

Assessment of Radionuclide Inventory Effects on Atmospheric Dispersion

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1. Introduction

Uranium-235 enrichment above 5% is being considered for PWR-SMRs to support higher discharge burnup and longer fuel cycles. Changes in enrichment and irradiation history can alter the radionuclide inventory and composition. Therefore, the offsite radiological consequences of the resulting core configurations should be evaluated directly rather than inferred from enrichment alone.

We compared a reference low-enriched uranium (LEU) core with a supplied LEU+ core configuration at 6% enrichment using MACCS. The two configurations differ in both radionuclide composition and release history, so the comparison concerns two specific core and accident-input combinations rather than an enrichment-only experiment. We then extended the single-module comparison with a simplified two-module sensitivity study, in which a second copy of the same fuel-specific input was introduced with a prescribed time offset. This tests whether the relative LEU/LEU+ difference persists when the assumed number and timing of releases change.

The distinction matters for emergency planning. The performance-based framework in 10 CFR 50.33(g)(2) considers accident likelihood, source term, release timing, and meteorology, together with the need for predetermined prompt protective measures [1]. Regulatory Guide (RG) 1.242 addresses event selection and frequency-based screening [2]. A computed consequence does not establish that its assumed accident combination is likely enough to be retained for emergency planning zone (EPZ) sizing. Our objective is therefore limited: compare conditional consequences, and state what additional evidence a frequency-informed interpretation would require.

Across the single-module baseline and all six timing cases, LEU+ mean doses remained roughly 38% below the matched LEU values. The following sections describe how that result was obtained and how far it can be carried.

2. Methods and Results

2.1 Supplied single-accident inputs

Core inventories and CINEMA [5] release histories were supplied for one representative less-severe accident

sequence per fuel configuration, with containment integrity maintained in the source-term calculations. Our contribution comprises MACCS input preparation, consequence calculation, and comparative interpretation. Independent source-term generation and validation of the in-containment retention mechanisms lie outside this scope.

The inventories were mapped to 11 MACCS chemical groups, and the release histories were represented by nominal one-hour plume segments: 92 segments for LEU and 93 for LEU+. Total radioactive inventory in the LEU+ core was about 3% higher, but the increase was nuclide dependent. The supplied LEU+ inventory is therefore not equivalent to multiplying the LEU inventory uniformly by 1.03. Only the containment-intact release family is examined here.

2.2 Consequence model and comparison basis

Atmospheric transport and early-phase doses were evaluated with the ATMOS and EARLY modules of MACCS 5.2 [3,4]. The principal calculations used 96-h emergency-phase dose-in-place settings, without credit for evacuation, sheltering, or relocation. Within each matched comparison, meteorological, dispersion, deposition, exposure, and dose-model inputs were held common between the fuels. A representative dry-deposition velocity of 0.01 m/s was used in place of a group-specific velocity set, and release heat was unavailable for a plume-rise treatment.

The two-module calculations retained the existing Gaussian transport configuration: IPLUME=3, the NEW meander option, the automatic area-source option, and the BRGBLD trapping and downwash treatment. The reference source representation was fixed throughout.

Reported means are statistics over meteorological trials, not calculations at an arithmetic-average wind speed. For the two-module results the quantity is the meteorological mean of the spatial-grid peak-dose statistic within a specified radial interval. It is not an area-average dose in an annulus, nor the exposure of a particular individual at the outer boundary.

2.3 Single-module baseline and release-fraction control

The single-module baseline used the larger of two criterion-crossing distances: 96-h mean total effective dose equivalent (TEDE) of 1 rem (0.01 Sv), and 96-h 95th-percentile TEDE of 5 rem (0.05 Sv). The

comparative candidate distance was

$$R^* = \max\{R(\text{mean}, 1 \text{ rem}), R(P95, 5 \text{ rem})\} \quad (1)$$

These are screening indicators for the present less-severe comparison rather than a complete implementation of regulatory EPZ determination. For consistency with the reporting convention used in this study, criterion-crossing results were summarized in 0.1-km distance intervals, and the upper end of the corresponding reporting interval was retained as the comparative candidate distance.

Table I: Single-module 96-h candidate distances

Fuel	Mean 1 rem (km)	P95 5 rem (km)	R* (km)
LEU	0.5–0.6	0.3–0.4	0.6
LEU+	0.4–0.5	0.2–0.3	0.5

The mean 1-rem criterion controlled both baseline results. With fuel-specific release histories, LEU+ gave the smaller candidate distance despite its higher total inventory. Applying the LEU release fractions to both inventories moved both cases into the same crossing interval, 0.5–0.6 km at 96 h and 0.3–0.4 km at 24 h. Equal intervals do not imply equal underlying doses; the inventory difference alone did not shift the result across an interval boundary at this resolution.

