Similarity Analysis between the MARINA(Molten Salt Reactor) and a Critical Experiment Facility Using Neutron Spectrum-Based Indices and the Sensitivity/Uncertainty Method

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1. Introduction

A critical experiment facility is being developed to validate the neutronic design methods and tools for the MARINA molten salt reactor (MSR), a fast-spectrum system fueled by a NaCl–KCl-UCl_3 based molten salt. To justify the use of such a facility for design-code validation and licensing, the degree of similarity between the facility and the target reactor must be quantified rather than assumed from qualitative features such as fuel type or enrichment.

The sensitivity/uncertainty (S/U) based correlation coefficient c_k is widely used for this purpose, but because it is derived from the sensitivity of k-eff to nuclear-data uncertainties, it can indicate a high similarity even between systems of quite different composition [1,2]. To complement this limitation, neutron spectrum-based indices have been proposed [3]. In this study the similarity between the MSR reactor and its critical facility is evaluated with c_k—including its E and G components resolved by reaction—and four spectrum-based indices (Index S, PCC, Cosine, JSD), with EALF as a complementary parameter, all computed with SCALE 6.3.1.

2. Methods

2.1. Computational models and geometry

Both systems were modeled with SCALE 6.3.1 using the continuous-energy (CE) ENDF/B-VII.1 library at 853 K, and the k-eff, 252-group flux spectrum, and EALF were obtained from the KENO-VI criticality sequence (CSAS6). Both cores share the same NaCl–KCl molten-salt fuel and MgO radial reflector with rotating B_4C control drums, but differ appreciably in size and shape: the MSR core has a fuel-bearing height of 432 cm with hemispherical end caps, whereas the critical facility is a compact 234 cm cylinder, giving a fuel-volume ratio of about 2.2. Figs. 1 and 2 show the geometry of the two systems, and Table 1 lists the principal parameters. The main fuel region was used consistently for spectrum extraction.

2.2. Sensitivity/uncertainty-based similarity

The S/U correlation coefficient c_k describes the correlation between two systems based on the sensitivity of k-eff to energy-dependent, nuclide-reaction-specific cross-section data propagated through the covariance matrix. It is a form of Pearson correlation bounded between −1 and 1; a value near 1 indicates that the systems respond similarly to nuclear-data perturbations. Sensitivity data files (SDFs) were generated for each system with TSUNAMI-3D, and c_k was computed with TSUNAMI-IP using the 252-group ENDF/B-VII.1 covariance library, treating MSR as the application and the critical facility as the experiment. TSUNAMI-IP also provides the sensitivity-only index E and the covariance-weighted index G, each resolved into fission, capture, and scattering contributions.

Parameter	MSR	Critical Ex.
Fuel salt	NaCl–KCl-UCl_3	
Fuel radius (cm)	76.0	70.0
Fuel-bearing height (cm)	432	234
Fuel shape	cyl.+hemi.	cylinder
Fuel-volume ratio	~2.2	1
MgO refl. o.r. (cm)	121.9	110.4
Vessel o.r. (cm)	134.4	115.4
Reflector/absorber	MgO/B_4C	MgO/B_4C
k-eff	1.06403	1.06383

Table 1. Geometry and core parameters of the two models.

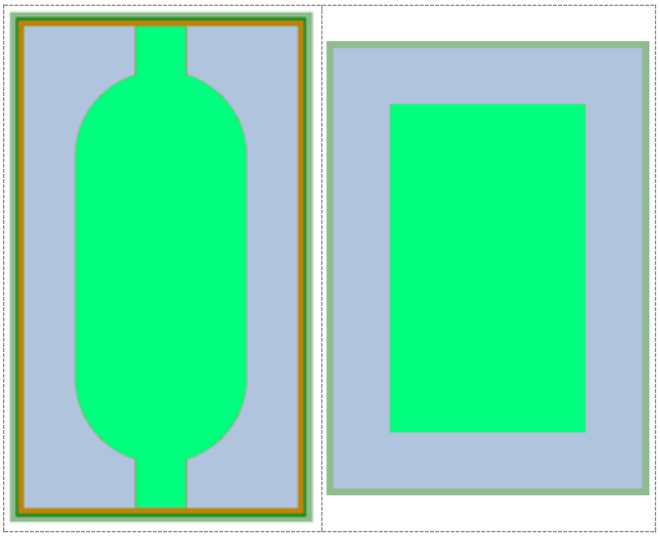


Fig. 1 (left) MSR core; Fig. 2 (right) critical experiment facility.

2.3 Neutron spectrum-based indices

Four indices were computed from the normalized 252-group flux vectors p and q. The Cosine metric is defined in Eq. (1):

$$\cos\theta = (A \cdot B) / (\|A\|\|B\|) \qquad (1)$$

The Pearson product-moment correlation coefficient (PCC) applies Eq. (1) after subtracting the mean of each spectrum. The Jensen–Shannon divergence (JSD, base 2) is given in Eq. (2), where M = (p+q)/2:

$$JSD(P\|Q) = \tfrac{1}{2}\Sigma\, p \log_2(p/M) + \tfrac{1}{2}\Sigma\, q \log_2(q/M) \qquad (2)$$

JSD is symmetric and bounded within [0,1]; 0 denotes identical spectra. Index S, the average weighted min-max ratio, is defined in Eq. (3) with weight w = (p+q)/2:

$$S = \Sigma\, w \cdot \min(p,q)/\max(p,q) \qquad (3)$$

For Index S, PCC, and Cosine, unity denotes identical spectra. To align the direction of JSD, the similarity form (1 − JSD) is also reported. Unlike Cosine and PCC, which are dominated by the largest flux components, Index S weights every group by its average share and retains sensitivity to differences in the low- and intermediate-energy tails.

