

Dynamic Cleanup and Safety-Isolation Design of Selective Ion-Exchange Beds for a Soluble-Boron-Free 140 MWe SMR

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Abstract — A selective ion-exchange cleanup concept for a soluble-boron-free 140 MWe small modular reactor is assessed using source-coupled and two-compartment inventory balances. The reference coolant inventory is 184 m³, with two trains rated at 12 m³/h each. At 95% single-pass removal, source-free mixed-volume 90% cleanup times are 37.2 and 18.6 h. In an assumed 10% slow-volume case with 1.2 m³/h intercompartment exchange, the corresponding inventory-average times become 41.5 and 22.5 h, while slow-volume times are 62.2 and 47.0 h. A sustained source can preclude the absolute cleanup target. Breakthrough limits are derived from required decontamination factors and outlet limits, with measurement and response-time margins; the former 5% and 10% values are retained only as worked examples. Safety-injection isolation remains independent of cleanup optimization. These calculations establish a testable design framework, not validated resin life, operating setpoints, or safety performance.

Keywords: ion exchange; nonideal mixing; source term; breakthrough; soluble-boron-free SMR

1. Introduction

Eliminating soluble boron from normal power operation does not eliminate corrosion products, fuel-leak products, or ionic impurities. A chemistry programme must define plant-specific limits, monitoring and corrective actions [1]. In the present concept, selectable ion-exchange beds optimize normal cleanup, whereas a separate isolation function preserves boron introduced by emergency injection.

Ion-exchange breakthrough depends on operational capacity and kinetics, not nominal resin volume alone [2]. Nuclear mixed-bed flow-rate and decontamination-factor measurements have been reported [3], while residence-time analysis provides a basis for examining nonideal mixing [4]. These references support the modelling approach; they do not calibrate this SMR or establish its setpoints. This paper adds explicit source and mixing sensitivities and a requirement-to-setpoint procedure.

2. Design Basis and Source-Coupled Model

2.1 Reference equipment and concentration basis

Table 1. Proposed reference equipment; not vendor-qualified.

Item	Reference value / duty
Coolant / trains	184 m ³ / two 12 m ³ /h trains
Prefilter	5 µm nominal; particulate control
Cation bed	0.50 m ³ ; EBCT 2.5 min; cations
Anion bed	0.50 m ³ ; EBCT 2.5 min; anions
Mixed bed	1.00 m ³ ; EBCT 5.0 min; polishing

Beds are independently selectable, not permanently in series. One train is the nominal duty arrangement; simultaneous operation provides 24 m³/h only when both trains treat the same target species. Empty-bed contact time (EBCT) is V_{bed}/Q , not proof of removal efficiency.

V and Q below use a common reference-density basis. Hot-system geometric volume and cooled-letdown volumetric flow must not be combined without density conversion; plant application requires consistent coolant-mass and mass-flow data.

2.2 Constant-source solution and target feasibility

For species i, C_i is concentration, S_i is its net input rate, λ_i is its radioactive decay constant, and η_i is single-pass removal. Concentration and source units must be consistent; for activity, they are Bq/m³ and Bq/h. Stable species have $\lambda_i=0$.

$$\begin{aligned} dC_i/dt &= S_i/V - k_i C_i \\ k_i &= \eta_i Q/V + \lambda_i \end{aligned} \quad (1)$$

For constant coefficients and source, the solution is:

$$\begin{aligned} C_i(t) &= C_{i,ss} + (C_{i,0} - C_{i,ss})e^{-k_i t} \\ C_{i,ss} &= S_i/(\eta_i Q + \lambda_i V) \end{aligned} \quad (2)$$

The source-free exponential is recovered only when $S_i=0$. For $r=C_{ss}/C_0$, an absolute target $C=0.1C_0$ is reached at:

$$\begin{aligned} t_{90,abs} &= k^{-1} \ln[(1-r)/(0.1-r)] \\ 0 &\leq r < 0.1 \end{aligned} \quad (3)$$

At $r \geq 0.1$, the target is not reached in finite time. The expression $\ln(10)/k$ instead measures 90% removal of the excess above C_{ss} , which is not the same target.

Table 2. Calculated source sensitivity: $Q=12$ m³/h, $\eta=0.95$, $\lambda=0$; assumed r, not measured source rates.

