Self-organized criticality model of the nuclear fuel structure evolution

L. Juodis[1], I. Petrashenko[2], G. Trinkūnas[1], and V. Remeikis[1]
[1]Institute of Physics, Savanorių 231, LT-02300 Vilnius, Lithuania
laurynas@ar.fi.lt
[2]Department of Theoretical Physics, Vilnius University, Saulėtekio 9, LT-10222 Vilnius, Lithuania

3-rd Annual Meeting COST Action P10 Physics of Risk joined with Workshop on
Complex System Science of ONCE-CS Action,
Vilnius, Lithuania, 13-16 May 2006

Motivation

- Nuclear fuel (NF) characteristics depend on its **material structure** which can change in course of reactor operation.
- Safety of NF during operation and its storage/disposal is influenced by the **change of NF material structure.**
  - Fission product release, decrease of thermal conductivity, mechanical interaction with cladding are side-effects reducing possibility to extend the fuel maximum burnup.

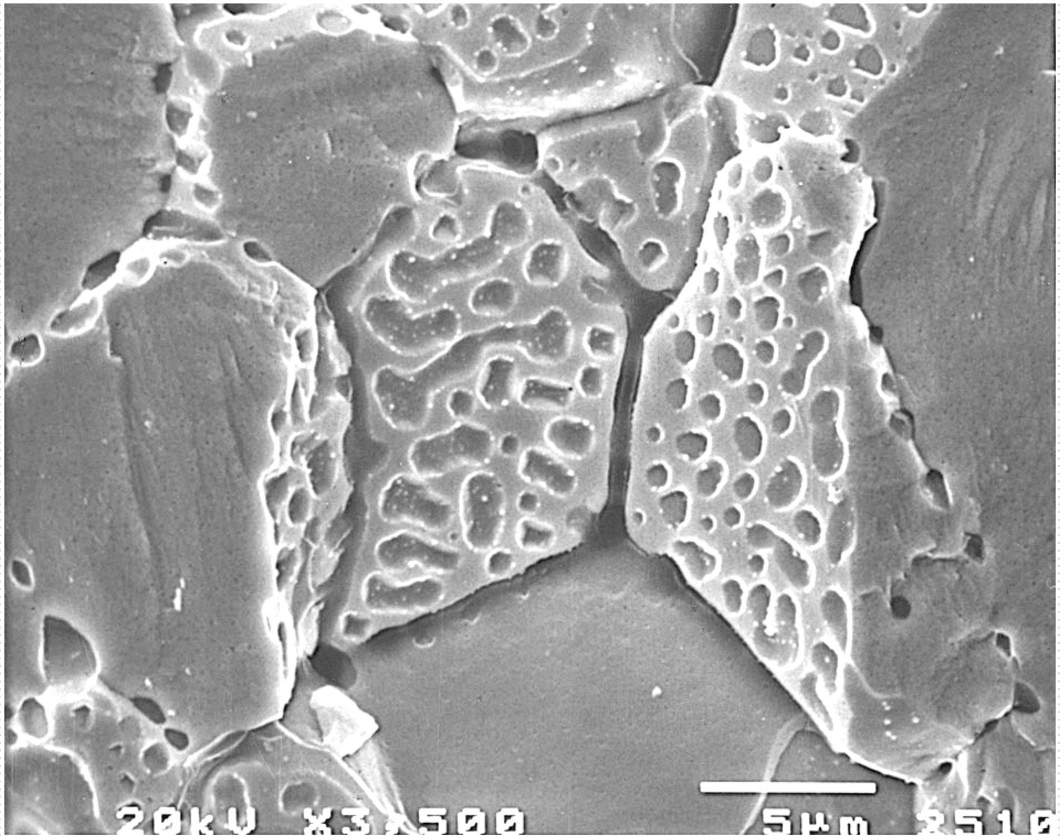
→ **It is important to have the model being able to predict the structure of NF !**

Nuclear fuel characterization

- The pellets of Light Water Reactors (PWR, BWR, VVER, RBMK) nuclear fuel are composed of polycrystalline UO_2.
- NF pellets are loaded into thin tubes - fuel rods.
- Fuel rods are composed into the fuel assemblies which are loaded into the core of nuclear reactor.

