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System-Level Design Closure and Verification Framework for a 450 MWth / 140 MWe Natural-Circulation SMR with BeO-Centered Fuel and Integrated Radioactive Waste Management

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Abstract - A system-level conceptual design is presented for a 450 MW thermal / 140 MW net electric natural-circulation small modular reactor. The contribution is the integration of fuel, heat transport, maintenance, safety and waste-management interfaces under a common design basis, rather than qualification of every subsystem. Seven separately submitted companion manuscripts address the component-level studies. The quantitative focus is the primary heat balance and the elevated once-through steam generator (OTSG): retained inputs give 1,452.954 kg/s primary flow, 17.129 kPa available buoyancy head and preliminary losses of 10.290 kPa clean or 10.761 kPa with 10% tube plugging. The selected tube geometry provides 12,065.2 m^2 of external heat-transfer area. A removable pressurizer (PZR) upper module connects compact integration with direct PZR service and OTSG inspection access. Safety, purification, severe-accident and waste provisions are retained at interface level. These results establish transparent screening relationships and unresolved verification requirements; they do not demonstrate a validated full-power operating point, fuel qualification or plant licensing readiness.

Keywords - conceptual SMR; system interfaces; natural circulation; Skewer-Type Fuel; integral PZR-OTSG

1. Introduction and Scope

This paper is the architectural parent study of the SMR140 concept. Its research question is how the principal subsystems can share one set of power, flow, inventory and operating-mode assumptions without incompatible interfaces. Whole-plant coverage is therefore intentional, but detailed component design is not repeated here.

Seven companion manuscripts have been submitted separately: the BeO-moderated fuel [1], PZR-OTSG maintainability [2], selective purification [3], waste solidification [4], severe-accident provisions [5], spent-fuel management [6], and YH_x/BeO material selection [7]. They identify the detailed study boundaries; submission is not evidence of completed qualification. The present paper remains self-contained for its principal energy and hydraulic screening checks.

The main contribution is limited to three linked elements: a common plant architecture, a reproducible natural-circulation/OTSG screening balance, and maintenance and safety interfaces that must be preserved during further design. Vessel thicknesses, stud sizing, material comparisons, detailed waste test results and alternative fuel-cycle economics are omitted from this parent paper.

2. Common Design Basis

Table 1 fixes the quantities shared by the subsystem studies [1,2,8]. Values are assigned design inputs or screening results, not measured plant performance. Water-property inputs are retained from the project calculation sheet [8] on an IAPWS-IF97 basis [9]. Earlier fuel-cycle values in that sheet are not used; fuel inventory follows the revised fuel study [1]. Natural-circulation verification follows a coupled-phenomena approach [10].

Table 1. Shared plant and fuel basis [1,2,8].

Quantity	Selected basis
Thermal / gross / net output	450 / 148 / 140 MW
Primary pressure	15.5 MPa
Core inlet / outlet temperature	275 / 330 °C
Primary mass flow	1,452.954 kg/s
Effective heat-centre separation	16.0 m
Core / active height	69 assemblies / 2.40 m
Fuel rods	236 per assembly; 16,284 total
U-235 enrichment	5.00 wt.%
Pellet outside / bore diameter	8.192 / 2.640 mm
Bare BeO diameter	2.590 mm
Core uranium inventory	17.029 tU
Normal soluble boron	0 mg B/kg solution
Reload screening target	23 assemblies / about 22 months

Here tU denotes metric tonnes of uranium. MW values in Table 1 distinguish thermal input, gross generation and net electrical output. Approximately 8 MW of auxiliary demand separates gross and net power.

2.1 Fuel interface and terminology

The advanced fuel option is termed *Skewer-Type Fuel* (STF): a continuous axial BeO member passes through a stack of annular UO_2 pellets, with opposed round Zr-Nb wires providing positioning and a supplementary heat path [1,7]. The selected geometry gives 9.9958 vol.% BeO and a 10.4779% geometric uranium-inventory reduction relative to the solid-pellet reference. This is not a demonstrated fuel-cost or cycle-length saving.

The approximately 22-month, three-batch case is a depletion-analysis target. Temperature coefficients, shutdown margin, power peaking and irradiation-dependent fuel performance remain to be demonstrated. Conventional UO_2 is retained as a fallback design option, not an already approved core [1,11].

