

Verification of Null-transient Analysis in MERCURY

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1. Introduction

Nuclear fuel performance codes are a principal means of evaluating nuclear fuel behavior, since experimental tests of nuclear fuel are costly, time-consuming, and constrained by safety considerations. To complement and reduce reliance on such tests, these codes are being actively developed [1-4]. In this context, MERCURY—a finite-element-based code capable of analyzing fuel behavior under transient and accident scenarios—has been developed at the Korea Atomic Energy Research Institute [5-7]. For transient analysis, proper initialization of the thermal and geometrical state is required. While coupled steady-state analyses typically provide these initial conditions, a standalone transient solver must internally generate them. To address this, a null-transient analysis function has been implemented in MERCURY. This study introduces the methodology of null-transient analysis and presents its verification.

2. Null-transient analysis

The null-transient module provides two mutually exclusive options: (i) computing the initial thermal steady-state under an applied power, or (ii) updating the geometry via thermo-mechanical expansion at that temperature. Users select one option per run to generate consistent initial conditions for the subsequent accident analysis.

2.1 Initial thermal steady-state

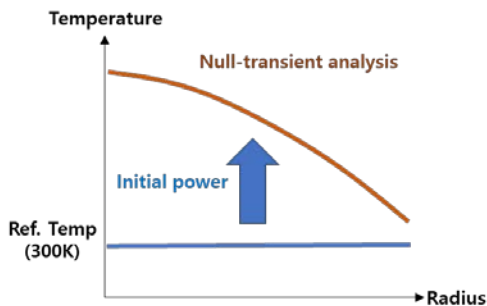


Fig. 1. Conceptual schematic of temperature rise to the initial thermal steady-state under an applied power

When power is initially applied to a fuel rod, its temperature rises until thermal equilibrium is achieved with the surroundings (Fig. 1). In MERCURY, the Null-

transient routine computes this steady-state temperature field, which is then passed to the transient solver as the initial condition. During this step, only displacement boundary conditions are enforced and no external mechanical loads are applied.

2.2 Thermo-Mechanical expansion

Prior to the accident simulation, MERCURY computes thermal expansion at the initialized temperature to ensure geometric consistency. Null-transient analysis accounts for this thermally induced deformation and provides corrected initial geometry for transient accident simulations. It also considers the cool-down stage as the temperature decreases after the transient event (Fig. 2).

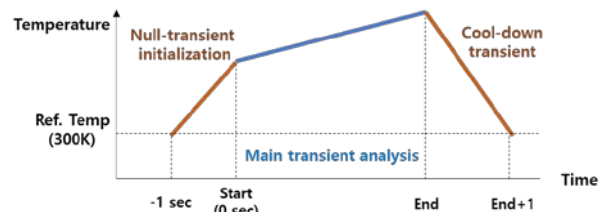


Fig. 2. Temperature-time history showing the null-transient analysis in the transient analysis.

3. Implementation and Verification in MERCURY

3.1 Implementation in MERCURY

The null-transient algorithm was integrated into the MERCURY framework by adding conditional modules around the existing FEM solver (Fig. 3). Four modes of calculation were defined (Table 1), corresponding to combinations of initialization and cool-down conditions.

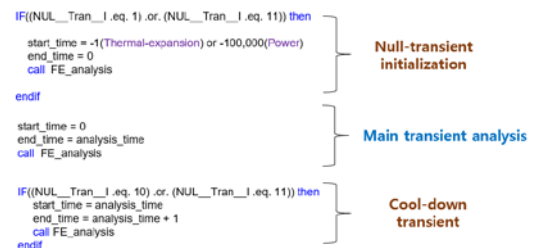


Fig. 3. Flowchart of the MERCURY with null-transient analysis

Table 1. Null-transient analysis modes

Mode	Null-transient initialization	Cool-down transient
0	No	No
1	Yes	No
10	No	Yes
11	Yes	Yes

Transient heat transfer is governed by Fourier's equation with appropriate thermal boundary conditions (Eq. 1). Because the heat input varies with time, the Null-transient initialization advances the thermal solution with a large pseudo-time step ($\approx 1.0 \times 10^5$ s) until a steady-state criterion is satisfied, after which the run proceeds to the main transient analysis.

$$\rho c_p \frac{\partial T}{\partial t} = -\nabla \cdot \mathbf{q} + \dot{q} \quad (\text{Eq. 1})$$

For the mechanical problem, the equilibrium equations (Eq. 2) are solved in a quasi-static framework. Because the solution is quasi-static, the nominal analysis time does not affect the result; accordingly, the null-transient expansion step uses an analysis time of 1 s.

$$\nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{b} = 0 \text{ in } \Omega \quad (\text{Eq. 2})$$

3.2 Verification of null-transient analysis

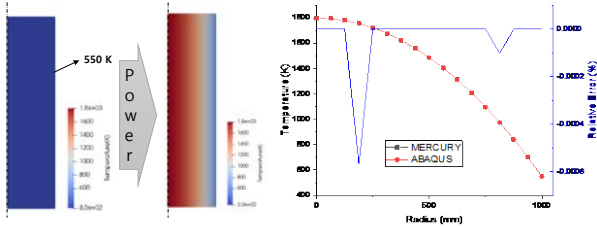


Fig. 4. Comparison of temperature distribution at initial steady-state under power : MERCURY vs. ABAQUS.

Verification was conducted using a simplified cylindrical model, comparing MERCURY results against the commercial FE code ABAQUS. For the thermal steady-state initialization with a 550 K boundary condition and internal heat generation, MERCURY agreed with ABAQUS within a maximum relative error of 6×10^{-6} (Fig. 4).

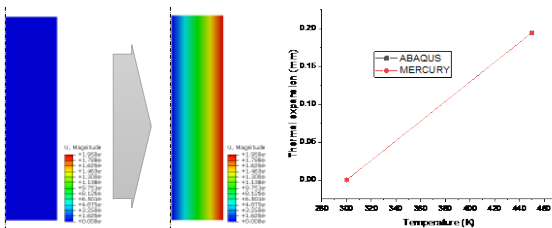


Fig. 5. Comparison of thermal expansion at 450 K : MERCURY vs. ABAQUS.

For the thermo-mechanical expansion case under an isothermal boundary of 450 K, the computed fuel expansion agreed with ABAQUS within a relative error of 6×10^{-6} (Fig. 5). These results confirm the reliability of the null-transient implementation.

3. Conclusions

The MERCURY code, a FEM-based nuclear fuel performance tool, has been enhanced with a null-transient analysis capability to provide accurate initialization for accident simulations. This functionality accounts for temperature rise and equilibrium under initial power, and thermal expansion associated with temperature increase and subsequent cool-down. Comparisons with ABAQUS demonstrated excellent agreement, with negligible numerical error. Future work will extend verification using experimental datasets from nuclear fuel accident simulations to further validate MERCURY's predictive accuracy.

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