

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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1. Introduction

An integral pressurized water reactor (iPWR) places the steam generator and the pressurizer inside the reactor pressure vessel. Since the large-diameter primary coolant piping is removed, the large-break loss-of-coolant accident (LOCA) no longer has to be considered in the design basis [1]. Korea's i-SMR is a reactor of this type. It produces 170 MWe per module, uses sealless integrated reactor coolant pumps for forced circulation during normal operation, and adopts a once-through helical-coil steam generator (HCSG) [2, 3].

The narrow downcomer annulus of an iPWR determines the geometry of the HCSG. The NuScale US460 design is at present the only iPWR HCSG for which a regulator has published a confirmatory instability analysis. In that design the tube outer diameter is 15.88 mm, the wall thickness is 1.27 mm, the inner diameter is 13.34 mm, and the developed tube length is 22.4 to 25.9 m. Secondary water enters at the bottom of the coil and leaves as superheated steam, so the transition from liquid to two-phase flow and then to vapor takes place entirely inside a small-bore, long and curved tube. These are conditions under which two-phase flow instability is likely to occur. Because the coils form part of the reactor coolant pressure boundary (RCPB), General Design Criteria (GDC) 4 and 31 require the resulting thermal and hydrodynamic loads to be treated as a licensing matter rather than as a design option [4].

This paper reviews how the instability modes of an iPWR HCSG have been screened, examines which parts of that screening cannot be applied directly to i-SMR, and suggests the regulatory actions that a domestic review would need to take.

2. Instability Modes and the Two Screening Axes

In a once-through steam generator the entire phase change occurs inside the tube. The delayed, out-of-phase pressure drop, which is made up of the two-phase region, the single-phase vapor region and the outlet, therefore becomes large compared with the immediate, in-phase pressure drop across the inlet flow restrictor and the single-phase liquid region. The ratio of the two,

$$R = (\Delta p_{\text{outlet}} + \Delta p_{2p} + \Delta p_{1\phi v}) / (\Delta p_{\text{inlet}} + \Delta p_{1\phi l})$$

is used as a measure of susceptibility to instability [4].

The curvature of the coil also produces a centrifugal force field, which changes the flow regime, the void distribution, the dryout location and the interfacial shear. The phenomena identification and ranking table (PIRT) prepared by the regulator ranks this effect as highly important but assigns it only a medium knowledge level, since a one-dimensional system code cannot model it explicitly. In TRACE the effect is instead represented by empirically fitted, Reynolds-dependent distributed loss factors of the form $k = a + bRe^c$. These correction terms become essentially zero at the low flow rates encountered during startup, which is the range in which instability occurs [4]. The inlet flow restrictor (IFR) is the design countermeasure. It adds an in-phase, single-phase pressure loss and thereby increases the denominator of R .

Two separate screenings have been carried out for this design. Because they were performed against different acceptance criteria, they reached different conclusions about the same mode. The results are summarized in Table I [4, 5, 6].

(a) *Core and protection system.* The stability methodology submitted by the applicant listed five static modes, namely Ledinegg flow excursion, boiling crisis, flow-pattern transition, flashing and geysering, together with eight dynamic or compound modes that include pressure-drop oscillation, acoustic oscillation, density wave, natural-circulation instability, parallel-channel coupling and primary-to-secondary or neutronic coupling [5]. In the safety evaluation the governing mode for the reference power module was the compound natural-circulation mode, which is also called the riser instability. Secondary-side density wave oscillation (DWO) was judged not to require a separate stability analysis, on the grounds that out-of-phase oscillations among the coils cancel one another and do not propagate to the primary side [6].

(b) *Coil structural integrity.* The same cancellation behavior was the reason for the confirmatory analysis carried out later by the regulator [4]. When the coil oscillations are incoherent, the total HCSG flow rate and differential pressure remain almost constant, so the oscillations do not appear in system-level or component-level instrumentation and may continue at their limit cycle without being noticed. Each individual coil, however, still experiences the full thermal and

hydrodynamic load. Incoherent DWO is therefore not screened out under GDC 4 and 31, and it is precisely the mode that the NRC confirmatory analysis set out to evaluate [4].

If these two screenings are described as one in which only DWO survived, the distinction between them is lost, and so is the argument that gives a domestic review of its structure. Ledinegg instability shows the same difficulty from the opposite direction. It is screened out of the static list because the pressure-drop versus flow characteristic of the coil is single-valued, but helical-coil tests at SIET observed it superimposed on DWO, and the DWO PIRT accordingly keeps it at high importance [4].

