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Qualification-Gated IVR-First Severe-Accident Mitigation for a 140 MWe SMR Using an Upward Absorber/Dilution Rod and Thermally Bridged Flat-Bottom Catcher

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Abstract – An IVR-first severe-accident concept for a 140 MWe SMR is assessed using reproducible geometric and energy screens. The upward absorber/dilution rod and thermally bridged flat-bottom catcher remain unqualified supplementary equipment. A 4.6 m working diameter provides 16.619 m² of plan area. With a 0.75 m curb, uniform retention of 11 and 12 m³ leaves only 0.0881 and 0.0279 m of geometric freeboard, respectively; these are not demonstrated usable capacities. A 180 mm rod ideally occupies 81.00%, 36.00%, 20.25% and 12.96% of centered 200–500 mm breach areas, without establishing discharge reduction. Assumed density and specific-enthalpy ranges give 0.3275–0.5153 GJ of heat uptake and 72.8–114.5 s of energy-equivalent time at 4.5 MW, not a demonstrated rod lifetime. Thermal-resistance definitions, a prospective criticality acceptance relation and staged validation requirements are provided. Arithmetic checks are completed; physical validation, non-interference with IVR and safety credit remain open.

Keywords: severe accident; in-vessel retention; corium catcher; absorber/dilution rod; model validation

1. Safety Position and Study Scope

The proposed architecture prioritizes in-vessel retention (IVR) by external vessel cooling, supported by cavity flooding and containment heat, pressure and hydrogen management. The upward rod and catcher are additional design-extension-condition (DEC) concepts. This hierarchy is a design intention, not proof that IVR or the supplementary equipment is qualified for this SMR [1].

The study asks whether nominal geometry and assumed material inventories support limited, testable claims. The sequence considered is lower-head breach, possible rod entry, sacrificial erosion and absorber delivery, followed by ex-vessel spreading and cooling. Failure, blockage or displaced debris from the added equipment must not compromise IVR or established plant safety functions.

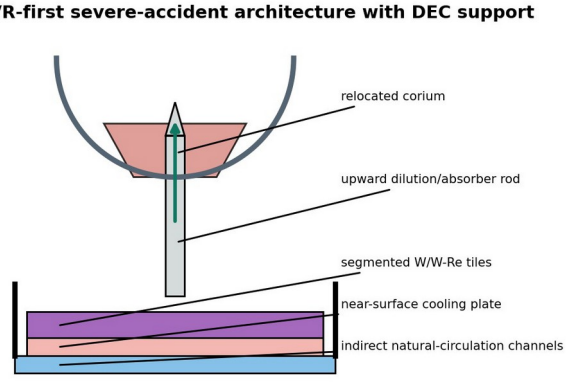


Fig. 1. Retained concept: lower-head melt and upward rod above a catcher with segmented W/W-Re tiles, a near-surface cooling plate and indirect cooling channels. Not to scale; channel and rod-guide details remain unresolved.

Table I: Input data

Parameter	Assigned value
Nominal plant power	450 MWth / 140 MWe
Catcher outer / working diameter	5.0 / 4.6 m
Curb height, H_c	0.75 m
Retained melt scenarios, V_m	11 and 12 m³
Rod diameter / active length	0.180 / 1.8 m
Assumed effective rod density	6,500–7,500 kg/m³
Assumed specific heat uptake	1.1–1.5 MJ/kg
Illustrative decay heat, Q_{dec}	4.5 MW
Segmented W/W-Re hot face	40 mm
Segmented ZrO_2/HfO_2 isolation	Approximately 150 mm
Structural support	Approximately 80 mm
Proposed channel stand-off	Approximately 25 mm
Proposed criticality target	Upper estimate < 0.95

Dimensions, material ranges and 11/12 m³ scenarios are retained author-assigned inputs, not measurements. The 4.5 MW heat load is 1% of nominal thermal power, not a calculated accident-time decay-heat history. The 25 mm stand-off requires reconciliation with the 40 mm tile geometry (Section 4).

Only geometry, dimensional consistency and arithmetic are checked here. No material fraction is qualified, no severe-accident or criticality calculation is reported, and no probabilistic reliability is assigned. Published spreading and coolability studies [2–5] identify relevant phenomena and future comparison data; they do not validate the proposed hardware.

2. Catcher Capacity and Spreading

For a horizontal circular working area without intrusions, the plan area A_c and uniform mean melt depth h_m follow directly from geometry and volume conservation:

$$A_c = \frac{\pi D_w^{\,2}}{4}; h_m = \frac{V_m}{A_c} \quad (1)$$

Here D_w is working diameter (m), V_m retained volume (m³), A_c area (m²), and h_m depth (m). Uniform geometric freeboard F and the gross volume to the curb V_g are

$$F = H_c - h_m; V_g = A_c H_c \quad (2)$$

With D_w = 4.6 m and H_c = 0.75 m, A_c = 16.6190 m² and V_g = 12.4643 m³. Table II uses unrounded intermediate values. Neither V_g nor the nominal 11 m³ inventory is a qualified usable capacity.

