

Partial-Group Operation of External Control Drums for Long-Life Fast Molten Salt Reactors

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withdrawal is blocked; when necessary, motion is permitted only in the negative-reactivity direction.

1. Introduction

Long-life fast molten salt reactors must compensate for long-term reactivity changes caused by variations in fuel-salt composition, fission-product buildup, and temperature conditions while maintaining multiple independent shutdown functions. B₄C-pad control drums located in the external reflector can reduce in-core structural requirements; however, their differential worth with respect to rotation angle is nonlinear and they interact through neutronic coupling [1,2]. Accordingly, safety should be assessed not simply from the number of drums, but also from permissible in-service position patterns, reactivity insertion rates, and withdrawal worth during accident conditions.

Under the baseline strategy, the eight control drums excluding the four shutdown drums are moved through the same angle to distribute and compensate the initial excess reactivity. This approach offers symmetry and procedural simplicity and avoids keeping individual drums deeply inserted, thereby reducing the potential reactivity worth of an inadvertent single-drum withdrawal. Conversely, uniform use of all drums limits the flexibility to allocate end-of-life control margin, equalize actuator usage, diagnose position errors, and assign fine/coarse control roles.

This study presents a conceptual design framework comparing uniform operation with two four-drum partial groups under the following conditions: 25 EFPY(Effective Full Power Year) of operation, 12 external drums (four shutdown drums and eight operating drums), an initial operating-drum angle of 120°, and an end-of-life angle of 0°. The framework organizes the intergroup angle difference calculated directly from the operating trajectories and separates the verification items needed for implementation: single-drum and group withdrawal worth, total reactivity insertion rate, and shutdown-margin verification for both the SD system and individual control drums.

2. System Configuration and Evaluation Method

2.1 Control-Drum Configuration and Operation

Figure 1 and Table I identify the drum numbering and groups. The shutdown drums (SD) are CD-01, 04, 07, and 10, arranged at 90° intervals and not used for normal operating control. The operating drums comprise interleaved G1 (CD-02, 05, 08, and 11) and G2 (CD-03, 06, 09, and 12). The four drums in each group receive the same target rotation-angle command, whereas actual position and drive status are independently fed back and monitored for each drum. If the difference between target and actual angle exceeds the allowable range, group motion is stopped or further

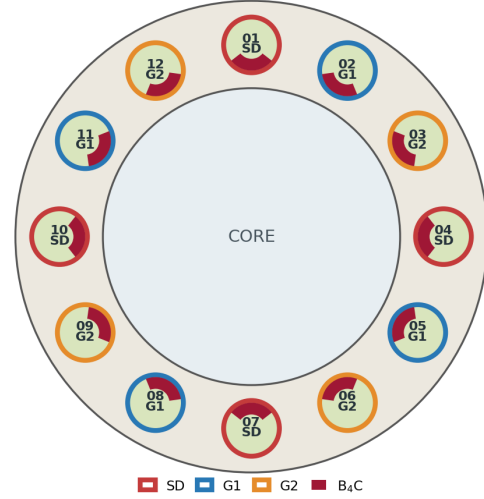


Fig. 1. Conceptual group arrangement of 12 external control drums (SD: shutdown drum; red pad: B₄C; not to scale).

Table I: Control-drum group configuration, operating function, and shutdown-margin role

Group	Drum IDs	Operating function and shutdown-margin role
SD	01, 04, 07, 10	Primary shutdown function; N-1 shutdown-margin assessment
G1	02, 05, 08, 11	Normal control; verify individual-drum shutdown margin
G2	03, 06, 09, 12	Normal control; verify individual-drum shutdown margin

Table II: Operating and safety characteristics of uniform and partial-group operation

Basis	8-drum uniform operation	4+4 partial-group operation
Reactivity	Eight-drum sharing; lower residual single-drum withdrawal worth	Common/differential control; higher worth possible for an inserted group
Operation / diagnostics	Simple command and verification procedure	Fine/coarse roles; individual feedback and role alternation
Shutdown margin	Verify SD and each control drum individually	Verify SD/CD margins and group position pattern
Operational constraint	No differential degree of freedom	State-dependent limits; more complex worth and procedures

2.2 Common and Differential Control Coordinates

Drum angle is defined to decrease as the absorber moves from the A state, in which it faces the core, toward the withdrawn W state. Thus, 120° represents the beginning-of-life inserted state and 0° represents the fully withdrawn state. The average angle θ_c and differential angle θ_d of the two groups are defined as follows.

$$\theta_c = \frac{1}{2}(\theta_{G1} + \theta_{G2}), \quad \theta_d = \frac{1}{2}(\theta_{G1} - \theta_{G2}) \quad (1)$$

θ_c compensates for long-term excess reactivity, whereas θ_d provides role sharing and reallocation of control margin. The reference mean trajectory is

defined as follows so that both groups are fully withdrawn simultaneously at 25 EFPY.

$$\tilde{\theta}(t) = 120(1 - t/25) \text{ [deg]}, \quad 0 \leq t \leq 25 \text{ EFPY} \quad (2)$$