Table I. Instability mode screening for an iPWR HCSG and the axis on which each mode was dispositioned [4, 5, 6]

Mode	Mechanism and disposition	Relevance to coil integrity
Ledinegg (flow excursion)	Screened out because the coil Δp -flow characteristic is single-valued, but observed superimposed on DWO in coil tests	Kept at high importance in the DWO PIRT; CHF exceedance and wall damage
Boiling crisis, flow-pattern transition, flashing, geysering and other static modes	Excluded by the CHF limit, or require low pressure, high quality, or a time scale or geometry that the design does not have	Not applicable, or aggravating only
Natural-circulation (riser) instability	Governing mode for the natural-circulation reference design; coupled with neutronic and secondary-side feedback	Not applicable to a pump-driven i-SMR loop. Its exclusion also removes the basis for taking over the reference secondary-side result
Secondary-side density wave oscillation	Delayed density and Δp feedback along the coil. Judged self-cancelling on the core axis; governing secondary-side mode on the integrity axis	Alternating thermal stress and fatigue, most likely at the tube-to-tubesheet weld
Parallel-channel (incoherent) coil oscillation	Out-of-phase coil flows leave the total HCSG flow and Δp almost constant	A detectability problem rather than a screening basis. No system-level indication, and therefore no measurable LCO
Condensation-induced water hammer	Requires two-phase reverse flow at the coil inlet; not obtained in any case or sensitivity	Impulse of 4 to 44.5 kN if credited, against 4 to 445 N for ordinary hydrodynamic forces

3. Density wave oscillation

A perturbation in the inlet flow is converted into a density perturbation that travels along the coil. The pressure-drop response is delayed and feeds back on the inlet flow, and the oscillation is sustained once this feedback becomes positive. In the HCSG the feedback acts mainly through the interaction between the inlet flow, and the coil pressure drop rather than through the gravitational head. The DWO PIRT ranks the gravity head as only medium importance, since the coils are under forced convection from the feedwater pumps. The

startup conditions covered by the 19-case matrix of the NRC confirmatory analysis correspond to subcooling numbers greater than 10 [4].

Helical coils do not show the L-shaped stability boundary at low subcooling that Ishii's vertical-channel theory predicts. Papini attributed this to the centrifugal field, and the practical consequence is that a vertical-channel stability map cannot be applied to a coil [3]. The relative single-phase liquid length was found to be a more reliable parameter. Most coils were unstable below a value of about 0.125, while stable points became common above it [4].

Sensitivity studies show that the IFR dominates stability behavior. When its form-loss coefficient K was reduced by 22 %, a coil in column 7 of Case 5, which had oscillated within ± 3 % of nominal flow at the reference value of K , showed inlet-flow deviations approaching -150 %. When K was increased by 44 %, the limiting deviation in a column-1 coil of Case 4 was reduced from about -200 % to -50 %, and many of the coils that had shown reverse flow became stable [4].

The confirmatory TRACE analysis covered a matrix of 19 startup cases, and the results show that instability is not a monotonic function of power [4]. At 5 % power the case with nominal feedwater temperature was unstable, while the high-temperature and low-temperature feedwater cases were both stable. At 15 % power all three cases with one HCSG in operation were unstable, whereas all three cases with two HCSGs were stable. The 20 % cases were stable or marginally stable, the marginal ones being the case with very high feedwater temperature and the case with 20 % coil plugging. Full power was not included in the matrix. It was expected to be stable based on non-dimensional scoping analysis, but it was not calculated [4]. This behavior is significant for a licensing review, because an argument that binds the problem by power level alone cannot be accepted. Coverage must be demonstrated over the actual startup trajectory, including feedwater temperature, the number of steam generators in operation and the allowable tube plugging.

None of the cases produced two-phase reverse flow at the coil inlet, so condensation-induced water hammer (CIWH) did not occur. This is an important result, since the CIWH loads were conservatively estimated at 4 to 44.5 kN, whereas the ordinary fluid and fluctuating forces are of the order of 4 to 445 N [3]. The exclusion of CIWH therefore depends entirely on the absence of voiding at the coil inlet, which in turn depends on the IFR characteristic. In cases of sensitivity with reduced outlet pressure, some coils did develop intermittent voids at the inlet, although no void collapse was detected [4].