Table II: Uniform retention screen

V_m (m³)	h_m (m)	F (m)
11.0	0.6619	0.0881
12.0	0.7221	0.0279

Increasing inventory by 1 m³ increases the uniform depth by 0.0602 m. The remaining geometric volume below the curb is 1.4643 m³ at 11 m³ retention and only 0.4643 m³ at 12 m³. Guides, solid debris, rod material and other intrusions must be included consistently; their displaced or added volume must not be counted twice.

Equation (1) is an identity for the stated idealization, not an upper bound on local depth. Real spreading, mounds, crusts and oxide/metal stratification can produce local levels above the mean and smaller local freeboard. Nominal uniform freeboard therefore cannot establish overflow prevention. Final inventory must follow the accident sequence, including relocated structures and sacrificial material [2,3].

A local level below the curb, with an uncertainty allowance appropriate to the application, is a necessary future retention check. It does not by itself demonstrate coolability, structural integrity or suppression of molten corium–concrete interaction (MCCI).

3. Breach Area and Rod Heat Buffer

3.1 Geometric blockage is not flow reduction

For a rigid rod normal to a centered circular breach, with full projected overlap and $D_r \le D_b$, the occupied projected area fraction B is

$$B = \frac{A_r}{A_b} = \left(\frac{D_r}{D_b}\right)^2 \quad (3)$$

D_r and D_b denote rod and breach diameters (m); A_r and A_b are their projected circular areas (m²). B is dimensionless. The percentages in Table III are 100B, not measured mass-flow reductions.

Table III: Ideal projected area blockage

D_b (mm)	100B (%)	Open area (%)
200	81.00	19.00
300	36.00	64.00
400	20.25	79.75
500	12.96	87.04

Eccentricity alone does not change B while the complete rod projection remains inside the opening. Partial overlap reduces the occupied area. Tilt, erosion, changing breach shape and transient pressure require a coupled hydraulic/mechanical model. A smaller opening area does not establish the same percentage reduction in discharge or a guaranteed accident delay.

3.2 Assumed heat-uptake envelope

$$V_r = \frac{\pi D_r^{\,2} L_r}{4}; m_r = \rho_r V_r \quad (4)$$

$$E_r = m_r \Delta h_r; \tau_E = \frac{E_r}{Q_{dec}} \quad (5)$$

L_r is active length (m), ρ_r effective density (kg/m³), and Δh_r assumed sensible-plus-latent uptake (J/kg). Equations (4)–(5) give V_r = 0.0458044 m³, m_r = 297.73–343.53 kg and E_r = 0.3275–0.5153 GJ. At 4.5 × 10⁶ W, τ_E = 72.8–114.5 s.

The interval combines the low/low and high/high input endpoints; it is not a statistical confidence interval or a verified mixture property. Initial temperature, composition, erosion and heat transfer govern accessible uptake. τ_E is an energy-equivalent time, not insertion survival, cooling duration or breach-sealing time.

4. Thermally Bridged Catcher and Cooling

The proposed segmented hot face and near-surface cooling paths seek to avoid routing all heat through a continuous thick insulating layer. Table IV assigns the entire illustrative decay heat to an effective bottom area A_w; top and side heat losses are not credited in this screen.

$$A_w = f_c A_c ; \bar{q}'' = \frac{Q_{dec}}{A_w} \tag{6}$$

The cooled-area fraction f_c is an added sensitivity assumption, not a measured wetted fraction or a melt-spreading fraction. With Q_{dec} in W and A_w in m², the mean required heat flux $\bar{q}''$ is in W/m².

Table IV: Required mean bottom heat flux at 4.5 MW

f_c	A_w (m²)	$\bar{q}''$ (MW/m²)
1.00	16.6190	0.2708
0.75	12.4643	0.3610
0.50	8.3095	0.5415

These are imposed decay-heat loads, not cooling capacities or local maxima. Transient sensible/chemical heat and heat-flux focusing are outside this screen. For each idealized path p, its area-specific series resistance is

$$R_p'' = \Sigma_j \frac{t_j}{k_j} + \Sigma_l R_{ct,l}'' + \frac{1}{h_{cool,p}} \tag{7}$$

Here t_j (m) and k_j (W/m/K) are thickness and conductivity of layer j along that path, $R''_{ct,l}$ is interface-l resistance (m²K/W), and $h_{cool,p}$ is the coolant-side coefficient (W/m²/K). Thus R''_p has units m²K/W, not K/W. The sums cover layers and interfaces along the same path.

$$U_{eff} = \frac{\varphi}{R_{br}''} + \frac{(1-\varphi)}{R_{ref}''} \tag{8}$$

In Equation (8), br/ref denote bridge/refractory paths and φ is bridge area fraction. Common hot-face and bulk-coolant temperatures are assumed, with difference ΔT (K). U_{eff} is in W/m²/K; $q'' = U_{eff}\,\Delta T$ is only a one-dimensional diagnostic. Conductivities, contacts, φ and coolant conditions are insufficiently specified for a qualified resistance ratio.

