

Burnup-Dependent Full-Core Sensitivity Analysis of PWR Fuel Performance to Fuel Properties and Design Parameters

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1. Introduction

Nuclear fuel development is a long-cycle, high-cost process that inherently involves a multiscale problem: small changes in material properties propagate through fuel-rod behavior and eventually affect system-level performance metrics in large light water reactors (LWRs). Even when the qualitative direction of material effects is known, quantitatively comparing their relative impact on system-level metrics remains challenging. Recent advances in fuel performance codes and computational resources have strengthened the foundation for systematically tracing these input–output linkages.

Previous studies have broadly presented sensitivity and uncertainty analysis methodologies, often under rod-scale or benchmark-oriented conditions [1,2]. However, studies that consistently integrate material-parameter effects across multiple Quantities of Interest (QoIs) under representative burnup conditions of large LWRs and translate them into decision-oriented prioritization are less commonly reported.

To address this gap, this study uses GIFT-based simulations to quantify how material-component variations influence system-level QoIs through local normalized sensitivity, while explicitly preserving burnup-dependent response behavior. Based on this framework, we identify QoI-specific dominant parameters, distinguish shared versus QoI-specific drivers, and organize the underlying design-interaction structure.

Accordingly, this study (i) provides a quantitative basis for material-to-performance coupling, (ii) identifies QoI-specific key drivers and prioritizes parameters for design and verification resource allocation, and (iii) improves the reproducibility and interpretability of LWR fuel design decision-making.

2. Methodology

We performed a core-wide QoI sensitivity analysis using GIFT code [3]; the overall procedure is summarized in Fig. 1. Here, QoI denotes the target output metrics of interest, specifically the peak values of Cladding Hoop Stress, Plenum Pressure, Fuel Centerline Temperature, Cladding Oxide Thickness, and Hydrogen Concentration during irradiation.

GIFT is an advanced multi-physics fuel performance code for LWR applications, designed to cover fuel

behavior from steady operation to spent-fuel storage conditions. Its modeling framework includes high-fidelity thermo-mechanical treatment, enabling physically detailed yet computationally practical analysis for large rod sets.

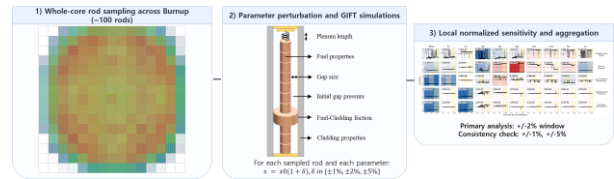


Figure 1. Workflow of the core-wide QoI sensitivity analysis using GIFT

As a first step shown in Fig. 1, we sampled 100 rods from the full core using quantile-based sampling to ensure approximately uniform discharge-burnup coverage across low-, mid-, and high-burnup regimes. This sample size was selected to balance representativeness and computational feasibility, with the total simulation requiring approximately 6–7 days on 20 CPU cores.

Table 1. Input parameters used for perturbation analysis, with definitions and abbreviations

Parameter	Abbr.	Parameter	Abbr.
Cladding corrosion resistance	ccr	Fission gas release	fgr
Cladding creep	ccre	Fuel-cladding friction	fcf
Cladding irradiation growth	cig	Fuel relocation	frel
Cladding shear modulus	csm	Fuel swelling	fsw
Cladding thermal conductivity	ctc	Fuel density	fdens
Cladding thermal expansion	cte	Fuel thermal conductivity	ftc
Cladding yield stress	cys	Fuel thermal expansion	fte
Cladding Young's modulus	cym	Plenum length	pl
Initial gap pressure	igp	Plenum spring diameter	psd
Initial gap size	igs	Plenum spring turns	pst

We then applied controlled perturbations to the selected material/model input parameters listed in Table 1. For example, *frel* denotes fuel relocation, representing inward pellet fragment displacement upon cracking; *fdens* is fuel theoretical density, governing pellet porosity, swelling, and densification behavior; *igp* is initial gas pressure; and *ccr* is cladding corrosion resistance, controlling oxide layer growth rate. Using these perturbed inputs, we executed modified GIFT simulations for each sampled rod and perturbation case.

