Preliminary assessment of transient performance of TRISO fuel particle

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1. Introduction

Load follow operation of a nuclear reactor is limited by the integrity of fuel and reactor components. In case of light water reactor (LWR), the departure-from-nucleate boiling ratio (DNBR) and the power change rate are the key parameters for maintaining the fuel integrity. In case of a single phase gas cooled reactor (GCR), the DNBR is not of concern. Integrity of the other components such as the pressure vessel, the pipes, the pump, and the steam generator are considered the same as a fossil power plant as well as a LWR. Nuclear graphite blocks in GCR are known to have much higher resistance to thermal transients than metallic alloys [1] so that its integrity is considered maintained.

It is also known that the thermal shock resistance of TRISO fuel particle is very high so that the load follow capability of a HTGR is excellent.[2] However, we were not able to find a quantitative analysis on the thermal shock resistance of TRISO particle. There are numerous computer models to describe TRISO fuel performance during a steady state irradiation such as COPA.[3] Since those are lacking the short time transient calculation capabilities, we have developed a new computer model and used it to simulate the stress behavior of a TRISO particle during transient including extreme one as well as load follow operation in this study.

2. Methods and Results

2.1 TRISO fuel particle model

TRISO fuel particle is in a spherical shape with 4 layers of ceramics coating over a spherical fuel kernel. Those layers are the buffer carbon(BuC), the inner pyrolytic carbon(IPyC), the silicon carbide(SiC), and the outer pyrolytic carbon(OPyC). Heat is produced in the kernel and conducted through the BuC, IPyC, SiC, and OPyC to outer surface of the TRISO particle.

Transient heat conduction equation is solved for given thermal conductivity and heat capacity as;

$$kT_{,ii} + q = \dot{T} / \rho C_p$$

In spherical symmetry, above equation is expressed in following form;

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left[kr^2 \frac{\partial T}{\partial r} \right] + q = \frac{1}{\rho C_p}\frac{\partial T}{\partial t}.$$

The heat generation rate, q , is assumed flat inside of a kernel since typical diameter of a kernel, 500 μm, is much shorter than the mean free path of a thermal neutron in uranium. Temperature, T , which is calculated from the transient conduction equation is used to determine the thermal strain of a mechanical stress equation. The steady state mechanical equation is used in this study, since the speed of sound is much faster than the heat diffusion speed. The stress-strain relations are;

$$\sigma_{ij} = \mu_{ijrs}\varepsilon_{rs} + \eta_{ij}$$

$$\sigma_{ji,j} + f_i = 0$$

$$\varepsilon_{ij} = u_{i,j}$$

We adopted the rheological model to describe stress-strain relations of the graphite and silicon carbide.[4]

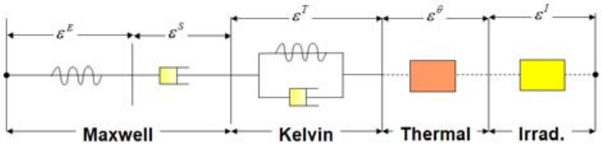

Figure 1. Rheological model

The strain tensor, ε , consists of 5 components; elastic strain ε^E , transient creep strain ε^T , steady state creep strain ε^S , thermal strain ε^θ , and irradiation strain ε^I as shown in Figure 1.

We assume the spherical symmetry of a TRISO particle. However, there exists an anisotropy in the material property between the radial and tangential directions. First 3 strain components are dependent on stress while thermal and irradiation components are not. In this case, vector elements of the stress tensor can be expressed in following matrix expression.

$$\begin{pmatrix} \sigma_{rr} \\ \sigma_{\theta\theta} \\ \sigma_{\phi\phi} \end{pmatrix} = \begin{pmatrix} \mu_r & \lambda_r & \lambda_r \\ \lambda_r & \mu_t & \lambda_t \\ \lambda_r & \lambda_t & \mu_t \end{pmatrix} \begin{pmatrix} \varepsilon_{rr} - \eta_r \\ \varepsilon_{\theta\theta} - \eta_\theta \\ \varepsilon_{\phi\phi} - \eta_\phi \end{pmatrix}$$

where μ_r , μ_t , λ_r and λ_r are derived by inverting the strain relation. η_r and η_t are related to thermal and irradiation strain as follows;

$\eta_r = \alpha_r (T - T_0) + \varepsilon_r^I$ and $\eta_t = \alpha_t (T - T_0) + \varepsilon_t^I$.

