# Test reactor irradiations in support of power reactor fuel R&D

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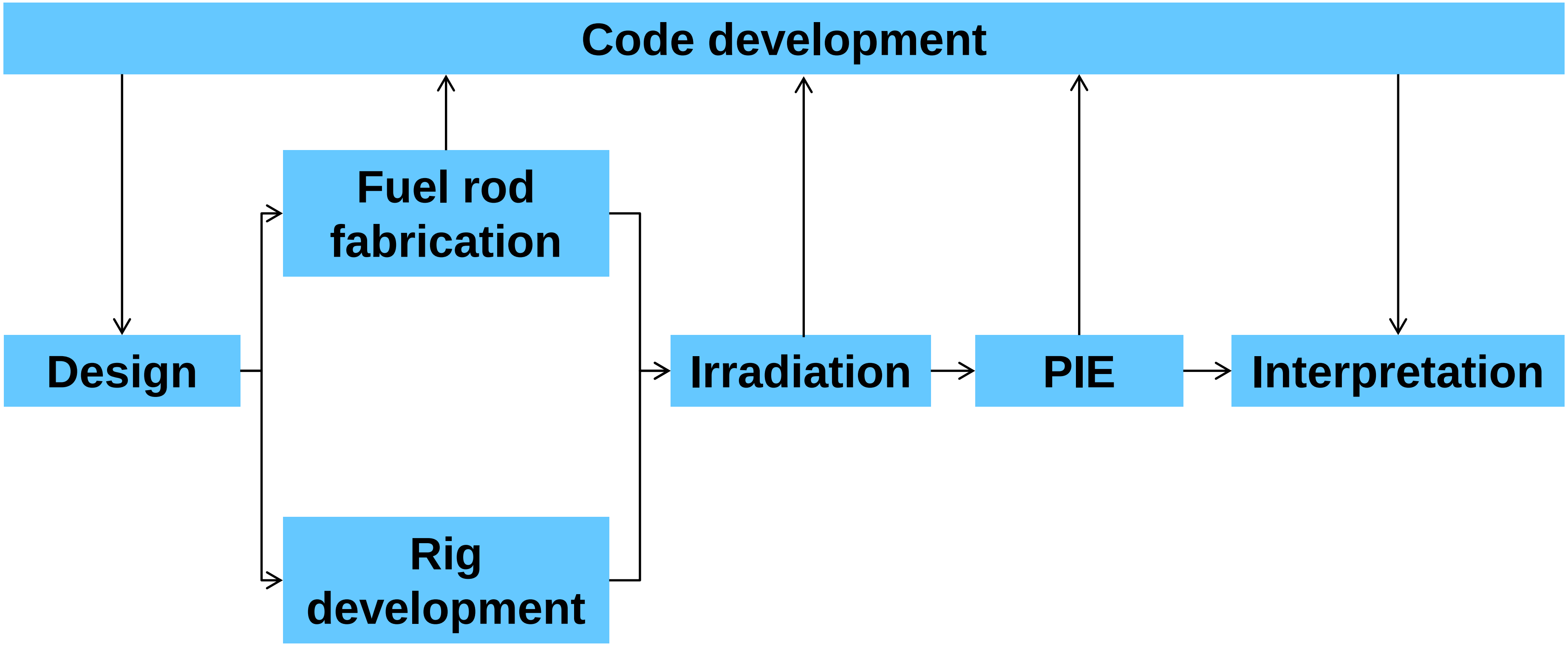
# Nuclear fuel research: an integrated approach



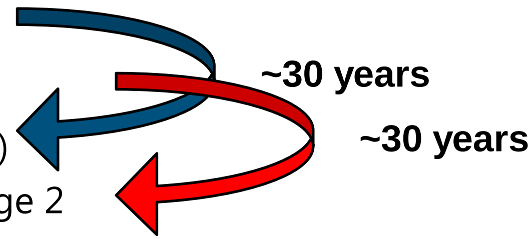
# Outline

- “Licensing support” R&D
  - Context
  - Example: CHIPS program on $(U,Pu)O_2$ fuel (2006-today)

- “Exploratory” R&D
  - Context
  - Example: $(Th,Pu)O_2$ research (2001-today)

# Context of "licensing support R&D"

- Some dates:
  - 1958: first MOX production (SCK•CEN)
  - 1963: first LWR MOX irradiation (BR3)
  - 1986: first industrial LWR MOX production (BELGONUCLEAIRE)
  - 1994: first MOX loading in the Belgian NPPs Doel 3 and Tihange 2




- Between 1986-2005, clad development and MOX licensing programs were conducted in BR-2 (clients: fuel vendors, utilities, licensing authorities):
  - Cladding: ZIRLO, Low-Sn Zr-alloys, duplex Zr-alloys
  - MOX: Typical Pu enrichment: 4-8 wt% Pu/(U+Pu)
  - BU range: 20-80 GWd/tHM
  - Base irradiation in PW loop & transient testing in PW capsule

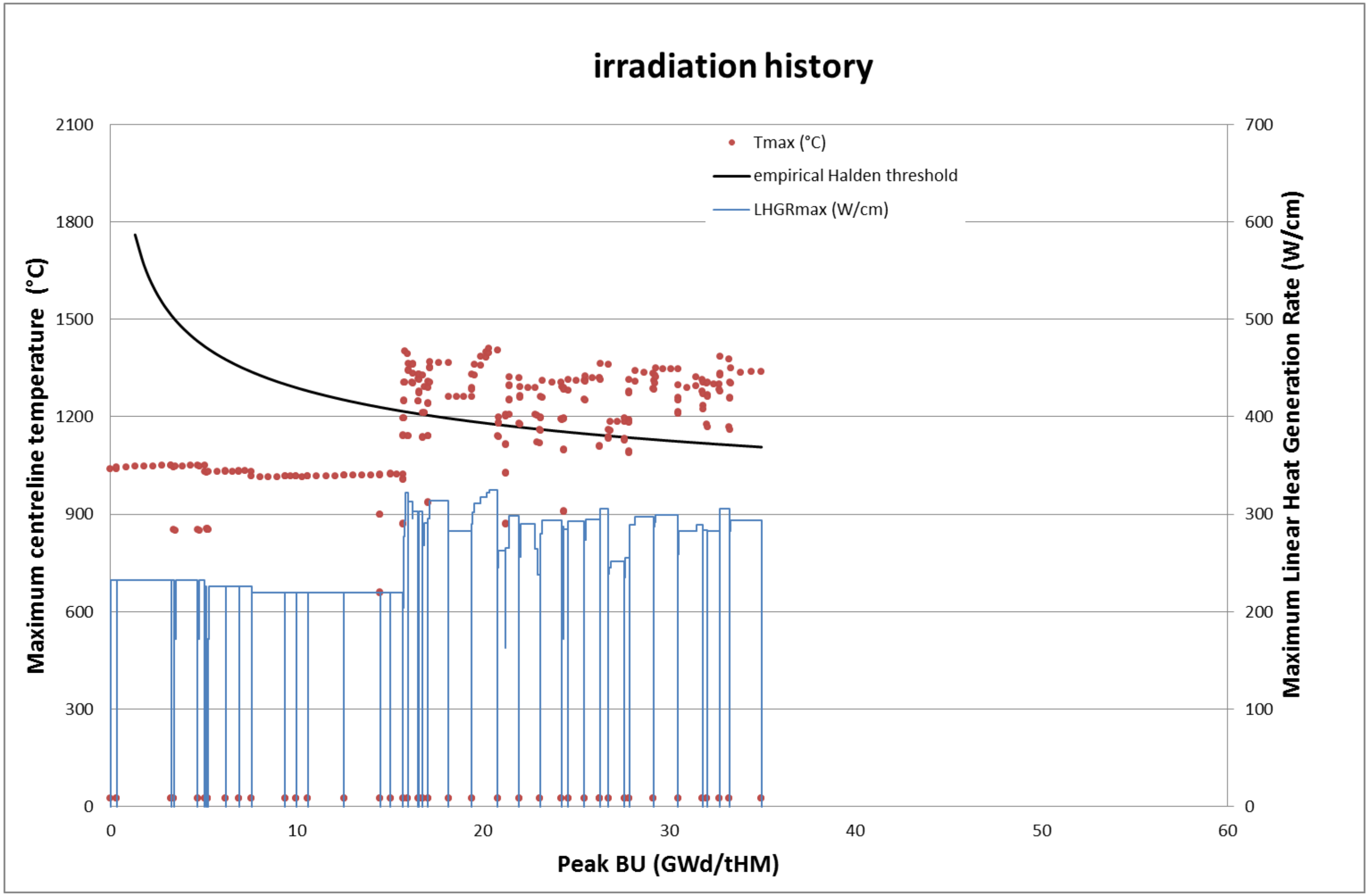
- In 2006, Japan's Nuclear Energy Safety organization (JNES) contracted two licensing support R&D programs (extend the enrichment range - broaden the high BU exp. basis) :
  - In Halden (HBWR Norway) and CEA (France), experimental MOX of ultra-high BU was studied
  - In SCK•CEN, commercial MOX with a bounding* enrichment of 14% was studied ("CHIPS")