Differential operation, in which G1 and G2 move in opposite directions, does not necessarily imply reactivity neutrality. Control-drum worth for the two groups varies with burnup, temperature, fuel-salt composition, and neutronic interaction among the drums. The automatic controller should use group differential worth calculated for the current reactor state to predict the total reactivity change after a group motion and dynamically limit the allowable intergroup angle difference accordingly.

$$\Delta\rho_{\text{pred}}(x) = g_{G1}(x)\Delta\theta_{G1} + g_{G2}(x)\Delta\theta_{G2} \quad (3)$$

2.3 25-Year Partial-Group Scenarios

The comparison includes a uniform baseline and four partial-group cases. Case 1 is a safety-first option that applies a $\pm 10^\circ$ differential deviation about the mean trajectory and resynchronizes at 12.5 EFPY. Case 2 is a fixed shim-trim option that assigns G1 to fine control and G2 to coarse/reserve control. Case 3 alternates the lead group every five years. Case 4 keeps one group in reserve during the latter half of life and is an upper-bound case for risk comparison.

Table III: Twenty-Five-Year Operating Scenarios and Angle Differences

Case	Angle trajectory / max G1-G2	Design intent
Uniform	$G1=G2=\tilde{\theta} / 0^\circ$	Symmetry; minimum complexity
Case 1	$\tilde{\theta} \pm 10\sin(2\pi t/25) / 20^\circ$	Bounded differential; midlife alternation
Case 2	$\tilde{\theta} \pm 22\sin(\pi t/25) / 44^\circ$	Fixed shim-trim
Case 3	Five-year cycle, $\pm 12^\circ / 24^\circ$	Balance actuator roles
Case 4	G1: years 0-15, G2: years 8-25 / 70.6°	Reserve-bank bounding case

Under the uniform baseline, all eight drums are synchronously controlled, prioritizing symmetry and distribution of withdrawal worth but providing limited role differentiation. Case 1 uses the most conservative strategy, with a small differential angle and midlife resynchronization. Case 2 separates G1 trim control from G2 shim/reserve duty, but requires strict control of G2 residual withdrawal worth. Case 3 equalizes actuator usage through five-year role alternation but strengthens handover and verification procedures. Case 4 is a bounding option that secures control reserve in the latter half of life but is not recommended for normal application because large intergroup angle differences increase the withdrawal-worth burden.

3. Results and Discussion

3.1 Comparison of Operating Trajectories

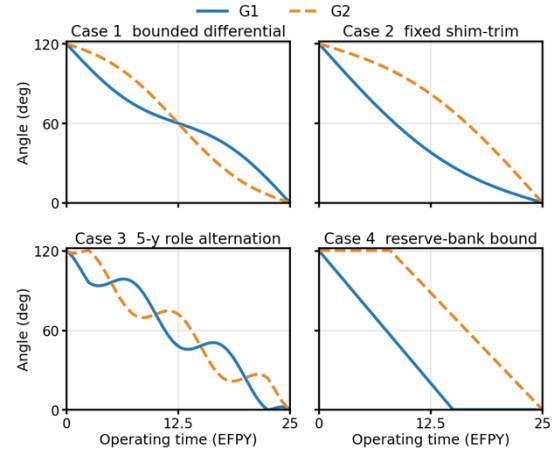


Fig. 2. Twenty-five-year G1/G2 rotation-angle trajectories for four partial-group operating cases.

In Fig. 2, Cases 1 and 3 periodically return to $\theta_d = 0$, providing clear position verification and lead-role handover. In Case 1, the maximum intergroup difference is limited to 20° , so roles may be exchanged around midlife without materially compromising the symmetry of the uniform baseline. Case 2 maintains a maximum offset of 44° , which clearly distinguishes fine and coarse control functions, but can increase the single-drum and simultaneous four-drum withdrawal worth of the more deeply inserted G2. In Case 4, the difference reaches 70.6° , providing a control reserve in the latter half of life but creating the greatest burden for a group-withdrawal accident.

These values are calculated directly from the prescribed angle trajectories and are not reactivity results. Because control-drum worth curves are nonlinear with angle and core state, and differences among analysis codes for partially rotated states have been reported [3], the merits of the cases cannot be determined from angle difference alone.

3.2 Overall Comparison of Operating Strategies

Table IV compares the roles, benefits, and constraints of the uniform baseline and four partial-group cases on the same basis. Evaluation of an operating strategy should not be determined solely by the magnitude of the intergroup angle difference; it must also meet requirements for state-dependent reactivity-prediction error, single- and four-drum withdrawal worth, shutdown margins for the SD system and individual control drums, and drive-system reliability. The adoption criterion for partial-group operation is therefore not a large differential angle, but whether the operating and maintenance benefits achieved within a bounded differential range outweigh the added verification burden.

