Review of progress in TRISO fuel performance analysis and current status of my PhD research

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Unia Europejska Europejski Fundusz Społeczny

New reactor concepts and safety analyses for the Polish Nuclear Energy Program
POWR.03.02.00-00.I005/17

Scope of the talk

- **Introduction**
- Literature review
  - General Phenomena
    - Heat generation and transfer
    - Anisotropy effects
    - Pressure build-up in buffer layer
    - Kernel migration
    - Fission products build-up and release
  - Chemical Phenomena
  - Mechanical Phenomena
- CRP-6 Benchmark
- Summary
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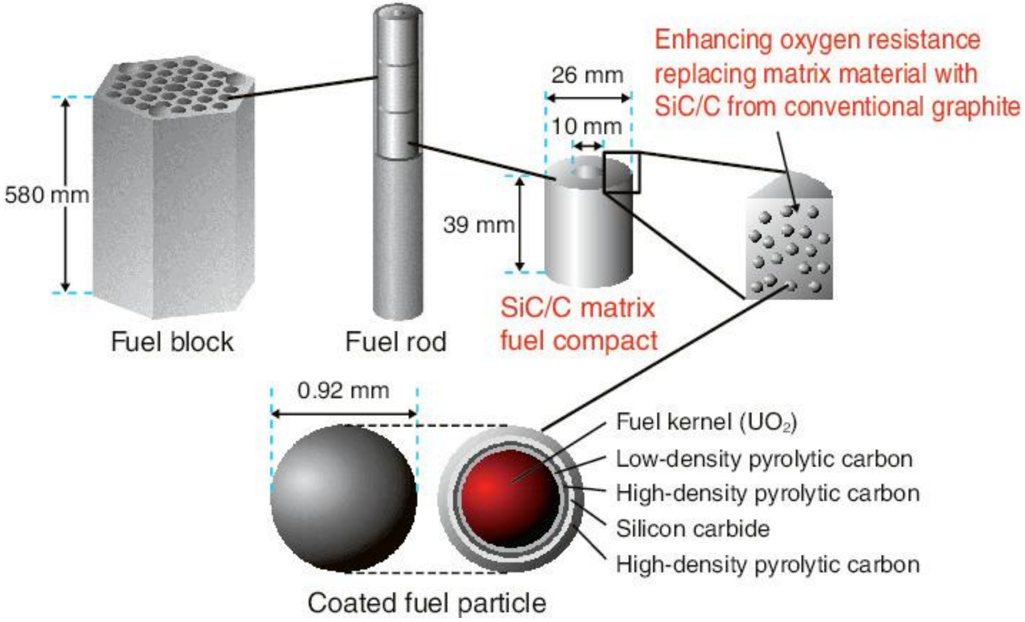
Introduction

- What is TRISO
- What is fuel performance ?
- Why is it important ?
- Did anybody do this analysis before ?
- What are main difficulties?



Aihara J., Goto M. et al., Nuclear Thermal Design of High Temperature Gas-Cooled Reactor with SiC/C Mixed Matrix Fuel Compacts, Proceedings of 8th International Topical Meeting on High Temperature Reactor Technology (HTR 2016), Las Vegas, Nevada, USA, 2016, p.814-822, in CD-ROM.

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Heat generation and transfer from the kernel

- The heat generation and temperature distribution in any substance is calculated by energy balance equation:

$$\frac{1}{r^2}\frac{d}{dr}\left(-r^2 K \frac{dT}{dr}\right) = Q, \text{ for the fuel (1)}$$

$$\frac{1}{r^2}\frac{d}{dr}\left(-r^2 K \frac{dT}{dr}\right) = 0, \text{ for the coating layers (2)}$$

- For fuel particles, the problem can be solved comparatively easier.

- The homogenization and Monte-Carlo based methods are used.