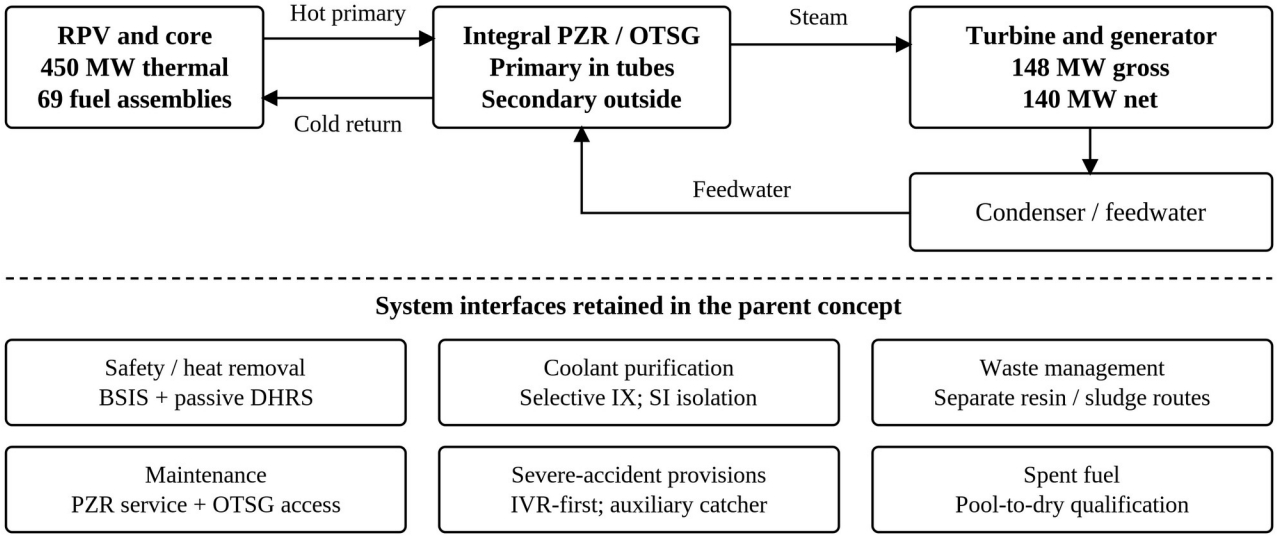


Fig. 1. Integrated concept and subsystem boundaries. Solid arrows identify the principal heat-transport and power-conversion paths; the lower boxes identify functional interfaces, not detailed piping or validated safety trains. All provisions remain subject to the verification requirements in Section 6.

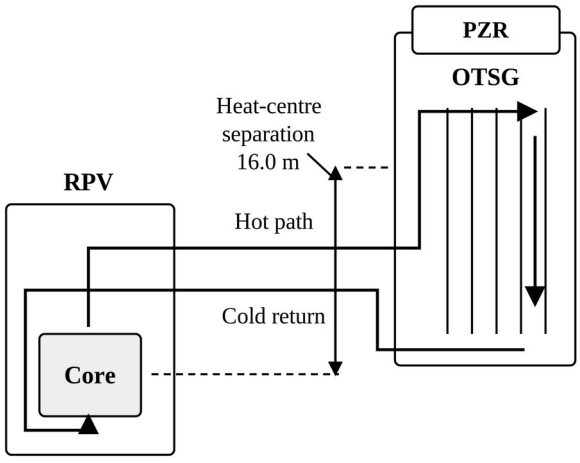
3. Primary Heat-Transport Screening

3.1 Energy balance and flow path

Figure 1 links core heat to the OTSG and turbine-generator. The corresponding primary path is shown in Fig. 2: hot coolant travels through the central coaxial duct and OTSG riser, descends through the straight tubes, and returns through the outer cold annulus. The PZR is pressure-coupled to the upper region and is not the main through-flow path [2].

At the Table 1 state, the retained enthalpies are h_c = 1,207.433 and h_h = 1,517.147 kJ/kg [8]. Using thermal power in kW, Eq. (1) gives the required primary mass flow. The displayed inputs are rounded; the result is retained at the precision of the design basis.

$$\dot{m} = \frac{Q_{\mathrm{th}}}{h_{\mathrm{h}} - h_{\mathrm{c}}} \approx 1{,}452.954 \text{ kg/s} \tag{1}$$



Schematic; elevations and lengths not to scale

Fig. 2. Primary circulation concept. The 16.0 m parameter is the assumed separation of heat centres, not the coaxial-connector length. The component outline and elevations are schematic [2,8].

