

Development of High-Fidelity Analysis System for the Evaluation of Fuel Irradiation Tests in HANARO

Seongwoo Yang*, Sung-Jae Park, Junesic Park, Ye-Eun Na
HANARO Utilization Division, Korea Atomic Energy Research Institute,
111, Daedeok-daero 989 beongil, Yuseong-gu, Daejeon, 34057

*Corresponding author: swyang@kaeri.re.kr

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1. Introduction

Verifying the in-pile performance and safety of advanced nuclear fuels—such as Accident-Tolerant Fuel (ATF), LEU+, and Small Modular Reactor (SMR) fuels—requires rigorous irradiation testing in research reactors prior to commercial deployment. However, HANARO, South Korea's multi-purpose research reactor, operates under low-temperature ($\sim 40^{\circ}\text{C}$) and low-pressure (atmospheric level) open-pool conditions, exhibiting substantial thermal-hydraulic discrepancies compared to commercial Pressurized Water Reactors (PWRs, $\sim 15.5\text{ MPa}$, $>300^{\circ}\text{C}$). Furthermore, the absence of a dedicated high-temperature and high-pressure in-pile loop poses challenges in directly extrapolating test data obtained from HANARO to commercial reactor environments. Conventional 1.5D fuel performance codes, such as FRAPCON[1], have critical limitations when applied to the unique irradiation environment of HANARO: Neutron Spectrum Discrepancies[2]:

- (1) The TUBRNP depletion module[3] in FRAPCON relies on constant effective cross-sections tuned for standard commercial LWR or HBWR spectra. In contrast, the OR test holes of HANARO, located adjacent to the heavy water reflector, form a distinctive soft spectrum where thermal neutron absorption is dominant (e.g., the effective U-235 fission cross-section is ~ 196.8 barns in HANARO OR4 compared to ~ 41.5 barns in standard LWRs).
- (2) Local Power Distortion: The real-time withdrawal and insertion of control absorber rods (CARs) induce severe axial and radial power tilting across the test rig throughout the operation cycle.
- (3) Multi-dimensional Geometric and Local Behaviors: Traditional 1D/1.5D axisymmetric representations cannot resolve complex local geometries, such as pellet dishes/chamfers, thermocouple instrumentation holes, pellet ridging/hour-glassing, and double cladding capsule structures.

To overcome these physical constraints and numerical limitations, this study establishes a high-fidelity multi-physics simulation system that organically

couples 3D Monte Carlo transport (MCNP6.1[4]), depletion analysis (ORIGEN-2.2[5]), and multi-dimensional finite element thermo-mechanical modeling (COMSOL Multiphysics[6]). The computational accuracy and applicability of the integrated system were systematically verified and validated (V&V) through a commercial fuel benchmark and actual HANARO in-pile measurement data.

2. Methods and Results

2.1 Integrated Multi-physics Coupling Methodology

To account for the steep power gradient induced by the soft neutron spectrum and the local power distortions caused by control rod movements, a three-phase coupling methodology was established as shown in Fig. 1. In Phase 1, a 3D full-core MCNP model was constructed with the fuel pellet discretized into 20 concentric radial rings, applying a fine-mesh scheme near the rim region to accurately capture the plutonium accumulation and rim effect. Depletion calculations were sequentially performed via ORIGEN using a predictor-corrector method synchronized with the 50 mm axial displacements of the HANARO CARs. In Phase 2, an external post-processing script transferred the spatial and time-dependent volumetric heat generation rate $Q_{\text{fiss}}(r, z, t)$, local accumulated burnup, and fast neutron fluence onto the finite element mesh of COMSOL Multiphysics. In Phase 3, a multi-dimensional thermo-mechanical analysis was performed using COMSOL. An assembly-based modeling approach was implemented to treat the pellet and cladding as discrete physical domains, utilizing penalty-based contact pairs to simulate interface discontinuities. Temperature- and burnup-dependent material properties were dynamically updated using the MATPRO library. The gap conductance model incorporated gas conduction, mechanical contact conductance, and radiative heat transfer. For pellet mechanical deformation, the total strain tensor was decomposed to account for elastic strain, thermal expansion, initial densification, burnup-dependent solid/gas swelling, and relocation-induced strain.