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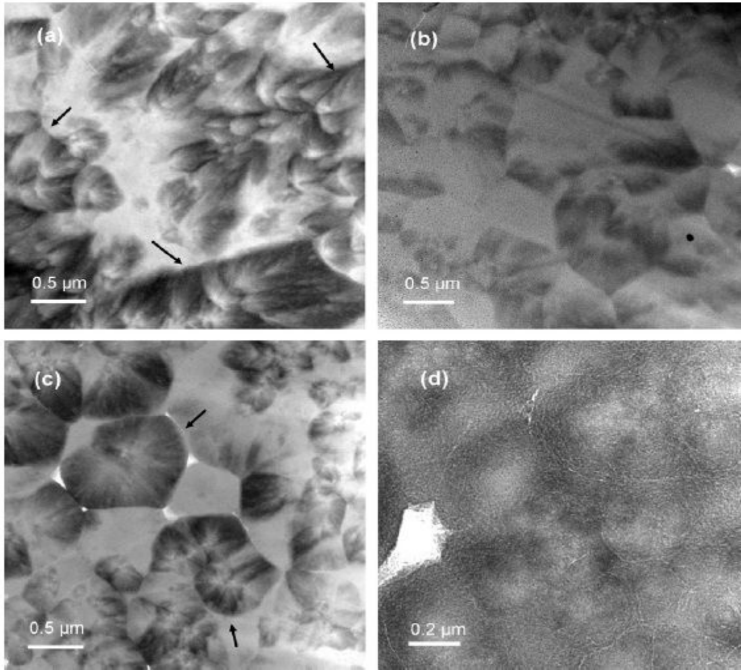
Anisotropy effects

- Graphite blocks are produced by extrusion or pressing, so there is an orientation.
- Blocks of graphite change dimensions under irradiation.
- To characterize the level of orientation of materials the BAF anisotropy factor is used (BAF).

BAF was reduced to 1.05 from 1.26 (IG-110).



https://doi.org/10.1016/j.carbon.2011.09.027

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Pressure buildup in buffer layer

The pressure buildup is a result of two main contributors:

- uranium/plutonium fission gases (mainly noble gases),
- gases formatted during oxygen interaction with carbon layer (CO, CO_2),
- ternary fission (mainly helium).

To calculate the pressure two methods are mainly used:

- the ideal gas law,
- the method of Redlich and Kwong.

$$P = \frac{RT}{V_m - b} - \frac{a}{\sqrt{T}} \frac{1}{V_m (V_m + b)}$$

Currently only CO, Xe and Kr are considered in pressure calculations.

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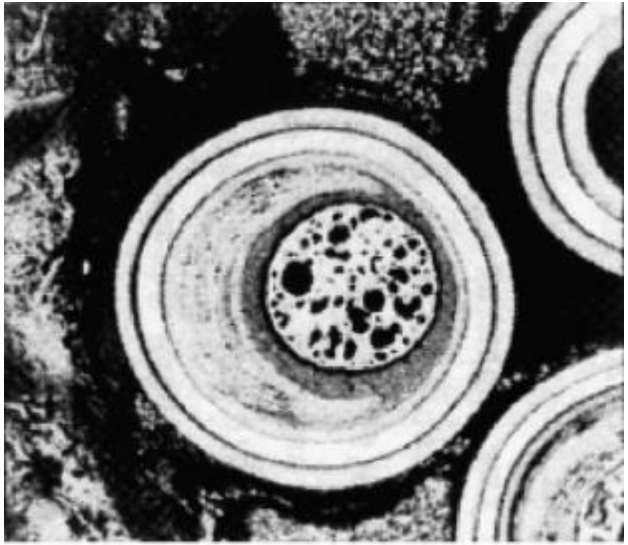
Kernel migration

- Kernel migration is defined as a movement of the kernel towards TRISO coated layers.
- The driving forces for the kernel migration are extreme operating conditions and asymmetrical kernel production during manufacturing.
- This is also known as an ”Amoeba effect” and it mainly depends on power density, temperature and temperature gradients across the fuel particle.



J. Maki, D.A. Petti, D.L. Knudson, G.K. Miller, J. Nuc. Mater. 371(2007) 270.

This effect is not well studied, there is only the experimental correlation of KM rate dependent on temperature.

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Fission products build-up and release

The products, which can be released from the fuel kernel, are usually classified into two groups: fission gases and metals.

The following effects should be considered:

- temperature,
- burnup,
- the mechanisms of a thermal diffusion and vacancy migration,
- grains and pores,
- buffer-recoil contributions,
- etc.

There are several tools developed by different countries, however there is a lack of experimental data for several fission gases and metals still.