(*) bounding for the licensing applications considered in the Pluthermal plan

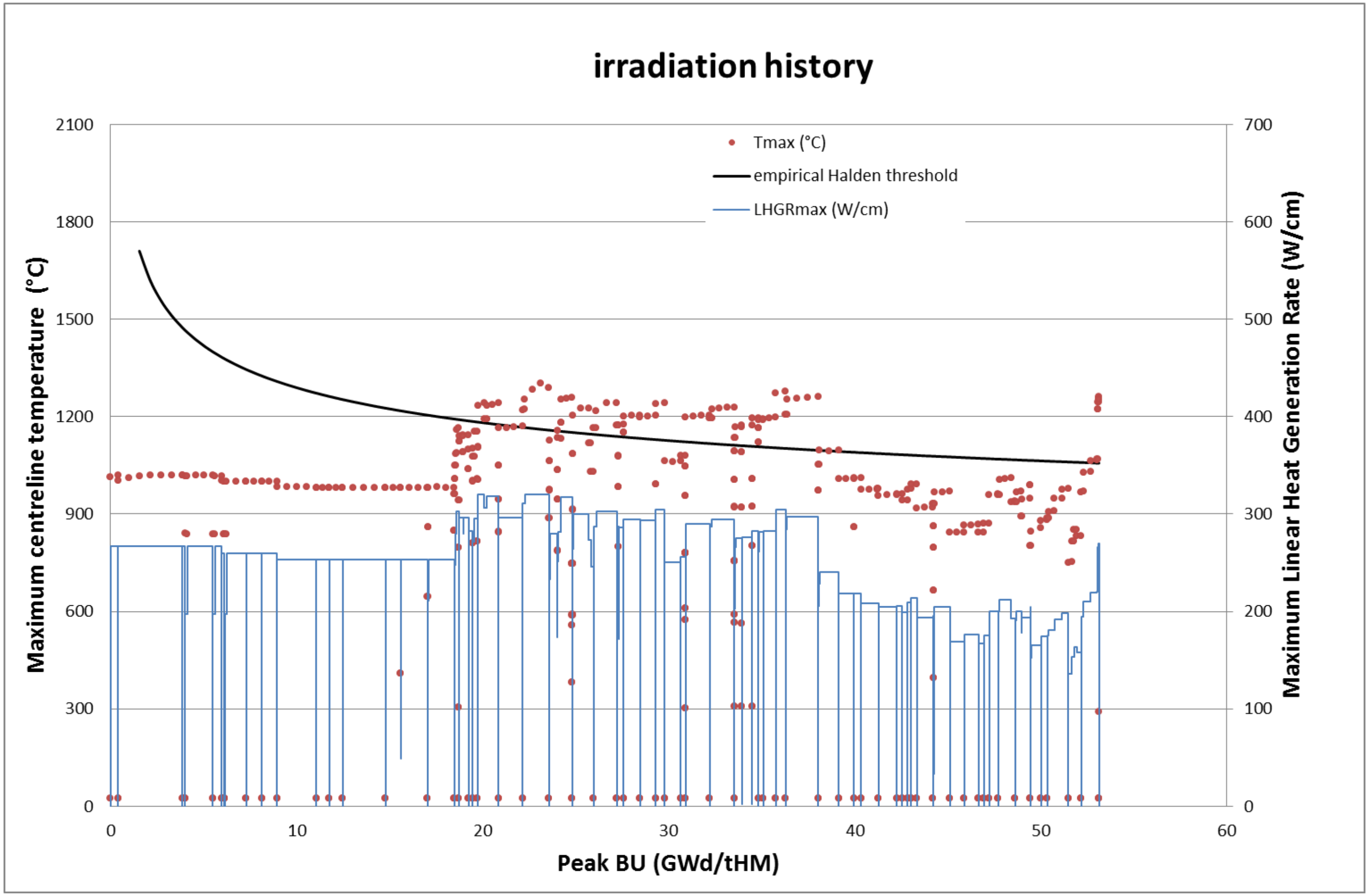
# Objectives of the CHIPS program

- In 2006, in view of the delay of their FBR program and to reduce the growing Pu stockpiles, Japan decided to utilize Pu in 1/3$^{rd}$ of their LWR reactor fleet
- Japan's licensing support organization decided to develop experimental datasets (independent of vendor or utility-owned datasets)
- Test irradiations and detailed post-irradiation investigations:
  - 35 GWd/tHM, high rating, no transient
  - 53 GWd/tHM, high rating, transient at EOI
  - 55 GWd/tHM, low rating, transient at MOI and EOI

