Flow Sensitivity of Reactivity Loss Caused by Delayed-Neutron Precursor Drift in a Molten-Salt Critical Experiment

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1. Introduction

In circulating-fuel molten-salt systems, delayed-neutron precursors are transported with the fuel salt. A fraction of the precursors can decay outside the active core, reducing the effective delayed-neutron fraction and producing a flow-dependent reactivity effect [1-5]. For a critical experiment intended to demonstrate this beta-effective loss, a larger external loop increases precursor residence time outside the core, but it also increases fuel-salt inventory and cost. The question of design is therefore not only whether the total loss is large, but whether a practical flow step produces a resolvable reactivity signal.

This study evaluates the preliminary sensitivity of a proposed molten-salt critical experiment using the MARINA six-group delayed-neutron data. The flow grid is fixed at 10% increments from 0 to 150% of nominal flow. The external-loop volume is expressed as a fraction of the core volume, because this ratio is a more direct measure of the additional fuel inventory than an absolute loop volume. The resulting pcm-scale reactivity discrimination is then compared with pump velocity resolution and with a separate detector-level count-rate requirement [7,8].

2. Methodology and Metrics

The reference core volume is 1.5 m3, the nominal volumetric flow rate is 0.03030 m3/s, and the salt density is 3300 kg/m3. The core flow area is 0.03030 m2, giving a nominal velocity of 1.0 m/s. The six delayed-neutron groups were taken from the MARINA calculation file and are summarized in Table I [9].

Table I: MARINA six-group delayed-neutron data used in the sensitivity calculation

Group	λi (s-1)	βi	Fraction (%)
1	0.0133663	0.0002219	3.01
2	0.0325244	0.0012159	16.51
3	0.12123	0.0012017	16.32
4	0.307416	0.0028526	38.74
5	0.867214	0.0013247	17.99
6	2.91278	0.0005467	7.42
Total	-	0.0073635	100.00

The core and external-loop residence times were calculated from the volumetric flow rate. For delayed-neutron group i, the precursor loss factor was evaluated using a steady-state residence-time approximation for a closed circulating-fuel loop [2-5].

$$\tau_c = \frac{V_c}{Q}, \quad \tau_L = \frac{V_L}{Q} \quad (1)$$

$$L_i = A_i B_i \quad (2)$$

$$A_i = \frac{1-e^{-\lambda_i \tau_c}}{\lambda_i \tau_c} \quad (3)$$

$$B_i = \frac{1-e^{-\lambda_i \tau_L}}{1-e^{-\lambda_i(\tau_c+\tau_L)}} \quad (4)$$

$$\beta_{eff}(Q, V_L) = \Sigma_i \beta_i (1 - L_i) \quad (5)$$

The reactivity signal was referenced to the nominal-flow state. A fixed 10% flow-step signal is denoted by S10%, and the pcm-scale discrimination condition is satisfied when S10% exceeds a candidate reactivity-resolution criterion Rρ.

$$\Delta\rho_{pcm}(Q) = 10^5[\beta_{eff}(Q) - \beta_{eff}(Q_{nom})] \quad (6)$$

$$S_{10\%}(f, V_L) = \mathrm{abs}[\Delta\rho(f + 10\%) - \Delta\rho(f)] \geq R_\rho \quad (7)$$

For the integrated sensitivity map, D10% is defined as the fraction of the 15 adjacent 10% flow steps in the 0-150% range that satisfy the pcm-scale criterion. This quantity is not a detector detection probability. A true detectability assessment requires the count-rate signal-to-noise ratio, including flux level, detector efficiency, background count rate, and integration time [7,8].

$$D_{10\%} = \frac{1}{N_{step}} \Sigma_j I[S_{10\%,j} \geq R_\rho] \quad (8)$$

$$\frac{\mathrm{abs}(\Delta C)}{\sigma_{\Delta C}} \geq k, \quad \frac{\sigma_C}{C} \approx N^{-1/2} \quad (9)$$

Table II: Definition of symbols used in the residence-time and reactivity-sensitivity model