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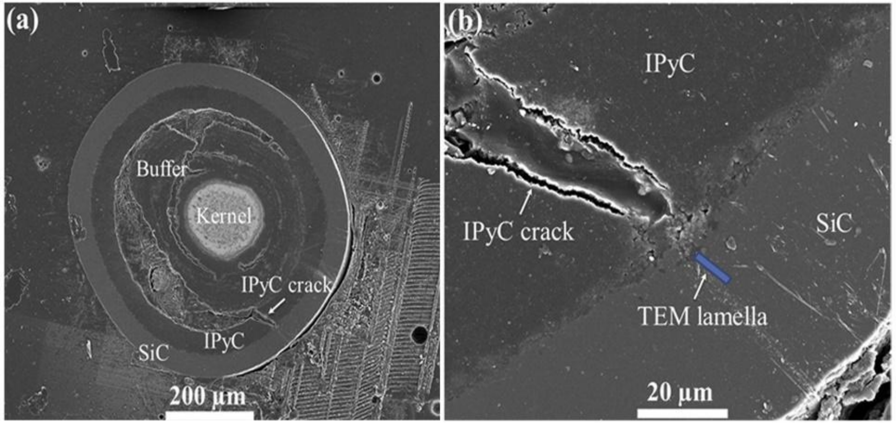
Chemical Phenomena

The release behaviour of FPs from TRISO fuel is dependent on its chemical state and temperature. In the case of UO2 kernels, the chemical state of each fission product and its amount are strongly dependent on oxygen potential, temperature and composition of FPs.



H. KLEYKAMP, The Chemical State Of The Fission Products In Oxide Fuels, Journal of Nuclear Materials, **131**, 221 (1985)

The following experimental observations have been done:

- Pd and Ag accumulated at the inner surface of the SiC layers and sometimes reacted with the SiC layers,
- Rhodium and ruthenium were also detected at the corroded areas in some particles,

Chemical Phenomena

- Tellurium was often observed in the buffer PyC layers on the cold side of the particle, but it did not penetrate through the IPyC layers in contrast with palladium,
- Cerium and barium presented similar behavior. Both of them were observed at the interface of the IPyC/SiC layers of the particles both with and without CO-SiC interaction (CO-SiC interaction means that the IPyC layer is breached),
- Cesium was observed in the buffer PyC and the IPyC layers. In contrast with the cases of palladium, tellurium, cerium and barium, no highly Cs-concentrated part was observed.
- The noble gas xenon was retained in the buffer PyC layer, similar to cesium.

Developed models are mainly considering short term irradiation and simplified environment (mainly the chemical active elements with high concentrations are considered), especially for oxidation and corrosion processes.

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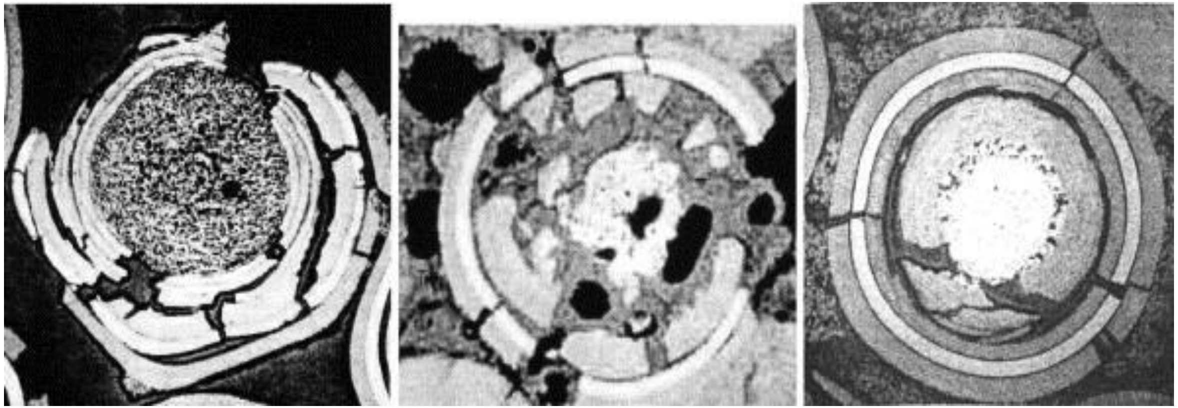
Mechanical Phenomena

To assess the mechanical behavior of the fuel the tangential and radial stresses of SiC layer should be calculated. Many parameters should be considered, such as neutron flux, anisotropy behavior of different layers, material properties (graines, pores), gas, pressure, etc.