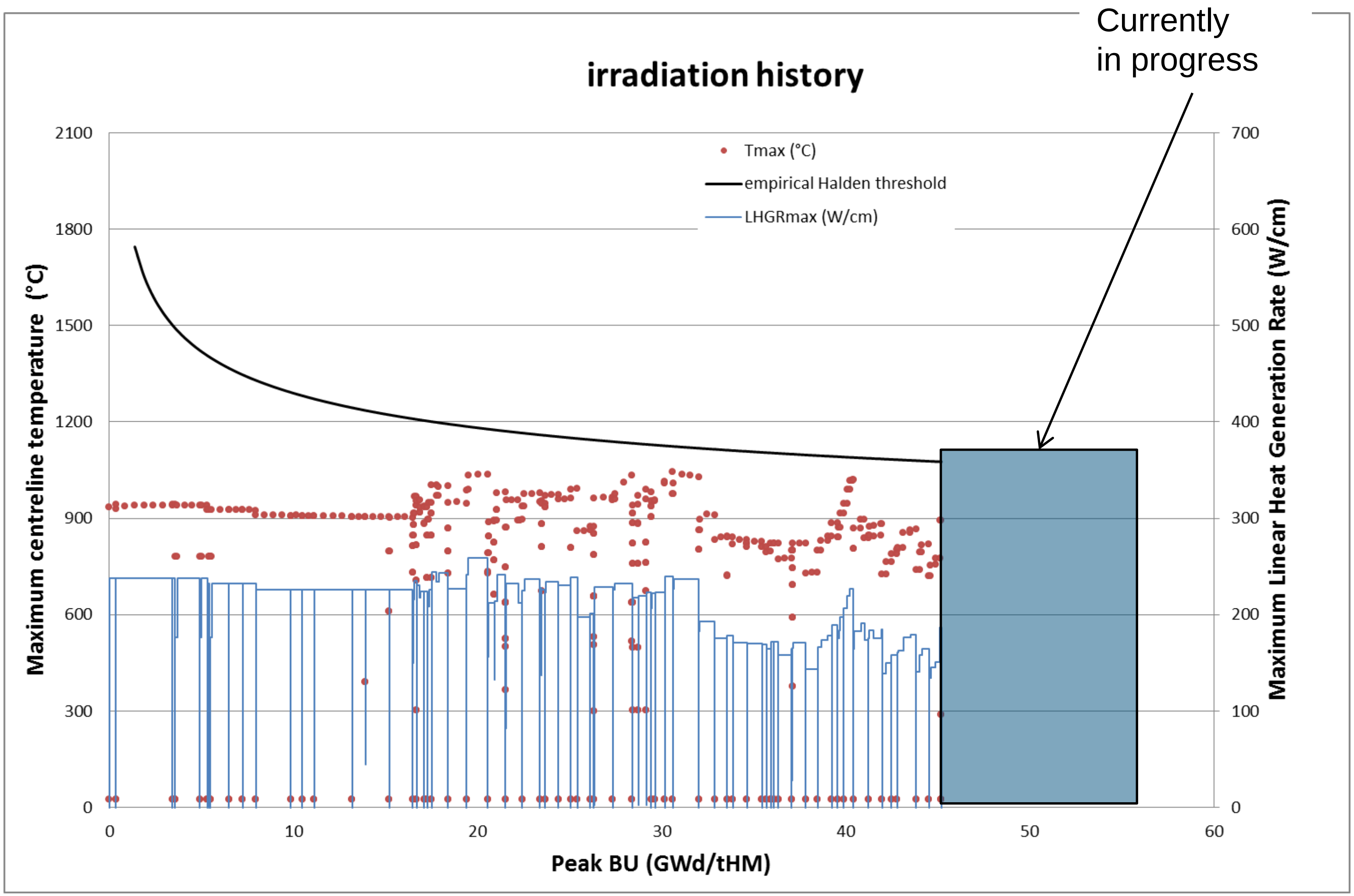
# High power, medium burnup



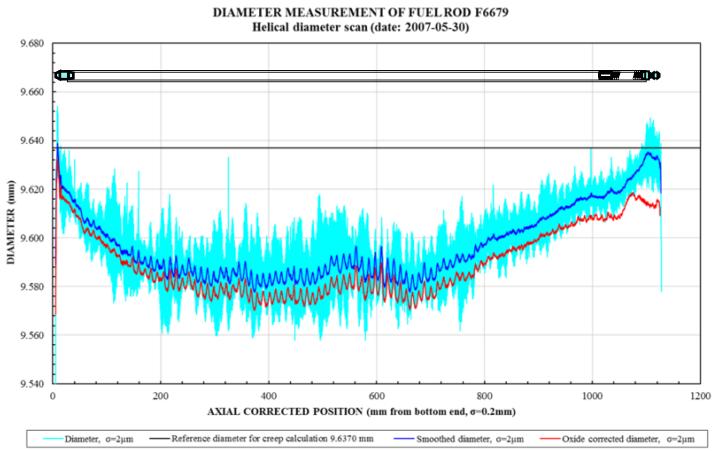
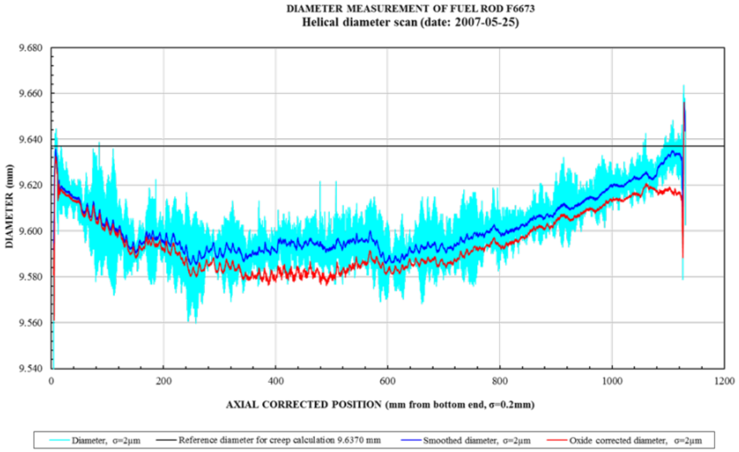
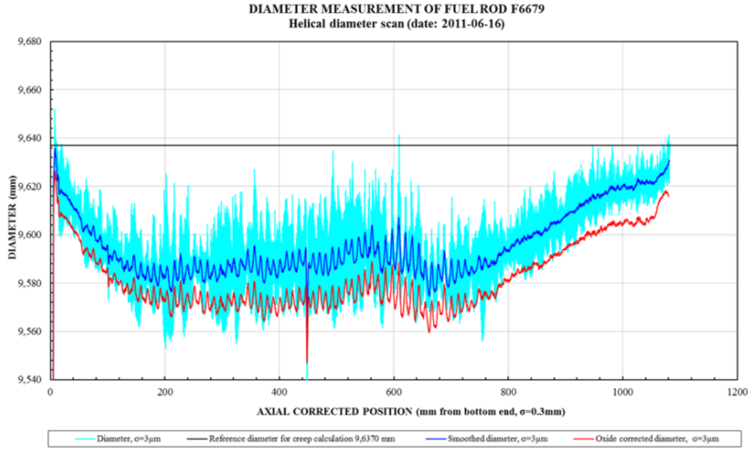
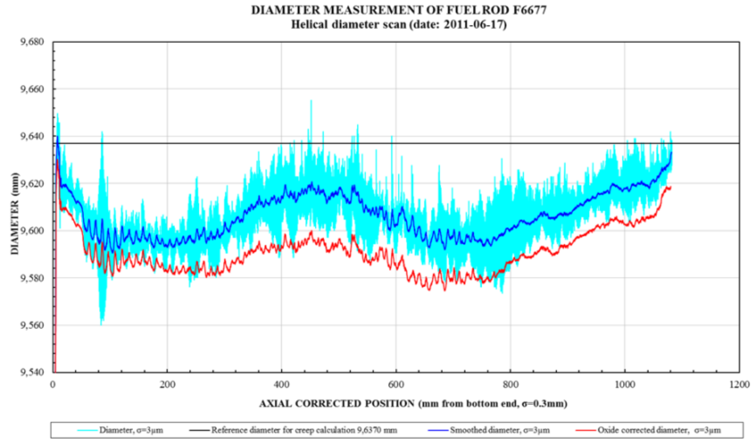
# High power, high burnup



# Low power, high burnup



# Comparison of PCMI

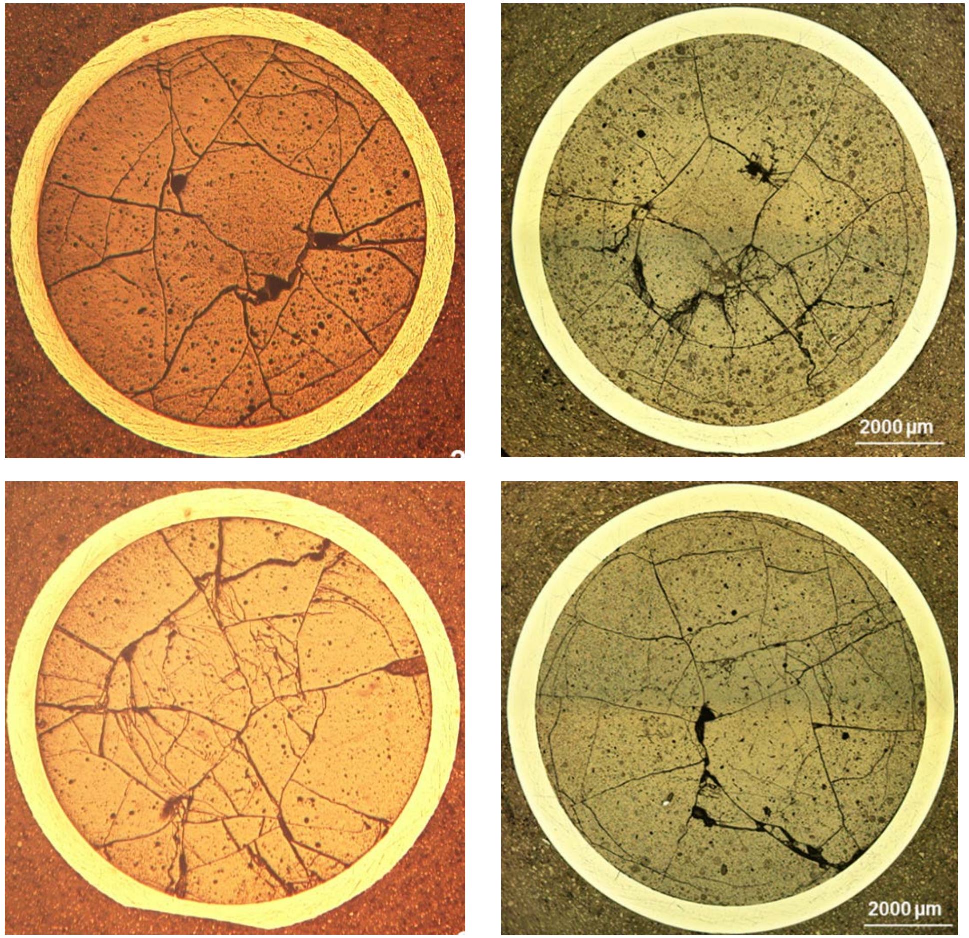
| | Low rating | High rating |
|---|---|---|
| Medium BU |  |  |
| High BU |  |  |

