# Finite Element Analysis of Unit Cell of Inverted Core Fuel for Micro Lead-cooled Fast Reactor

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## 1. Introduction

The preliminary design of ultra-long life micro lead-bismuth eutectic (LBE) cooled fast reactor is studied as a nuclear propulsion system for icebreakers. In the case of a marine nuclear power reactor, cladding failure due to fretting wear between the spacer grid and cladding due to the vibration of the ship is highly probable. To ensure the long-term mechanical integrity of nuclear fuel rods, a concept of inverted core fuel is considered. Inverted core fuel concept has the form where multiple coolant channels pass through the nuclear fuel block.

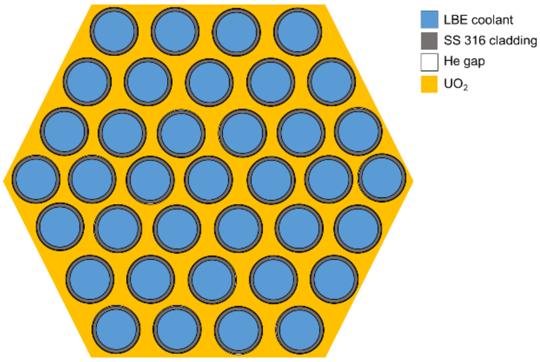



Fig. 1. A conceptual design of an inverted core

The fuel assembly grid structure can be eliminated by adopting the inverted core fuel design. Therefore, long-term cladding failure resistance can be improved because fretting wear of cladding is eliminated. Also, natural circulation of liquid metal coolant is maximized because pressure drop can be reduced by removing flow friction by grids [1].

In this study, the temperature and thermal stress of the unit cell of inverted core fuel were calculated by using finite element analysis through COMSOL-multiphysics. Material properties of $UO_2$ fuel, type 316 austenitic stainless steel, He gap, and lead-bismuth eutectic coolant were implemented.

## 2. Methods and Results

### *2.1 Simulation conditions*

*Table I: Fuel rod design for the inverted fuel in this study*

| *Design Factor* | *Design Value* |
|---|---|
| *Fuel material* | *$UO_2$* |
| *Cladding material* | *SS316* |
| *Fill gas material* | *He* |
| *Fuel pitch / Cladding thickness(mm)* | *30.0/0.95* |
| *Coolant channel diameter (mm)* | *15* |
| *Fuel power density ($W/cm^3$)* | *32.7* |
| *Coolant Pb/Bi composition (wt%)* | *44.5/55.5* |
| *Bulk Coolant temperature(℃)* | *300* |
| *Coolant heat transfer coefficient ($W/cm^2K$)* | *14509* |

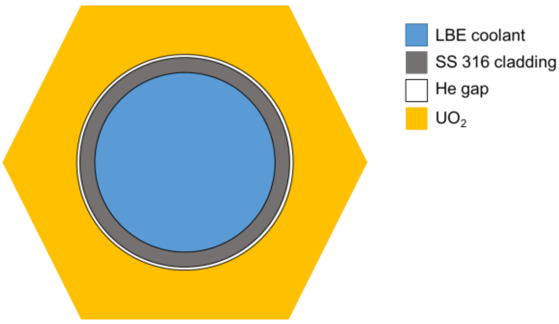



Fig. 2. Schematic cross-section image of a unit cell inverted core fuel

Before evaluating the thermal and mechanical properties in the full fuel assembly, the evaluation was conducted at the low level unitcell. In the fuel module, thermal conductivity, heat capacity density, thermal expansion were implemented for the thermal analysis. Also, Young's modulus and poissons's ratio were inputted for the mechanical analysis. Similarly, in the cladding module, thermal conductivity, heat capacity, thermal expansion, and modulus were implemented. Roller boundary conditions of the upper surface unit cell of fuel and cladding were assumed. Also, point of the under left corner of hexagonal fuel was fixed as a constraint. The heat transfer coefficient of the LBE coolant was input as a constant and the bulk temperature was fixed at 300℃. Open boundary conditions were adapted to the outer surface of unit cell thermal analysis. The design parameters of the inverted fuel rod design are summarized in Table I.

### *2.2 Inverted core fuel temperature calculation*

The temperature profile inside the fuel, cladding, and coolant was calculated. Because there is a coolant channel inside the fuel, the fuel temperature increases as the distance from the channel center increases. The temperature difference occurs at both ends of the red line and the black line of Fig. 3. This is because the distance from the coolant is different according to the direction in the case of the hexagonal unit cell. At the end of the black line which is the shortest direction, the maximum temperature was 1118K, and at the end of the red line which is the longest direction, the maximum temperature was evaluated as 1174K.

