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Thermal-Hydraulic Closure and Maintainability of a Natural-Circulation OTSG with an Integral Pressurizer and Removable ECT Cartridge for a 140 MWe SMR

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Abstract – A vertically elevated once-through steam generator (OTSG) with an integral pressurizer and removable maintenance module is assessed for a 450 MWth / 140 MWe natural-circulation SMR. A three-zone heat balance makes the thermal-area screen reproducible. With an explicitly assumed outside-area clean coefficient of 0.90 kW m^{-2} K^{-1} in each zone, the economizer, evaporator and superheater logarithmic mean temperature differences are 54.61, 45.65 and 53.63 K. The resulting required area is 10,565.7 m^2, compared with 12,065.2 m^2 selected, giving an area ratio of 1.1419. A separately identified fouling sensitivity of 1.0×10^{-4} m^2 K W^{-1} reduces this ratio to 1.0476, or 0.9429 when combined with 10% tube plugging. Hydraulic head-to-loss ratios of 1.665 and 1.592 are prescribed-flow screens, not solved operating points or stability evidence. The removable upper module targets access to pressurizer internals and the upper tubesheet for eddy-current testing (ECT); lower-end tube isolation remains a separate requirement. The contribution is a traceable conceptual assessment and a testable maintenance architecture, not qualified thermal performance, code compliance, or demonstrated outage savings.

Keywords – natural circulation; OTSG; integral pressurizer; thermal-area screening; fouling; ECT

1. Introduction

The 450 MWth / 140 MWe system concept [1] removes reactor-coolant pumps and uses an elevated OTSG. Its feasibility depends on low hydraulic resistance, sufficient heat-transfer area and maintainable pressure-boundary interfaces. This paper links those requirements without treating a favorable screening ratio as qualification.

Figure 1 shows the primary flow path. The thermal-area denominator is made explicit through zone balances. Geometric surplus is distinguished from fouling and tube-plugging effects. The inspection concept is evaluated as an access objective rather than as demonstrated inspection reliability.

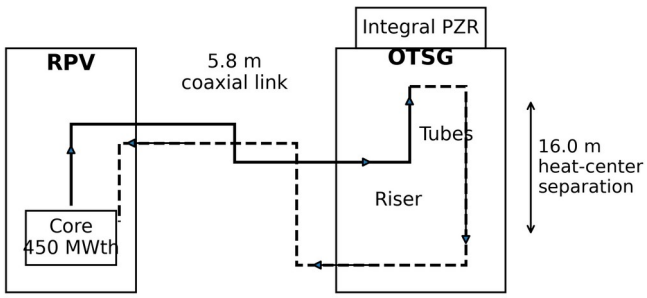


Fig. 1. Primary flow path and heat-center separation (schematic, not to scale). Solid and dashed paths indicate hot delivery and cold return, respectively.

2. Natural-Circulation and Coaxial Connection

Hot primary water travels through the inner coaxial duct and central OTSG riser, turns in the upper plenum, descends inside the straight tubes and returns through the coaxial annulus. The outer sleeve is a reactor-coolant pressure boundary. The inner duct is an internal flow separator, not an inventory-retaining boundary; its failure requires mixing, load and core-cooling analysis rather than an assumed benign trip.

Table 1 gives the principal inputs. IAPWS-IF97 [2] yields primary inlet/outlet enthalpies of 1,207.433/1,517.147 kJ kg^{-1} at 15.5 MPa and 275/330°C. Using these hot/cold enthalpies, the prescribed rated flow of 1,452.954 kg s^{-1} follows from:

$$\dot{m} = \frac{Q_{\mathrm{core}}}{h_{\mathrm{hot}} - h_{\mathrm{cold}}} \tag{1}$$

Table 1. Conceptual system and component inputs.

Parameter	Value
Core / electrical concept	450 MWth / 140 MWe
Primary pressure / temperatures	15.5 MPa / 275–330°C
Secondary pressure / temperatures	4.5 MPa / 180–290°C
Primary / secondary mass flow	1,452.954 / 209.440 kg s^{-1}
Heat-center separation	16.0 m
Coaxial length / support stations	5.8 m / 5
Outer sleeve ID / nominal wall	1.75 m / 150 mm + cladding
Inner duct ID / OD	1.10 / 1.18 m
OTSG shell ID / triangular pitch	3.70 m / 24.5 mm
Tube number / OD / wall / length	14,400 / 19.05 mm / 1.09 mm / 14.0 m

Cold/hot densities are 772.823/651.527 kg m^{-3}. The legacy head screen [3] uses $gH(\rho_c - \rho_h)$ = 19.032 kPa and an explicit 10% derating to 17.129 kPa. The inherited rated-flow loss estimates are 10.290 kPa without plugging and 10.761 kPa with 10% plugging (Fig. 2). The derating is an assumption, not a substitute for integrating the actual density profile.