$r = C_{ss}/C_0$	$t_{90,abs}$ (h)	Interpretation
0	37.2	No ongoing source
0.02	40.4	Finite source floor
0.05	47.5	Finite source floor
0.10	Not finite	Asymptotic target

At $\eta=1$ and $S=\lambda=0$, the original ideal benchmarks remain 35.3 h (12 m³/h) and 17.7 h (24 m³/h). At $\eta=0.95$, they become 37.2 and 18.6 h. For fixed S, doubling Q also reduces C_{ss} ; r must therefore be recalculated rather than held fixed.

The tables set $\lambda=0$ to separate removal from radioactive decay. Time-dependent release, resin degradation, or changing flow requires numerical integration of Eq. (1), not reuse of Eq. (2).

3. Nonideal Mixing and Sensitivity

3.1 Two-compartment balance

A reduced two-compartment model tests sensitivity to a slowly exchanging region. The main volume $V_m=(1-f)V$ is connected to the purification train; the slow volume $V_s=fV$ exchanges coolant with it at q_m in each direction. This is an author-derived mass balance motivated by nonideal residence-time analysis [4], not a calibrated hydrodynamic model.

$$V_m \frac{dC_m}{dt} = S_m - \eta Q C_m + q_m(C_s - C_m) - \lambda V_m C_m \quad (4a)$$

$$V_s \frac{dC_s}{dt} = S_s + q_m(C_m - C_s) - \lambda V_s C_s \quad (4b)$$

The inventory-average concentration is $\bar{C}=(V_m C_m + V_s C_s)/V$. Adding Eqs. (4a,b) cancels internal exchange exactly: $V d\bar{C}/dt = S_m + S_s - \eta Q \bar{C} - \lambda V \bar{C}$. Thus purification acts on C_m , not automatically on $\bar{C}$.

For the screening cases, $V=184 \text{ m}^3$, $f=0.10$, $\eta=0.95$, $S_m=S_s=\lambda=0$, and $C_m(0)=C_s(0)=C_0$. The selected $q_m=1.2$, 12 and 120 m^3/h values span two orders of magnitude solely to test model sensitivity. They are not inferred plant exchange rates.

Table 3. Calculated times to $0.1C_0$; assumed 10% slow volume. All flow rates are in m^3/h .

Q	q_m	$t_{90, \text{average}}$ (h)	$t_{90, \text{slow}}$ (h)
12	1.2	41.5	62.2
12	12	37.5	39.0
12	120	37.2	37.3
24	1.2	22.5	47.0
24	12	19.0	20.5
24	120	18.6	18.8

At $q_m=1.2 \text{ m}^3/\text{h}$, doubling purification flow does not halve the slow-volume cleanup time (62.2 to 47.0 h). When $\bar{C}/C_0=0.1$, C_s/C_0 is still 0.257 for one train and 0.410 for two trains. A satisfactory main-stream sample therefore does not establish uniform cleanup.

3.2 Calculated response and numerical checks

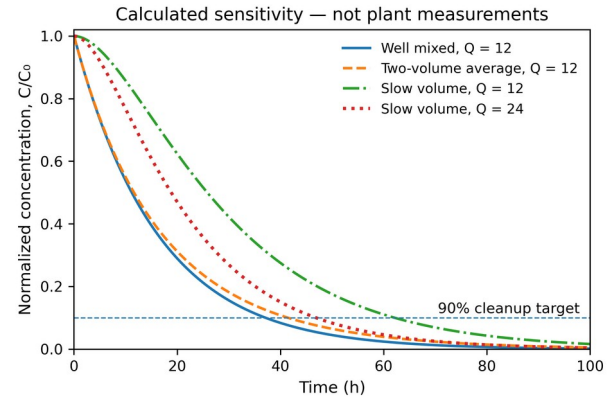


Fig. 1. Calculated responses for $f=0.10$, $q_m=1.2 \text{ m}^3/\text{h}$, $\eta=0.95$ and $S=\lambda=0$. Q is in m^3/h . The $0.1C_0$ inventory target is distinct from bed breakthrough $b=0.10$.

The constant-coefficient system was solved by matrix exponentiation and independently integrated with DOP853 (relative tolerance 2×10^{-12} , absolute tolerance 10^{-13} , maximum step 0.1 h). Across all six cases on a 0–150 h grid with 0.5 h spacing, the maximum difference in normalized concentration was below 2×10^{-12} ; the relative inventory-balance residual was below 5×10^{-15} . These are numerical consistency checks, not physical validation.