Symbol	Definition
V_c	Fuel-salt volume in the core
V_L	Fuel-salt volume in the external circulation loop
Q	Volumetric flow rate
Q_{nom}	Nominal volumetric flow rate
τ_c	Core residence time
τ_L	External-loop residence time
λ_i	Decay constant of delayed-neutron precursor group i
β_i	Delayed-neutron fraction of group i
A_i	In-core residence-time correction factor
B_i	Out-of-core decay correction factor
L_i	Precursor loss factor for delayed-neutron group i
β_{eff}	Effective delayed-neutron fraction under flowing conditions
$\Delta\rho_{pcm}$	Reactivity change relative to the nominal-flow condition, in pcm
$S_{10\%}$	Reactivity signal for an adjacent 10% flow-rate step
R_ρ	Reactivity-resolution criterion
$D_{10\%}$	Fraction of 10% flow steps satisfying the reactivity-resolution criterion
I[*]	Indicator function; 1 if the condition is true and 0 otherwise
C	Detector count or count rate
ΔC	Change in detector count or count rate
σ_C	Standard uncertainty of the detector count or count rate
$\sigma_{\Delta C}$	Standard uncertainty of the count-rate difference
N	Accumulated number of counts
k	Statistical decision threshold or confidence-level multiplier

3. Results and Discussion

Figure 1 shows that increasing Vloop/Vcore increases the difference between the static-salt condition and nominal flow. At Vloop/Vcore=10%, the static-to-nominal signal is 39.9 pcm. At Vloop/Vcore=150%, it increases to 110.8 pcm. The additional benefit becomes progressively smaller, which is important because the external-loop inventory grows in direct proportion to Vloop.

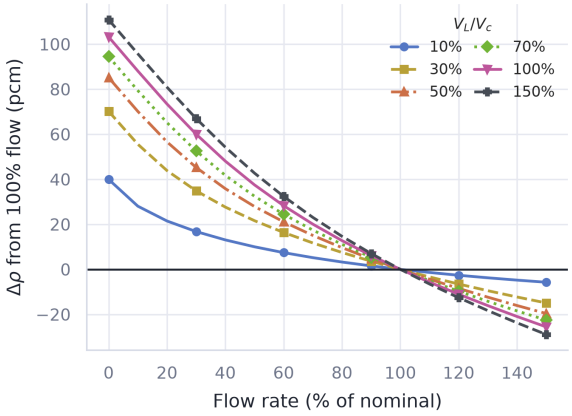


Fig. 1. Flow-dependent reactivity change caused by beta-effective loss for selected external-loop/core-volume ratios.

The adjacent 10% step signal, rather than the full static-to-flow difference, governs the experimental discrimination of a flow-step campaign. As shown in Fig. 2, the smallest step signals occur in the high-flow region. For Vloop/Vcore=10%, the minimum 10% step signal over 0-150% flow is only 0.95 pcm, whereas Vloop/Vcore=100% gives 4.61 pcm.

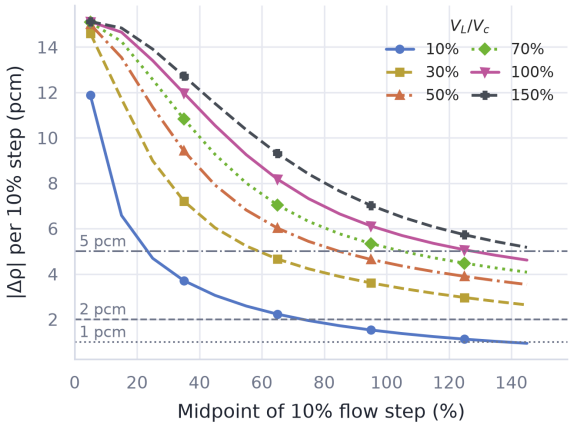


Fig. 2. Reactivity signal produced by adjacent 10% flow steps

Table III: Selected sensitivity results for the 10% flow-step campaign

Vloop/ Vcore (%)	Vloop (m3)	Salt mass (kg)	Static-nominal Δρ (pcm)	Min. step (pcm)	D10% at 3 pcm (%)
10	0.15	495	39.9	0.95	33
20	0.30	990	58.4	1.92	60
40	0.60	1,980	78.6	3.15	100
100	1.50	4,950	103.2	4.61	100
150	2.25	7,425	110.8	5.17	100

Figure 3 and Table IV translate the reactivity-discrimination criterion into the required external-loop/core-volume ratio. Over the full 0-150% flow range, all 10% steps exceed 2 pcm only when Vloop/Vcore is about 21% or larger. The corresponding requirements for 3 pcm and 5 pcm are about 37% and 132%, respectively.