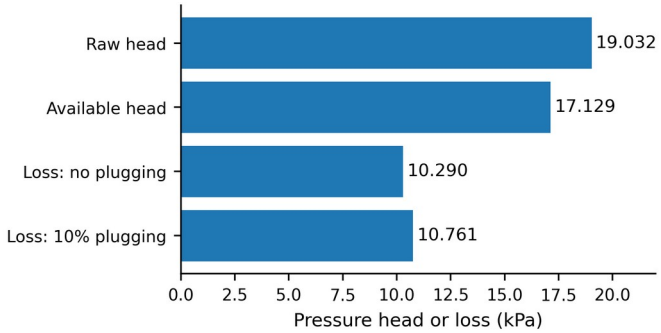


Fig. 2. Independent prescribed-flow head and loss estimates. The 10% head derating is distinct from the 10% tube-plugging case.

At a natural-circulation operating point, driving head and total loss must balance. Their ratio at a prescribed flow only indicates a preliminary pressure budget. The coupled flow/temperature solution, local-loss validation and transient stability are not established here.

3. OTSG Thermal Sizing

3.1 Geometry and Reproducible Zone Balance

The selected Alloy 690TT tube geometry gives an external area $A_{selected} = N\pi D_o L$ = 12,065.2 m^2. All heat-transfer coefficients and fouling resistances below use this same outside-area basis. The thermal model assumes steady counterflow, negligible environmental heat loss and constant pressure within each side. No flow-arrangement correction is applied (F_i = 1).

At 4.5 MPa, the saturation temperature is 257.439°C. IF97 secondary enthalpies for feedwater, saturated liquid, saturated vapor and outlet steam are 764.963, 1,122.143, 2,797.997 and 2,913.549 kJ kg^{-1} [2]. These give 209.440 kg s^{-1} and duties of 74.8078, 350.9910 and 24.2012 MW for the economizer, evaporator and superheater, respectively.

Primary interface temperatures are obtained by allocating those duties to the primary enthalpy rise, starting from the 275°C cold end: $h_{p,j} = h_{p,cold} + \Sigma Q_i/\dot{m}_p$. Inversion at 15.5 MPa gives 285.144°C and 327.501°C. Table 2 reports actual inlet-to-outlet temperatures for each stream; thus primary and secondary directions are opposite.

For each zone, terminal differences are paired at the same axial locations: $\Delta T_{1,i} = T_{p,in,i} - T_{s,out,i}$ and $\Delta T_{2,i} = T_{p,out,i} - T_{s,in,i}$. The logarithmic mean is $(\Delta T_{1,i} - \Delta T_{2,i})/\ln(\Delta T_{1,i}/\Delta T_{2,i})$. The three-zone screening requirement is

$$A_{required} = \sum_i \frac{Q_i}{U_{o,i} F_i \Delta T_{lm,i}} \quad (2)$$

Here i denotes the three zones; $U_{o,i}$ = 0.90 kW m^{-2} K^{-1} is an assumed clean reference value in every zone, $\Delta T_{lm,i}$ = 54.6102/45.6540/53.6340 K, and the reference fouling resistance is zero. The coefficient is retained from the earlier screening record [3], not fitted to recover 10,142 m^2 and not derived from a validated boiling correlation. A common value is used because independent zone coefficients have not been substantiated.

Table 2. Three-zone thermal screen; temperatures are in °C.

Quantity	Economizer	Evaporator	Superheater
Duty (MW)	74.8078	350.9910	24.2012
Primary inlet → outlet	285.144 → 275.000	327.501 → 285.144	330.000 → 327.501
Secondary inlet → outlet	180.000 → 257.439	257.439 → 257.439	257.439 → 290.000
ΔT_1 / ΔT_2 (K)	27.704 / 95.000	70.062 / 27.704	40.000 / 70.062
ΔT_{lm} (K)	54.6102	45.6540	53.6340
$U_{o,c}$ (kW m^{-2} K^{-1})	0.9000	0.9000	0.9000
$A_{req,c}$ (m^2)	1,522.1	8,542.3	501.4
$U_{o,f}$ (kW m^{-2} K^{-1})*	0.825688	0.825688	0.825688
$A_{req,f}$ (m^2)*	1,659.0	9,311.1	546.5

* Illustrative added fouling resistance $R_{f,o}$ = 1.0 × 10^{-4} m^2 K W^{-1}; not a qualified service allowance. Totals use unrounded values: 10,565.7 m^2 (reference), 11,516.6 m^2 (fouling sensitivity).