Nuclear fuel micro-structure

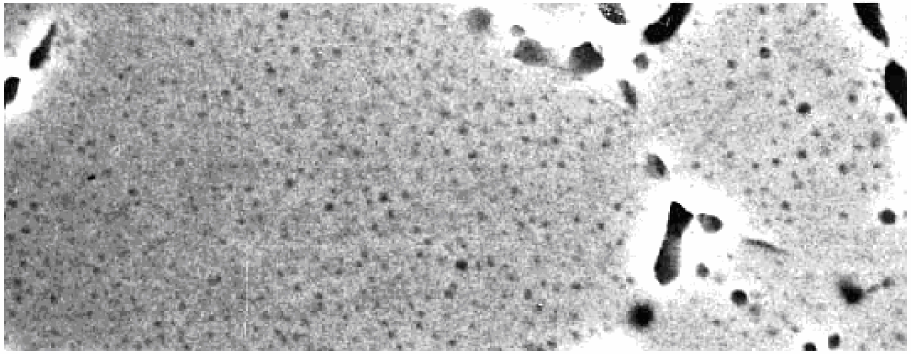
- The UO_2 is composed of separate crystals – grains, which form the fuel pellets.
- Grain size is predetermined by fabrication process and is 5 – 10 µm.



Zacharie I. et al., J.of Nucl.Mater. 255, 1998.

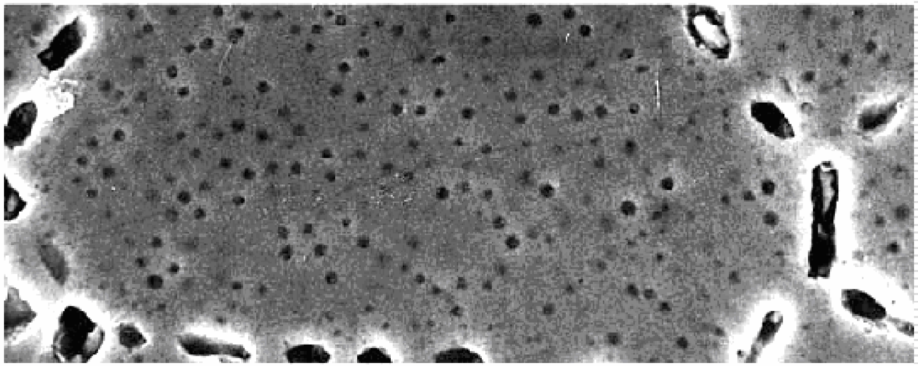
Nuclear fuel micro-structure

- FP are generated continuously in NF during reactor operation and accumulate in the bubbles.
- Inter- and intra- granular **bubbles** are formed during fabrication of NF pellets and reactor operation.



1715°C/30 min

Zacharie I. et al., J.of Nucl.Mater. 255, 1998.



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Fission product release

- UO_2 grain structure greatly influences fission product (FP) release from NF:
  - Intra-granular bubbles act as traps for FP;
  - Inter-granular bubbles can interconnect and form venting tunnels resulting in FP enhanced release.
- A model for bubble size distribution could be useful for prediction of FP release and fuel performance.

Aim and idea

- The aim is to develop the model being able to describe the NF structure depending on burnup.
- The idea is the hypothesis that the dynamics of the NF structure can be described by similar laws observed in the real biological evolution of nature.

The concept

☐ In real nature the interaction of species is similar process to the dynamics of bubbles in burning UO_2!

- The bubbles undergo dynamic changes due to temperature, irradiation, hydrostatic pressure, etc.
- Small bubbles build up at the lattice defects and are destroyed and afterwards built up again due to collision of fission fragments with UO_2.
- The **biggest bubbles** are most probable to be changed by the environmental influence.

The process can probably be described by **dynamics of self organized critical system!**

The model

- The self-organized criticality model established by P.Bak and K.Sneppen [Bak P., Sneppen K., Phys.Rev.Let., 71, 4083-4086, 1993] to describe the biological evolution could be applied to predict the NF structure evolution.

