TRIPLE: A 3D Finite Element Code for TRISO Fuel and Its Application to HTGR Design and Multiscale Fuel Analysis

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1. Introduction

Tristructural-Isotropic (TRISO) fuel represents an advanced nuclear fuel concept in which a central fuel kernel is surrounded by multiple ceramic coating layers engineered to enhance retention of fission products and improve overall safety performance. Due to its high mechanical robustness and superior containment capability, TRISO fuel has been widely adopted in high-temperature gas-cooled reactors (HTGR).

To evaluate the performance and safety of HTGR fuel elements, understanding the multiphysics behavior of individual TRISO particles is essential. This paper introduces TRIPLE, a 3D FEM-based code for high-fidelity TRISO performance analysis. The study presents its fundamental models and verification results, followed by a multiscale strategy to link microscale analysis with macroscopic fuel design.

2. Model description

TRIPLE has been developed to simulate the multiphysics behavior of TRISO fuel under a wide range of operating conditions. The code accounts for heat generation and conduction, mechanical deformation, fission gas release, and the consequent gap formation within the particle. The overall computational procedure implemented in TRIPLE is illustrated in Fig. 1.

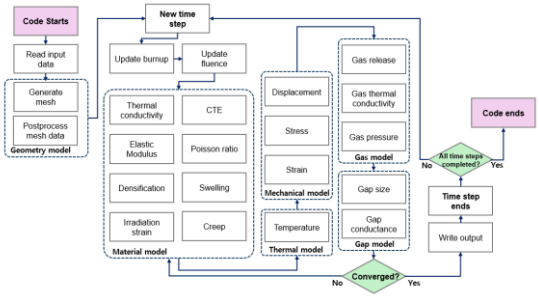

Fig. 1. Computational workflow of TRIPLE.

The analysis begins with the definitions of particle geometry based on user-specified input parameters, followed by the assignment of the corresponding material properties. Using these inputs, the code sequentially evaluates the temperature distribution, mechanical response, and fission gas release. These calculations are performed in a coupled and iterative manner until prescribed convergence criteria are satisfied, thereby providing stable and consistent predictions of fuel performance.

TRIPLE performs fully three-dimensional simulations to evaluate the behavior of TRISO fuel. The modeled domain can be configured according to the specific analysis objective, ranging from a single isolated particle to a configuration consisting of multiple particles dispersed within a surrounding matrix. A representative example of the geometric model and corresponding mesh configuration is presented in Fig. 2. In all cases, the spatial discretization is constructed using structured meshes composed of linear hexahedral elements.

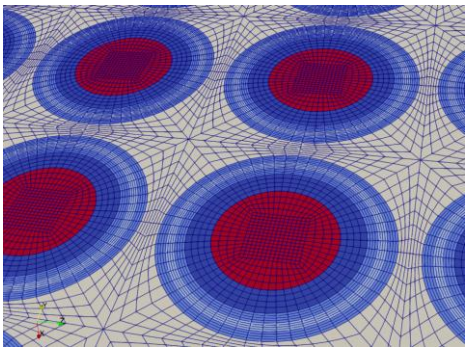

Fig. 2. TRISO-embedded matrix geometry and corresponding mesh configuration of TRIPLE.

TRIPLE predicts the thermomechanical response of TRISO fuel by solving the governing field equations in a fully coupled framework. For thermal analysis, the code solves Eq. (1) to evaluate internal heat generation, heat transfer, and the resulting temperature distribution within the particle:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = q''' \quad (1)$$

where ρ denotes the material density, C_p the specific heat capacity, T the temperature, t the time, k the thermal conductivity, and q''' the volumetric heat generation rate.

Eq. (2) is solved to evaluate the mechanical response, where σ denotes the Cauchy stress tensor and f represents the body force:

$$\nabla \cdot \sigma + \rho f = 0 \quad (2)$$

In the present formulation, the mechanical behavior is described using a nonlinear elastic constitutive model to account for material nonlinearity and geometric nonlinearity.

TRISO particles experience deformation arising from multiple interacting phenomena during operation. The dominant deformation mechanisms associated with each layer are summarized in Table I [1]. In addition, the TRIPLE framework incorporates the formation of the buffer-IPyC gap as part of the mechanical analysis.