I.J. VAN ROOYEN, M.L. DUNZIK-GOUGAR, P.M. VAN ROOYEN, Silver (Ag) transport mechanisms in TRISO coated particles: a critical review, Nucl. Eng. Des., **271**, 180 (2014)

Mechanical Phenomena

The following futures of TRISO fuel have been investigated during the latest studies:

- radial shrinkage cracks in the IPyC and OPyC layers, and partial debonding between the buffer, IPyC and the SiC layers.
- shrinkage cracks in the IPyC layer can contribute significantly to the failure of fuel particles.
- the grain size in TRISO fuel particles is not constant and grows considerably with thickness.
- deposition of SiC 1500C temperature results in an increase in coating density and anisotropy.

Further study for the size effect (both for fuel kernel and coating layers) analysis is recommended. Different methods and models are used in those tools, and it is recommended to develop a new combined software using all the best adapted available methods/models.

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Case 1 - Fuel has only 35 μm thick SiC layer. The coating behaviour is elastic.

Case 2 - simple BISO; this particle is the same as in case 1, except that the single coating is a 90 μm thick IpyC layer.

Case 3 - IPyC/SiC composite without fluence; this particle has two coating layers, an IPyC and SiC layer.

Case 4 - IPyC/SiC composite with constant creep and fluence dependent swelling;

Case 5 - TRISO, 350 μm kernel; this is a full three layer (TRISO) coated particle with a 350 μm diameter kernel under realistic service conditions.

Case 6 - TRISO, 500 μm kernel;

Case 7 - TRISO, high BAF(1.06).

Case 8 - TRISO, cyclic temperature history; 10 cycles 873K - 1273K, each cycle 100 d.

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Case 9 - HRB-22 experiment; these are LEU TRISO coated particles irradiated 89 days until 4.79% FIMA and 2.1 × 10 25 n/m 2 (E > 0.18 MeV).

Case 10 - HFR-K3 experiment, pebble B/2; these are LE-U TRISO irradiated 359 days until 10% FIMA and 5.3 × 10 25 n/m 2 (E > 0.18 MeV).

Case 11 - HFR-P4 experiment, fuel element 3; these are LEU TRISO coated particles irradiated 351 days until 14% FIMA and 7.2 × 10 25 n/m 2 (E > 0.18 MeV).

Case 12 - NPR-1 experiment, compact A5; these are HEU TRISO irradiated 170 days until 79% FIMA and 3.8 × 10 25 n/m 2 (E > 0.18 MeV).

Case 13 - HFR-EU1 experiment; these are LEU TRISO irradiated 600 days until 20% FIMA and 5.4 × 10 25 n/m 2 (E > 0.18 MeV).

CRP-6 Benchmark

Participant country/organization	FRANCE	GERMANY	JAPAN	REPUBLIC OF KOREA	RUSSIAN FEDERATION
Code name	ATLAS	PANAMA	RIGID SIC	COPA	GOLT
Code statistical methodology	Weibull, Importance Sampling	Weibull	Weibull	Monte-Carlo calculation	Weibull, Monte-Carlo calculation
Thermal model:					
Fuel element	Yes	No	No	Yes	No
Fuel particle layers	Yes	Yes	No	Yes	Yes
Buffer densif., gap formation	Yes	No	No	Yes	Yes
Gap conductance effects	Yes	No	No	Yes	Yes
Kernel burnup effects on conductivity	yes	No	No	Yes	No
Thermomechanical particle structures modeled:					
Intact	Yes	Yes	Yes	Yes	Yes
Any number of coating layers	Yes	≤ 4	4	Yes	Yes
Cracked layers	Yes	No	SiC	Yes	Yes
Debonded layers	Yes	No	No	Yes	Yes
Faceted particles	yes	No	No	No	No
Influence of buffer on stress history in dense layers	Yes	No	No	Yes	Yes
As-manufactured defects (missing or failed) layers	Yes	No	Yes	Yes	Yes