The model

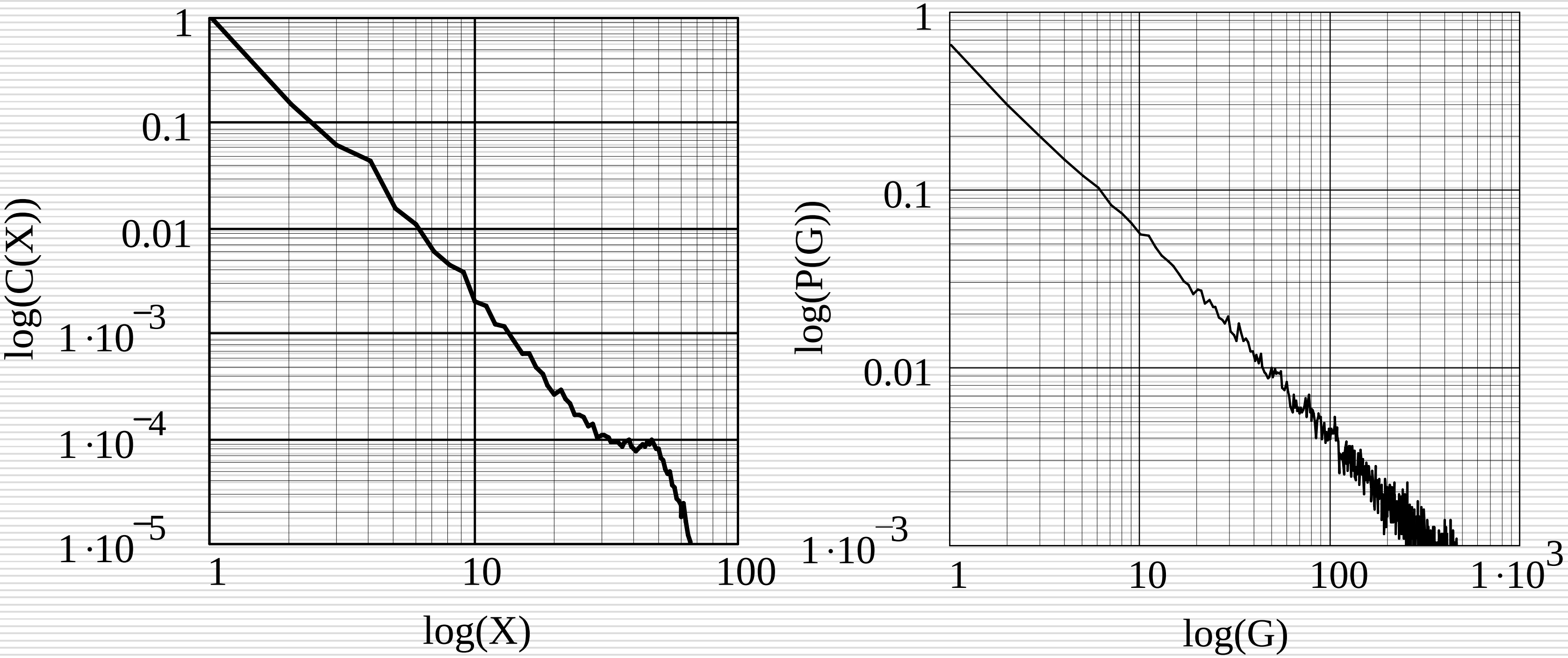
- We describe the bubbles contained in the fuel matrix as a 2D array of some N barriers.
- Each bubble has a random value $B_i(t)$ from interval {0; 100}.
- At each time step the **biggest** bubble changes (mutates, due to irradiation, pressure, FP transport) to the new random value $B_i(t+1)$.
- Neighbor bubbles change randomly too, from interval {0; 100}.

- We repeat the cycle until the system evolves into the self-organized critical state with characteristic parameters.

Simulation results

- The system evolves into the self-organized critical steady state.
- Correlations in space and time between events are distributed without any characteristic scale.

Simulation results



Normalized number of occurrences of distance *X* between mutating bubbles and stasis time *G*, accordingly.