3.2 Buoyancy and loss allocation

The retained cold- and hot-leg densities are 772.823 and 651.527 kg/m^3 [8]. With g = 9.80665 m/s^2 and H_{eff} = 16.0 m, the endpoint-density approximation in Eq. (2) yields 19.032 kPa raw buoyancy head.

$$\Delta P_{\mathrm{b}} = g\, H_{\mathrm{eff}} \left(\rho_{\mathrm{c}} - \rho_{\mathrm{h}} \right) \tag{2}$$

A retained design factor η = 0.90 gives 17.129 kPa available head. This factor is an engineering allowance, not a statistically established uncertainty bound. Table 2 makes the preliminary loss budget explicit. The head-to-loss discriminator is defined by Eq. (3).

$$\Pi_{\mathrm{NC}} = \frac{\eta\, \Delta P_{\mathrm{b}}}{\Sigma\, \Delta P_{\mathrm{i}}} \tag{3}$$

Table 2. Retained rated-flow loss allocation [2,8].

Contribution	ΔP (kPa)
Core friction	1.30
Spacer grids and local losses	2.60
OTSG tubes	1.66
OTSG inlet / turn / outlet	0.35
Central hot riser	0.70
Coaxial hot duct	1.55
Cold annulus	0.73
Plenums	0.65
Engineering allowance	0.75
Total, clean	10.290
Total, 10% plugged case	10.761

The clean and plugged ratios are 1.665 and 1.592, respectively. A positive reserve at an assumed flow is not a solved natural-circulation equilibrium. The coupled operating point must satisfy equality of distributed buoyancy and losses as temperatures and flow change. Stability, startup, flow reversal and asymmetric plugging require validated models and experiments [10].

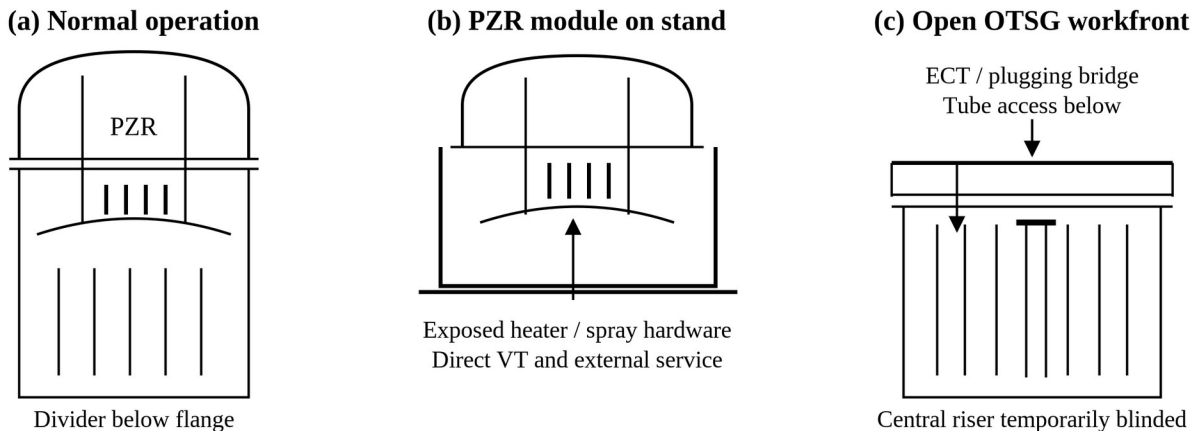


Fig. 3. Maintenance interface of the PZR-OTSG concept [2]. (a) The divider lies below the vessel separation plane. (b) After cooldown, depressurization, isolation, drainage and removal, the PZR module is supported on a stand for visual testing (VT) and service. (c) The separately accessible OTSG accepts an ECT/plugging bridge after temporary riser isolation. No work beneath a suspended module is implied; the drawing is not to scale.

3.3 OTSG area and secondary balance

Table 3 gives only the OTSG/PZR quantities needed for the parent-level interface. The external tube area follows directly from the selected geometry [2,8]:

$$A_{HT} = N_t \pi D_o L_t \quad (4)$$

For N_t = 14,400, D_o = 0.01905 m and L_t = 14.0 m, Eq. (4) gives 12,065.2 m^2. Against the retained project required-area screen of 10,142 m^2, the clean area ratio is 1.1896. The required area is not independently validated here; heat-transfer coefficients, secondary boiling, fouling and plugging must be recalculated together. Area reserve cannot substitute for hydraulic stability.