# Comparison of fuel behaviour

***CT1, 35*** Rod 1 Rod 2 ***CT3, 52***

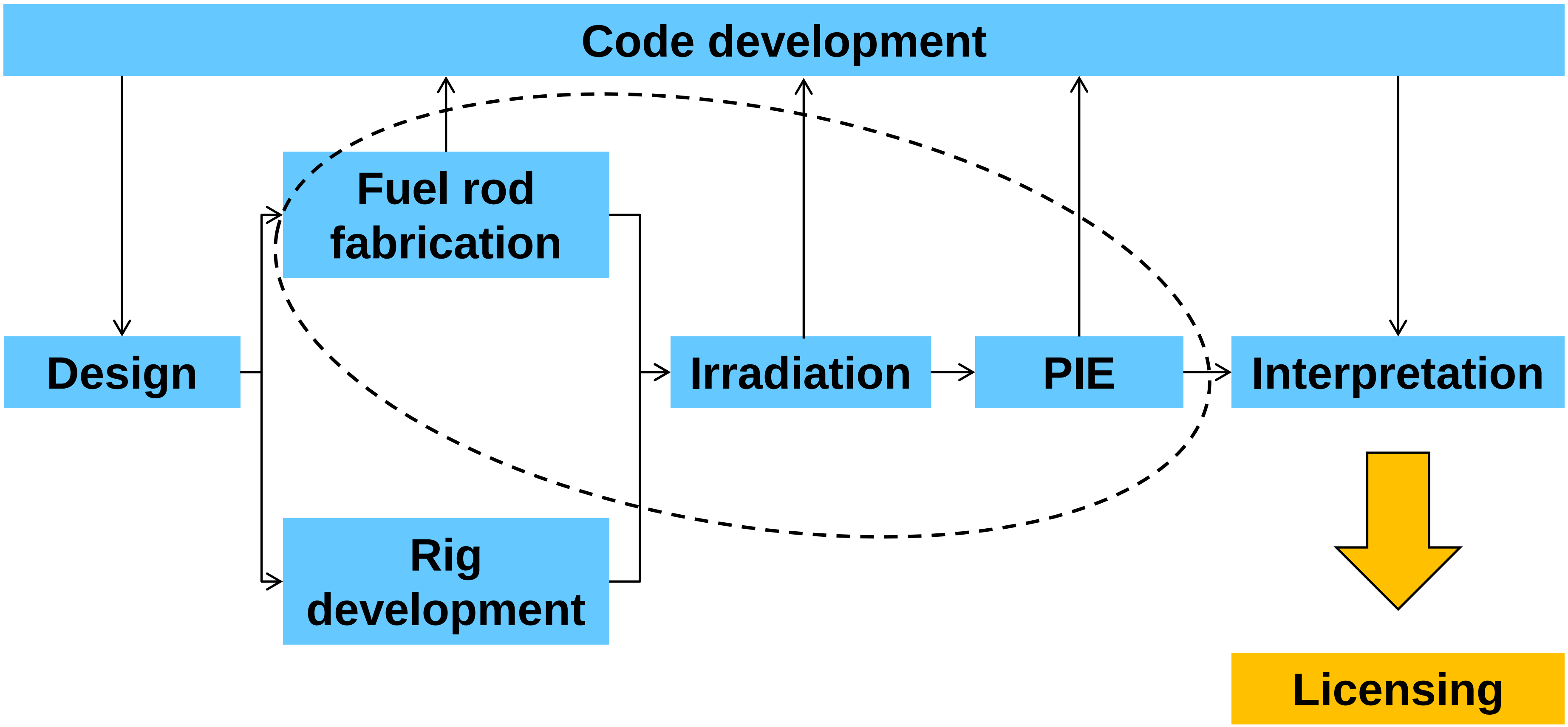
High rating

Low rating




***CT2b, 25*** ***CT5, 41***

# Outcome of licensing support program



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# Alternatie vuur"

Jonathan Witteman – 08/01/13

© belga. De kerncentrale van D

**Terwijl veel Europese tijdperk vaarwel zegg ontwikkeling van een thorium, door voorsta energiedoorbraak sin**

Dat is misschien wat overdreven, zegt Geoff kernenergie-expert van universiteit van Cambr

DDS DE DAGELIJKSE STANDAARD

# Thorium: alternatief vo

f D

Door Hans Labohm 22 oktober 2014

Foto: Thorium reactor

DINSDAG 17 SEPTEMBER 2013

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# Azië werkt aan energiewonder van thorium

Door: Jonathan Witteman – 08/01/13, 06:27

© AFP. De Verenigde Staten bij nacht, op een foto van Nasa. Thorium zou in potentie de hele wereld tienduizenden jaren van elektriciteit kunnen voorzien.

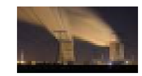
**China, Japan en India hebben zich gestort op kernenergie uit het metaal thorium. De gevolgen kunnen revolutionair zijn.**

Terwijl veel Europese landen na de Fukushima-ramp het nucleaire tijdperk vaarwel zeggen, storten China, Japan en India zich op de ontwikkeling van een alternatief: kernenergie uit het metaal thorium, door voorstanders al aangekondigd als 'grootste energiedoorbraak sinds het vuur'.

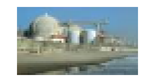
> *In potentie is er voldoende thorium om de hele wereld tienduizenden jaren van elektriciteit te voorzien.*
>
> *Jan Leen Kloosterman, reactorfysicus van de Technische Universiteit Delft*

MEER OVER

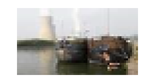
Kernenergie | Energie | Japan | Wetenschap