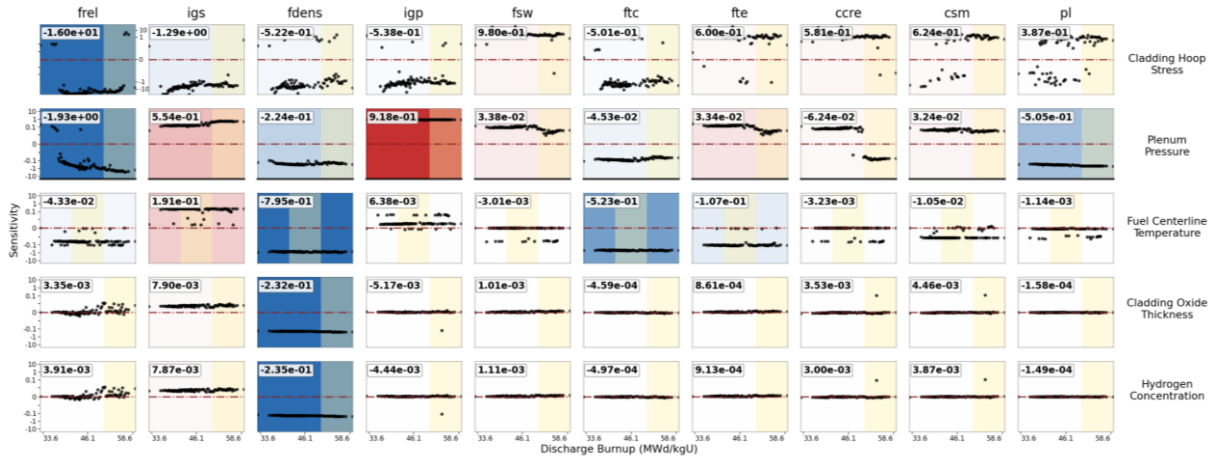


Figure 2. Burnup-resolved local sensitivity map for five QoIs and 10 selected input parameters. x-axis: discharge burnup (MWd/kgU); y-axis: local normalized sensitivity. Black lines show $\pm 3\%$ window sensitivity trajectories; red dash-dot line indicates zero sensitivity. Light-yellow vertical band marks the QoI-specific impact zone. Cell background color reflects impact-zone mean sensitivity (blue: negative, red: positive, white: near zero).

Using GIFT outputs, we quantified local input-to-QoI response by burnup-dependent normalized sensitivity:

$$S = \frac{\Delta y/y_0}{\Delta x/x_0} \approx \left. \frac{d \ln y}{d \ln x} \right|_{x_0}$$

where x is an input parameter and y is a QoI. The $\pm 3\%$ perturbation window was selected based on a cross-window consistency assessment spanning $\pm 1\%$ to $\pm 5\%$, as it provided the best balance between numerical stability and robustness of sensitivity rankings across adjacent window sizes. For each input parameter, we thereby obtained burnup-resolved QoI sensitivity trajectories describing how the parameter-induced QoI response varies with discharge burnup. For example, a sensitivity of -0.2 for the *ccr*–Cladding Oxide Thickness pair indicates that a $+1\%$ increase in *ccr* yields an approximately -0.2% decrease in oxide thickness.

As a final step, we aggregated these burnup-wise sensitivities within QoI-specific impact zones, defined as the discharge-burnup range in which a given QoI exhibits its highest absolute values. The impact-zone mean sensitivity was then used to rank input parameters for each QoI, providing a consistent basis for identifying which material and model parameters most strongly influence each QoI across burnup while preserving stable directional information.

3. Results and Discussion

Figure 2 presents burnup-resolved sensitivity trajectories for the 10 highest-impact parameters, selected from the original 20 candidates based on their impact-zone mean sensitivity magnitude across all QoIs. Note that the (*frel*, Cladding Hoop Stress) cell uses a separate y-scale due to its outlier magnitude relative to all other cells.

QoI-specific Impact Interpretation

Before interpreting the results, two methodological cautions should be noted: one concerning a specific input parameter, and one concerning a specific QoI.

First, although Fig. 2 reflects only the $\pm 3\%$ window, a cross-window assessment spanning $\pm 1\%$ to $\pm 5\%$ revealed that *frel* exhibits sensitivity rankings that vary substantially across window sizes, motivating additional robustness checks beyond local OAT analysis.

Second, the Cladding Hoop Stress QoI itself shows repeated zero-crossings and abrupt burnup-dependent shifts across multiple parameters. This behavior is physically consistent with PCI-coupled contact evolution and mechanical state transitions, which naturally amplify local nonlinearity.

In the high-burnup, high-CHS regime, sensitivity drivers split into two physically distinct groups. Gap-state and thermal-redistribution parameters (*frel*, *igs*, *igp*, *ftc*) act as negative drivers, primarily governing contact-state redistribution and reducing net hoop stress. In contrast, stress-building parameters (*fsw*, *fcf*, *csm*, *fte*, *ccre*) promote positive stress accumulation through swelling, friction, creep, and thermal expansion pathways. This two-group split is physically consistent with PCI-governed contact evolution and provides a coherent mechanical interpretation of the impact-zone sensitivity hierarchy.