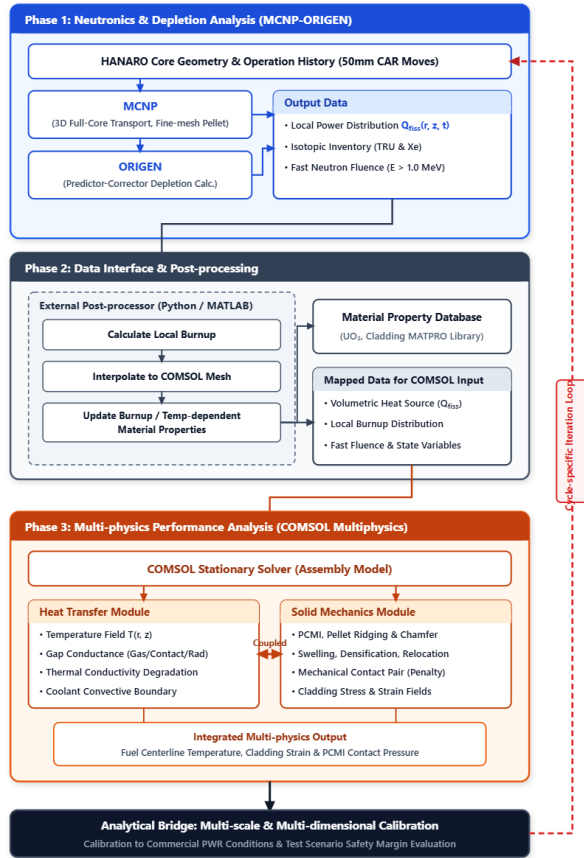


Fig. 1. Flow chart of multi-physics coupling methodology for HANARO fuel test

2.2 Numerical Verification via APR1400/PLUS7 Benchmark

The numerical reliability of the proposed framework was verified through a code-to-code benchmark against FRAPCON-4.0 using the geometry and power history of the commercial APR1400/PLUS7 fuel[7]. A 1D radial model representing the peak power node was analyzed under identical boundary conditions and material models as shown in Table I and II. The calculated fuel centerline temperature showed excellent consistency with FRAPCON predictions across the entire burnup range, exhibiting deviations within 14 Kelvin once the initial relocation gap closed beyond 10 GWd/MTU. The radial displacement of the fuel pellet agreed within a few micrometers, confirming the numerical equivalence of the implemented strain decomposition formulation. Although the stationary solver omitted time-dependent cladding creep relaxation, this simplification yields conservative stress values, which is well-justified for research reactor environments where coolant pressure differentials are minimal. Furthermore, the single-offset contact method in COMSOL accurately reproduced the timing of gap closure and the initiation of Pellet-Cladding Mechanical Interaction (PCMI) contact pressure consistent with FRAPCON's dual-gap model. Note that the small negative gap distance observed in

COMSOL after day 491 is a numerical artifact resulting from the penalty-based contact method upon PCMI initiation. Unlike FRAPCON, which retains a finite residual gap based on surface roughness after contact, COMSOL permits slight numerical penetration across the contact boundary to balance contact pressure.

Table I: Benchmark calculation result (pellet deformation and centerline temperature)

Day	Pellet deformation			Centerline temperature		
	FRAPCON (cm)	COMSOL (cm)	Differences (μ m)	FRAPCON (K)	COMSOL (K)	Differences (K)
0.1	0.41336	0.41320	1.57	1215.1	1261.0	-45.9
10	0.41266	0.41288	-2.20	1222.0	1257.6	-35.6
20	0.41292	0.41294	-0.16	1205.5	1247.7	-42.2
30	0.41309	0.41307	0.24	1195.5	1236.6	-41.1
40	0.41325	0.41321	0.39	1187.0	1226.9	-39.9
50	0.41338	0.41332	0.59	1180.0	1218.7	-38.7
78	0.41349	0.41357	-0.76	1171.5	1201.4	-29.9
157	0.41371	0.41387	-1.64	1156.7	1173.6	-16.9
235	0.41397	0.41407	-1.01	1142.2	1154.4	-12.2
319	0.41419	0.41428	-0.85	1129.5	1135.8	-6.3
362	0.41455	0.41435	2.03	1099.2	1116.4	-17.2
404	0.41449	0.41448	0.12	1097.8	1114.7	-16.9
447	0.41425	0.41461	-3.60	1100.4	1108.9	-8.5
491	0.41399	0.41476	-7.66	1102.7	1111.5	-8.8
610	0.41349	0.41497	-14.83	1035.1	1043.7	-8.6
729	0.41386	0.41532	-14.61	1037.7	1047.5	-9.8

Table II: Benchmark calculation result (cladding deformation and gap distance)

Day	Cladding inside deformation			Gap distance		
	FRAPCON (cm)	COMSOL (cm)	Differences (μ m)	FRAPCON (cm)	COMSOL (cm)	Differences (μ m)
0.1	0.41771	0.41889	-11.83	0.00435	0.00569	-13.40
10	0.41789	0.41843	-5.43	0.00523	0.00555	-3.23
20	0.41772	0.41822	-4.98	0.00480	0.00528	-4.82
30	0.41759	0.41808	-4.90	0.00450	0.00501	-5.14
40	0.41748	0.41796	-4.85	0.00423	0.00475	-5.24
50	0.41737	0.41785	-4.80	0.00399	0.00453	-5.39
78	0.41711	0.41759	-4.85	0.00361	0.00402	-4.09
157	0.41648	0.41690	-4.17	0.00278	0.00303	-2.53
235	0.41590	0.41625	-3.47	0.00193	0.00218	-2.46
319	0.41531	0.41559	-2.85	0.00111	0.00131	-2.00
362	0.41501	0.41531	-2.97	0.00046	0.00096	-5.00
404	0.41484	0.41502	-1.80	0.00035	0.00054	-1.92
447	0.41460	0.41472	-1.24	0.00035	0.00011	2.36
491	0.41434	0.41443	-0.90	0.00035	-0.00033	6.76
610	0.41383	0.41372	1.14	0.00035	-0.00125	15.97
729	0.41419	0.41385	3.35	0.00033	-0.00147	17.96