For large q_m , the model approaches the mixed-volume result. With $q_m=0$, the disconnected 10% volume retains its initial concentration and sets an average inventory floor of $0.1C_0$. These limits provide independent checks on the interpretation of Table 3.

3.3 Removal efficiency and parameter uncertainty

In the source-free mixed case, reducing η from 1.0 to 0.80 increases the one-train t_{90} from 35.3 to 44.1 h. First-order sensitivity is $\delta t/t \approx \delta V/V - \delta \eta/\eta - \delta Q/Q$. An illustrative simultaneous corner sweep with $V \pm 10\%$, $Q \pm 10\%$, and $\eta=0.80\text{--}1.00$ gives 28.9–53.9 h. This deterministic range is neither a confidence interval nor a validated plant envelope.

The lumped balances omit spatial deposition/resuspension, multicomponent sorption kinetics and daughter ingrowth. Removal efficiency applies only to the specified exchangeable species. Colloids and nonionic forms require filtration or separately demonstrated capture; their removal is not implied by a cation-bed label [2].

4. Performance-Based Breakthrough Control

4.1 From process requirements to allowable breakthrough

For time-aligned inlet and outlet concentrations of species i , define $b_i = C_{out,i}/C_{in,i}$, $DF_i = 1/b_i$, and $\eta_i = 1 - b_i$. These relations describe single-pass performance, not the fraction of the total coolant inventory remaining after a cleanup campaign.

IAEA TRS 408 gives a requirement-based example: a required DF of 100 corresponds to replacement at 1% breakthrough [2, p. 10]. Accordingly, neither 5% nor 10% is a universal nuclear-service limit. The plant chemistry and radiological programme must first establish $DF_{req,i}$ and the allowable outlet concentration $C_{out,lim,i}$.

$$b_{lim,i} = \min[1/DF_{req,i}, C_{out,lim,i}/C_{in,i}] \quad (5)$$

Equation (5) requires a positive, quantifiable inlet concentration and $DF_{req,i} \geq 1$. It defines a true performance boundary, not the measured actuation setting. Under transients, the inlet value must conservatively bound the concentration during the response interval. The RCS steady and local concentration limits must also be met; a satisfactory bed DF alone does not ensure acceptable C_{ss} .

Table 4. Algebraic interpretation of example breakthrough values; no qualified setpoint is implied.

b	DF	η	Mixed t_{90} (h)
0.01	100	0.99	35.7
0.05	20	0.95	37.2
0.10	10	0.90	39.2

Table 4 uses $V=184 \text{ m}^3$, $Q=12 \text{ m}^3/\text{h}$, $S=\lambda=0$. Relative to $\eta=1$, $b=0.05$ and 0.10 increase the ideal cleanup time by 5.3% and 11.1%, respectively. This explains their process consequences, but it does not establish that $DF=20$ or 10 is adequate for the target nuclide or chemistry condition.

The earlier 5% warning / 10% replacement pair is therefore replaced by a requirement-based procedure. A 5% warning is retained only as an illustration of early preparation; a 10% value is used only as an assumed performance boundary. A DF requirement of 100 would make both values unsuitable.

4.2 Measurement and actuation margins

Let $U_{b,i}$ bound underestimation of breakthrough, $r_{b,i}$ bound its positive rate of increase, and T_{act} include sample transport, counting/integration, confirmation, logic and valve response. A candidate measured action setting must satisfy:

$$b_{act,i} \leq b_{lim,i} - U_{b,i} - r_{b,i} T_{act} \quad (6)$$

Equation (6) is a conservative linear margin rule, valid only if those bounds remain applicable over T_{act} . It must not be used for an unbounded step change or extrapolated beyond tested conditions. Earlier direct chemistry or safety isolation overrides the trend rule.

Worked example — assumed values, not recommended settings.

Assumed input	Value
True boundary b_{lim}	0.10
One-sided bound U_b	0.01 (1 percentage point)
Positive slope bound r_b	0.02 h^{-1}
Total delay T_{act}	0.5 h
Maximum b_{act}	$0.10 - 0.01 - 0.02 \times 0.5 = 0.08$

Thus a 10% true boundary would require action at no more than 8% measured breakthrough in this example. A 5% warning provides 1.5 h to the 8% action setting at the assumed maximum slope; preparation must fit within that interval. No fixed persistence delay is authorized by this calculation.

