Advanced Post-Irradiation Examination Methods

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(with the collaboration of J. Thomazet

for AREVA-NP documents)

What is a hot laboratory used for?

- Fuel R&D => Surveillance programme
  - Cladding
  - Fuel
- RPV Irradiation surveillance programme
- Material development (GenIV, ODS, SiC, fusion,..)
- Reprocessing R&D - Chemistry
- Radioisotope production

What is an irradiation surveillance programme?

Task sharing, fuel manufacturing, irradiation

On-site examinations

“Classical” hot cell Post-Irradiation Examinations (PIE)

- Non destructive PIE
- Metallography,
- H_2 measurement in the cladding
- Mechanical testing

Providing fuel to other programmes

“Specific” hot cell examinations

=> An example of results = Cladding development

Surveillance programme

– Irradiation of new fuels is investigated on a limited number of special or lead assemblies or even limited to a few rods inside standard assemblies

– To limit costs and risks

⇒ Used for testing:

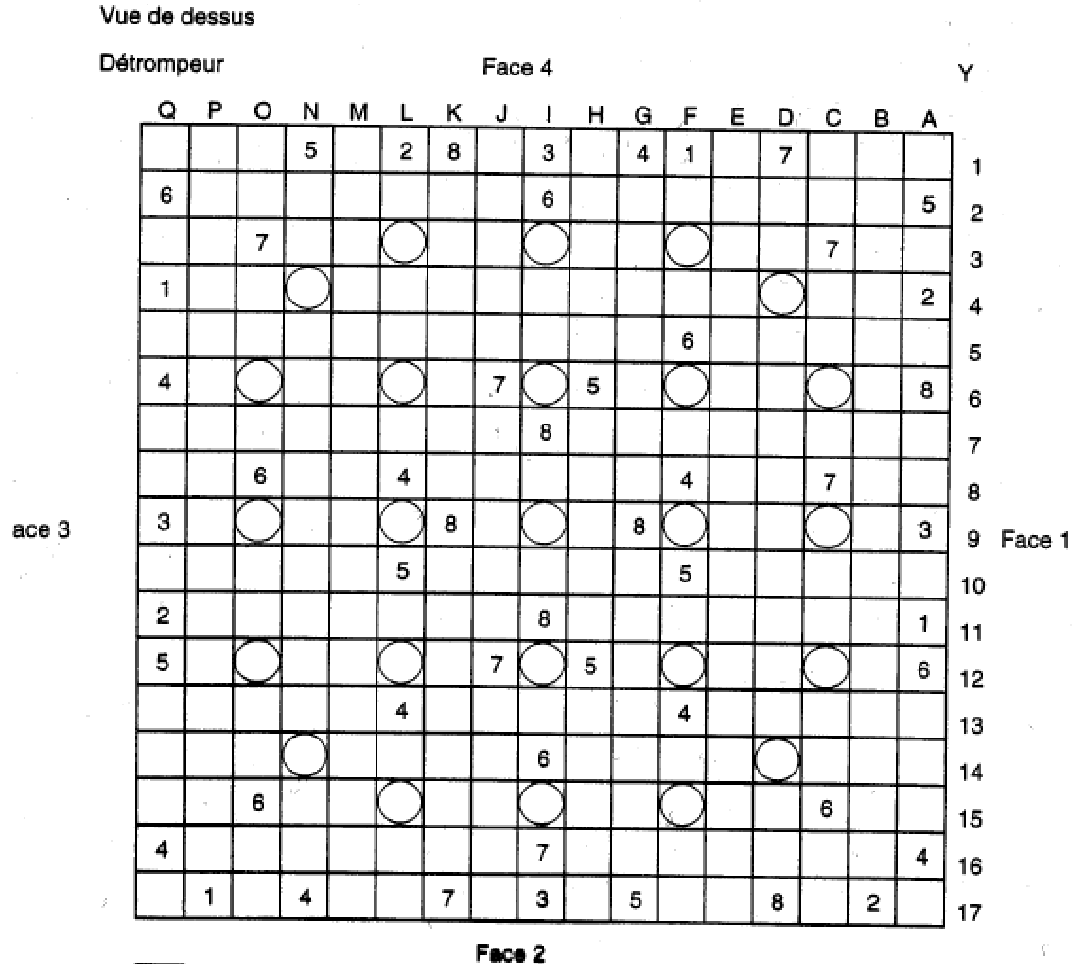
- New types of alloys.
- New assembly designs.
- Higher burn-ups,
- MOX, Reprocessed Uranium fuels.
- Fuel plant management (load follow, water chemistry).
- Fuel cladding interaction solutions (ex. doped UO_2),
- etc…

Examples of lead assemblies:

– X1 2nd phase Corrosion: 4 ass. AFA 17x17.
  - Initial ^{235}U enrichment = 4.5%, to reach 5 or even 6 cycles.
  - 16 “atypical” rods per assembly,
  - 8 types of claddings:
    - – massive or duplex.
    - – 4 types of Zr alloys (with various Sn, V and Nb contents).

– 6th and 7th cycles with M5 cladding (Zr-1%Nb):
  - 2 x 4 fuel rods, irradiated 5 cycles.
  - Inserted inside two 3-cycles assemblies
  - Re-irradiated 1 year → **6 cycles.**
  - Re-irradiated 2 years → **7 cycles.**

Example of lead assembly



1	M5pc
2	D2pc
3	Zy4pc
4	M2pl
5	M5pl
6	D2pl recristall
7	D2pl
8	D5pl
	Zy4pl

pl: long pellets

pc: short pellets

- 5 types of clads
- 2 types of pellets

Fuel characterization:

– Fuel rods and lead assemblies manufactured for surveillance programmes are specially characterised (to have a better comparison with PIE results):

- Pellets, claddings, fuel rods
- Assemblies.

Irradiation:

– An irradiation report giving irradiation data is necessary for the hot cell PIE.

– For power ramping tests, power history is provided for a fuel segment (stage).