A channel within 25 mm of the surface is not automatically compatible with a 40 mm tile; channel embedding, tile ligament and interfaces remain unresolved. Lateral spreading resistance, boiling, dryout, erosion, coolant leakage and steam interaction require coupled analysis and tests [2,4,5].

5. Dilution, Absorption and Criticality

The retained material concept is a protective shell around an Fe-based sacrificial matrix containing a pre-oxidized non-fissile diluent and B_4C and/or Hf-bearing absorber phases. Fractions remain unspecified. Their selection must address phase compatibility, absorber partition, hydrogen generation, viscosity, rod strength and manufacturability; homogeneous mixing is not presumed.

The criticality statement is a future acceptance objective, not a calculated result. A transparent reporting relation for a credible state x is

$$k_U(x) = k_{calc}(x) + \delta_b(x) + U_{joint}(x) \tag{9}$$

All terms are dimensionless. k_{calc} is the calculated multiplication factor, δ_b a conservatively applied method-bias correction, and U_{joint} a joint uncertainty allowance constructed by an applicable validated method. The study proposes $\max_x k_U(x) < 0.95$. The 0.95 value is an author-selected screening target, not a claim that this concept meets a universal regulatory limit.

Bias uncertainty, numerical/statistical uncertainty, application tolerances, validation gaps and any nuclear-data contribution must be handled consistently, with dependence and double counting considered. A favorable bias must not be used without methodological justification. The original fixed 1.645 multiplier has been removed: a one-sided normal quantile does not alone establish a 95/95 tolerance limit or an approved upper subcritical limit [6,7].

The state set must include dry and flooded configurations, potentially most reactive water content, porous debris, oxide/metal layering, intact/partially dispersed/segregated absorber, and credible composition and geometry uncertainties. Inputs must include the relocated fissile-isotope inventory, oxidation state, temperatures and actual absorber distribution. Moderation is not assigned a beneficial safety function.

No k_{calc} values, benchmark results or absorber-mass requirement are reported in this work. Future calculations must establish benchmark applicability to the application, quantify bias and uncertainty, and address gaps before the target can be assessed [6,7]. Comparison with another code is a consistency check; it is not a replacement for comparison with relevant physical measurements.

Neither assumed dilution nor nominal absorber inventory establishes subcriticality after segregation or water ingress. A failure to support the intended composition or geometry with evidence requires redesign or withdrawal of the corresponding claim, rather than additional unvalidated credit.

6. Next Steps and Model Validation

6.1 Completed verification and remaining gap

Equations (1)–(6) were recalculated with unrounded intermediate values. Independent mm-to-m unit paths, volume and energy identities, reference area ratios, and monotonicity checks were applied in a reproducible script. These checks verify the reported arithmetic only. Equations (7)–(9) define unevaluated thermal and criticality frameworks; no physical validation is claimed.

6.2 Evidence-based sequence

Table V: Proposed validation and qualification sequence

Stage	Evidence and decision
1. Source term	Bound accident-dependent melt inventory, composition, temperature, decay heat and breach history. Reconcile all input inventories before sizing retention and cooling.
2. Benchmarks	Compare selected spreading/cooling models with applicable MCCI and ROSAU data [2,3,5], where accessible. Match materials and boundary conditions; quantify residuals and scale limitations.
3. Components	Measure rod entry, force and erosion; absorber partition and gas production; tile/bridge temperature, heat flux, contact degradation and dryout under adverse conditions.
4. Integration	Test eccentric/irregular discharge and cooling transients. Demonstrate local retention, sustained heat removal and IVR non-interference; complete criticality validation [6,7].

Public project descriptions establish relevant phenomena, not possession of complete test data or validation of this design. The in-vessel simulant study [4] concerns different hardware and is not transferable qualification evidence for the present ex-vessel catcher.

Calibration and independent validation cases must be separated. Before testing, specify observables, measurement uncertainty, allowable prediction errors and their design basis. Compare local rather than only average levels and heat fluxes; judge cooling against experimentally supported limits. The 4.5 MW and material-input envelopes must be replaced by sequence-specific, traceable inputs.

6.3 Safety-credit boundary

Component and integrated tests must cover failure to insert, rod or tile debris obstruction, loss of coolant, leakage into hot material and unfavorable absorber segregation. Acceptance requires that added equipment not impair the IVR-first strategy. Reliability or probabilistic risk-assessment (PRA) credit is deferred until applicable performance and failure evidence exists [1].

7. Conclusions

The concept is retained as an IVR-first, qualification-gated DEC supplement. The 4.6 m working diameter provides a reproducible geometric screen, but freeboard falls from 0.0881 to 0.0279 m when inventory rises from 11 to 12 m³. Ideal rod blockage is not hydraulic performance. The assumed 0.3275–0.5153 GJ heat buffer gives only 72.8–114.5 s of energy-equivalent time, not a qualified service life.

Explicit resistance definitions and a prospective criticality criterion expose inputs still needed for performance assessment. The contribution is a checkable set of limited claims and decision-linked next steps. Long-term coolability, absorber effectiveness, safe deployment and licensing or PRA credit are not demonstrated by the present calculations.

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