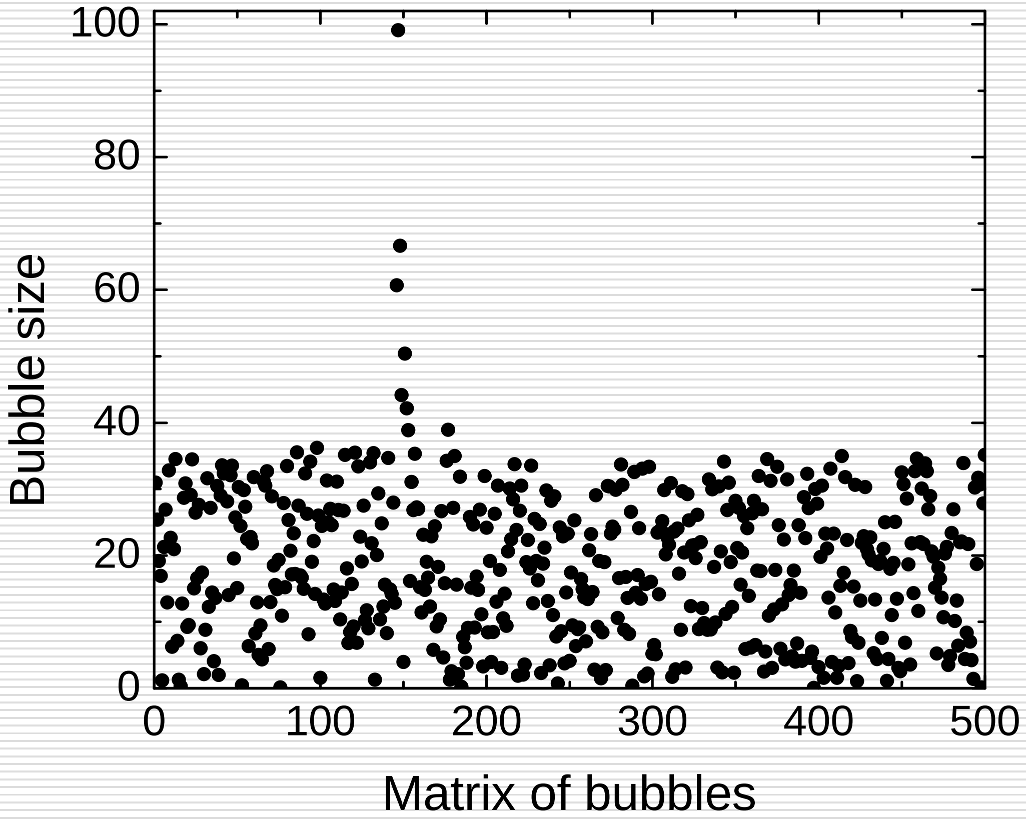
Simulation results

Model parameters	a	b	c
B_{cr}	53 ± 1	68 ± 1	79 ± 1
$C(X)$	$X^{-3.15 \pm 0,01}$	$X^{-3.05 \pm 0,01}$	$X^{-3.0 \pm 0,01}$
$P(\mathrm{G})$	$G^{-1.18 \pm 0,01}$	$G^{-1.121 \pm 0,001}$	$G^{-0.995 \pm 0,001}$
Fuel burnup, MWd/kgU	16.4	54.8	65,0

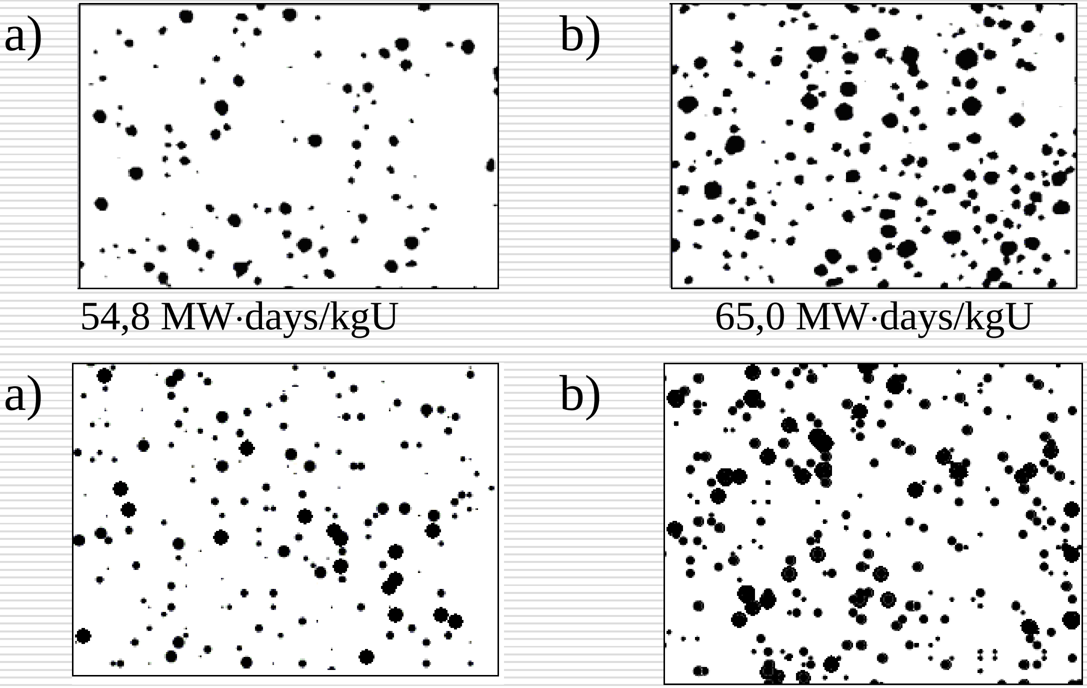
☐ The fuel burnup is directly proportional to the number of mutating neighbor bubbles to the critical bubble.