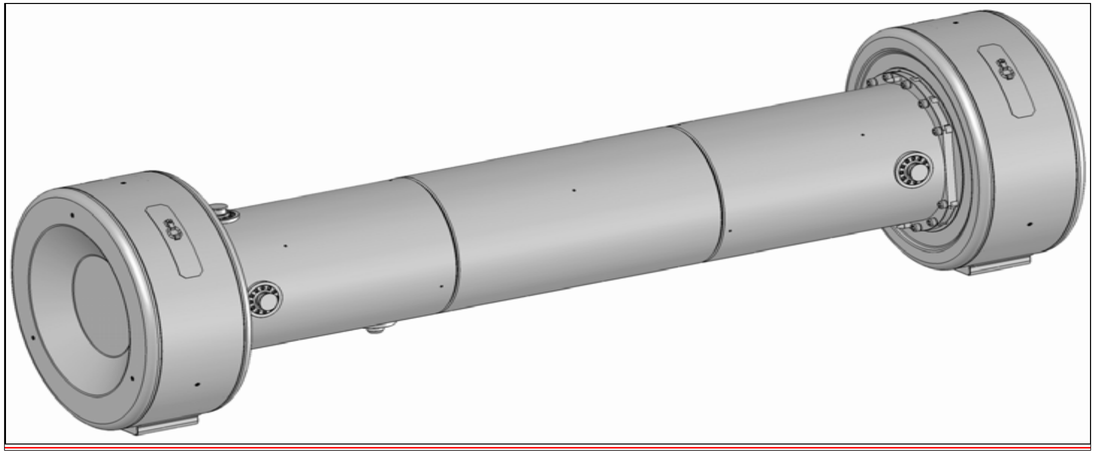
On-site examinations. Several tools are available:

– Visual and dimensional remote control of the assembly with "Diva" tool (PADEC),
– ZrO_2 thickness on peripheral rods.
– ZrO_2 thickness on internal and peripheral rods "Sabre" ("Sword"),
– Diameter with "DICCO" tool,
– Extraction forces measurements,

For hot cell examination
– Extraction of some chosen rods,
– Insertion of new rods (less enriched).
– Transport using R62 cask, soon R72 (EDF/Robatel) or BG18 (Transnubel).

Transportation:

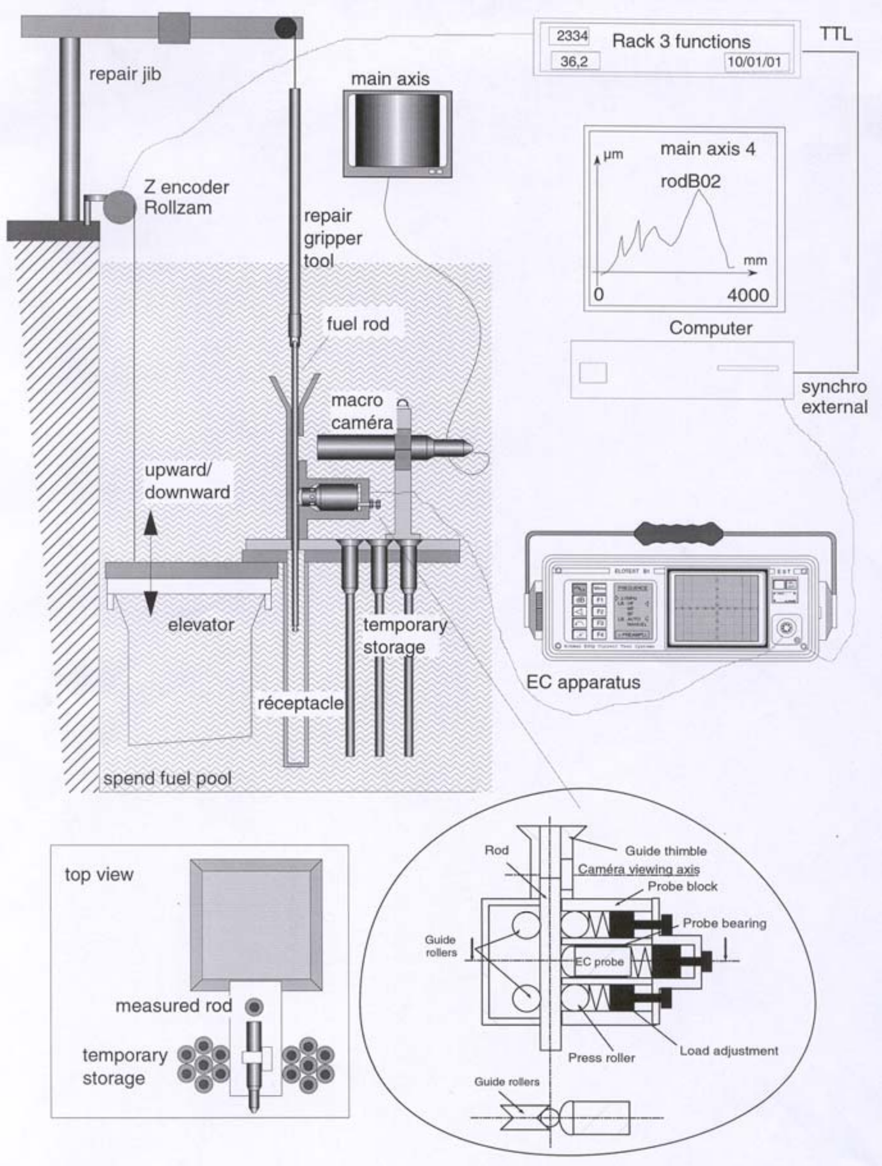
BG 18 (photo Transnubel)



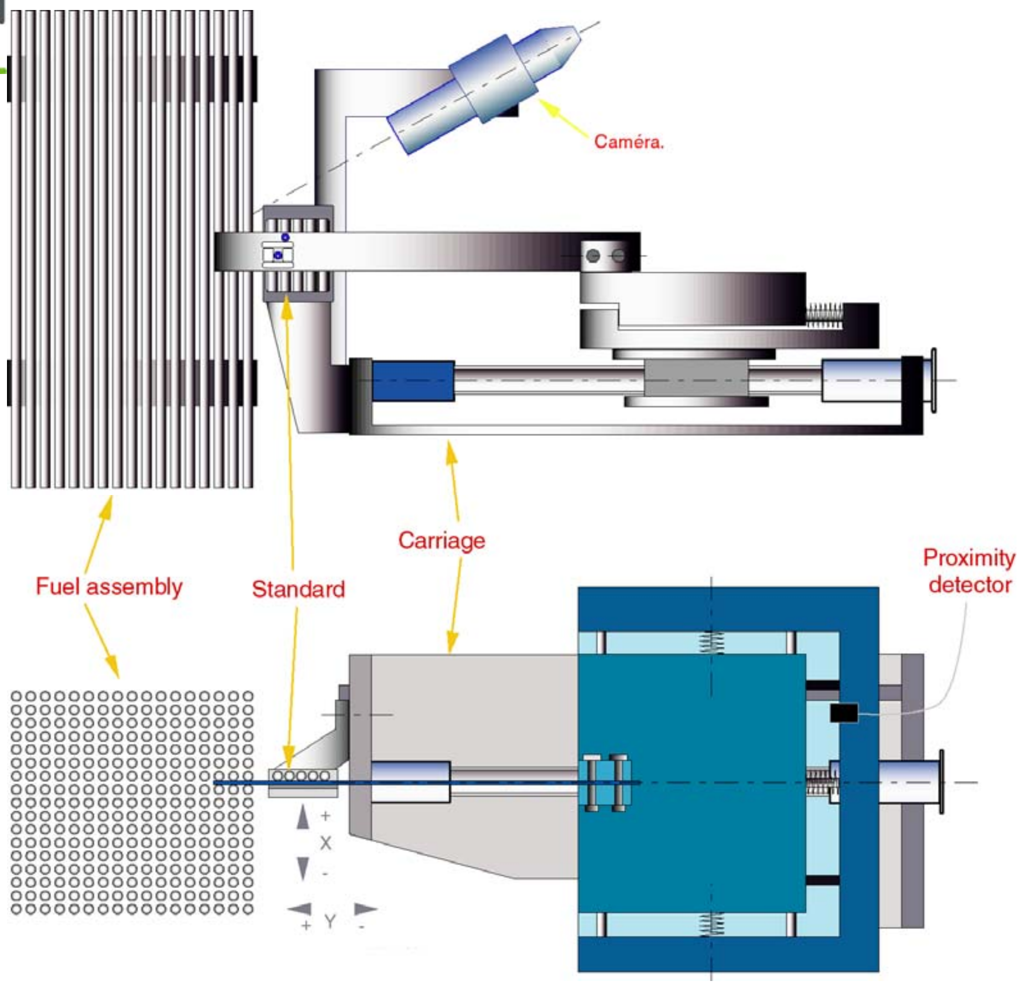
R72
(EDF slide)