A complementary 21-run study scaled the LEU inventory uniformly by factors $SF = 1.0\text{--}3.0$ in increments of 0.1, giving empirical fits $R96 = 0.325 + 0.240 SF$ and $R24 = 0.202 + 0.127 SF$ with distances in kilometers. Uniform scaling preserves the reference nuclide mixture, whereas the LEU+ input changes it. Read together, the control and scaling results attribute the baseline difference to the supplied inventory-and-release combination rather than to enrichment alone.

2.4 Two-module construction

Multi-unit Level 3 PSA generally requires consequence results for multi-unit accident combinations to be linked with their corresponding scenario frequencies [6]. For each fuel, the single-module input was copied to represent a second nominally identical module. Module 1 retained its reference initiation time and Module 2 received an offset of 0, 6, 24, 36, 48, or 72 h, denoted DT00 through DT72. Including M1 for each fuel gives 14 matched cases. The combined inputs contain 184 plume segments for LEU and 186 for LEU+, with source timing processed through the existing MACCS multi-source workflow.

The duplication preserves the prescribed inventories and segment release assumptions, and no second CINEMA calculation was performed. Both modules are therefore forced to experience the same type of containment-intact release, differing only in onset. This is an equivalent-source consequence exercise, not a site-layout-resolved accident model: inter-module separation, shared systems, resource competition, and accident propagation are all absent.

The six offsets are sensitivity points, not a probability distribution of accident delays. They carry no assigned occurrence probabilities and must not be summed as independent contributions to annual risk. DT00 represents complete temporal coincidence of the prescribed releases, but a different and more severe release combination could exceed it.

2.5 Matched fuel and timing indicators

Let $D(f, s, j)$ denote the reported mean dose for fuel f , timing case s , and radial interval j . The fuel-comparison indicator is

$$F(s, j) = D(\text{LEU+}, s, j) / D(\text{LEU}, s, j) \quad (2)$$

with percentage reduction $100[1 - F(s, j)]$. Two-module amplification is $D(f, s, j)/D(f, M1, j)$, and delay reduction relative to coincidence is $100[1 - D(f, s, j)/D(f, DT00, j)]$. These are ratios of reported means, not means of trial-by-trial ratios.

Table II and Fig. 1 use the 450–550 m radial interval, which appears as 0.5–0.6 km in the rounded output summary. Input-grid boundaries rather than display labels define the interval. This bin illustrates the paired comparison without emphasizing the extreme first 0–50 m bin.

Table II: Two-module 96-h mean doses at 450–550 m

Case	LEU (Sv)	LEU+ (Sv)	Reduction (%)
M1	0.0110	0.00685	37.7
DT00	0.0220	0.0137	37.7
DT06	0.0216	0.0134	38.0
DT24	0.0195	0.0121	37.9
DT36	0.0180	0.0112	37.8
DT48	0.0165	0.0103	37.6
DT72	0.0134	0.00839	37.4

Within this interval, LEU+ doses are 37.4–38.0% below the matched LEU values, and the ratio stays near 0.62 from M1 through DT72. At DT00, doses are twice their respective M1 values. That factor of two is the expected consistency behavior when two identical sources are duplicated under common assumptions, not independent validation of multi-module accident physics.

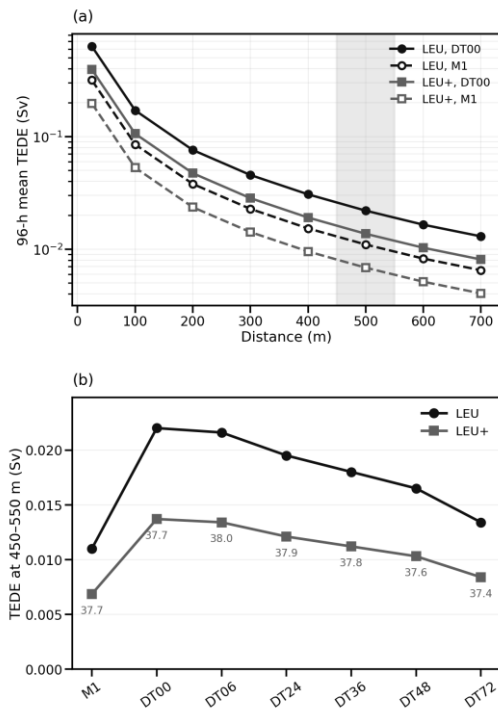


Fig. 1. Comparison of 96-h mean TEDE for LEU and LEU+: (a) radial dose profiles; (b) two-module timing sensitivity at 450–550 m