Table 3. OTSG/PZR interface quantities [2,8].

Quantity	Design input / target
OTSG shell inside diameter	3.70 m
Tube number / effective length	14,400 / 14.0 m
Tube outside / inside diameter	19.05 / 16.87 mm
Tube wall thickness	1.09 mm
Selected outside area	12,065.2 m^2
Secondary pressure	4.5 MPa
Feedwater / steam temperature	180 / 290 °C
Secondary mass flow	209.44 kg/s
PZR volume / heater power	50 m^3 / 4 × 1 MW
ECT opening / free-height target	≥2.85 m / ≥3.2 m

Using the retained secondary enthalpies, 2,913.549 kJ/kg for steam and 764.963 kJ/kg for feedwater, 450,000/2,148.586 gives 209.44 kg/s [8,9]. The retained heat allocation is 74.81 MW economization, 350.99 MW evaporation and 24.20 MW superheating. The 148 MW gross / 140 MW net values remain power-conversion assumptions; a vendor heat balance must include cycle losses and auxiliary demand.

4. Maintainability as a System Interface

Compact integration is useful only if inspection and service remain possible. Figure 3 therefore makes the removal plane part of the system architecture. In the proposed arrangement, the PZR upper module carries the divider and associated heater/spray hardware. On a supported stand, the flange-to-divider gap exposes those components for external visual inspection and service [2].

The same removal leaves the OTSG upper region accessible for eddy-current testing (ECT), tube-end inspection, plugging and foreign-material retrieval. The nominal 2.85 m opening and 3.2 m free-height values in Table 3 are tooling-envelope targets, not proof that every tube can be inspected. Reach, probe routing, tube identification, plug installation and retrieval must be demonstrated in a full-scale mock-up. Geometric access must also be distinguished from detection reliability [12].

This is a one-removal/two-work-area concept: PZR work occurs at the supported module, while OTSG work occurs at the protected vessel opening. Independence of the work areas does not imply that every task can proceed simultaneously. Lifting paths, temporary shielding, contamination containment, foreign-material exclusion and closure restoration constrain outage sequencing.

The lower shell and mating flange remain in place; the assembled upper module and closure are also part of the operating pressure boundary. The internal divider is a flow/thermal separator, not a full-pressure isolation barrier. Its differential loading, bypass flow and thermal response require separate analysis. Detailed stud dimensions and lifting-capacity calculations are not repeated in this system paper [2].

Better visibility and reduced confined-entry dependence are intended benefits, not measured dose or outage savings. Any quantitative claim requires task-specific source terms, shielding, worker position, stay time and remote-tool assumptions, consistent with occupational-radiation-protection practice [13].

5. Safety, Chemistry and Waste Interfaces

Table 4 preserves whole-plant coverage while limiting each subsystem to its role, connection and unresolved requirement. It is the interface summary for Fig. 1; component ratings alone are not credited as evidence of safety performance.

Table 4. Operating-mode and subsystem-interface summary [2–6].

Mode / function	Interface retained in this paper	Verification still required
Normal power	Natural circulation → OTSG → turbine-generator; selective coolant purification; no routine soluble boron.	Coupled flow/temperature solution, core limits and chemistry control.
Safety injection / borated mode	BSIS feeds the cold annulus/downcomer; ion-exchange beds isolate to retain emergency boron.	Mixing, shutdown effectiveness, valve actuation and common-cause assessment.
Loss of feedwater / power	Two passive secondary DHRS branches connect to the OTSG; injection and heat removal have different functions.	Single-OTSG dependencies, actuation, stability and time-dependent heat-sink inventory.
Outage and inspection	PZR module moves to a supported stand; protected OTSG opening receives ECT/plugging tooling.	Lift and seal qualification, temporary riser isolation, tooling coverage and dose study.
Waste and spent-fuel handling	Spent resin → polymer route; sludge → separate cementitious route; spent fuel → pool-to-dry assessment.	Source terms, waste acceptance, cask/pool thermal, criticality and shielding analyses.
Severe accident	IVR/external vessel cooling is the intended first layer; upward rod/catcher are supplementary provisions.	Coolability, melt interaction, hydrogen and criticality; no assumed qualified accident credit.