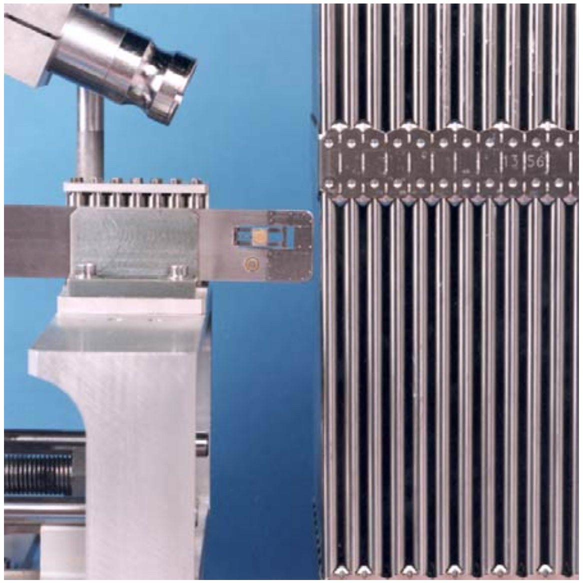
“MEDOC” tool from AREVA-NP: oxide thickness measurement on extracted fuel rods.

(Areva doc):



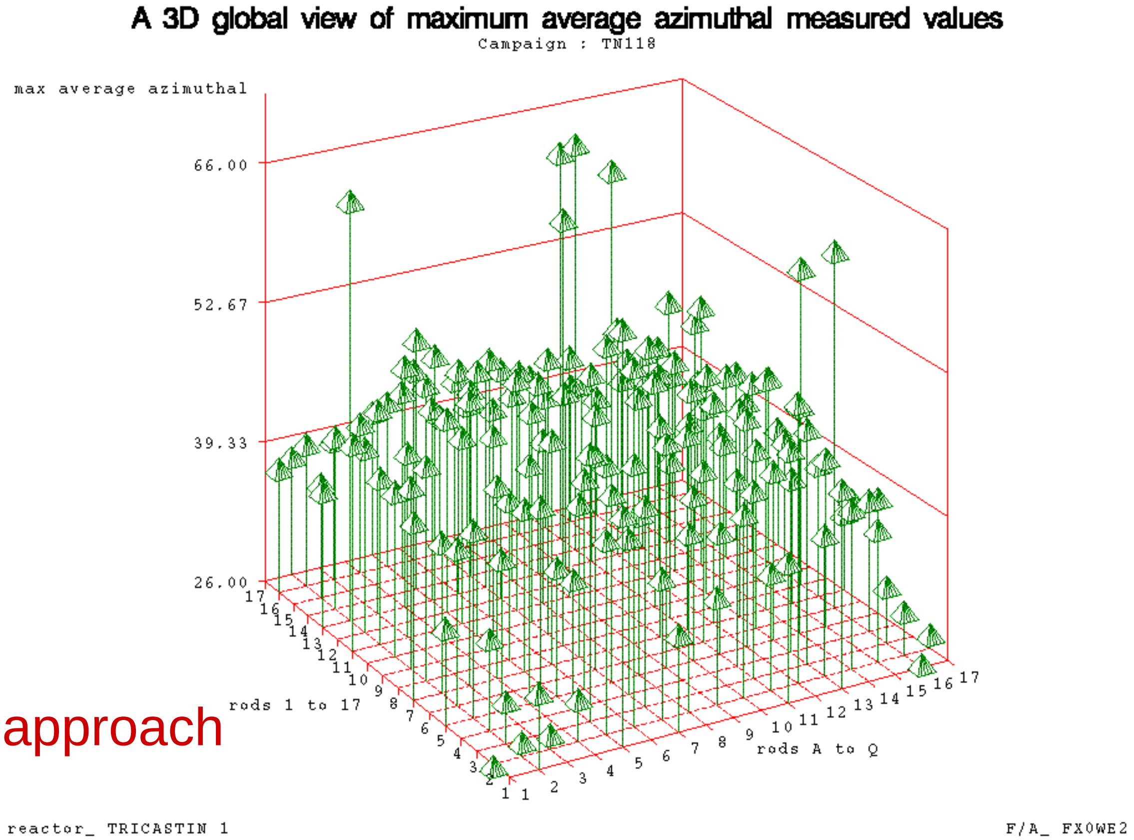
Continuous oxide measurement on extracted rods





“SABRE” (“Sword”) tool from Areva-NP: oxide thickness measurement on internal fuel rods
(Areva doc.)

