Modeling Fully Ceramic Microencapsulated (FCM) fuel – description of the research objectives

NATIONAL CENTRE FOR NUCLEAR RESEARCH
ŚWIERK

- Zuzanna Krajewska

Division of Nuclear Energy and Environmental Studies

- Zuzanna.Krajewska@ncbj.gov.pl

Fundusze Europejskie
Wiedza Edukacja Rozwój

Rzeczpospolita Polska

Unia Europejska
Europejski Fundusz Społeczny

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

Main points of the presentation

- Good understanding of failure-free performance of Tri-structural ISOtropic (**TRISO**)-particle fuel is a key for safe and efficient operation of High Temperature Gas-cooled Reactors.

- The research on TRISO fuel would focus on examining the **degradation process** of such fuel and on ways to reduce the number of defects in the TRISO particle.

TRISO-coated particle

Each layer has the following dimensions:

- the fuel kernel with diameter in the range of 350-600 µm;
- porous pyrocarbon buffer layer thickness in range of 90 to 100 µm;
- the IPyC layer thickness is typically in range 35 to 40 µm;
- the thickness of SiC layer is around 35µm;
- the OPyC layer thickness is typically in range 35 to 40 µm.

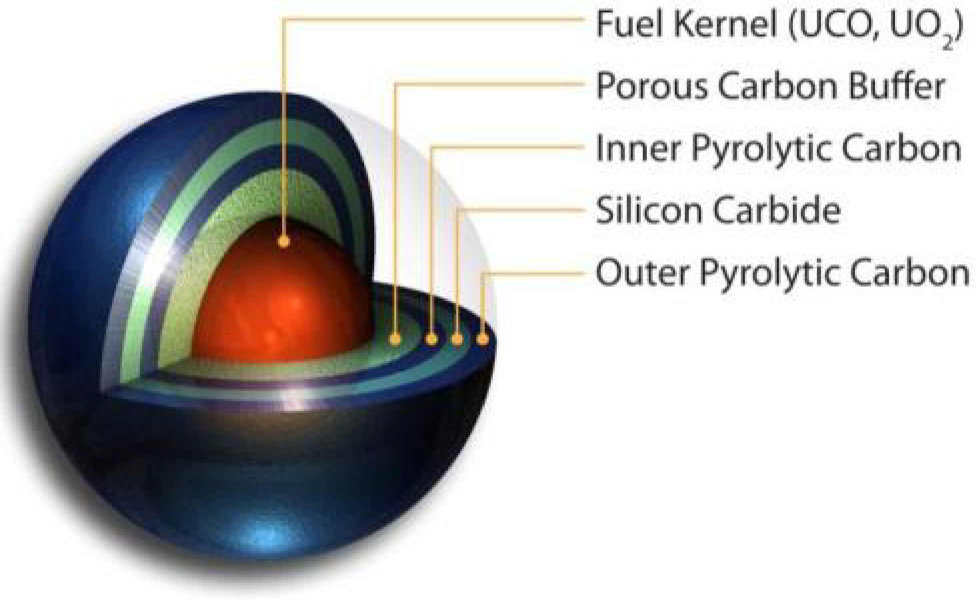

Fig. 1 TRISO fuel cross-section

TRISO fuel failure mechanisms

During irradiation partial or complete failure of the TRISO particle may occur, caused by the failure mechanisms which can be categorized:

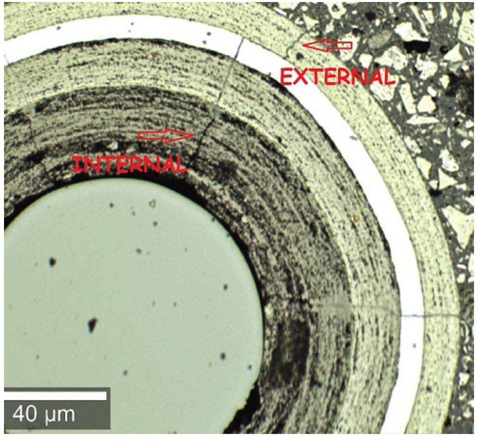

Fig. 2 Damage location

Damage location	Damage factor	Cause of the damage
External area of the particle	Mechanical	Mechanical
Internal area of the particle	Chemical	Chemical