The earlier 10,142 m^2 follows arithmetically from 450,000/(0.90 × 49.3) [3], but the 49.3 K aggregate temperature difference was not independently established. It is therefore superseded by the three-zone result. The single whole-exchanger terminal LMTD is also not used to represent the phase-changing temperature profile.

This is a piecewise-LMTD approximation. A diagnostic integration of $dQ/(U_{o,c}\Delta T)$ along the IF97 enthalpy profiles gives 10,431.7 m^2, 1.27% below the three-zone estimate, for the same constant coefficient. This checks temperature-profile discretization only; it does not validate the coefficient, boiling, dryout or flow distribution.

3.2 Fouling and Tube-Plugging Sensitivity

No quantified service fouling allowance is credited in the reference case. To expose its effect, an illustrative added resistance $R_{f,o}$ = 1.0 × 10^{-4} m^2 K W^{-1} is applied uniformly on the outside-area basis. Using $U_{o,f} = (1/U_{o,c} + R_{f,o})^{-1}$, with $U_{o,c}$ = 900 W m^{-2} K^{-1}, gives 825.688 W m^{-2} K^{-1}. This assumed resistance is not a measured deposit value, a vendor recommendation or a prescribed code allowance.

For a plugging fraction p, the available geometric area is $(1 - p)A_{selected}$. At p = 0.10, 1,440 tubes are unavailable and 10,858.7 m^2 remains. Figure 3 and Table 3 separate the effects. In this sensitivity only, duty, terminal temperatures and the assumed coefficient in the remaining tubes are held fixed; coupled redistribution is not resolved.

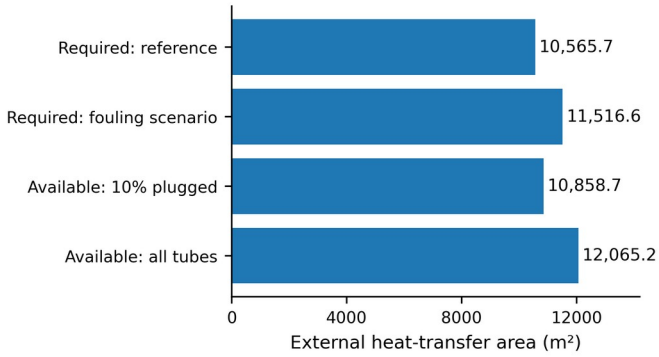


Fig. 3. Selected/available areas versus the three-zone reference and illustrative fouling requirements. Bars are independent comparisons, not additive quantities.

Table 3. Thermal-area ratios for declared assumptions.

Case	Required area (m^2)	Available area (m^2)	Area ratio
Reference; no plugging	10,565.7	12,065.2	1.1419
Reference; 10% plugging	10,565.7	10,858.7	1.0277
Fouling scenario; no plugging	11,516.6	12,065.2	1.0476
Fouling scenario; 10% plugging	11,516.6	10,858.7	0.9429

The combined fouling/plugging scenario does not meet the area screen at the specified duty. Under these frozen-profile assumptions, the maximum added resistance compatible with 10% plugging is only 3.08 × 10^{-5} m^2 K W^{-1}. This is a model threshold, not an allowable operating limit. A 10% plugging authorization cannot be inferred from the hydraulic ratio alone.

4. Integral PZR, Closure, and ECT Cartridge

Figure 4 clarifies the operating pressure boundary and the maintenance state. The retained SG shell and flange, removable pressure-retaining PZR upper module, seals and studs together form the intended Class 1 boundary during operation. “Cartridge” here denotes that removable upper maintenance package; it must not be interpreted as a non-pressure assembly removable while the reactor-coolant boundary remains pressurized.

The KONEC draft specification [4] places the operating flange above a convex divider supported from the removable vessel by hollow vertical conduits. A peripheral gap provides primary-water communication. The divider is a flow/thermal internal, with an approximately 0.5 MPa differential-pressure screening target; it is not the full-system-pressure boundary. Its bypass, transient loads, vibration and supports require dedicated analysis.