Table IV: Overall comparison of uniform and partial-group operating scenarios

Case	$\Delta\theta$ max	Role / benefit	Risk / constraint
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Case	$\Delta\theta$ max	Role / benefit	Risk / constraint
Uniform	0°	Eight-drum synchronous control; symmetry, simple procedure, distributed worth	Limited fine/coarse role allocation
Case 1	20°	Bounded differential and midlife resynchronization; most conservative	State-dependent reactivity compensation and monitoring needed
Case 2	44°	G1 trim, G2 shim/reserve; separated control functions	Higher G2 single-/four-drum withdrawal worth possible
Case 3	24°	Five-year role alternation; balanced actuator loading	Complex role-transfer and verification procedures
Case 4	70.6°	Latter-life control reserve	Highest group-withdrawal and non-neutrality burden

3.3 Accident and Shutdown-Margin Evaluation

The allowable region for partial-group operation is first limited by single-drum and group withdrawal worth at every burnup, temperature, and salt-composition state x_t . The first quantity is the reactivity worth of inadvertent withdrawal of any operating drum from its current position to 0°; the second is the group withdrawal worth when the four drums of G1 or G2 move to 0° because of a common cause. Separately, the SD system and each control drum should be designed and verified to satisfy independent shutdown-margin requirements.

$$\Delta\rho_{i,}(t) = \rho(\theta_i \rightarrow 0, x_t) - \rho(\theta_i, x_t) \quad (4)$$

$$\Delta\rho_{g,}(t) = \rho(\theta_g \rightarrow 0, x_t) - \rho(\theta_g, x_t) \quad (5)$$

Each accident should be assessed with a transient analysis that combines control delay, maximum rotation speed, temperature feedback, circulating-fuel dynamics, and total reactivity insertion rate. High-fidelity analyses of inadvertent control-drum rotation likewise identify the coupling of rotation-speed-dependent reactivity insertion and temperature feedback as key variables [4]. Shutdown margin should be confirmed by treating the primary shutdown-drum system and the control-drum system as independent shutdown paths, including single-failure conditions at the allowable state of maximum reactivity [5].

$$SDM_{SD,N-1} = -\rho(\theta_{SD}, SD^*; x_{max}) \geq SDM_{req,SD} \quad (6)$$

$$SDM_{CD,i} = -\rho(\theta_{CD,i}; x_{max}) \geq SDM_{req,CD} \quad (7)$$

The final differential limit is set to the minimum value permitted by single- and group-withdrawal worth, shutdown margins for the SD system and individual control drums, the allowable dynamic reactivity insertion rate, drive speed, and mechanical limits. That is, $\theta_{D,max}(x) = \min(\theta_{p1}, \theta_{p4}, \theta_{SDM}, \theta_{dyn}, \theta_{mech})$; this map is generated in advance using full-core Monte Carlo/diffusion calculations and representative transient analyses.

3.4 Automatic Control and A↔W Transition

At the conceptual-design stage, Case 1 is the preferred option. During normal operation, the θ_D target is maintained near 0°, with a $\pm 10^\circ$ deviation (20° between groups) used as a provisional upper bound; it is reduced to 0° at beginning and end of life in consideration of mechanical end stops and worth gradients. The long-term reactivity demand is reflected in the θ_c target. Fine A↔W transitions are performed

under supervisory control: only one group at a time moves in the positive-reactivity direction by a bounded step $\Delta\theta_{step}$, after which the reactor period, predicted total reactivity, and group and individual position deviations are checked.

At the 12.5-EFPY role change, the two groups are first resynchronized, and lead-group authority is transferred after position verification. If command-feedback disagreement, a single-drum stuck condition, or an unanticipated reactivity insertion occurs, further withdrawal is blocked and the system either holds its current position or permits only motion in the negative-reactivity direction. Reactor-trip signals and drive logic are separated from the group-operation controller, and independent verification paths are maintained for the primary shutdown-drum system and for the shutdown margin of each control drum.

4. Conclusions

For a long-life fast MSR(Molten Salt Reactor) operating for 25 years, configurations with four shutdown drums and eight operating drums were compared for 12 external control drums under uniform full-bank operation and 4+4 partial-group operation. Uniform operation provides a clear baseline in terms of symmetry, procedural simplicity, and distribution of individual withdrawal worth. Partial-group operation offers flexibility for fine/coarse role assignment, in-life role alternation, control reserve, and fault diagnosis, but can increase single- and group-withdrawal worth for the more deeply inserted group. Moreover, grouping itself does not substitute for the demonstration of shutdown margin; the SD system and each control drum must independently demonstrate their shutdown margins.

Accordingly, Case 1, which maintains the same mean angle as the uniform baseline, limits the intergroup difference to 20°, and resynchronizes at midlife, is suitable as an initial operating strategy. The 20° value, however, is an exploratory range rather than a design value. Final adoption should be determined through lifetime state-dependent differential and integral worth maps, transients for inadvertent single- and four-drum withdrawal, total reactivity insertion rate, shutdown margins for the SD system and individual control drums at the maximum-reactivity state, and common-cause failure analysis of the drive system.

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