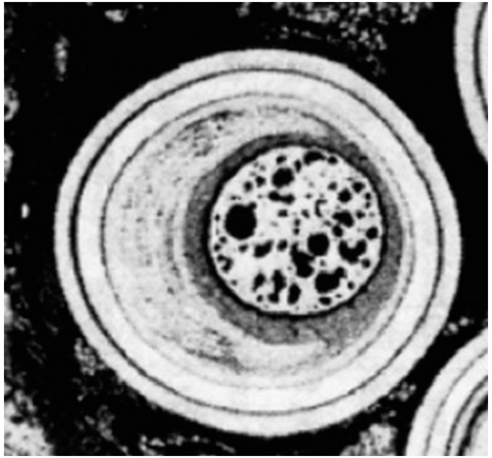

Fig. 3 Kernel migration

Quality Control (QC)

- **Kernels**
  - Dimensions
  - Density
  - Chemistry
  - Enrichment
  - Impurities
  - Microstructure
- **TRISO Particles**
  - Layer thickness
  - Layer density
  - Aspect Ratio
  - PyC anisotropy
  - PyC defects
  - SiC microstructure
- **Compacts**
  - Dimensions
  - U loading
  - Impurities
  - Matrix density
  - Dispersed U
  - TRISO defects

The technical parameters to be considered for TRISO particle analysis are:

· **geometry** - kernel diameter and sphericity, layer thicknesses and cylindrical/spherical fuel element dimensions;

· **density** - of the kernel; buffer, IPyC, SiC, OPyC layer, and matrix material density.

Stages of the experiment

The stages of damage testing have been identified:
· **front-end**;
· simulation of irradiation with ion implantation;
· real irradiation in Maria research reactor;
· post-irradiation experiment.

As a starting point for the research, the focus was on the stage **front-end** and modeling irradiation with ion implantation.

The experiment will be carried out in two steps:
· **step 1** – analysis of the intact “virgin” sample (front-end);
· **step 2** – analysis of the sample after ion implantation as a reflection of the stage of irradiation of TRISO particle in the Maria reactor.

The step1 and step2 will be performed using the Raman spectroscopy method.

Raman spectroscopy

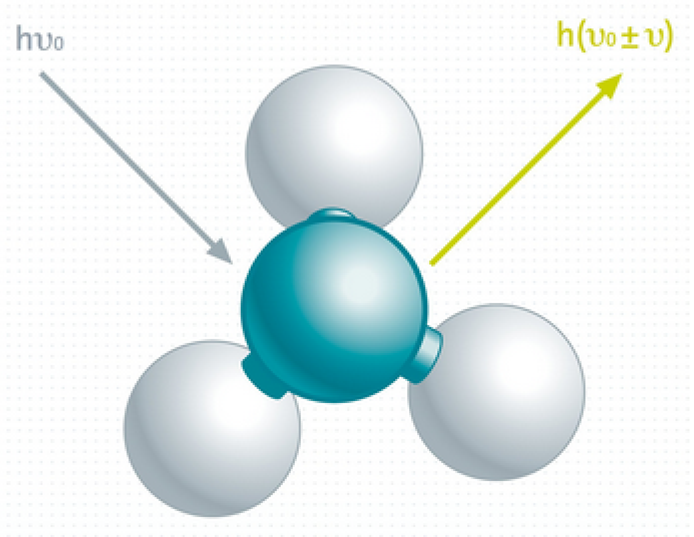

Fig. 4 Raman effect

- Non-destructive
- Non-invasive
- Can be used for imaging
- Provides a chemical "fingerprint" of the investigated compounds