4. Thermal Fatigue and the Fatigue Basis

The limiting thermal result was a wall centerline temperature swing of 40.9 K near the coil inlet, which corresponds to an alternating stress of 72.4 MPa against

an ASME endurance limit of 93.8 MPa (13.6 ksi) [4]. Three points should be noted about this 23 % margin.

First, the calculation is illustrative rather than a demonstration of compliance. The strain coefficient of $17.65 \mu\epsilon/^\circ\text{C}$ is a published value for SS304, and the Young's modulus was taken from measurements on thermally treated Alloy 690. The strain-gauge correlation for the actual coil material was submitted by the applicant as proprietary information and is not available in the open literature [4].

Second, the likely crack initiation site is the tube-to-tubesheet weld rather than the parent tube. Component-level resonance bending tests on $\Phi 16 \times 3$ mm 316L butt-welded pipe gave a 95 %/95 % design fatigue strength of 148.7 MPa at 10^7 cycles, which is 1.59 times the corresponding code reference value, and all failures initiated at the weld toe, where the measured stress concentration factor was 1.26 to 1.47 [7]. These results indicate that an assessment based on base-metal curves together with a generic fatigue strength reduction factor can be considerably conservative for a sound weld. They cannot be applied to the HCSG directly, however, since the material, the environment (room-temperature air as against secondary-side water at operating temperature), the loading frequency (58 Hz mechanical resonance as against DWO periods of about 8 to 10 s) and the joint geometry are all different. These component-level tests show the value of testing the joint itself rather than the base metal, but the equivalent data for the tube-to-tubesheet weld are not available in the open literature [7].

Third, the accumulated number of cycles is not explicitly accounted for. Table 3.9-1 of the safety analysis report for the reference design contains no design transient corresponding to DWO. The Level A entries closest in character are power ascent from hot shutdown, with 700 cycles over a 60-year design life, and steady-state fluctuations, with 5×10^6 cycles [8]. If the oscillation period is 8 to 10 s and one hour is spent in the unstable band during each ascent, the number of cycles is roughly 360 to 450 per ascent, or 2.5 to 3.2×10^5 over the plant life, and about 40 hours per ascent would be needed to reach 10^7 cycles. Management by residence time is therefore workable, provided that the residence-time limit and the startup trajectory are themselves treated as licensing commitments. If the alternating stress remains below the endurance limit, the number of cycles is not controlling quantity. If the use of actual material properties raises stress above 93.8 MPa, however, the cycle count becomes controlling, and a margin of 23 % is not large enough to rule this out.

5. Regulatory Implications for i-SMR

The review should follow the two axes described in Section 2, which are often treated as one. The first axis concerns whether power oscillation can violate the specified acceptable fuel design limits and whether it is detected and suppressed by the module protection

system. In the U.S. framework this became DSRS Section 15.9.A, "Thermal Hydraulic Stability", which was newly developed for an iPWR after SRP 15.9, "Boiling Water Reactor Stability", had been deleted as not applicable [9]. The second axis concerns whether the coils and their welds can withstand the loads under ASME Section III. This is covered by SRP 3.9.1 for design transients and fatigue cycle counts, SRP 3.9.2 for flow-induced vibration and the comprehensive vibration assessment program, and SRP 3.9.3 for Code Class 1 stress limits, together with DSRS 5.4.2, "Steam Generator Materials", and DSRS 10.4.7, "Condensate and Feedwater System" [8, 9].

Work on the corresponding domestic basis has already begun. The Nuclear Safety and Security Commission has issued a regulation on the acceptance of alternative technical standards for reactor facilities, together with an i-SMR safety review guideline, and its SMR regulatory roadmap calls for a detailed restructuring in 2027, sequential amendment of the relevant statutes and standards from 2028, and a complete licensing framework by 2030 [10]. The question is therefore 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.

Five items prevent the U.S. conclusion from being applied directly to i-SMR. The corresponding actions are summarized in Table II [4].

(1) *Primary-side boundary conditions.* The reference design circulates the primary coolant by natural circulation, whereas i-SMR uses pump-driven forced circulation. Riser instability, which arises only in a natural-circulation loop, therefore, does not occur. This does not mean that primary-side damping is lost, since the NRC confirmatory analysis decoupled the primary and secondary sides on the grounds that the loop gain is small and that a critical core tends to stabilize the feedback [4]. What changes is the shell-side boundary condition. With pumped primary flow, the shell-side heat transfer coefficient at 5 to 20 % power is not reduced in proportion to power as it is under natural circulation, so the boiling boundary becomes shorter and the coil less stable. In its shell-side heat transfer sensitivity study, a change of $\pm 20\%$ in the heat transfer coefficient reversed the stability classification of several coils, which suggests that this effect is not of second order [4]. The stability boundary should therefore be recalculated for i-SMR conditions.