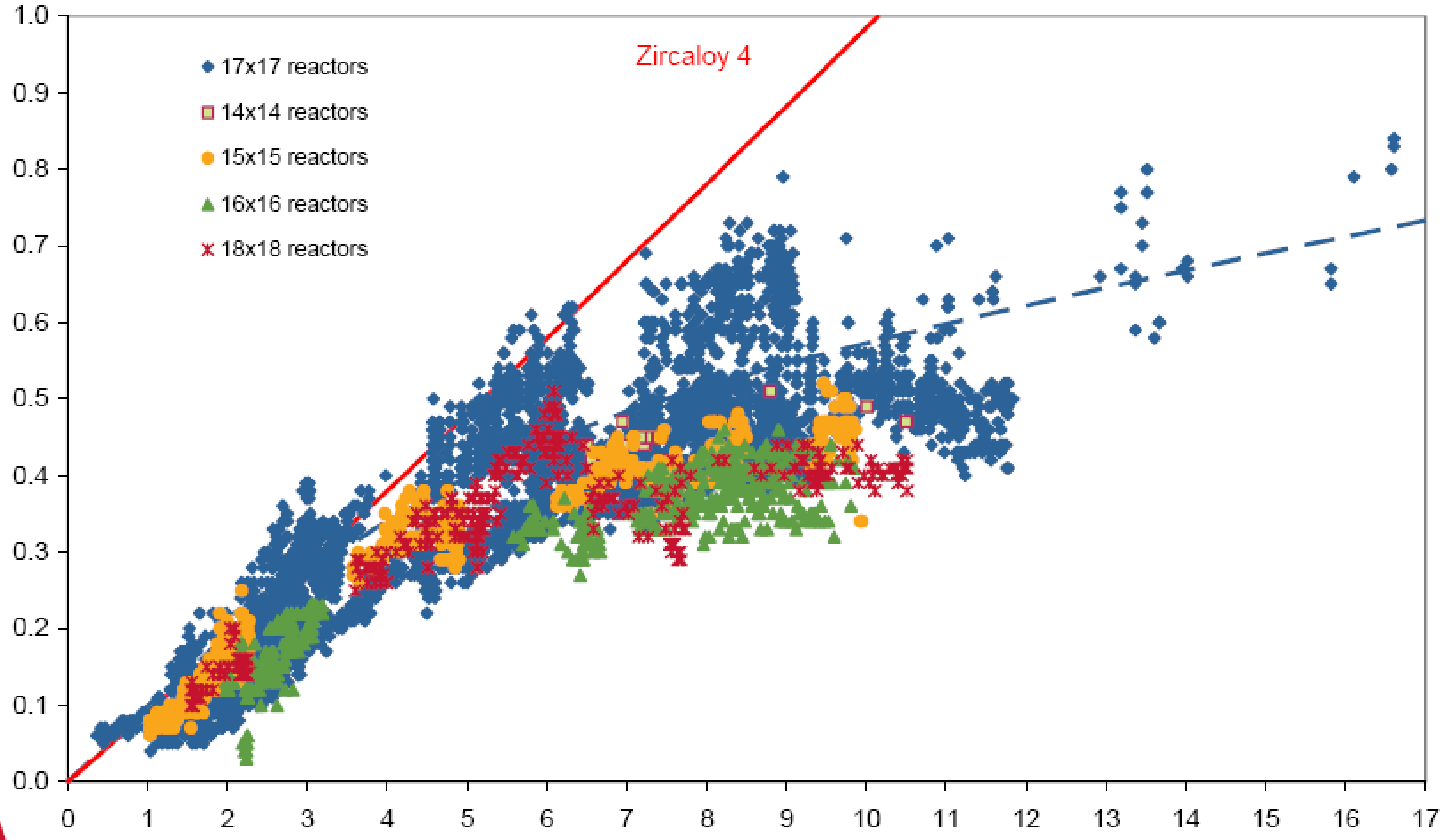
"SABRE" tool from Areva-NP (doc. Areva): example of 3D oxide thickness measurements presentation on a PWR fuel rod assembly.



=> Statistical approach

M5 fuel rod elongation is smaller than stress-relieved Zy-4 & has a slower increase at high fluence.

Rod elongation, in %

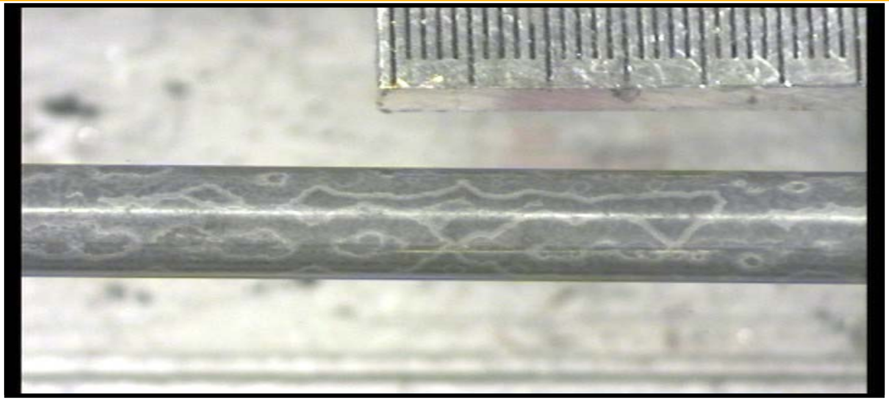


Fast fluence, E > 1 MeV, 10^{21} n/cm^2

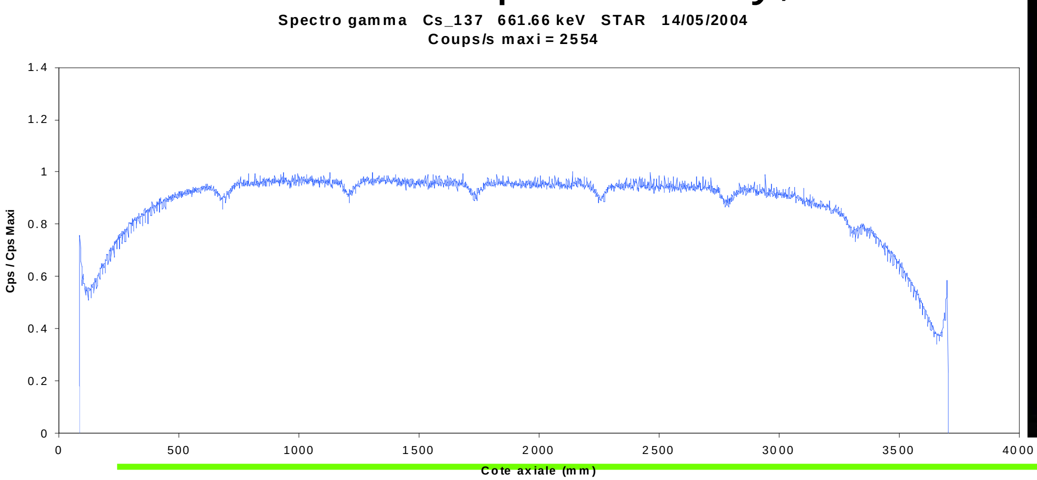
Hot cells:

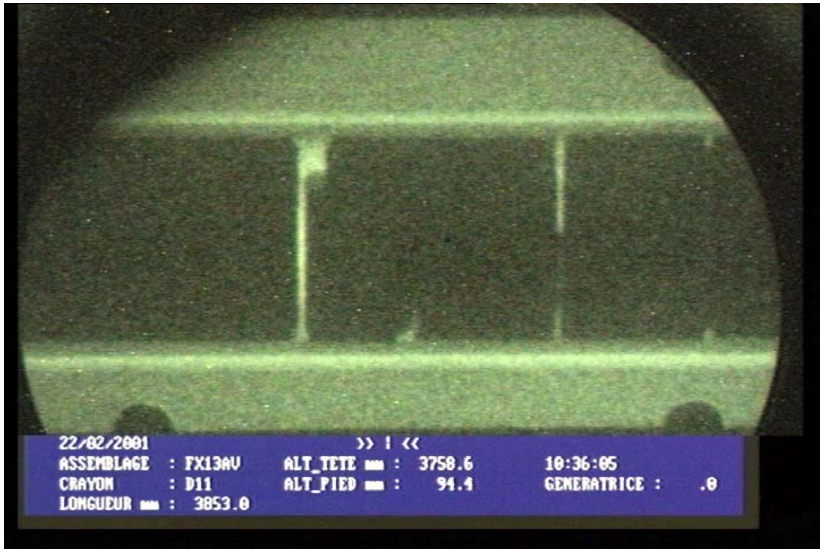
1) Non destructive PIE:

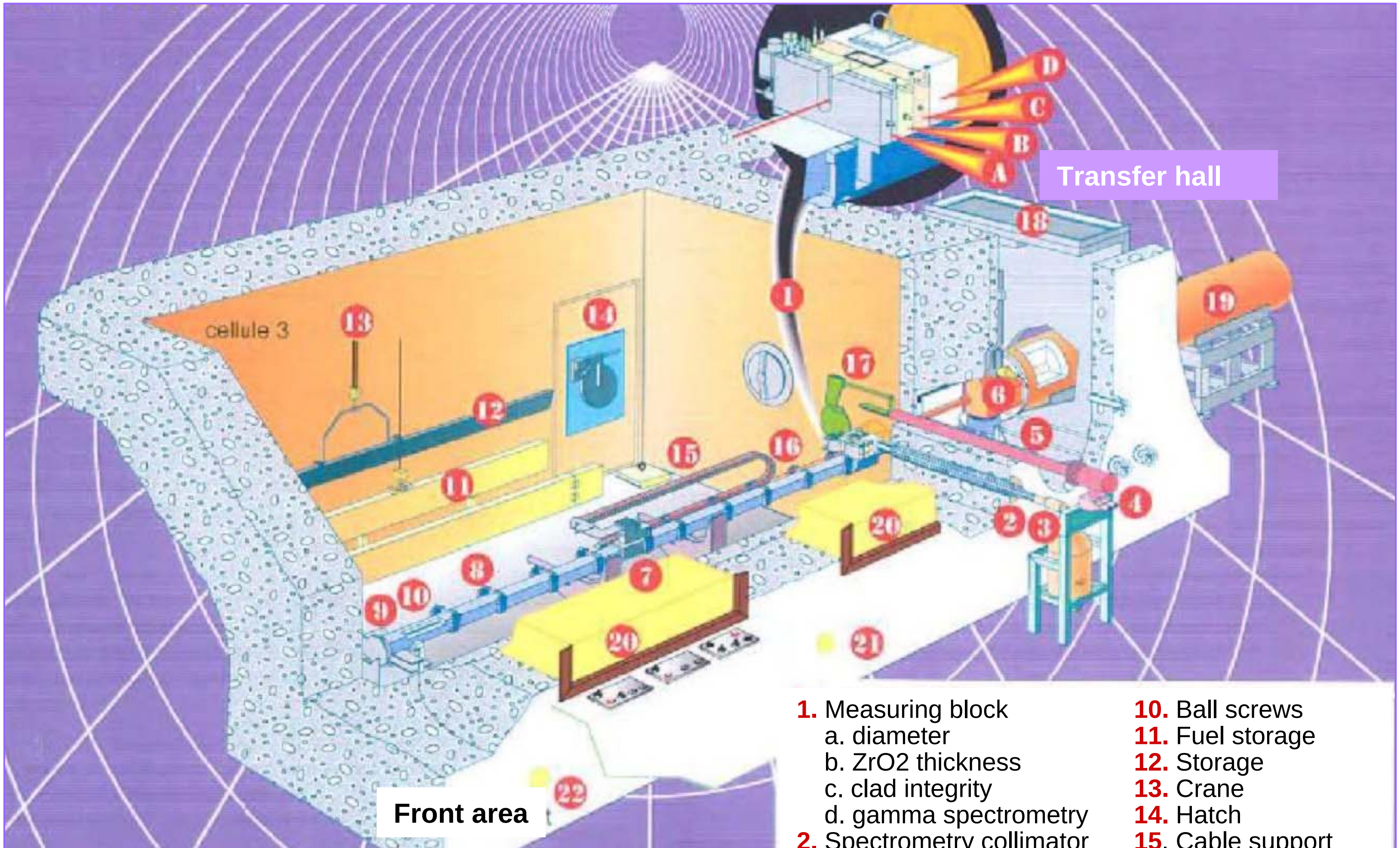
CORROSION LOCALISÉE (M5)



- –Visual examination,
- –Length measurement,
- –Diameter on 4 generatrices,
- –ZrO_2 thickness (by eddy currents punctual probe), 8 generatrices,
- –Cladding integrity (by eddy currents – circling probe),
- –X-rays radiography.
- –Gamma spectrometry,