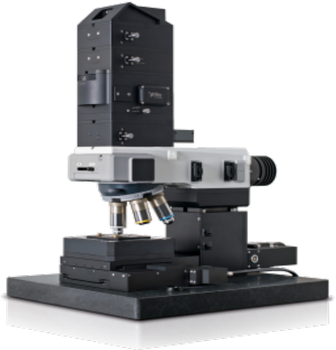

Fig. 5 Raman microscopes: WITec, Renishaw

Raman spectrum

The main parameters characterizing the band are :

- half width (Δv1/2) - this is the width of the band contour, determined in the middle of its height,
- frequency (v0) - it is a value corresponding to the maximum height of the contour of the tested band,
- intensity (Imax) - this is the height of the band contour measured from the background level,
- integral intensity (I∞) - this is the area bounded by the band contour and the background.

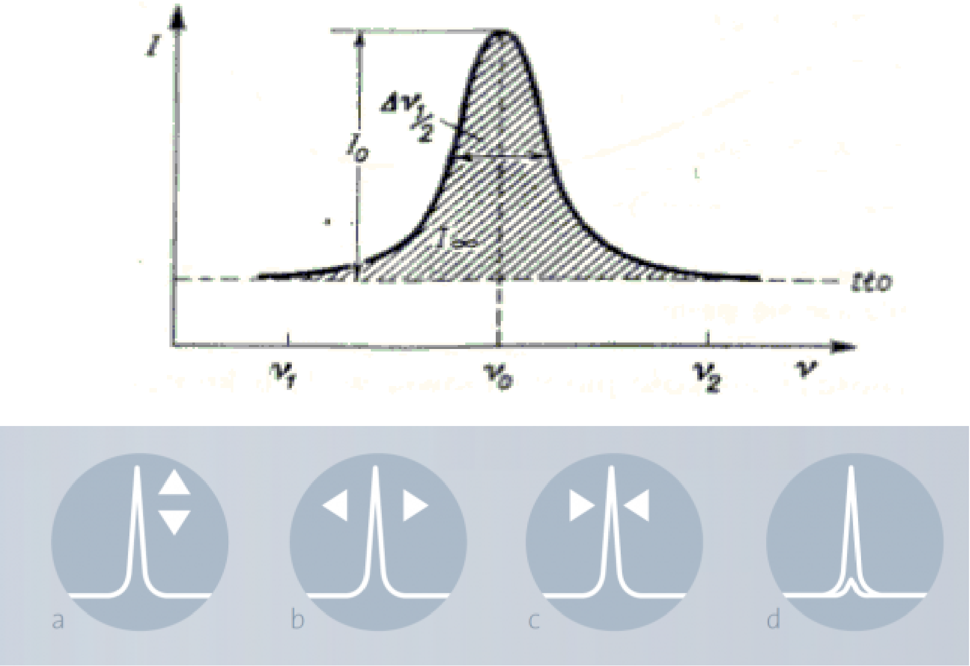

Fig. 6 Raman spectrum

Ion implantation

Ion-beam irradiation technique is used to simulate neutron irradiation process, because it allows study of irradiation damage without needs to deal with radioactive materials and in relatively short time.

Typically ion implantation is with noble-gas ions like: Ar+, **He+**, Xe+, Ne+ and Kr+.

Assumptions to the experiment

The experiment will be divided into five parts:

· TRISO sample preparation;

· verification of compliance of the virgin TRISO sample with the manufacture's data, using Raman method;

· TRISO sample ion implantation;

· verification of TRISO sample, after ion irradiation, using Raman method;

· comparison of the results**.**

Assumptions for the experiment:

· examine the TRISO-coated particle with a middle SiC layer, in both steps. In the second step, assuming helium ion implantation with fluence in range of 10^12 and 10^17 ions/cm2 ;

· examine the TRISO-coated particle with a middle ZrC layer, in both steps. In the second step, assuming helium ion implantation with fluence in range of 10^12 and 10^17 ions/cm2 ;

· comparison of both particle types, at both stages, in terms of thickness of each layer, kernel radius, changes in Raman spectrum and predictable damage locations.