CRP-6 Benchmark

Participant country/organization	FRANCE	GERMANY	JAPAN	REPUBLIC OF KOREA	RUSSIAN FEDERATION
Code name	ATLAS	PANAMA	RIGID SIC	COPA	GOLT
Physio-chemical related models:					
Short-lived fission gas release	Yes	No	No	Yes	No
Long-lived fission gas release	Yes	Yes	Yes	Yes	Yes
CO/CO_2 production	Proksch	Proksch	Proksch	Homan	Homan or Proksch for UO_2 code ASTRA or analytical approach for PuO_{2-x} based fuel
Equation of state for fission gases, CO and CO_2	Ideal gas law	Ideal gas law	Ideal gas law	Redlich–Kwong	Redlich–Kwong or Ideal gas law
Kernel swelling	Yes	No	No	Yes	Yes
Buffer densification	Yes	No	No	Yes	Yes
Layer interaction models:					
Amoeba effect	Yes	No	No	No	Yes
Fission product/SiC interactions	Pd corrosion model	As SiC thinning rate after Montgomery	No	Yes	As SiC thinning rate after Montgomery
Thermal decomposition of SiC	No	As SiC thinning rate after Benz	No	Yes	As SiC thinning rate after Benz

CRP-6 Benchmark

Participant country/organization	Turkey	USA (INL)	USA (GA)	UK
Code name	TRFUEL	PARFUME	PISA, CAPPER	STRESS3
Physio-chemical related models:				
Short-lived fission gas release	No	Yes	Yes	Yes
Long-lived fission gas release	Yes	Yes	Yes	Yes
CO/CO_2 production	Yes	Chemical equilibrium	No	Chemical Equilibrium
Equation of state for fission gases, CO and CO_2	Redlich–Kwong	Redlich–Kwong	Programmable	Redlich–Kwong
Kernel swelling	No	Yes	No	Yes
Buffer densification	No	Yes	No	Yes
Layer interaction models:				
Amoeba effect	No	Yes	No	No
Fission product/SiC interactions	No	Yes	No	No
Thermal decomposition of SiC	No	No	Yes	Yes

CRP-6 Benchmark

Participant country/organization	Turkey	USA (INL)	USA (GA)	UK
Code name	TRFUEL	PARFUME	PISA, CAPPER	STRESS3
Code statistical methodology	Weibull	Weibull, Monte-Carlo or Direct integration calculation	Deterministic	Weibull Monte-Carlo
Thermal model:				
Fuel element	Yes	Yes	Yes	Yes
Fuel particle layers	Yes	Yes	Yes	Yes
Buffer densif., gap formation	No	Yes	No	Yes
Gap conductance effects	No	Yes	No	No
Kernel burnup effects on conductivity	No	Yes	No	No
Thermomechanical particle structures modeled:				
Intact	Yes	Yes	Yes	Yes
Any number of coating layers	4	≤ 4	No	6
Cracked layers	No	Yes	No	Yes
Debonded layers	No	Yes	No	Yes
Faceted particles	No	Yes	No	No
Influence of buffer on stress history in dense layers	No	No	No	Yes
As-manufactured defects (missing or failed) layers	Yes	Yes	Yes	Yes

Stress and Strain calculations

$$\varepsilon_{r,\theta}^{total} = \varepsilon_{r,\theta}^{el} + \varepsilon_{r,\theta}^{cr} + \varepsilon_{r,\theta}^{sw} + \varepsilon_{r,\theta}^{th}$$

$$\varepsilon_r^{total} = \frac{\partial u}{\partial r}; \quad \varepsilon_\theta^{total} = \frac{u}{r}$$

$$\varepsilon_r^{el} = \frac{1}{E}(\sigma_r - 2\mu\sigma_\theta),$$

$$\varepsilon_\theta^{el} = \frac{1}{E}\left((1-\mu)\sigma_\theta - \mu\sigma_r\right),$$

$$\varepsilon_r^{cr} = \int K(\sigma_r - 2\nu\sigma_\theta)\, d\Phi,$$

$$\varepsilon_\theta^{cr} = \int K\left((1-\nu)\sigma_\theta - \nu\sigma_r\right) d\Phi$$

$$\frac{\partial^2 u}{\partial r^2} + \frac{\zeta_1}{r}\frac{\partial u}{\partial r} + \frac{\zeta_2}{r^2}u = \lambda_1 + \frac{\lambda_2}{r}$$

