: Forced circulation removes riser instability but shortens the boiling boundary and destabilises the coil. Coils were unstable at 5–15 % power and marginal at 20 %; the 72.4 vs 93.8 MPa margin rests on surrogate properties.**
- **Domestic technical gaps: A stability acceptance criterion over 0–20 % on both axes, statistical uncertainty, weld S–N data, an explicit DWO transient with a cycle budget, IFR-wear inspection, and a proprietary-access procedure.**