Reactorblok kerncentral afgesloten na brand



Kerncentrale Californië gesloten



Belgische kernreactoren

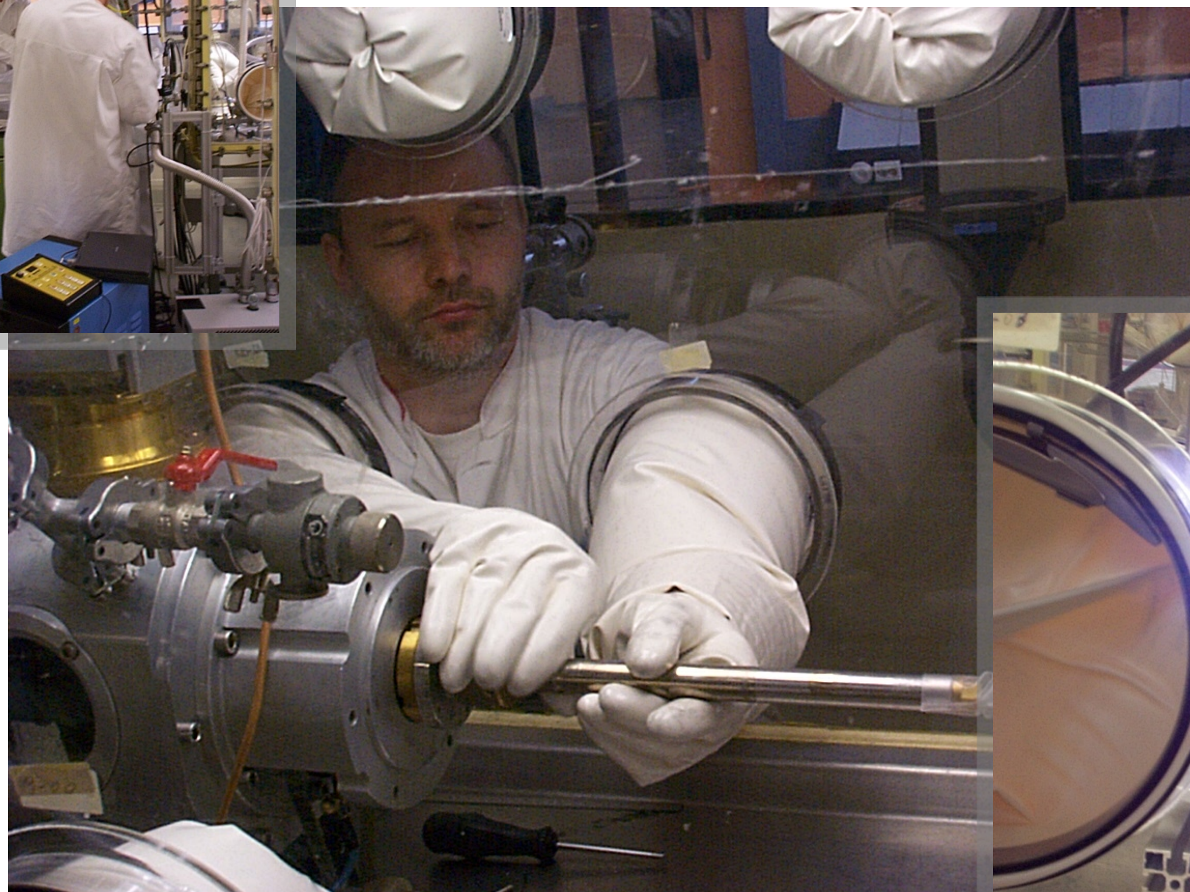
Geen haarscheurtjes in r Borssele

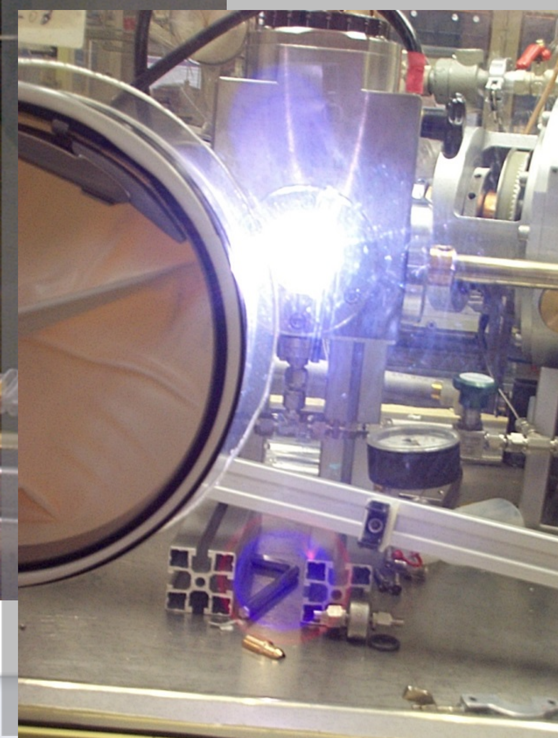
# Outline

- Experimental Thorium program (2001-today)
  - Part I - Integral $(Th,Pu)O_2$ programs
  - Part II - Fabrication and solid state research
  - Outlook: where do we stand and what's next?

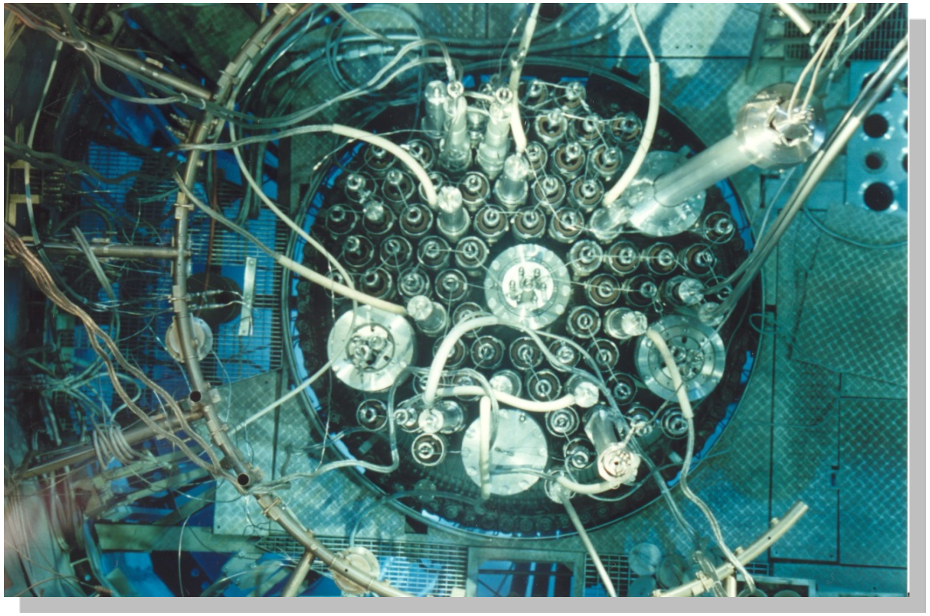
# OMICO (2001-2007)

# Instrumented pin assembly at ITU





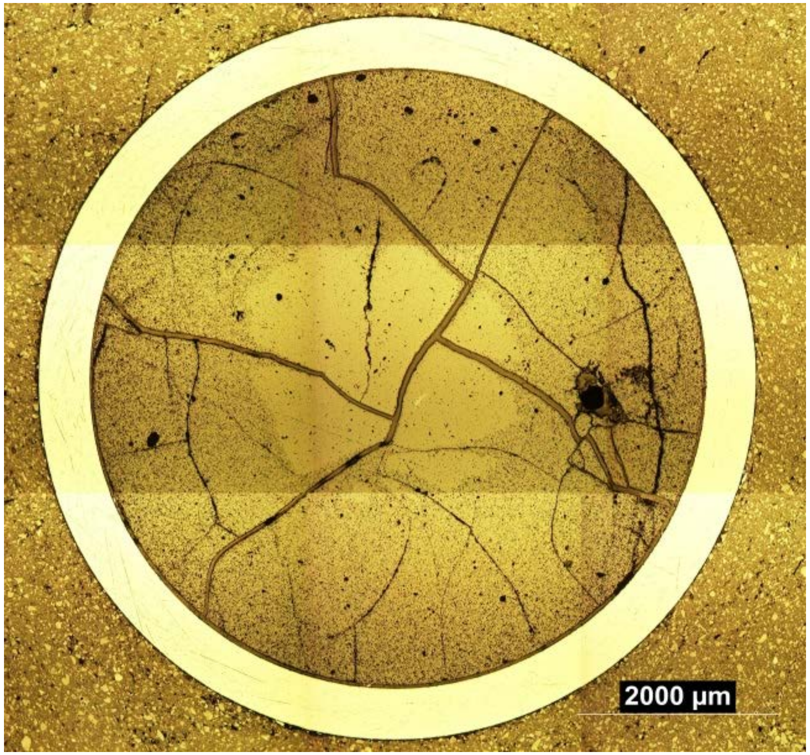
# Assembly & irradiation: TCH & BR-2

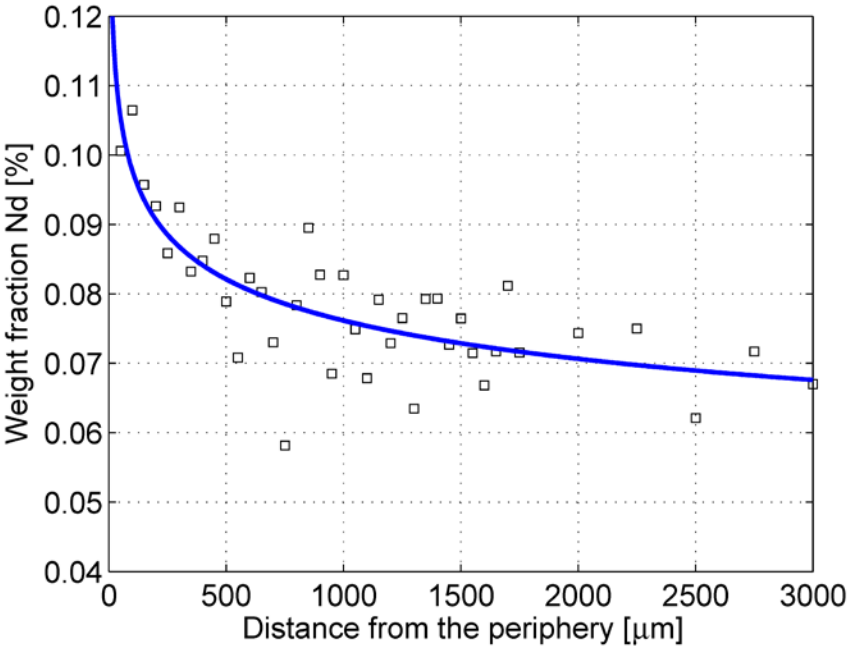


OMICO ready to be transferred to BR-2
(29-10-2004)