TRISO Preparation

Fig. 7 TRISO particles

Fig. 8 Pastille with polished TRISO

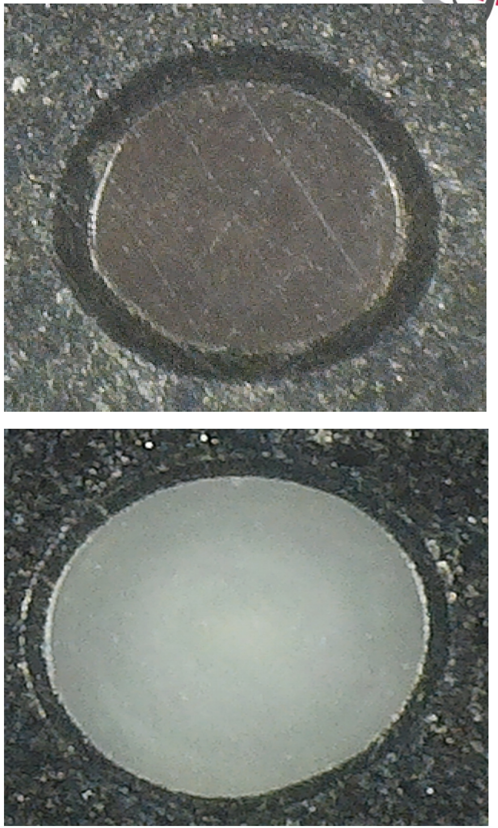

Fig. 9 Two types of TRISO (under the microscope)

Line focus mapping

the laser illuminates a line on the sample.

This enables to simultaneously collect spectra from multiple positions on the sample.

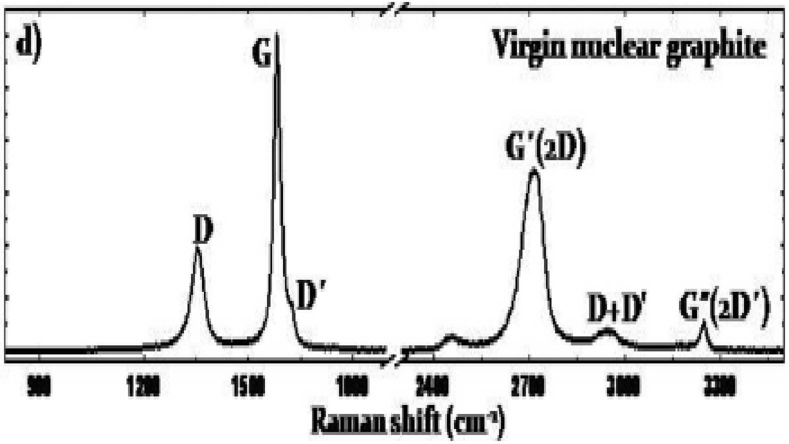

Fig. 10 Raman spectrum of virgin nuclear graphite

G-peak mainly at position 1580[cm-1]

D-peak at position 1355[cm-1]