(2) *Detectability and operability.* Incoherent DWO produces no signature in system-level instrumentation [4]. A limiting condition for operation cannot be written for a quantity that cannot be measured, so the control must be administrative. The startup trajectory, an upper limit on the residence time within the unstable band, and the associated recording and surveillance requirements should be established as licensing commitments rather than left to operating procedures.

(3) *Aging of the inlet flow restrictor.* K is the dominant stability parameter, and wear or erosion of the restrictor reduces it. This creates positive feedback in which degradation increases the oscillation amplitude, and the larger amplitude in turn accelerates the degradation. The NRC confirmatory analysis identifies this wear-driven runaway mechanism but places it outside its scope [4]. Domestic in-service inspection requirements contain no specific provision for IFR wear. Such a provision should be added, with the inspection interval justified against the calculated sensitivity of stability to K rather than against a generic wear allowance.

(4) *Treatment of uncertainty and the plugging allowance.* The NRC confirmatory analysis treated uncertainty by one at a time sensitivity studies rather than by statistical tolerance limits and identifies systematic uncertainty quantification as future work. Case 19, in which 20 % coil plugging produced marginal stability, indicates that the tube plugging limit should be justified against stability as well as against heat-transfer capacity.

(5) *Access to proprietary information.* The IFR loss coefficient, the coil geometry ratios and the applicant's strain-gauge correlation are all withheld [4]. A procedure for regulatory access to proprietary information is a prerequisite for any independent confirmatory analysis and should be arranged before the review begins.

Table II. Identified gaps and recommended regulatory actions [4]

Gap	Recommended action	Review section
No domestic acceptance criterion confirmed for HCSG thermal-hydraulic stability	Confirm whether a stability section exists and add one if it does not, with criteria covering both the fuel design limits and coil integrity	DSRS 15.9.A equivalent
Qualification range of the evaluation model undefined for 0 to 20 % power	State explicitly which power range the evaluation model has to be qualified over	DSRS 15.9.A equivalent
No DWO entry in the design transient table	Require an explicit DWO transient with the number of cycles per power ascent and a 60-year budget	SRP 3.9.1
Uncertainty treated by one-at-a-time sensitivity studies	Require statistical tolerance limits obtained from a systematic uncertainty quantification	DSRS 15.9.A equivalent
No component-level fatigue data for the tube-to-tubesheet weld	Require S–N data for the actual material, environment and frequency range	SRP 3.9.3; DSRS 5.4.2
No in-service inspection requirement for IFR wear	Add an IFR wear inspection with the interval justified against the sensitivity of stability to K	ASME Sec. XI / KEPIC MI
Tube plugging limit not justified against stability	Tie the plugging limit to a stability criterion as well as to heat-transfer capacity	Technical Specifications
Proprietary design information withheld	Establish an access procedure before the confirmatory analysis begins	Review procedure

6. Conclusion

Two separate screenings have been applied to instability in an iPWR HCSG, and they should not be described as one. On the core and protection axis the governing mode for the natural-circulation reference design was the riser instability, and secondary-side DWO was judged to be self-cancelling. On the coil integrity axis, the same cancellation is what makes incoherent DWO undetectable, and this is the mode that has to be evaluated under GDC 4 and 31. In i-SMR, forced circulation removes the riser instability, but it also changes the shell-side boundary condition on which the secondary-side result depends. The DWO stability boundary should therefore be recalculated rather than taken over from the reference design.

The confirmatory analysis found the coils to be unstable at 5 to 15 % power for combinations of feedwater temperature and steam generator availability, and marginally stable at 20 %. Instability was not monotonic in power, and the limiting alternating stress of 72.4 MPa against an endurance limit of 93.8 MPa was obtained using surrogate material properties. The domestic gaps identified in this study are an acceptance criterion for thermal-hydraulic stability covering the 0 to 20 % power range on both axes, statistically quantified uncertainty in place of one-at-a-time sensitivity studies, component-level fatigue data for the tube-to-tubesheet weld in the actual material, environment and frequency range, an explicit DWO design transient with an associated cycle budget, an in-service inspection requirement for inlet flow restrictor wear, and a procedure for regulatory access to proprietary design information.

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