Simulation results

Bubble dynamics in self-organized critical state.



Simulation results

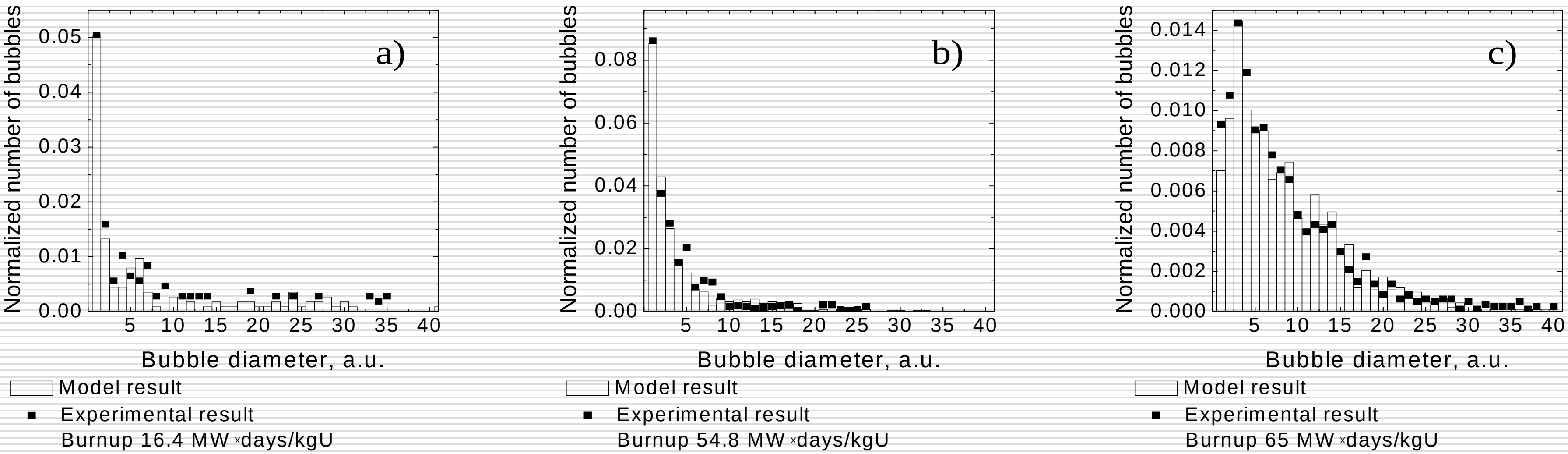


54,8 MW·days/kgU

65,0 MW·days/kgU

Experimental [Antoniou I., et.al., Chaos, Solitons and Fractals, 18, 1111–1128, 2003] (above) and modeled (below) structure of nuclear fuel bubbles corresponding to 54,8 MW·days/kgU (a) and 65,0 MW·days/kgU (b).

Simulation results



Bubble size distribution for modeled burnup cases 16.4, 54.8 and 65.0 MW*days/kgU, bars represent experimental [Antoniou I., et.al., Chaos, Solitons and Fractals, 18, 1111–1128, 2003], points represent model results.

Conclusions

- On the basis of presented results we state that the microstructure of **the nuclear fuel in irradiation conditions is in self-organized critical state** and its evolution takes place via local avalanche processes.
- Similarity of the model and the experimental results at **different burnup levels is attained when adjusting the relevant number of the neighboring bubbles** undergoing mutation together with the critical bubble.

Acknowledgements

- This work was supported by the Lithuanian State Science and Studies Foundation under the project No. C - 03049.

Thank you for your attention!