The PZR concept retains 50 m^3 volume and four 1 MW heater banks. The preliminary removable mass is approximately 170 t and the handling concept assumes a 250 t nominal crane; rigging mass, center of gravity, dynamic loads and dropped-load protection remain to be qualified. Crane rating is not a demonstrated proof load. The candidate closure has 96 M120×6 studs at 2.8 MN each, giving 268.8 MN preload versus a 160.8 MN pressure-separation screen.

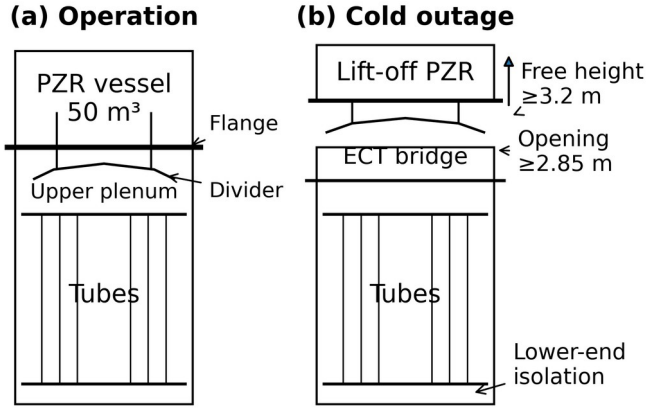


Fig. 4. Operating pressure-retaining PZR module and cold-outage upper-tubesheet access. The layout develops the removable-vessel concept in [4]; dimensions are access targets, not demonstrated clearances.

The 160.8 MN separation load is an inherited mechanical input [3], not a code acceptance load combination. Design-pressure/effective-seal-area consistency, flange rotation, seal seating, preload scatter, thermal relaxation, fatigue and seismic loads must be resolved within the project-selected code basis. NRC SRP 5.4.2.1 and the 2025 ASME III-NB/XI framework are cited for scope, not as evidence of completed compliance [5,6].

After cooldown, depressurization, drainage to the approved level, verified isolation and service disconnection, the module would be lifted to a protected stand. A temporary central-riser blind and foreign-material-exclusion (FME) controls precede installation of the ECT bridge. The targets are an opening of at least 2.85 m and free height of at least 3.2 m, without worker entry into the PZR vessel.

Physical access alone does not establish ECT reliability: noise, flaw detection and sizing require representative qualification [7,8]. Upper access supports ECT and tube-end tooling, but complete retirement of a straight tube requires qualified isolation of both primary ends or an approved repair method. Lower-plenum access is a separate unresolved interface. No complete plugging capability is claimed from upper access alone.

5. Safety and Qualification Gates

The single OTSG creates common-cause concerns involving tube rupture, loss of feedwater, steam isolation and maintenance unavailability. Table 4 identifies the corresponding evidence requirements. Independent decay-heat-removal capability, qualified relief and isolation functions, and protection against maintenance-induced damage are plant-level requirements, not demonstrated outcomes of the present area calculation.

Table 4. Required evidence before performance or safety credit.

Issue	Required evidence	Acceptance focus
Thermal sizing / deposits	Validated local coefficients; pressure-drop/dryout model; chemistry and deposits	Duty with declared fouling, plugging and uncertainty
Natural circulation	System-code validation; integral-loop startup and transient tests	Balanced stable operating point; no unacceptable reversal
ECT / tube repair	Detection/sizing trials; two-end isolation; repair tests; vibration/fretting tests	Coverage, detection reliability and tube/repair integrity
Module lift	1:1 mock-up; qualified rigging, supports and dropped-load assessment	No common-cause damage; recoverable load path
Pressure boundary	Project code analysis; closure cycling; leak tests	Repeatable leak-tight restoration
Plant transients	Tube rupture; feedwater/steam isolation; decay-heat-removal single-failure analysis	Core cooling and pressure control

6. Integrated Verification Programme

Verification proceeds from component flow and heat-transfer data to an integral natural-circulation loop, a validated plant transient model, pressure-boundary analysis and a full-scale outage mock-up. Figure 5 defines the maintenance work package. Measured outputs include tool reach, ECT coverage/detection performance, repair quality, seal/stud repeatability, critical-path time and collective dose. No time or dose reduction is credited before representative comparison testing.

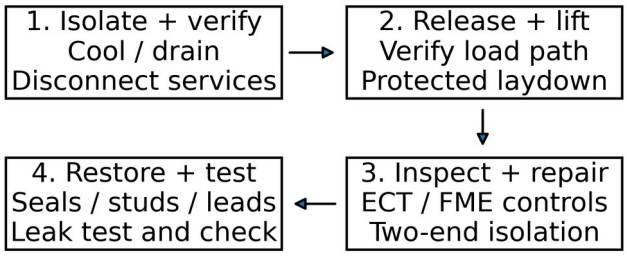


Fig. 5. Proposed outage work package. Each step requires verified prerequisites; lower-end isolation is not replaced by the upper access route.