5.1 Injection, heat removal and purification

The retained borated safety injection system (BSIS) concept has two trains. Each includes a 150 m^3 usable borated-water tank and a 55 m^3 injection-tank rating. The nominal concentration is 4,500 mg elemental B/kg solution. With the explicit screening density 1,000 kg/m^3, the 150 m^3 inventory contains approximately 675 kg B [8]. Usable injected volume, mixing and shutdown worth are not established by tank rating alone.

Each passive secondary decay-heat-removal system (DHRS) branch retains an initial 35 MW target and a 600 m^3 water-inventory target. The 72 h objective requires integration of decay heat over time, with usable inventory, heat transfer and single-failure assumptions. Two branches attached to one OTSG do not remove all common-component failure modes. Passive heat transport does not by itself eliminate instrument or valve-actuation dependencies [2,10].

The reactor-coolant purification system (RCPS) uses selectable, not permanently series-connected, ion-exchange (IX) beds. For the retained 184 m^3 inventory, each train treats 12 m^3/h. A safety-injection signal or a preliminary threshold above 50 mg B/kg solution latches borated mode and isolates all beds. This separates normal chemistry cleanup from emergency boron preservation; the threshold and isolation response require plant-specific demonstration [3].

5.2 Waste and spent-fuel boundaries

Spent resin is routed to a dedicated polymer-solidification process, whereas sludge is characterized and sent to a physically separate cementitious-solidification route. No common process path is assumed. The parent paper specifies segregation, batch traceability and the waste-acceptance interface; it does not reproduce formulation details or claim that existing waste-form tests qualify every future SMR waste stream [4].

The companion spent-fuel study [6] receives the same assembly count, uranium inventory and irradiation-history assumptions. Pool-to-dry timing remains a separate decay-heat, criticality, shielding, drying and cask-qualification problem. An in-reactor fuel-temperature benefit cannot by itself justify earlier dry transfer. No independent storage performance is claimed in this paper.

5.3 Severe-accident provisions

In-vessel retention (IVR), supported by external vessel cooling, is the intended first severe-accident layer. An upward absorber/dilution rod and a flat-bottom catcher are supplementary concepts, not assumed leak-tight plugs or qualified long-term heat sinks [5]. Their thermal, chemical and criticality assessments remain in the dedicated study and further experimental programme.

Accordingly, this paper claims an accident-management interface, not an established severe-accident success probability. Integration must address cavity flooding, containment conditions, hydrogen and the dependencies between mitigation functions. The separate status of prevention, mitigation and verification is consistent with the accident-management framework in SSG-54 [14].

6. Verification Framework and Limitations

The evidence hierarchy is deliberately limited. Level 0 comprises conservation, geometry and capacity checks; Level 1 comprises preliminary one-dimensional correlations and loss allocations. Levels 2 and 3 require validated multidimensional/component analyses and integral/qualification tests, respectively. This paper reports only Levels 0–1. A proposed verification programme is not a completed validation exercise [10,11].

The most important unresolved coupling is the primary flow solution. Table 2 must ultimately be replaced by validated resistance functions; temperature profiles must replace the endpoint-density approximation. The same coupled calculation must then establish core cooling limits, OTSG duty, startup behaviour and single-OTSG transients. A heat-transfer-area surplus cannot compensate for an unstable hydraulic operating point.

Fuel qualification, maintenance access, pressure-boundary integrity, emergency-boron retention, passive heat-sink endurance and waste acceptance each require their own evidence. Favourable results in one domain cannot be counted twice or used to waive a failure in another. The companion papers [1–7] provide dedicated study boundaries, not substitutes for these acceptance demonstrations.

7. Conclusions

A 140 MW net electric SMR concept is defined by shared plant assumptions and explicit interfaces. The primary/OTSG screen retains 1,452.954 kg/s flow, 17.129 kPa available head, 10.290/10.761 kPa clean/plugged losses and 12,065.2 m^2 selected area. The arithmetic is transparent, but the natural-circulation operating point and stability remain unvalidated.

The architectural contribution combines this heat-transport basis with STF fuel interfaces, removable PZR/OTSG maintenance access, safety/chemistry separation and segregated waste handling. Seven companion studies carry the detailed subsystem work. The paper should therefore be interpreted as an integrated conceptual-design and interface study, not final component qualification or construction/licensing approval.

REFERENCES

References [1–7] are separately submitted companion manuscripts for the 2026 KNS Autumn Meeting; they are not cited as published or accepted validation evidence.

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