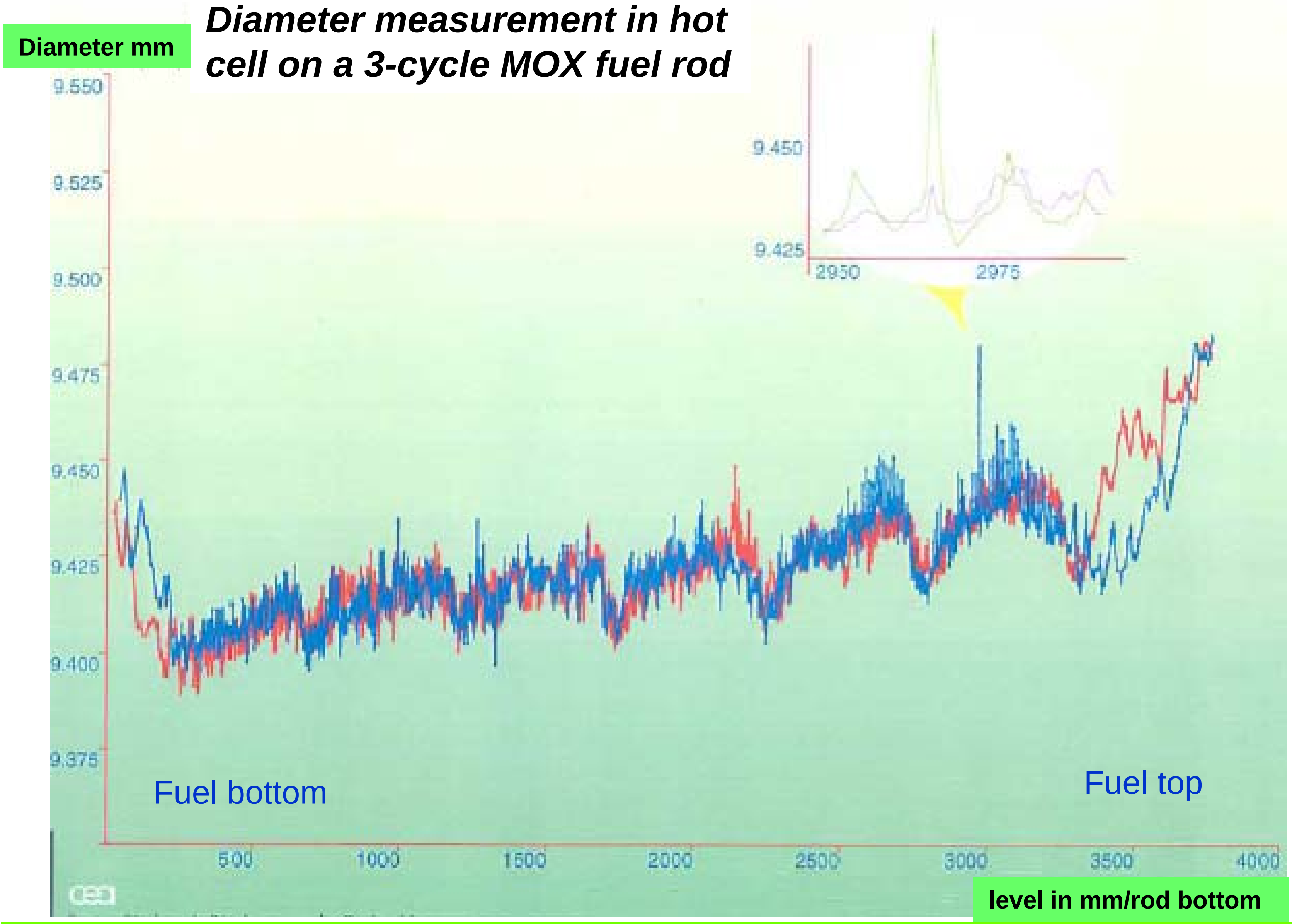
1. Measuring block
   a. diameter
   b. ZrO2 thickness
   c. clad integrity
   d. gamma spectrometry
2. Spectrometry collimator
3. Spectrometry probe
4. Periscope
5. Brilliance amplifier
6. X-rays generator
7. Mandrel – motor for rotation
8. Supporting fingers
9. Motor for translation.
10. Ball screws
11. Fuel storage
12. Storage
13. Crane
14. Hatch
15. Cable support
16. Fuel rod
17. Shutter
18. X-ray cabinet
19. Appendix
20. Windows
21. Measure plug
22. Power plug

Non destructive measurement bench for PWR fuel rods in STAR (Cadarache)

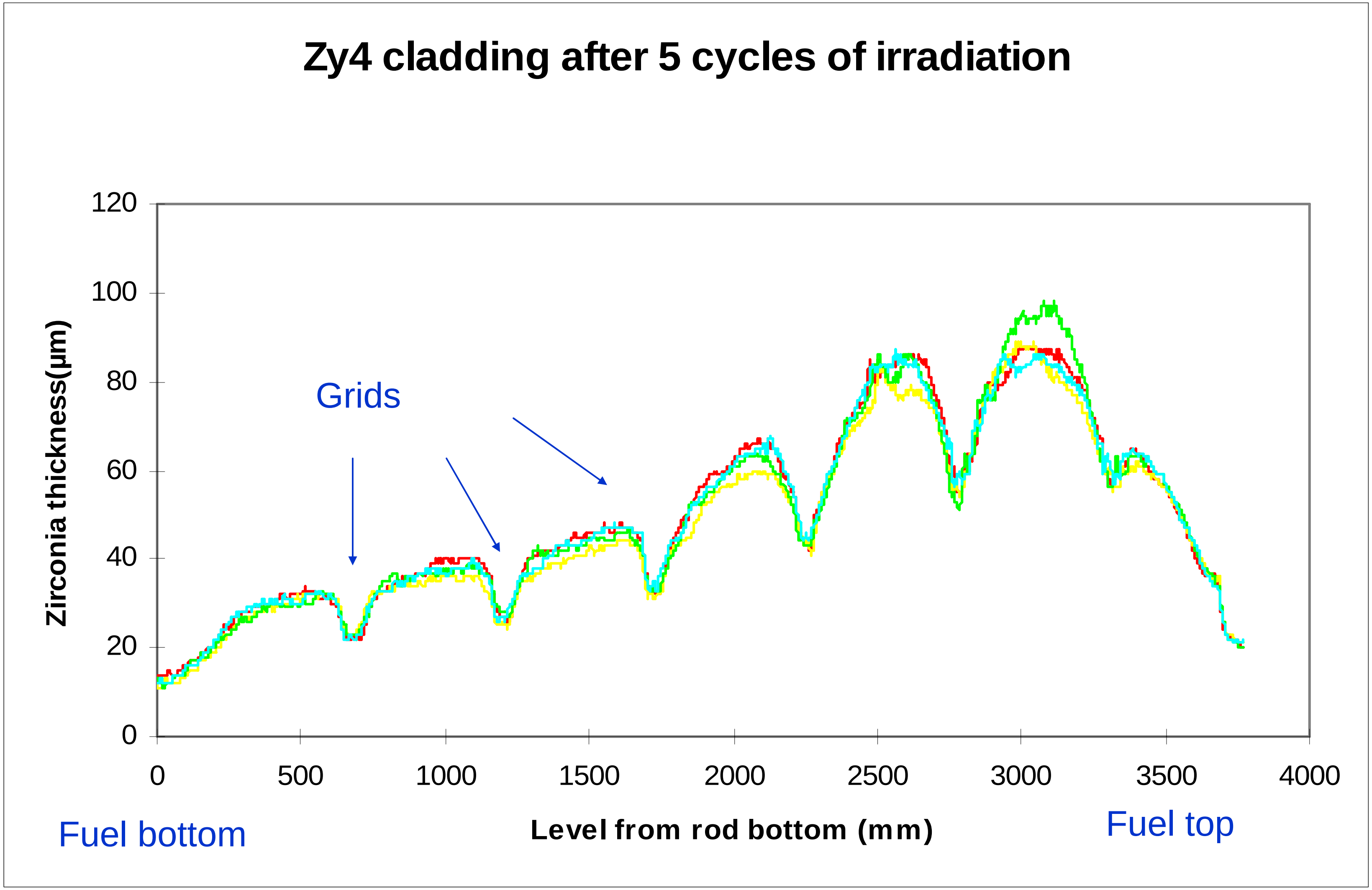
Visual examination in hot cell:

6- cycle UO_2 fuel rod, Zy4, 64481 MWdtU, spalling at span 6

Diameter measurement in hot cell on a 3-cycle MOX fuel rod

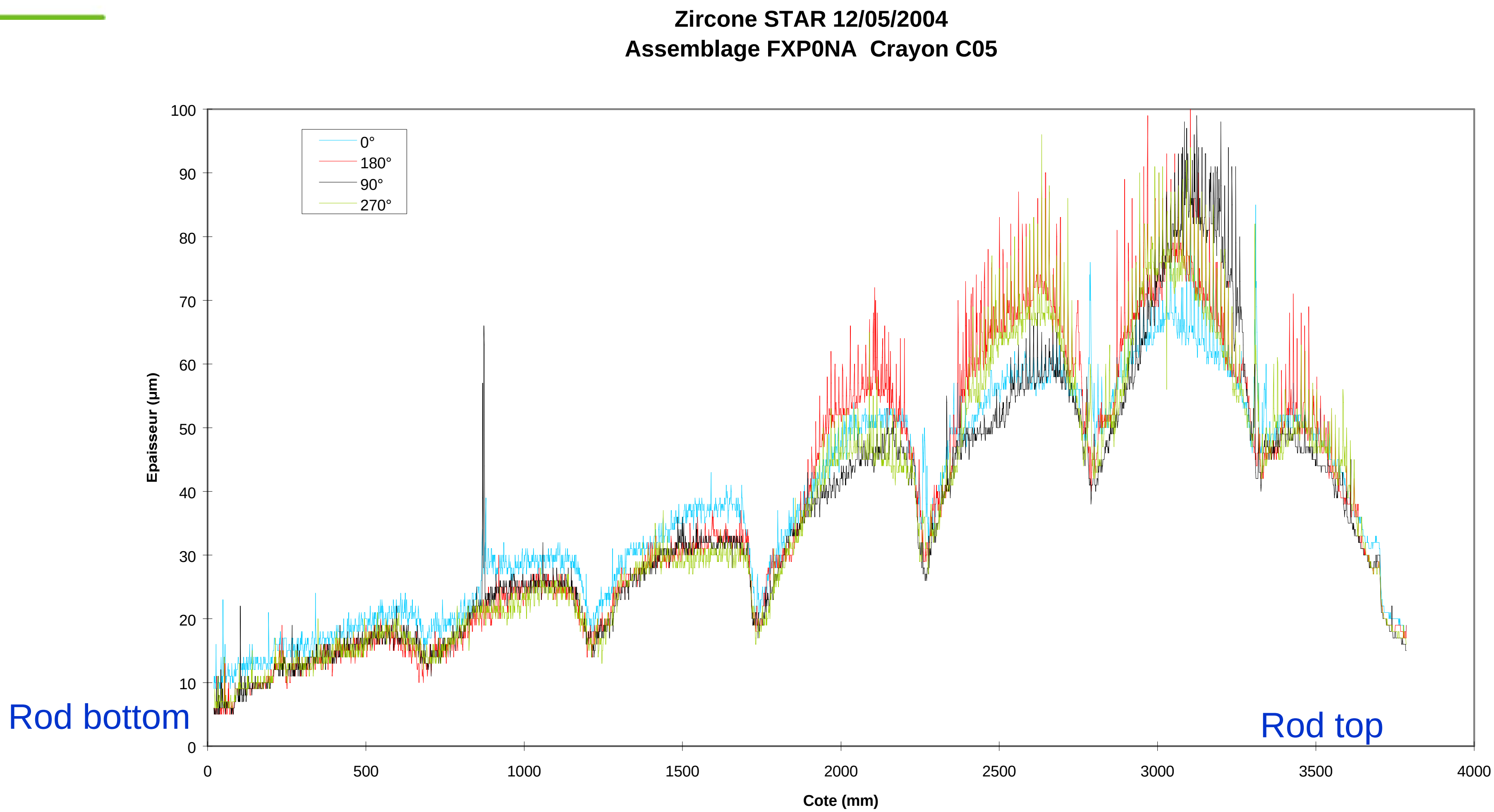


Zirconia thickness in hot cell:



Zirconia thickness in hot cell:

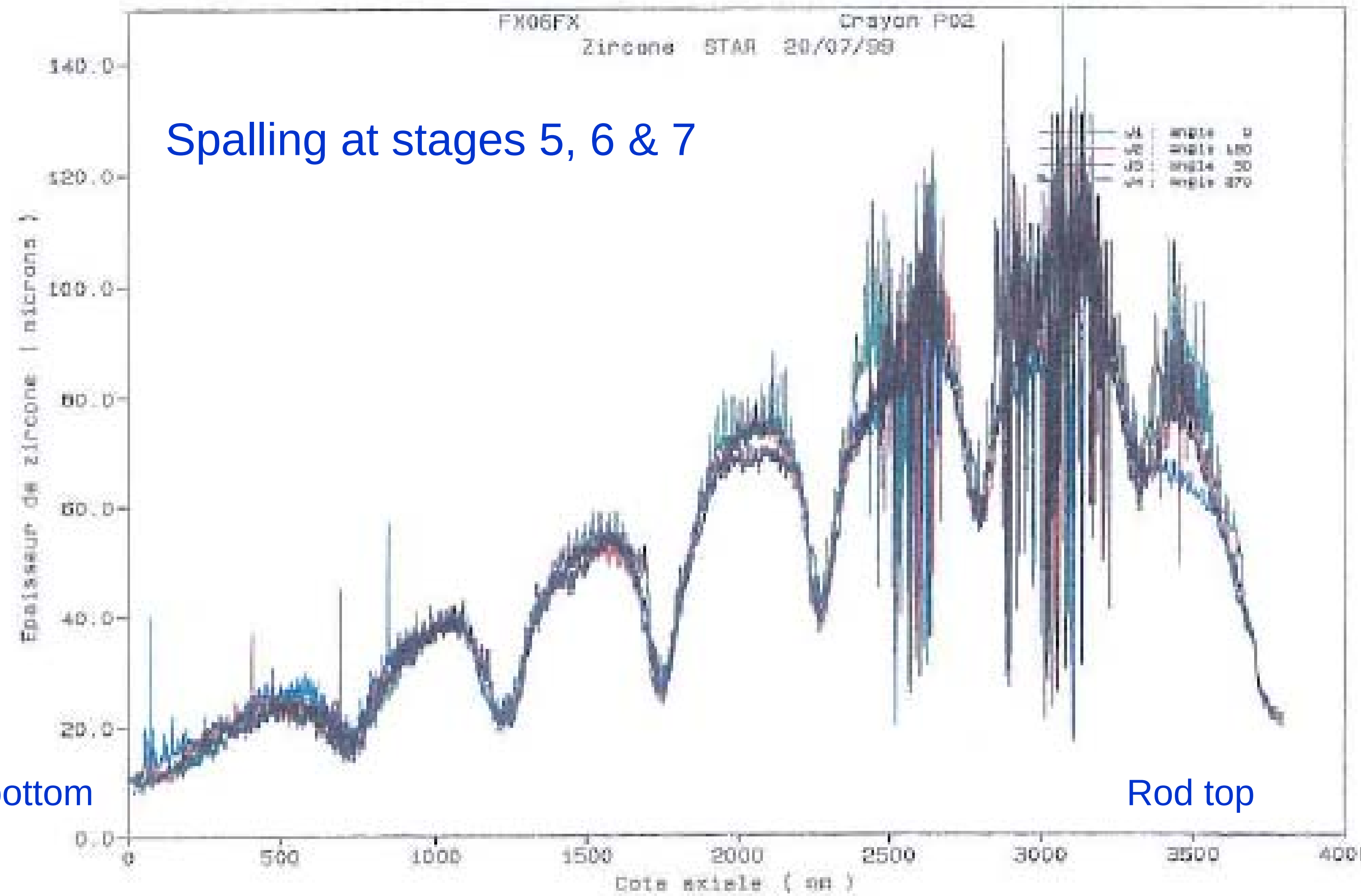
On a MOX fuel rod, irradiated 4 cycles, low-tin Zy4 cladding