2.3 Experimental Validation against HANARO 02F-11K In-pile Test Data

To evaluate the predictive accuracy under actual research reactor conditions, the framework was validated against real-time centerline temperature data measured during the 02F-11K instrumented capsule irradiation test (Rod #1) conducted in the OR5 hole during HANARO operation cycles 24 and 25. A 2D axisymmetric (R-Z) finite element model was established to resolve the five-pellet stack, faithfully incorporating pellet dishes, chamfers, and the centerline micro-hole (diameter of 1.5 mm) machined into the upper pellets for thermocouple (diameter of 1.0 mm) insertion as shown in Fig. 2. This multi-dimensional geometry allowed the model to capture the axial thermal asymmetry that 1.5D codes inherently fail to resolve. A total of 16 evaluation points reflecting cycle-specific core histories were analyzed as shown in Fig. 3. Excluding the transient power calibration stage at the beginning of the cycle (green arrows), the simulated centerline temperatures closely matched the thermocouple measurements across the remaining burnup steps. This demonstrates that the MCNP-ORIGEN-COMSOL platform reliably predicts localized multi-physics behaviors under HANARO's distinct neutronic and hydraulic environment.

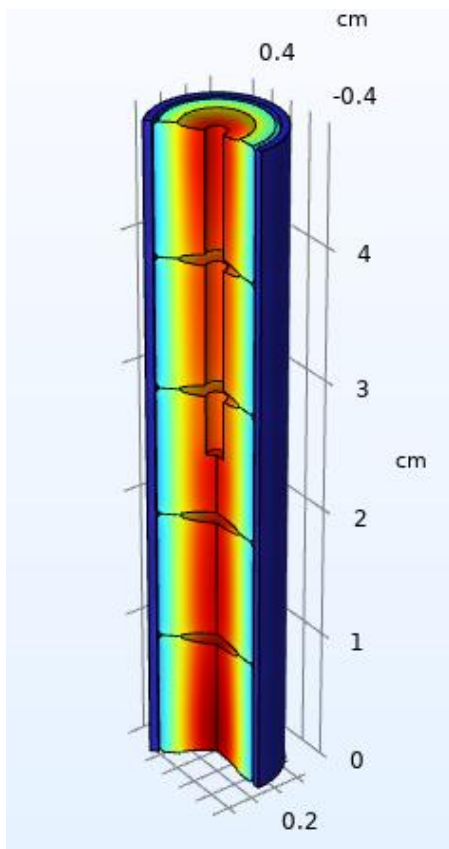


Fig. 2. Modeled geometry of rod #1 for HANARO test (02F-11K)

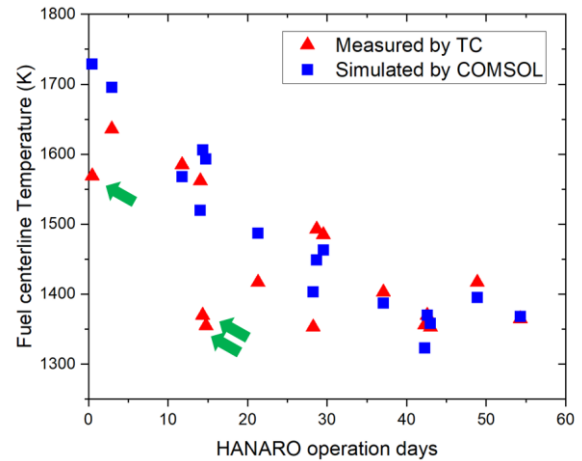


Fig. 3. Comparison results between measured and evaluated data for 02F-11K rod #1

3. Conclusions

- (1) Establishment of High-Fidelity Simulation Framework: An integrated multi-physics analysis system coupling MCNP-6.1, ORIGEN-2.2, and COMSOL Multiphysics was successfully developed to precisely evaluate the complex nuclear and thermal-mechanical phenomena in HANARO fuel irradiation tests.
- (2) Comprehensive Verification and Validation (V&V): The numerical accuracy of the thermo-mechanical formulation was verified through benchmarking against FRAPCON-4.0 for APR1400/PLUS7 fuel, and its physical validity was demonstrated through excellent agreement with real-time temperature measurements from the HANARO 02F-11K instrumented capsule.
- (3) The established platform serves as a critical analytical bridge capable of overcoming HANARO's hardware constraints by numerically optimizing non-standard test designs, such as double-cladding capsules and reduced-gap specimens, thereby facilitating independent safety assessments for future dynamic testing (e.g., power ramp and load-following tests) and the licensing of next-generation nuclear fuels.

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