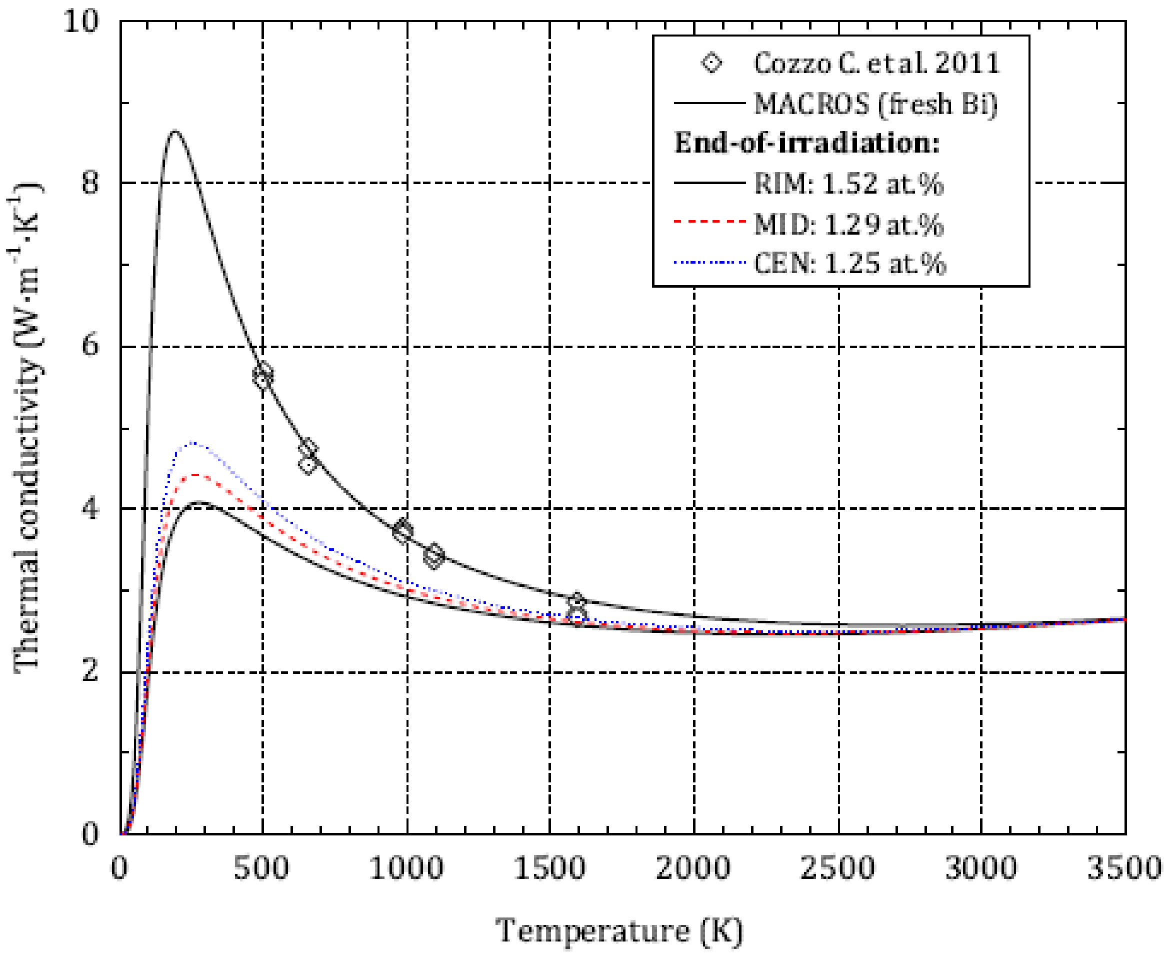
# LWR-DEPUTY (2006-2011)