We can obtain the stress equation for spherical geometry expressed in displacement u_r as follows;

$$r\frac{d\sigma_{rr}}{dr} + 2\sigma_{rr} - \sigma_{\theta\theta} - \sigma_{\phi\phi} = 0$$

$$\sigma_{rr} = \mu_r \frac{du_r}{dr} + 2\lambda_r \frac{u_r}{r} - \mu_r\eta_r - 2\lambda_r\eta_t$$

$$\sigma_{\theta\theta} = \lambda_r \frac{du_r}{dr} + (\mu_t + \lambda_t)\frac{u_r}{r} - \lambda_r\eta_r - (\mu_t + \lambda_r)\eta_t$$

2.2 Finite element method

To find a solution of the thermal conduction equation, we used the finite element method (FEM) using the weak formulation with r^2 weighting using quadratic Lagrange(L2) polynomial base function. For time direction, we use the simple theta weighting method. L2 FEM gives exact solution for homogeneous medium problems.

L2 FEM is also used to solve the stress equation.

$$\int drw \begin{Bmatrix} r\frac{d}{dr}\left[\mu_r \frac{du_r}{dr} + 2\lambda_r \frac{u_r}{r} - m_r T - s_r\right] \\ +2\left(\mu_r-\lambda_r\right)\frac{du_r}{dr} + 2\left(2\lambda_r - \mu_r - \lambda_t\right)\frac{u_r}{r} \\ -m^0 T - s^0 \end{Bmatrix} = 0$$

with two types of boundary conditions;

$u_r = 0$ at center, and

$\sigma_{rr} + P = 0$ at surface.

2.3 Irradiation effect

We have adopted material properties from recent papers on material properties[5,6,7], CEGA report for PyC and SiC[8], and CEA model for UO_2[9] . Figure 2 displays the result for typical TRISO design.[10]

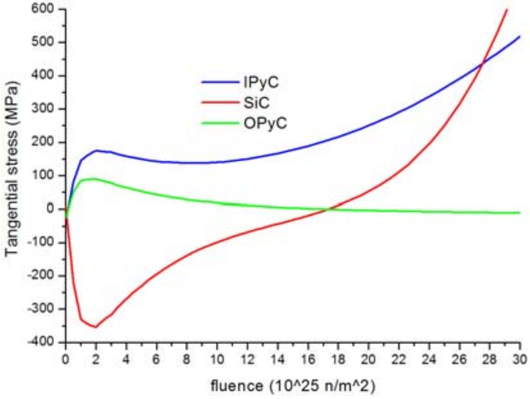

Figure 2. Tangential stress by irradiation

Strong negative tangential stress on SiC layer occurs at early irradiation and it rises as irradiation induced dimensional change (IIDC) grows as observed from other computer models [11].

2.4 Thermal resistance

Figure 3 displays the tangential stress on SiC layer in case of a sudden quench to 300K from operating temperature 1300K at $2x10^{25}n/m^2$ fluence. It shows large overshoot in the tangential stress which may induce failure of the SiC coating layer. The overshoot is occurred by strong temperature gradient between IPyC and OPyC during inward propagation of temperature shock front. The temperature gradient decreases rapidly within few milli-seconds. External layer of graphite outside of TRISO absorbs the initial thermal gradient, so that the gradient in coating layers decreases. Additional layer of few milli-meters was sufficient to suppress the overshoot within reasonable range.

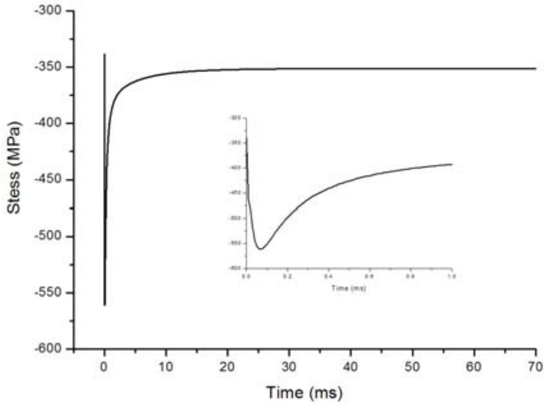

Figure 3. Transient stress during quench

3. Conclusion

TRISO is strongly resistant against thermal transient. Thus there should be no practical limit on fuel for the load following operation. Further calculations shows that, additional graphite layer of few milli-meter is sufficient to ensure the thermal resistance under extreme quench.

ACKNOWLEDGEMENTS

This work is carried under Nuclear Hydrogen Development project (NHDD) supported by MSIP.

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