Raman mapping 2/3

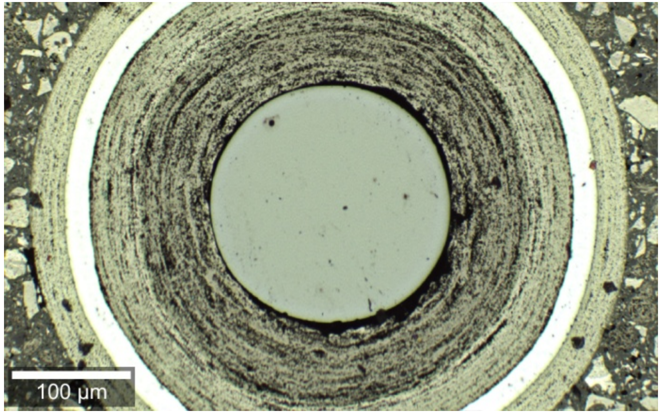

Fig. 11 TRISO under a microscope

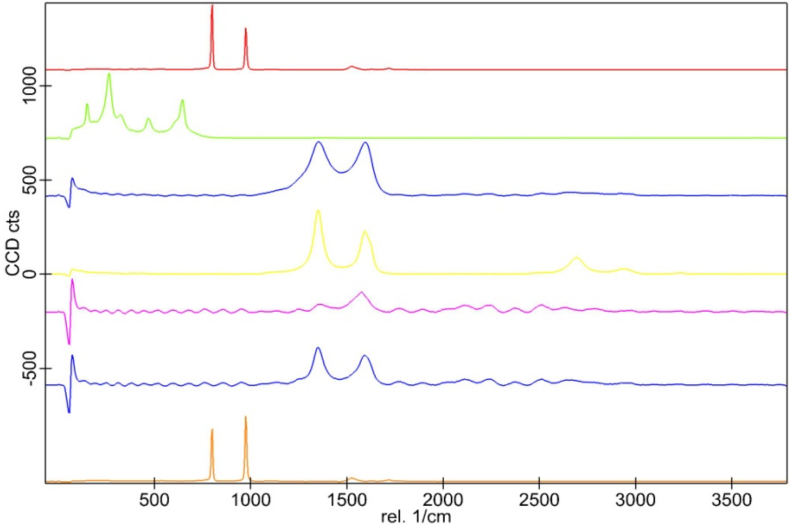

Fig. 12 Raman spectrum of TRISO particle

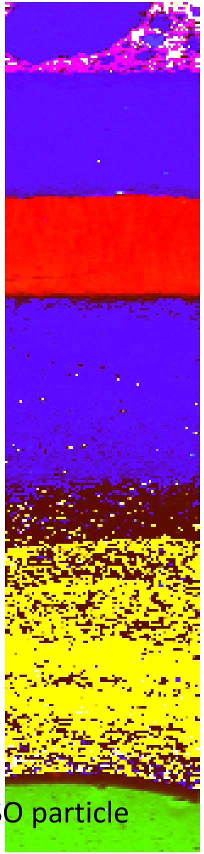

Fig. 14 Raman map of TRISO particle

Raman mapping 3/3

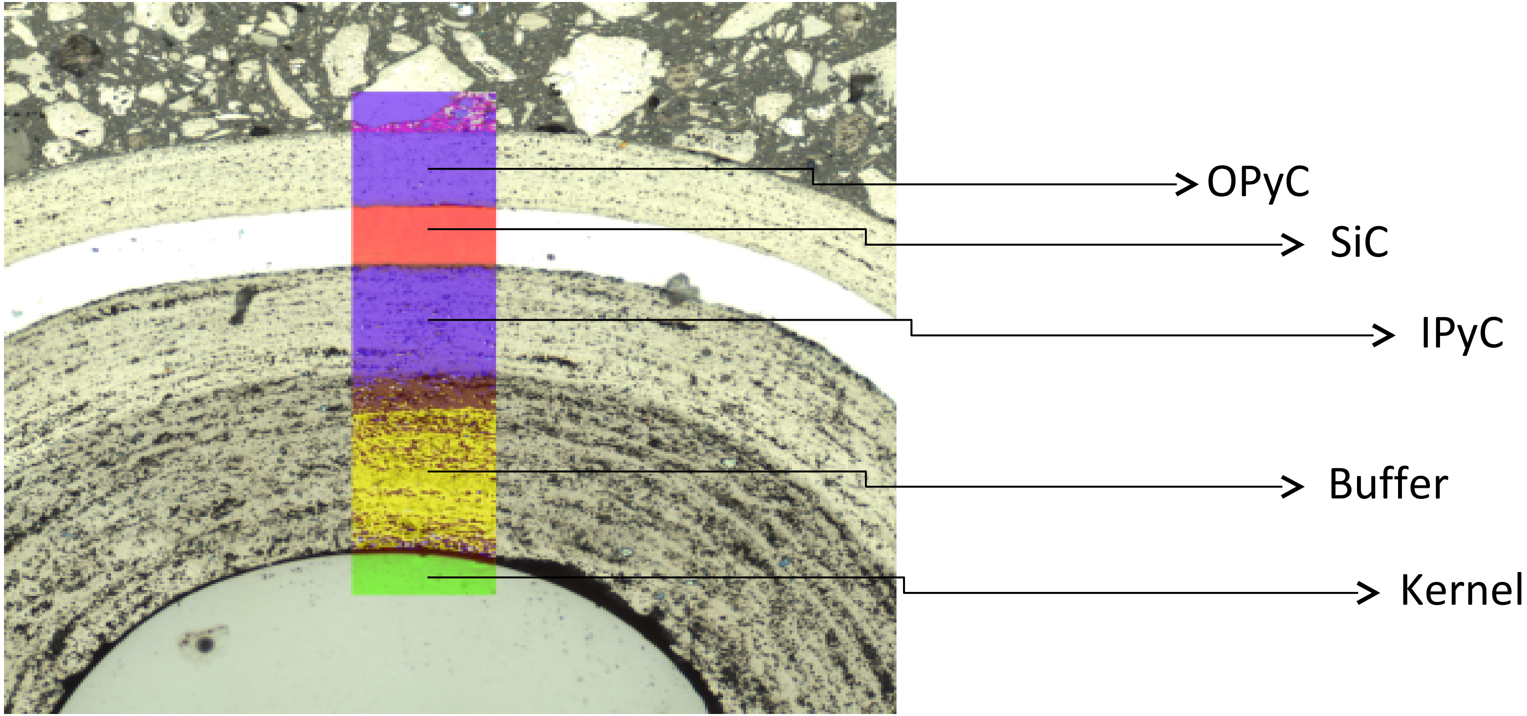

Fig. 15 The map of TRISO structure made by Raman spectroscopy

Conclusions

- Raman spectroscopy is a good method to checked the TRISO particle structure.

- The conclusions based on the Raman spectrometer measurement will be used to improve the structure of TRISO fuel layers.

In the next step, ion implantation should be performed on polished samples, then the Raman method should be used and the results should be compared.

Literature

- P. Demkowicz, TRISO Fuel: Design, Manufacturing and Performance, ART INL, NRC HTGR Training July 16-17, 2019.
- J.R. Ferraro, K. Nakamoto, C.W. Brown, Introductory Raman Spectroscopy, Academic Press, 2003.
- T. Dieing, O. Hollricher, J. Toporski, Confocal Raman Microscopy, Springer, Berlin Heidelberg, 2010.
- M.R. Ammar, N. Galy, J.N. Rouzaud, N. Toulhoat, C.E. Vaudey, P. Simon , N. Moncoffre, Characterizing various types of defects in nuclear graphite using Raman scattering: Heat treatment, ion irradiation and polishing, Carbon 95, p. 364-373, 2015.
- H.X. Xu, J. Lin, J.J Li, Z.Y. Zhu, G.L. Zeng, J.D. Liu, B.C. Gu, B. Liu, Characterization the microstructure and defects of matrix graphite irradiated with Xe ions, Nuclear Instruments and Methods in Physics Research B 406, p. 638-642, 2017.
- A.C. Ferrari, J. Robertson, Resonant Raman spectroscopy of disordered, amorphous, and diamodlike carbon, Physical Review B, Vol. 64, 2001.
- https://www.renishaw.com
- https://www.witec.de/

Thank you for attention

- Zuzanna Krajewska

Division of Nuclear Energy and Environmental Studies

- Zuzanna.Krajewska@ncbj.gov.pl

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Fundusze Europejskie Wiedza Edukacja Rozwój

Rzeczpospolita Polska

Unia Europejska Europejski Fundusz Społeczny

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