# Post-irradiation examinations of $(Th,Pu)O_2$



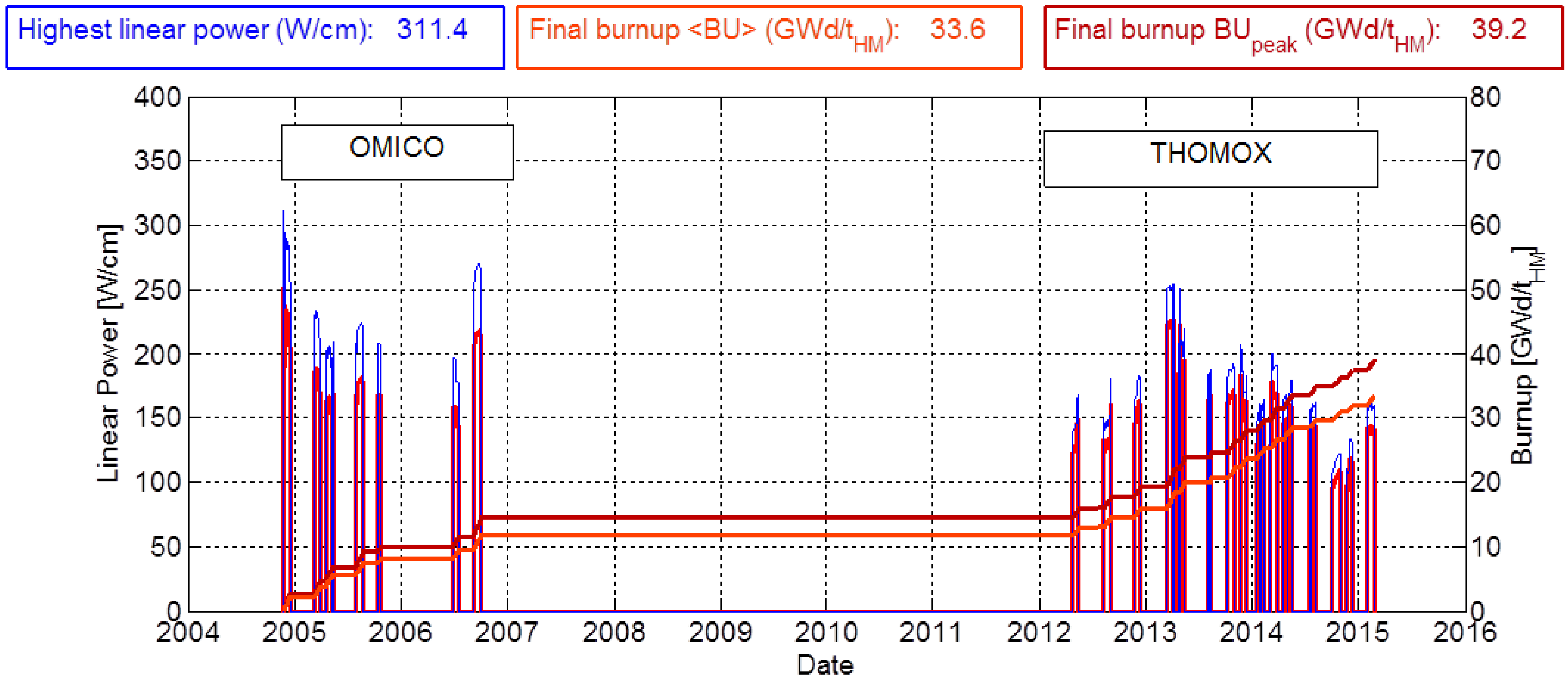



# $(Th,Pu)O_2$: Thermal conductivity measurements & model



# THOMOX (2012-2015)

# In-reactor performance of $(Th,Pu)O_2$ in BR2
## Irradiations 2004-2015

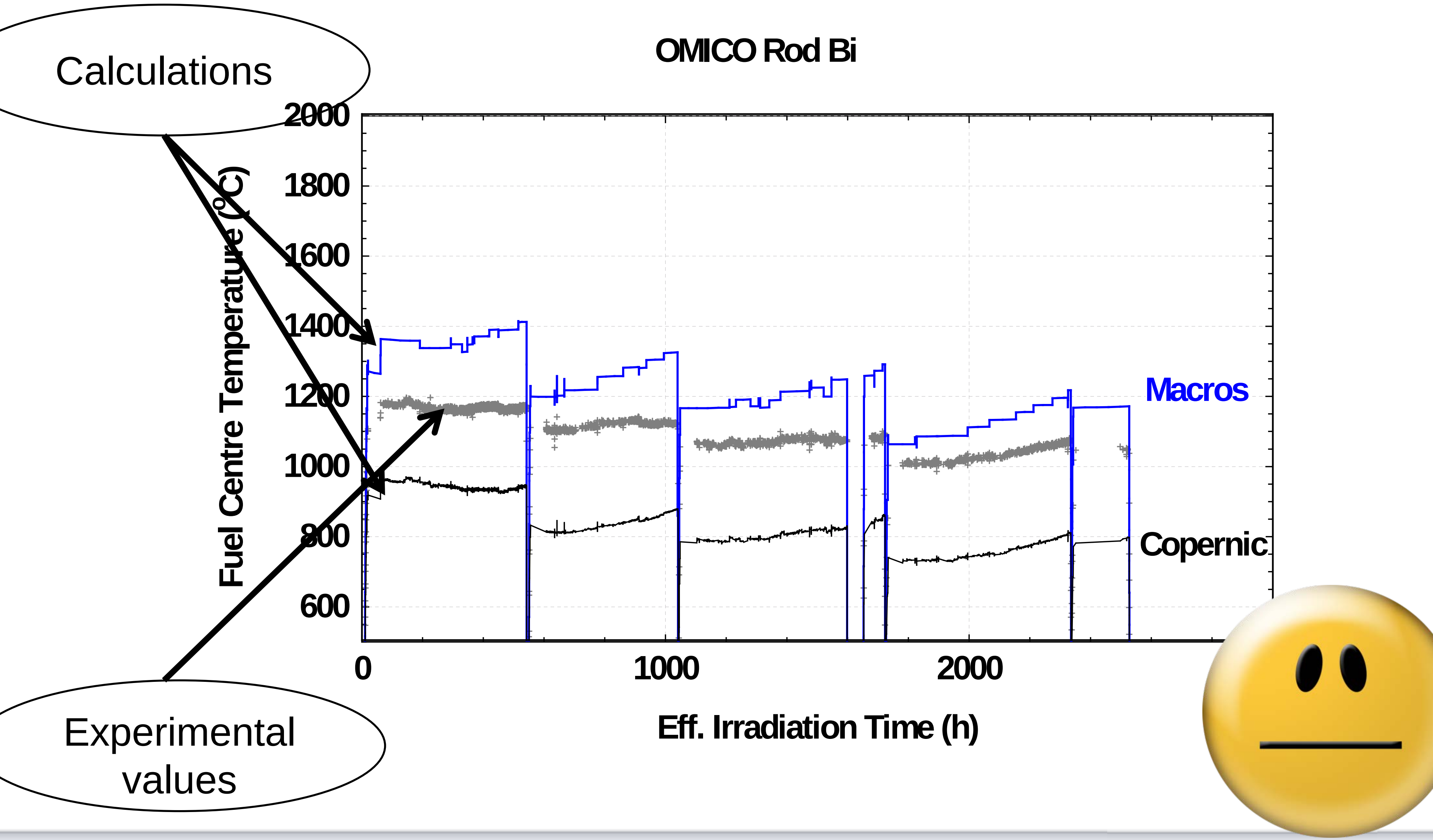



Non-instrumented $(Th,Pu)O_2$ irradiations
Objective: reach ca. 40 $GWd/t_{HM}$ (industrially-relevant burnup)

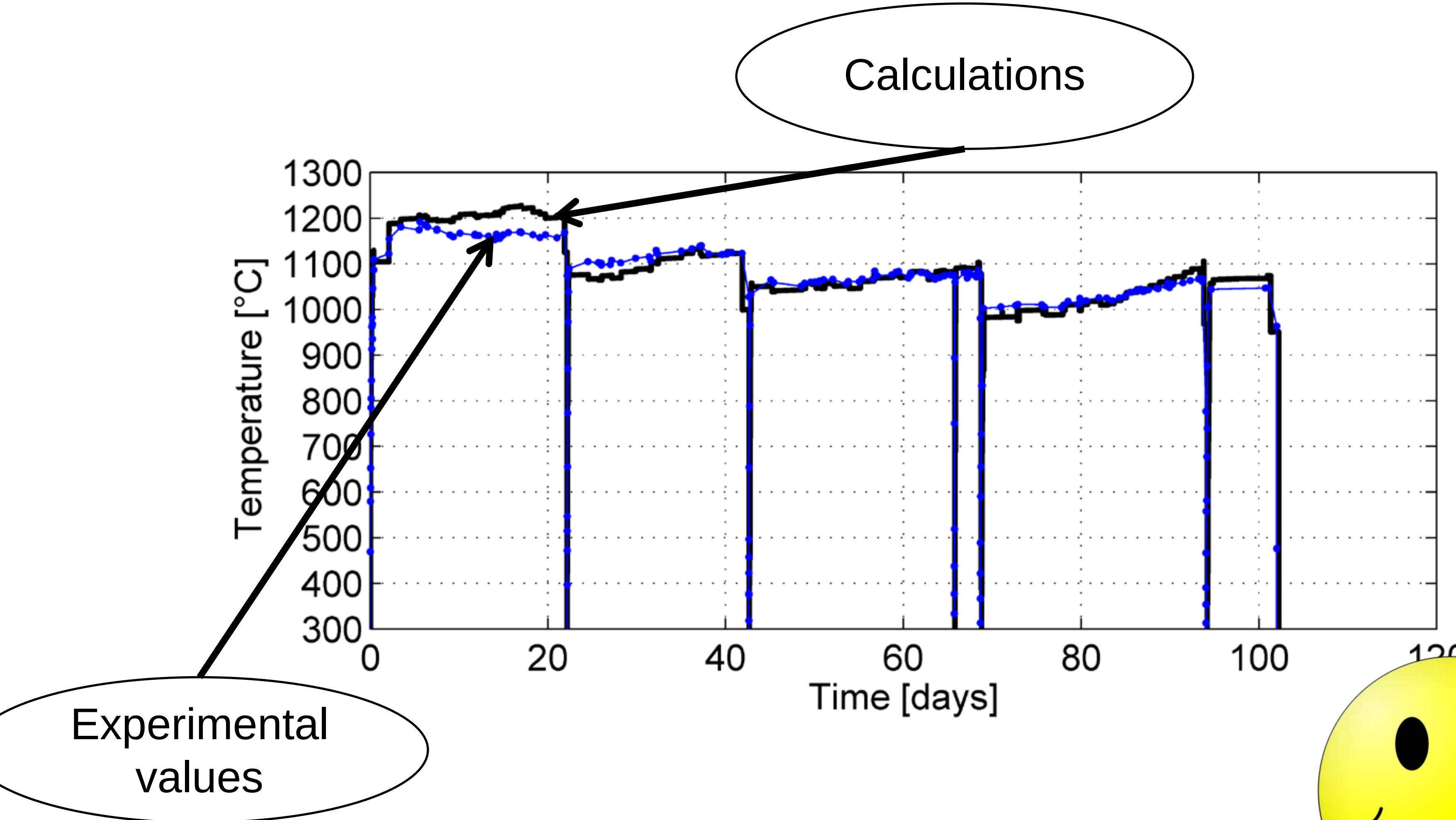
# What did we learn?