6.1 Dimensionless Closure and Evidence Maturity

Two dimensionless screening indicators distinguish the hydraulic pressure budget from the thermal-area comparison:

$$\Pi_{\mathrm{NC}} = \frac{\Delta P_{\mathrm{avail}}}{\Delta P_{\mathrm{loss}}} \tag{3}$$

$$M_{\mathrm{A}} = \frac{A_{\mathrm{selected}}}{A_{\mathrm{required}}} \tag{4}$$

At the prescribed rated flow, Π_{NC} is 1.665 without plugging and 1.592 at 10% plugging. For the declared three-zone clean-reference assumptions, M_A is 1.1419. For a plugged configuration, the numerator in Eq. (4) is replaced by the remaining available area. Table 3 gives the resulting ratios. Hydraulic surplus cannot compensate for thermal-area shortfall, and neither ratio establishes dynamic stability.

The closure-force indicator is defined separately:

$$M_{\mathrm{F}} = \frac{F_{\mathrm{preload}}}{F_{\mathrm{pressure}}} \tag{5}$$

It gives 268.8/160.8 = 1.6716 before code load combinations and seal/flange qualification. It is not an allowable-stress, fatigue or leakage acceptance margin. Likewise, approximately quadratic distributed pressure loss under fixed properties implies about 10.25% higher loss for 5% higher flow, but the coupled natural-circulation head and temperatures would also change.

The evidence boundary is explicit: geometry and IF97 enthalpy balances are reproducible calculations; U, fouling sensitivity, local losses, lift mass and access dimensions are screening inputs or targets. Local boiling, asymmetric plugging, non-condensable gases, flow-induced vibration, pressure-boundary integrity and maintenance execution remain qualification tasks. Failure of any gate returns the affected design to analysis; it cannot be covered by another favorable ratio.

7. Conclusions

The 14,400-tube geometry provides 12,065.2 m^2 of external area. A traceable three-zone screen with common assumed clean U_o = 0.90 kW m^{-2} K^{-1} requires 10,565.7 m^2, giving M_A = 1.1419. The illustrative fouling case raises the requirement to 11,516.6 m^2; combined with 10% plugging, the ratio is 0.9429. Therefore the present calculation does not support an unconditional 450 MW duty claim at 10% plugging with that added resistance.

The removable pressure-retaining PZR package offers a testable route to pressure-control equipment and upper-tubesheet access, while lower-end repair access and restoration of the Class 1 boundary remain separate gates. The preserved hydraulic and closure-force ratios are screening comparisons only. Final design decisions require validated local thermal coefficients, a defined fouling/plugging envelope, coupled natural-circulation analysis, project code qualification and full-scale inspection/maintenance demonstration.

REFERENCES

[1] KONEC, “Integrated System-Level Conceptual Design of a 450 MWth / 140 MWe Natural-Circulation SMR,” KNS Autumn Meeting manuscript, 2026 (unpublished at the time of revision).

[2] IAPWS, Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam, R7-97(2012), 2007, editorial revision 2012.

[3] KONEC, Conceptual-design calculation records supporting Paper 26A-123: natural-circulation pressure budget, OTSG thermal sizing and head-closure screening, 2026 (unpublished).

[4] KONEC, “Nuclear Reactor Steam Generator in Easy Maintenance,” draft patent specification, 2026 (unpublished; cited for the removable-vessel arrangement only).

[5] U.S. NRC, NUREG-0800, Standard Review Plan, Sec. 5.4.2.1, “Steam Generator Materials and Design,” Revision 4, 2016.

[6] ASME, Boiler and Pressure Vessel Code, Sec. III, Div. 1, Subsec. NB, Class 1 Components; and Sec. XI, Div. 1, Rules for Inspection and Testing of Components of Light-Water-Cooled Plants, 2025 editions.

[7] S. Bakhtiari, D. S. Kupperman, and W. J. Shack, Assessment of Noise Level for Eddy Current Inspection of Steam Generator Tubes, NUREG/CR-6982, March 2009.

[8] D. S. Kupperman et al., Evaluation of Eddy Current Reliability from Steam Generator Mock-Up Round-Robin, NUREG/CR-6785, September 2002.