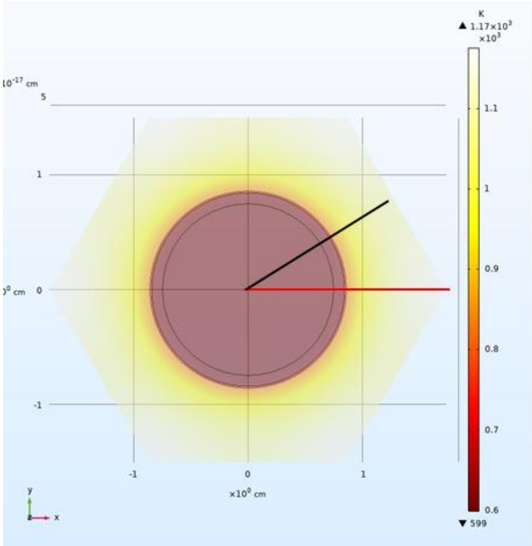


Fig. 3. Temperature calculation results

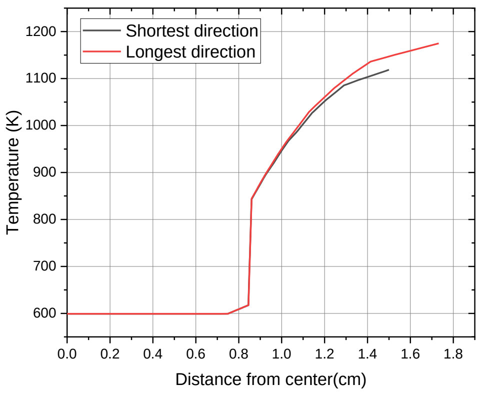
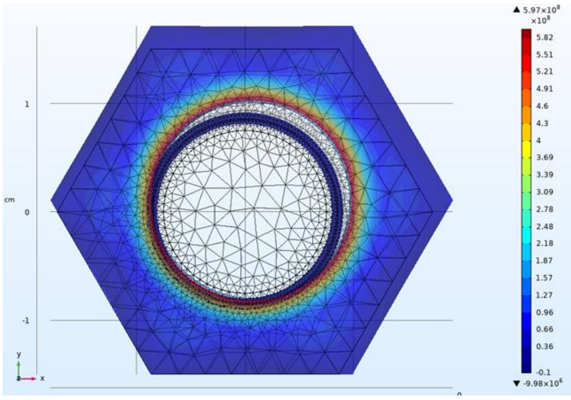



Fig. 4. Radial temperature profile calculation results

*2.3 Inverted core thermal stress calculation*

In this section, thermal stress due to temperature gradient and thermal expansion of fuel and cladding is discussed. The stress concentration at the inner surface of the fuel is observed. According to Fig.5.(a), it is calculated that the first principal stress, which is the tensile stress, rises to a maximum of 600 MPa. Also, as mentioned in section 2.1, the hexagonal corner has a higher temperature due to the asymmetric geometry. Therefore, the compressive stress is calculated as a maximum of 65 MPa by this thermal gradient according to Fig 5.(b). Also, since the lower-left vertex was specified as a constraint point, thermal expansion occurred in the upper right direction. The fracture strength of $UO_2$ between 800℃ and 1200℃ is similar to the yield strength, which is about 200 MPa at 800℃ [2]. Therefore, the current stress level exceeds the fracture strength of $UO_2$, and a thermal crack inside the nuclear fuel will occur.

(a) 1st Principal Stress ($N/m^2$)



(b) 3rd Principal Stress ($N/m^2$)

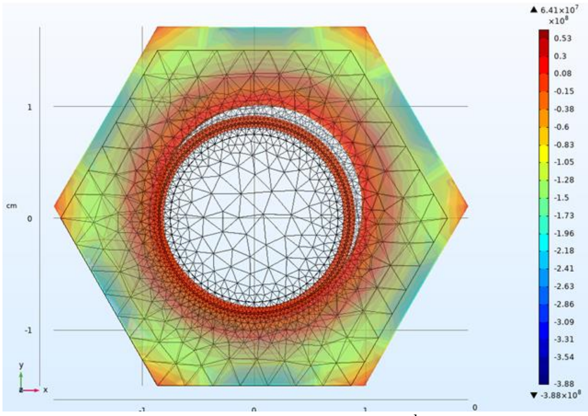


Fig. 5. (a) 1st principal stress and (b) 3rd principal stress of inverted core fuel

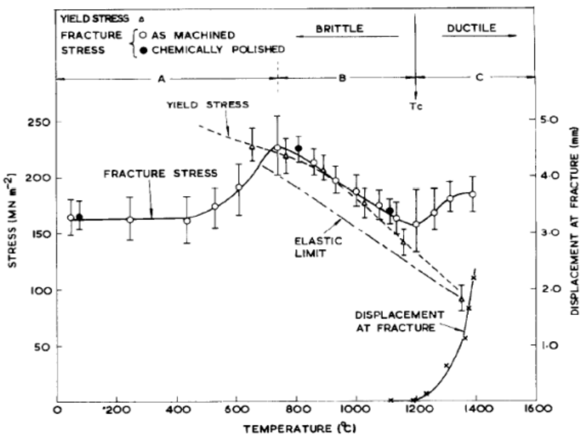



Fig. 6. Stress to failure of $UO_2$ at a temperature from 25℃ to 1400℃ [2]

## 3. Conclusion

In this study, the thermal and mechanical properties of unit cell inverted core fuel were evaluated by finite element analysis. The material properties of $UO_2$, type 316 austenitic stainless steel, He gap, and LBE coolant, were used.

First, it was calculated that fuel temperature gradients arise due to the hexagonal asymmetric fuel geometry. In addition, due to the thermal gradient, there was compressive thermal stress in the corner of the hexagon unit cell. At the inner surface of the inverted core fuel channel, tensile stress was calculated, which exceeds the fracture strength of $UO_2$ at the temperature.

## ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF, No. 2019M2D1A1067210) grant funded by the Korea government (MSIT)

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[2] A.G. Evans, R.W. Davidge, The strength and fracture of stoichiometric polycrystalline UO2, J. Nucl. Mater. (1969). https://doi.org/10.1016/0022-3115(69)90019-1.