For LEU, DT24, DT48, and DT72 give doses 11.4%, 25.0%, and 39.1% below DT00; the corresponding LEU+ reductions are 11.7%, 24.8%, and 38.8%. A 6-h offset changes the result by only 1.8% for LEU and 2.2% for LEU+, while DT36 reduces it by about 18.2% for both. The timing response is thus close to identical for the two fuels even though their absolute doses differ by nearly 40%. Figure 1(a) compares the radial dose profiles for M1 and DT00, while Fig. 1(b) shows the complete timing comparison within the 450–550 m interval. The finding is persistence of the fuel ordering within this restricted input family.

2.6 Interpretation of the finite evaluation horizon

The timing comparison retains the same 96-h emergency-phase settings. A longer offset changes how the prescribed release history and its radioactive evolution are represented relative to that horizon and to the sampled meteorological sequence. The observed reductions cannot be attributed exclusively to atmospheric separation of two plumes, and they do not translate into a comparable reduction in annual risk.

Separating the contributions of finite-horizon coverage, radioactive decay, weather sequencing, and spatial peak selection would require time-resolved or longer-horizon results with a verified time origin. Because the reported quantity involves a spatial maximum, subtracting the M1 mean from the two-module mean does not isolate the dose attributable to Module 2 at a common receptor: the statement that DT72

is 1.22 times M1 refers to the total reported statistic alone.

2.7 Accident frequency and screening applicability

These results are conditional consequences. No verified joint accident frequency has been assigned to the duplicated source combinations, and a frequency established for a single-module source-term category cannot be transferred merely because both are described as containment intact. Joint occurrence is also not obtained by squaring a single-module frequency, since the product of two annual rates omits the coincidence interval and the dependence structure. Shared initiating events, common-cause failures, and inter-module interactions require a joint-event model.

RG 1.242 Appendix A-3.1 calls for consideration of internal and external initiating events together with multi-module accidents and interactions, while Appendix B-3 requires a technical basis for excluding scenarios on grounds of low likelihood or long progression time [2]. The two-module combinations assumed here might be screened from quantitative EPZ sizing if a technically adequate PRA demonstrated sufficiently low frequencies under a justified screening approach. That demonstration is not part of this work.

2.8 Limitations

The restricted source-term basis is the principal limitation. Both nominal modules use the same supplied less-severe release history for their fuel, whereas actual joint accidents could involve different operating states, inventories, containment failures, or release pathways. The present analysis is not intended to bound more-severe accident combinations or releases from other onsite radioactive inventories.

The comparison also relies on one fixed atmospheric-model chain and meteorological dataset. Near-field model applicability, group-dependent deposition, release heat, and site-specific release geometry all remain relevant to absolute dose accuracy, and similarity of the paired fuel ratios does not demonstrate that these uncertainties cancel. For that reason, the baseline candidate distances and the two-module results are reported separately rather than pooled into a new EPZ determination.

3. Conclusions

We compared supplied LEU and 6% LEU+ inputs with MACCS, extending a single-module baseline to a deliberately simplified two-module release sensitivity. Baseline candidate distances were 0.6 km for LEU and 0.5 km for LEU+, and a common-release-fraction control placed both inventories in the same reported interval. These results concern the supplied accident-input combinations, not enrichment alone.

In the 450–550 m interval, LEU+ mean doses stayed 37.4–38.0% below LEU across M1 and all six timing cases. Coincident duplicated releases produced twice the

M1 dose, and delays of 24, 48, and 72 h reduced the reported mean by roughly 11%, 25%, and 39% relative to coincidence for both fuels under the retained 96-h settings. Within this simplified input family, the relative LEU/LEU+ difference was largely insensitive to the assumed module-release timing.

The two-module calculation resolves neither coupled accident progression nor the occurrence frequency of the assumed combinations. Low-frequency screening may prove appropriate after a qualified joint-scenario PRA and uncertainty assessment, but that case is not made here. What the results support is a persistent conditional fuel comparison within one prescribed release family — not a general safety ranking, a frequency-weighted site risk, or an approved EPZ determination.

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