Table I: Deformation mechanisms

Fuel kernel	thermal expansion, swelling, densification
PyC, SiC, Graphite	thermal expansion, irradiation-induced dimensional change (IIDC), irradiation creep

Fission gas release from the fuel kernel proceeds through a series of microscale transport processes. In TRIPLE, this behavior is represented using the Booth equivalent sphere diffusion model [2]. The released fission gas is retained within the particle, where it contributes to internal gas pressure and influences both the thermal transport characteristics and the mechanical response of the fuel system.

3. Verification

To verify the accuracy of TRIPLE, a benchmark assessment was performed using the cases defined in the IAEA Coordinated Research Program (IAEA-CRP-6) on HTGR reactors [3]. The benchmark suite consists of 16 cases, spanning from simplified SiC coating models to more complex analyses of irradiated TRISO particles. Representative result for selected case is shown in Fig. 3, where the maximum tangential stress in the SiC layer for Case 12 is compared. The comparisons demonstrate consistent trends with only minor discrepancies, confirming the reliability of the computational framework.

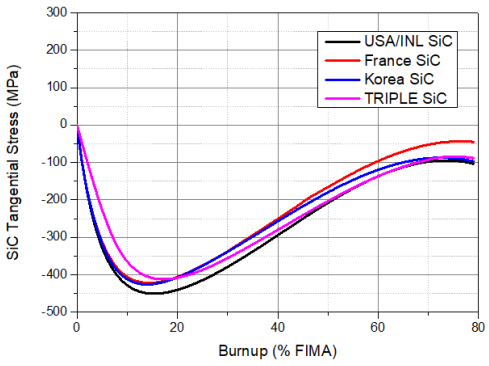

Fig. 3. Result comparison of maximum tangential stress of the SiC layer for benchmark case 12.

4. HTGR multiscale coupling strategy

As presented in the previous sections, the TRIPLE code has successfully simulated the complex thermo-mechanical behavior of individual TRISO particles through its 3D FEM multiphysics capabilities. However, actual HTGR fuels are heterogeneous composites in which tens of thousands of TRISO particles are dispersed within a graphite matrix. To practically apply the verified microscale capabilities of TRIPLE to macroscopic fuel performance evaluations, a multiscale analysis methodology is required as a future extension.

To this end, the TRIPLE code can be effectively integrated into a unit cell based homogenization framework. By defining a single TRISO particle and its surrounding matrix as a Representative Volume Element (RVE), the code can evaluate the microscale thermo-mechanical response and subsequently calculate the macroscopic effective properties of the fuel medium. For instance, Fig. 4. demonstrates the effective thermal conductivity of the RVE as a function of temperature, derived from the TRIPLE code's microscale analysis.

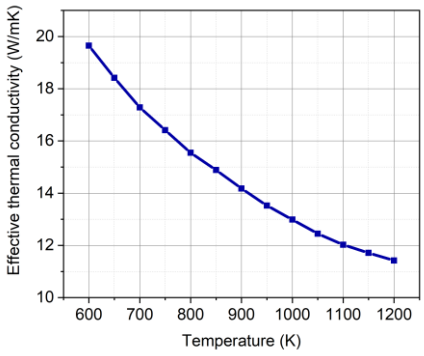

Fig. 4. Temperature-dependent effective thermal conductivity of the RVE calculated from TRIPLE

Based on this effective property evaluation capability, TRIPLE can serve as a core module in an advanced multiscale coupling scheme for HTGR fuel design. To overcome the computational burden, building a pre-computed material library is highly practical. By performing prior RVE analyses across various expected macroscopic operating conditions, TRIPLE can construct a comprehensive map of effective properties. Macroscopic fuel performance codes can then efficiently update material behaviors by interpolating the pre-calculated library.

5. Conclusion

This paper presented TRIPLE, a 3D FEM multiphysics code developed and verified for high-fidelity TRISO fuel analysis. To extend its microscale capabilities to macroscopic HTGR fuel evaluations, a multiscale coupling strategy based on unit cell homogenization was proposed. By utilizing TRIPLE to construct a pre-computed material library, macroscopic

codes can efficiently update effective properties. This framework suggests that TRIPLE can serve as a valuable computational foundation for advanced HTGR fuel design.

ACKNOWLEDGEMENT

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