Inlet/outlet data require matched calibration and correction for sampling and bed-transit delays. U_b must include counting, background, calibration and sampling effects. Near the inlet quantification limit, the ratio is indeterminate; a nondetect is not zero. Use qualified absolute-concentration limits and confirmatory sampling instead of interpreting a noisy ratio. Stable ions require species-appropriate chemical analyses; conductivity alone is not nuclide-specific. These provisions are consistent with monitoring and sampling guidance in Ref. [1, Sec. 7].

4.3 Captured inventory and independent limits

$$dA_{bed,i}/dt = Q(C_{in,i} - C_{out,i}) - \lambda_i A_{bed,i} \quad (7)$$

For C in Bq/m^3 , Eq. (7) gives activity in Bq; it is not a chemical-capacity or bed-life equation. Competing-ion equivalents, selectivity and ageing must be evaluated separately [2]. Any applicable chemistry, pressure-drop, dose, inventory, temperature or mechanical limit removes the bed from service; criteria are not averaged.

5. Boron Preservation and Qualification

5.1 Independent safety-isolation function

A safety-injection (SI) signal commands closure of every bed inlet and return isolation valve and latches BORATED MODE, without waiting for breakthrough confirmation or a boron sample. Anion and mixed beds can remove borate and must not deplete emergency negative reactivity; all-bed isolation is the selected conservative architecture. This safety-preservation function is distinct from normal purification optimization. The conventional CVCS review context is provided by NRC SRP 9.3.4 [5]; the present design still requires plant-specific safety analysis.

The original 50 ppm-B RCS indication is retained only as a candidate diverse backup, not a qualified safety setpoint. The 4,500 ppm-B design value describes borated injection inventory, not a guaranteed uniform RCS concentration. Neither number is validated by the normal-cleanup calculations.

Any bypass/storage path must exclude unqualified ion exchange and be separately assessed for accident routing. Restart requires signal reset, confirmed chemistry and independent operator authorization. Fail-closed behavior, isolation leakage, closure time, loss of instrument power, a stuck valve and common-cause failures require testing before safety credit.

5.2 Qualification gates and waste interface

Table 5. Required evidence before operating/safety credit; these activities are not reported as completed.

Evidence to obtain	Parameter / decision supported
Plant source terms and chemistry targets	S_i , $DF_{req,i}$, concentration limits
Representative tracer / mixing tests	Slow fraction f , exchange q_m , sample representativeness
Species-specific column tests over flow, chemistry, crud and ageing	$b_i(t)$, $r_{b,i}$, operational capacity and pressure drop
Detector and sampling qualification	$U_{b,i}$, quantification limit, transport and counting delays
Dynamic SI / valve / power-loss tests	Response time, leakage, latched isolation and safe restoration

The earlier 100/150 kPa differential-pressure values remain screening references only; actual settings require vendor hydraulic limits and flow-dependent clean-bed baselines. Spent-resin transfer retains the proposed shielded 30 m³ gross / 24 m³ working tank, with batch identity, capacity and radiation checks. Downstream solidification qualification is separate and cannot validate cleanup kinetics or setpoints.

6. Conclusions

The selective-bed concept is supported by a reproducible hierarchy of inventory balances rather than a single ideal exponential. Source-free mixed-volume cleanup remains a useful reference, but source floors and slowly exchanging volumes can change both target feasibility and the benefit of parallel-train operation. In the selected slow-mixing case, the two-train slow-volume cleanup time is 47.0 h, not the mixed-volume value of 18.6 h.

The 5% and 10% breakthrough values are not established as universal alarm or replacement criteria. Required DF and outlet chemistry determine the true limit; measurement error and response time require earlier action. The worked 10% boundary / 8% action example demonstrates the method, not an approved operating instruction.

The contribution is a quantitative, testable connection between normal cleanup performance, species-specific bed monitoring and independent emergency-boron preservation. Numerical consistency is demonstrated, but plant mixing, source terms, resin kinetics, detector performance and isolation behavior remain to be qualified. No validated resin life, construction readiness or licensing credit is claimed.

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