3. Results and Discussions

3.1. Neutron spectrum comparison

Fig. 3 compares the normalized neutron spectra in the main fuel region. Both exhibit a hard, fast spectrum peaking near 0.5–1 MeV and nearly overlap over the full range. The fast-neutron fraction (>100 keV) is 0.673 for MSR and 0.660 for the critical facility, the epithermal fraction is 0.326 and 0.338, and both thermal fractions are below 0.2 %. The total variation between the two normalized spectra is only 0.024, confirming a high degree of spectral agreement despite the ~2.2-fold difference in fuel volume and the different core shape.

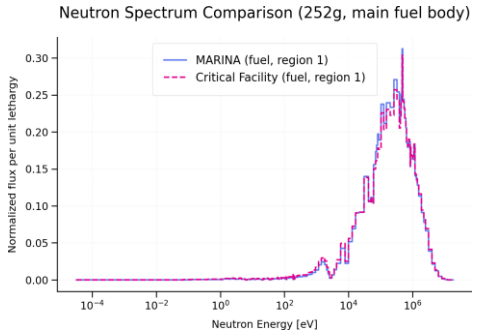


Fig. 3. Neutron spectrum comparison (252-group, main fuel region).

3.2. Integral similarity indices

Table 2 summarizes the integral indices. The S/U correlation coefficient is very high (c_k = 0.9985 ± 0.0013), well above the 0.90 threshold commonly recommended for criticality-safety validation. The four spectrum-based indices are likewise high, confirming that the facility faithfully reproduces the MSR spectrum. Among them, Index S (0.9547) provides the strongest discrimination, whereas Cosine (0.9993) and PCC (0.9992) are saturated close to unity because they are dominated by the large flux components near the spectral peak; the raw JSD is 0.0011 (1 − JSD = 0.9989). This is consistent with the reference study [3] and indicates that Index S and JSD are the more sensitive discriminators for fast-spectrum systems.

Index	MSR vs Critical
c_k (S/U)	0.9985 ± 0.0013
E (sensitivity)	0.9934 ± 0.0028
G (cov-weighted)	0.9335 ± 0.0143
Index S	0.9547
PCC	0.9992
Cosine	0.9993
JSD (raw)	0.0011
1 − JSD	0.9989
EALF, MSR	1.555×10^4 eV
EALF, Critical	8.626×10^3 eV

Table 2. Integral similarity indices between the two systems.

3.3. Reaction-wise E and G components

Table 3 breaks E and G into fission, capture, and scattering contributions. The fission and capture channels dominate: E(fis) = 0.9980 and E(cap) = 0.9962 are close to unity, and G(fis) = 0.9353 and G(cap) = 0.9308 remain above 0.93. In contrast, the scattering channel is much lower—E(sct) = 0.7993 with a very large standard deviation (2.58)—and G(sct) is effectively zero. The elastic-scattering sensitivities, dominated by the light salt constituents (Na, Cl, K) and the MgO reflector, are only weakly correlated through the covariance data and contribute little to the overall k-eff sensitivity. Thus the total G (0.9335) is governed almost entirely by fission and capture, which explains why G is lower than E and c_k, and confirms that the strong overall similarity is driven by the fissile/absorbing nuclides shared by both systems.

Component	E	G
Total	0.9934	0.9335
Fission	0.9980	0.9353
Capture	0.9962	0.9308
Scatter	0.7993	0.0000

Table 3. Reaction-wise components of the E and G indices.

Finally, the EALF values differ by a factor of about 1.8 (1.555×10^4 vs 8.626×10^3 eV). Although the normalized flux spectra are nearly identical, the EALF is weighted by the fission cross section, which rises steeply at lower energies, so small differences in the low-energy tail are amplified. The EALF is therefore retained only as a complementary indicator, in agreement with traditional practice.

4. Conclusions

The similarity between the MSR and its critical experiment facility was quantified with SCALE 6.3.1 using c_k and four neutron spectrum-based indices. Despite a ~2.2-fold difference in fuel volume and a

different core shape, the high c_k (0.9985) and spectrum indices (Index S = 0.9547, Cosine = 0.9993, PCC = 0.9992, 1 − JSD = 0.9989) consistently demonstrate that the compact facility adequately represents the target reactor. The reaction-wise decomposition showed that fission and capture (E ≈ 0.996–0.998, G ≈ 0.93) drive the similarity, whereas the weakly correlated scattering channel lowers the total G. Among the spectral metrics, Index S offered the best discrimination. These results provide a quantitative basis for using the critical facility in the validation and licensing of the MSR neutronic design methods.

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