$$\lambda_1 = \frac{\partial}{\partial r}\left(\varepsilon_r^{(n-1)} + \Delta\varepsilon_r^{th,(n)} + \Delta\varepsilon_r^{sw,(n)}\right) + \zeta_3\frac{\partial}{\partial r}\left(\varepsilon_\theta^{(n-1)} + \Delta\varepsilon_\theta^{th,(n)} + \Delta\varepsilon_\theta^{sw,(n)}\right)$$
$$-\zeta_4\frac{\partial\sigma_r^{(n-1)}}{\partial r} - \zeta_5\frac{\partial\sigma_\theta^{(n-1)}}{\partial r},$$

$$\lambda_2 = \zeta_6\left(\varepsilon_r^{(n-1)} + \Delta\varepsilon_r^{th,(n)} + \Delta\varepsilon_r^{sw,(n)}\right) + \zeta_7\left(\varepsilon_\theta^{(n-1)} + \Delta\varepsilon_\theta^{th,(n)} + \Delta\varepsilon_\theta^{sw,(n)}\right)$$
$$-\zeta_8\sigma_r^{(n-1)} - \zeta_9\sigma_\theta^{(n-1)},$$

$$\zeta_1 = \frac{g_{12} + 2g_{11} - 2g_{21}}{g_{11}} + \frac{r}{g_{11}}\frac{\partial g_{11}}{\partial r}, \quad \zeta_2 = \frac{g_{12} - 2g_{22}}{g_{11}} + \frac{r}{g_{11}}\frac{\partial g_{12}}{\partial r},$$

$$\zeta_3 = \frac{g_{12}}{g_{11}}, \quad \zeta_4 = \frac{b_{11}}{g_{11}}, \quad \zeta_5 = \frac{b_{12}}{g_{11}},$$

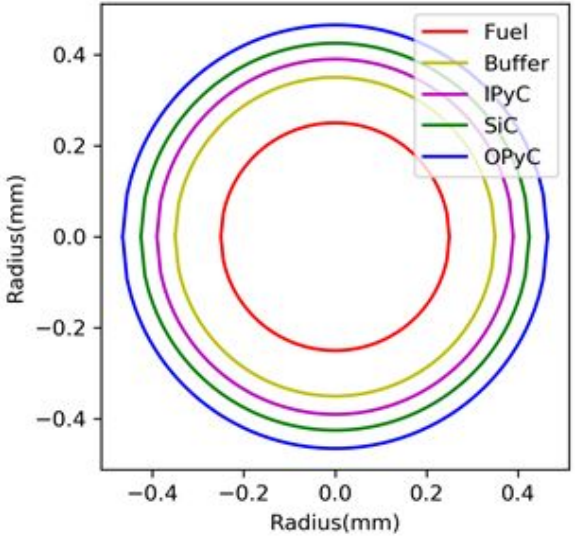
$$\zeta_6 = 2\frac{g_{11} - g_{21}}{g_{11}} + \frac{r}{g_{11}}\frac{\partial g_{11}}{\partial r}, \quad \zeta_7 = 2\frac{g_{12} - g_{22}}{g_{11}} + \frac{r}{g_{11}}\frac{\partial g_{12}}{\partial r},$$

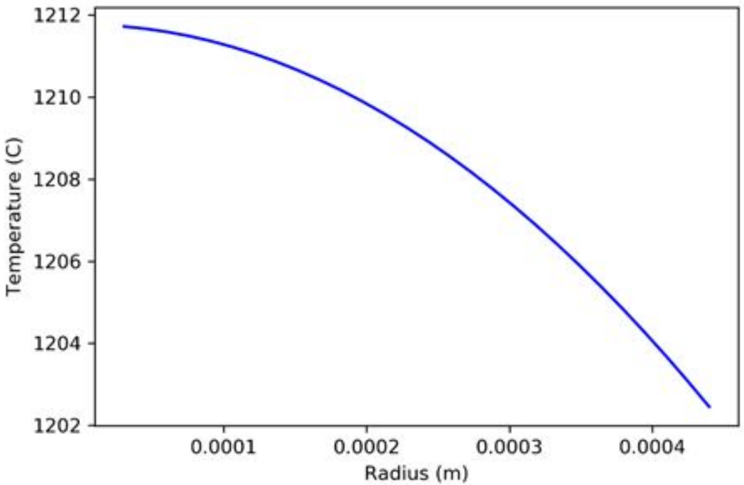
$$\zeta_8 = 2\frac{b_{11} - b_{21}}{g_{11}} + \frac{r}{g_{11}}\frac{\partial b_{11}}{\partial r}, \quad \zeta_9 = 2\frac{b_{12} - b_{22}}{g_{11}} + \frac{r}{g_{11}}\frac{\partial b_{12}}{\partial r}.$$