# In-reactor performance of $(Th,Pu)O_2$ in BR2

## Model predictions (2007) versus experiment: SCK•CEN & AREVA

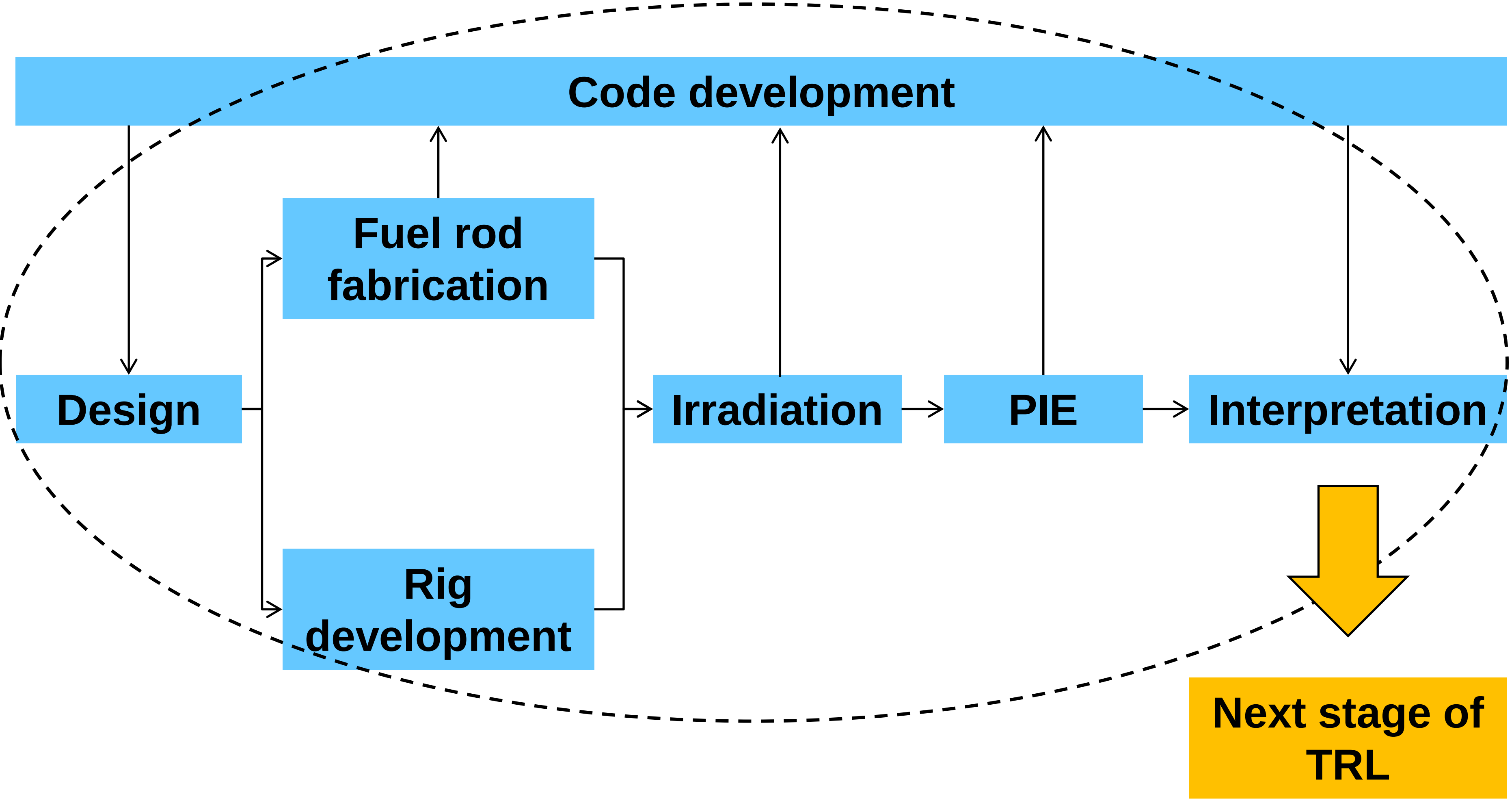


# In-reactor performance of $(Th,Pu)O_2$ in BR2
## Model predictions (2015) versus experiment




B. Boer, S. Lemehov, M. Wéber, Y. Parthoens, M. Gysemans, J. McGinley, J. Somers, M. Verwerft, *Irradiation performance of $(Th,Pu)O_2$ fuel under Pressurized Water Reactor conditions*, J. Nucl. Mater., 471 (2016) 97-109.

# Outcome of exploratory R&D



# Where do we stand today?

Table 1
Proposed application of technical readiness levels to reactor fuel development and qualification

| TRL | TRL Function | Generic Definition | Fuel Development-Specific Definition | Fuel Dev. Phase |
|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | Technical review leading to [illegible] for candidate selection | |
| 2 | Technology Down-Selection | Technology concepts and/or applications formulated | Fuel candidates selected from options, based on selection criteria | 1 |
| [illegible] | | Analytical and experimental demonstration of critical function and/or proof of concept | Calculational analysis and lab-scale experimentation and characterization addressing feasibility, including: fabrication process development, property measurement, and ex-pile tests | |
| 4 | Final Process [illegible] and integration | Component and/or bench-scale validation in a laboratory environment | Establish proof of concept. Fabrication of [illegible] with QA requirements. Design parameters and features established. Performance phenomena identified with [illegible] | 2 |
| 5 | | Component and/or breadboard validation in a relevant environment | Irradiation testing of prototypic [illegible] representative conditions (e.g., fission densities, fuel and cladding temperatures, cladding damage rates) is performed and assessed | |
| 6 | Full-scale integrated testing | System/subsystem model or prototype demonstration in relevant environment | Prototypic rod/compact and assembly/element irradiation in representative environment, under full range of relevant normal and off-normal conditions. Representative compositions Design parameters investigated Information is sufficient to support a Fuel Specification and a Fuel Safety Case (which, in turn, support larger System Demonstration to achieve TRL7) | 3 |
| 7 | | System prototype demonstration in prototypic environment | Fabrication of reference fuel derived from production supply sources irradiated to design conditions and utilization Irradiation in representative environment Prototypic design. Prototypic fabrication processes. Representative compositions | 4 |
| 8 | Full-scale demonstration | Actual system completed and qualified through test and demonstration | | |
| 9 | | Actual system proven through successful mission operations | | |

Screening

Pre-qualification

Qualification

Demonstration

- **Performance qualification of $(Th,Pu)O_2$ has been achieved**
- **Open issues**:
  - Elaborate production routes that *can be implemented industrially*
  - *Demonstrate* the in-reactor performance *in a power plant*
  - *Quantify the fuel back-end options*

# Outline

- Experimental Thorium program (2001-today)
  - Part I - Integral $(Th,Pu)O_2$ programs
  - Part II - Fabrication and solid state research
  - Outlook: where do we stand and what's next?

# Solid state research and fabrication aspects of $ThO_2$

- *"$UO_2$ and $ThO_2$ doped nuclear fuel"* (A. Baena, 2011-2016 PhD thesis)
  - Solid state study on the fluorite structure effects upon doping with different lanthanides
  - Associated master thesis / internships:
    - *"Advanced manufacturing routes for $ThO_2$ doped with lanthanides"* (M. Pasniewsky)
    - *"Synthesis of $ThO_2$ doped with Gd via wet chemical routes"* (P. Zsabka)
    - *"Recycling of $ThO_2$ scrap from nuclear fuel pellets fabrication"*(A. Schneider, L. Gijsemans)

- *"Improving the sintering behaviour of $ThO_2$"* (T. Wangle, 2015-2019 PhD thesis, industrial sponsor: Solvay)
  - Converting thorium nitrate into sinterable oxide powders
  - Associated master thesis / internships:
    - *"Effect of pH, T and concentration on the oxalic precipitation of Th4+ from nitric acid media"* (M. Beliš)

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# Thorium fuel -outlook

- The next steps:
  - **Elaborating production routes that can be implemented industrially**
    - We’re working on it …
  - **Demonstrate in-reactor performance**
    - Qualification of neutronics codes: benchmarking and uncertainty analysis
    - Assembly design (neutronic) for given core management
    - AOO, DBA analysis
    - Perform lead irradiation tests (power reactor: normal operation, test reactor: off-normal conditions)

    - … still a lot to do …

# Thorium and thorium-plutonium fuel R&D
## Where do we stand today and where do we go?

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Screening

**2001**

Pre-qualification

**2016**

Qualification

Demonstration

**2031**