For Plenum Pressure (PP), the sensitivity structure is comparatively cleaner than that of CHS. A higher initial gas pressure (*igp*) directly elevates plenum pressure, while a larger initial gap size (*igs*) acts through a thermal pathway: the increased gap thermal resistance raises fuel centerline temperature, promoting fission gas release and thereby increasing plenum pressure. Plenum length (*pl*) provides additional free volume that attenuates pressure buildup, acting as a negative driver. In contrast to CHS, the PP sensitivity shows fewer sign changes across discharge burnup, allowing impact-zone trends to be interpreted with higher directional confidence.

For Fuel Centerline Temperature (FCT), *fdens* and *ftc* emerge as dominant negative drivers in the high-burnup, high-FCT regime, while most other parameters remain secondary. Higher fuel density reduces pellet porosity,

which improves effective thermal conductivity and lowers centerline temperature; higher thermal conductivity directly enhances heat conduction to the cladding. Both parameters thus act through improved thermal transport pathways, supporting a heat-transfer-centered interpretation of FCT sensitivity.

Cladding Oxide Thickness (COT) and Hydrogen Concentration (HC) show a largely shared sensitivity structure, reflecting their physical coupling: oxidation growth drives hydrogen uptake at the cladding surface. Accordingly, they are interpreted jointly. *ccr* and *fdens* emerge as the dominant drivers for both QoIs. The effect of *ccr* is direct: higher corrosion resistance suppresses oxide layer growth rate and consequently hydrogen uptake. *fdens* acts through two independent pathways: it directly scales the neutron fast flux ($\propto 1/\text{density}$), elevating the post-transition corrosion rate constant; and it governs swelling and densification magnitudes via as-fabricated pellet density, which alters gap closure timing, PCI contact conductance, and local cladding thermal conditions, further affecting oxidation growth and hydrogen uptake. Therefore, *ccr* and *fdens* should be interpreted as direct and indirect dominant drivers, respectively.

Table 2. Top five influential input parameters for each QoI based on impact-zone mean local sensitivity

Rank	Cladding Hoop Stress	Plenum Pressure	Fuel Centerline Temperature	Cladding Oxide Thickness	Hydrogen Concentration
Rank 1	frel (-1.603e+01)	frel (-1.932e+00)	fdens (-7.950e-01)	fdens (-2.318e-01)	fdens (-2.354e-01)
Rank 2	igs (-1.292e+00)	igp (9.180e-01)	fic (-5.227e-01)	ccr (-1.446e-01)	ccr (-1.463e-01)
Rank 3	fsw (9.805e-01)	igs (5.541e-01)	igs (1.910e-01)	igs (7.901e-03)	igs (7.868e-02)
Rank 4	fcf (8.308e-01)	pl (-5.046e-01)	fic (-1.067e-01)	igp (-5.169e-03)	igp (-4.445e-03)
Rank 5	csm (6.237e-01)	fdens (-2.236e-01)	frel (-4.325e-02)	csm (4.460e-03)	frel (3.905e-03)

Across all QoIs, *fdens* emerges as a recurring dominant parameter, appearing as a top driver for FCT, PP, COT, and HC through distinct but physically coherent pathways. This cross-QoI recurrence suggests that fuel-state variables represent the highest-leverage targets for design and R&D prioritization. The top five influential parameters for each QoI are summarized in Table 2.

4. Conclusion

In this study, we established a core-wide, burnup-resolved sensitivity framework using GIFT and quantified how material and model input perturbations propagate to system-level QoIs. By combining local normalized sensitivity with QoI-specific impact-zone averaging, we identified QoI-specific dominant drivers and organized a cross-QoI prioritization structure, providing a quantitative foundation for material-to-performance coupling interpretation under representative LWR burnup conditions.

A key limitation of the current framework is that it is primarily based on local (one-parameter-at-a-time) sensitivity and does not fully resolve higher-order interaction effects. Parameters exhibiting non-monotonic response behavior (e.g., *frel*, *fdens* for certain QoIs) require analysis beyond local OAT sensitivity, which will be

addressed in a follow-up global sensitivity study using Sobol indices, enabling explicit decomposition of main and interaction contributions.

In addition, the present analysis is based on an 18-month core condition. As a next step, we will extend the framework to a 24-month core to evaluate how longer-cycle operation modifies interaction structure, burnup-dependent dominance, and QoI-level sensitivity hierarchy. Based on these results, we plan to introduce a parameter optimization stage for material and model settings informed by interaction-aware sensitivity evidence. Finally, the derived prioritization will be compared against R&D occurrence and frequency trends to assess practical relevance: whether the parameters identified as high-impact in simulation are also emphasized in current development activities, and where further investigation is still needed. Through these extensions, the framework will evolve from sensitivity screening toward interaction-informed, decision-oriented fuel design guidance.

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