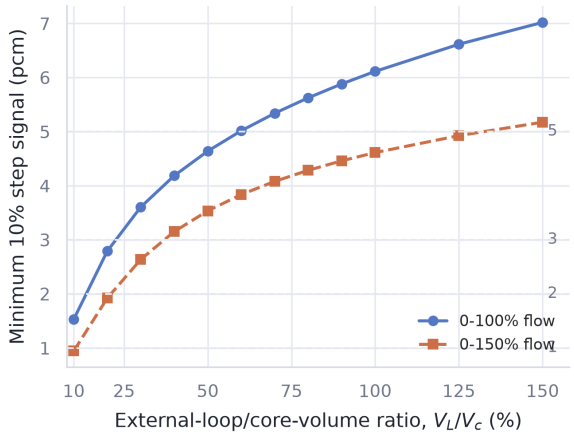


Fig. 3. Minimum 10% step signal as a function of external-loop/core-volume ratio.

Table IV: External-loop/core-volume ratio required for all 10% steps to exceed Rρ

Rρ (pcm)	Req. ratio 0-150% (%)	Salt mass 0-150% (kg)
1	10.5	521
2	21.0	1,039
3	36.7	1,818
5	132.0	6,533

The heat-map in Fig. 4 summarizes the interaction between loop inventory and the pcm-scale criterion. Color denotes D10%, the fraction of the fixed 10% flow steps that exceed Rρ. The dotted gray, dashed orange, and solid black contours mark D10%=0.5, 0.8, and 1.0, respectively. Because D10% is based only on calculated reactivity separation, it must not be interpreted as the probability that a detector will resolve the step.

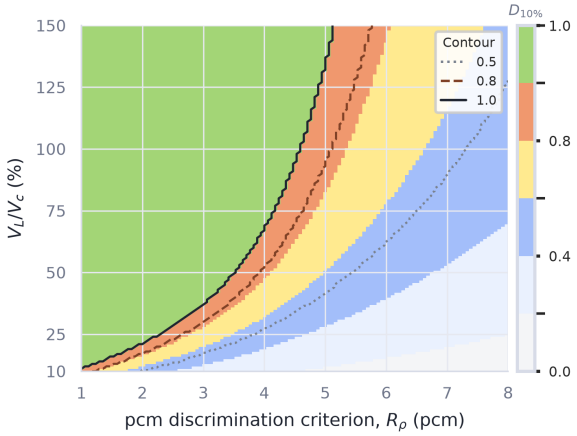


Fig. 4. Integrated pcm-step coverage for the 10% flow-step campaign (contours: D10%=0.5, 0.8, and 1.0)

The pump must also implement the selected flow grid. With the present area and nominal velocity, a 10% flow increment corresponds to a pump velocity increment of 0.10 m/s. At Vloop/Vcore=100%, a 0.05 m/s increment gives only 2.89 pcm near nominal flow, while the 10% increment gives 5.69 pcm. Thus, pump resolution, pcm-

scale discrimination, and detector count-rate sensitivity must be treated as simultaneous constraints.

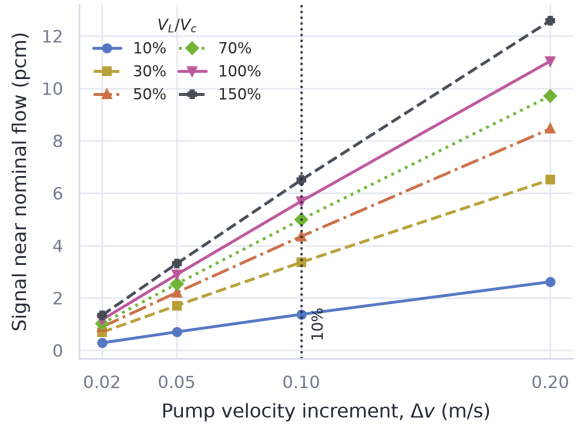


Fig. 5. Reactivity signal near nominal flow for selected pump velocity increments.

4. Conclusions

A preliminary closed-loop residence-time model was used to estimate the reactivity signal caused by flow-dependent beta-effective loss in a molten-salt critical experiment. For MARINA delayed-neutron data, Vloop/Vcore=10% gives a static-to-nominal signal of 39.9 pcm but a minimum 10% step signal of only 0.95 pcm over the 0-150% campaign. To make every 10% step exceed 2 pcm, 3 pcm, and 5 pcm over the same range, the required Vloop/Vcore values are approximately 21%, 37%, and 132%, respectively.

The results show that increasing external-loop volume is effective but inventory-limited. If the achievable Rρ is several pcm, a core-sized or larger external loop may be required; alternatively, the experiment should consider larger or nonuniform flow steps, a restricted flow range, repeated measurements, or regression-based estimation. Finally, pcm-scale separation alone is not a detector-level proof. A final design should couple this reactivity model to flux, detector efficiency, background rate, and integration-time statistics before claiming experimental detectability [7,8].

Acknowledgements

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