Heat transfer calculations

Temperature distribution

$$T_{par}(r)=\frac{q_f'''r_f^3}{3}\left[\frac{1}{k_O}\left(\frac{1}{r_S}-\frac{1}{r_O}\right)+\frac{1}{k_S}\left(\frac{1}{r_I}-\frac{1}{r_S}\right)+\frac{1}{k_I}\left(\frac{1}{r_g}-\frac{1}{r_I}\right)+\frac{1}{k_g}\left(\frac{1}{r_b}-\frac{1}{r_g}\right)+\frac{1}{k_b}\left(\frac{1}{r_f}-\frac{1}{r_b}\right)+\frac{1}{2k_f}\left(\frac{1}{r_f}-\frac{r^2}{r_f^3}\right)\right]+T_{pars}$$





Pressure buildup in buffer layer

$$P = \frac{RT}{V_m - b} - \frac{a}{\sqrt{T}} \frac{1}{V_m (V_m + b)}$$

$$P^{tot} = P^{Xe} + P^{Kr} + P^{CO} + P^{CO2}$$

$$V_m = \frac{V}{N}$$

$$N^{Xe,Kr} = V^f * \rho_f * \frac{BU}{100} * \gamma^{Xe,Kr} * f\left(\frac{X^U}{M^U}\right)$$

$$\log\{(O/F)/t^2\} = -0.21 - 8500/(T + 273)$$

E. PROKSH, A. STRIGL, H. NABIELEK, Production of CO during burnup of UO2 kerneled HTR fuel particles, Journal of Nuclear Materials, **107**, 280 (1982);

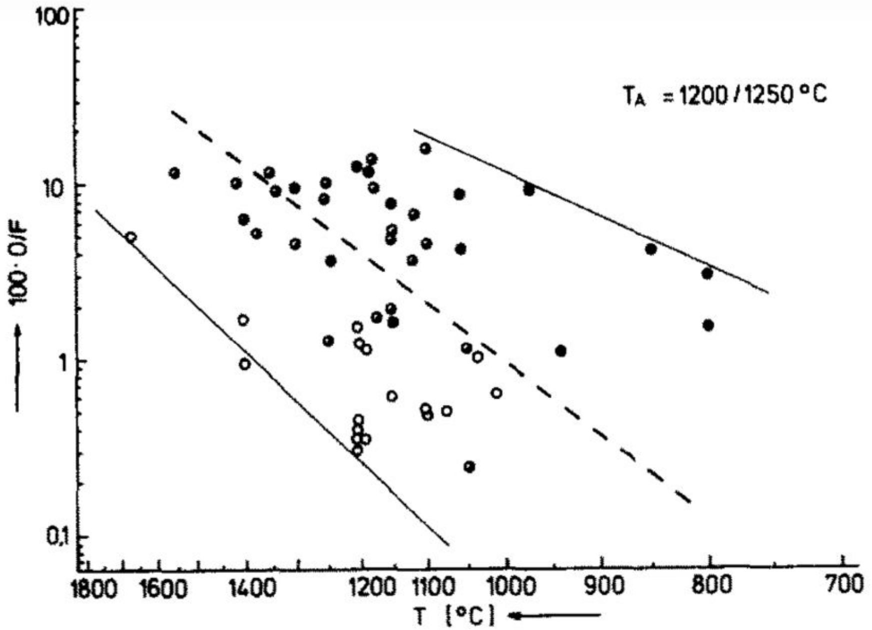


Fig. 1. Measured oxygen release O/F at 1200/1250°C analysis temperature as a function of irradiation temperature *T*. ○ Irradiation time 66 to 149 days, ◕ irradiation time 150 to 300 days, ● irradiation time 301 to 550 days.

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Summary

- There are many uncertain issues in fuel performance analysis,
- There is a lack of experiments related to some phenomena,
- The need of new modeling tools/models is still necessary.

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Thank you for your attention!

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