Zirconia thickness in hot cell:

UO_2 fuel rod, **Zy4 clad 1.3% Sn**, 6 cycles, 65 GWd/tU

Spalling at stages 5, 6 & 7

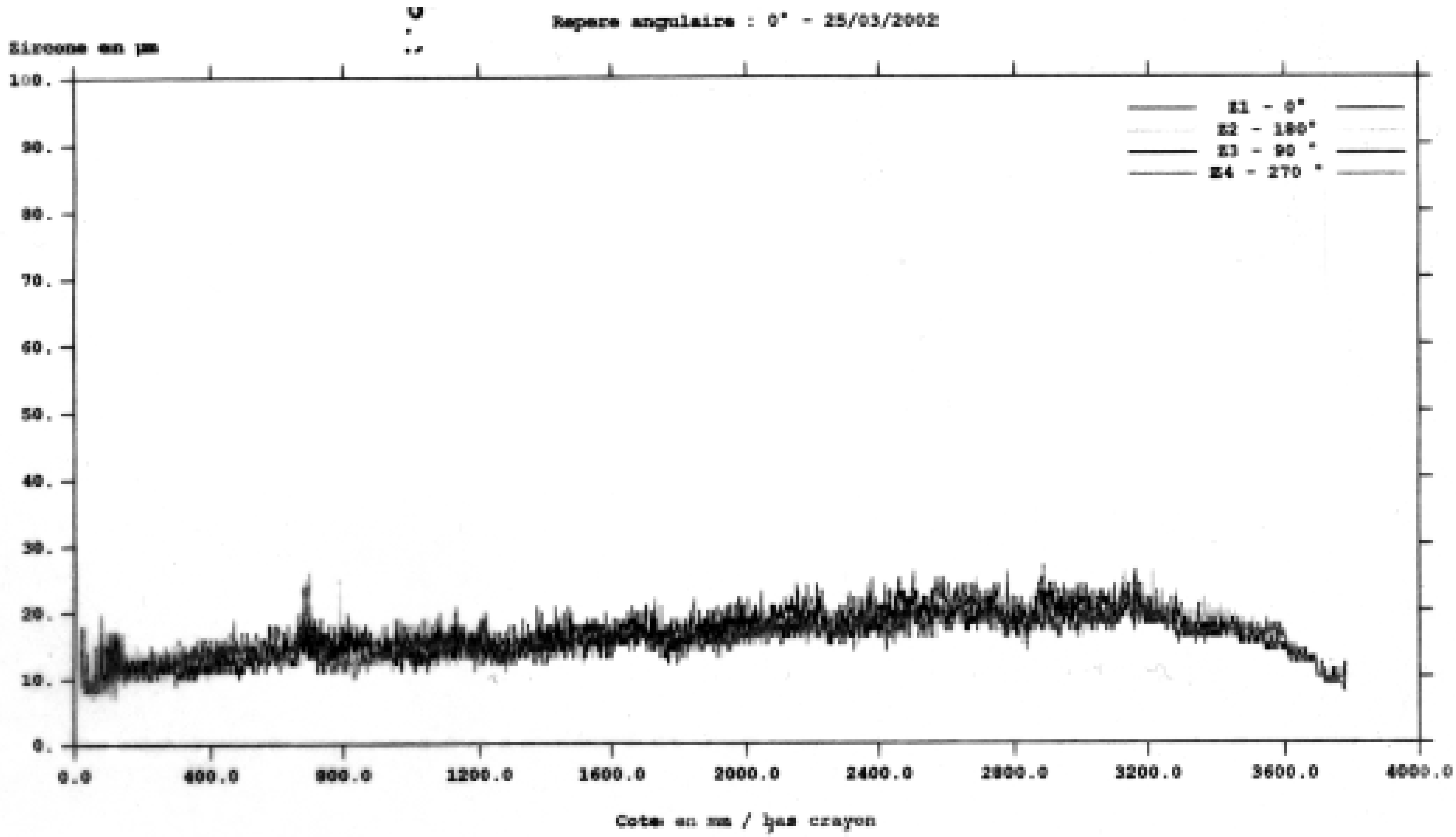


Rod bottom

Rod top

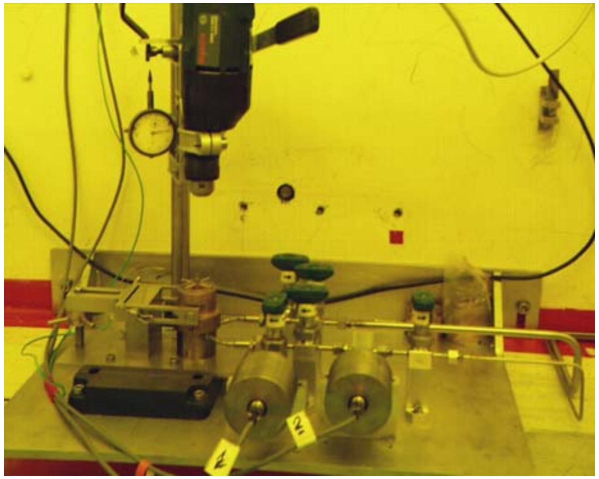
Zirconia thickness in hot cell:

M5 alloy cladding, 6 cycles, 67 MWd/tU mean rod value

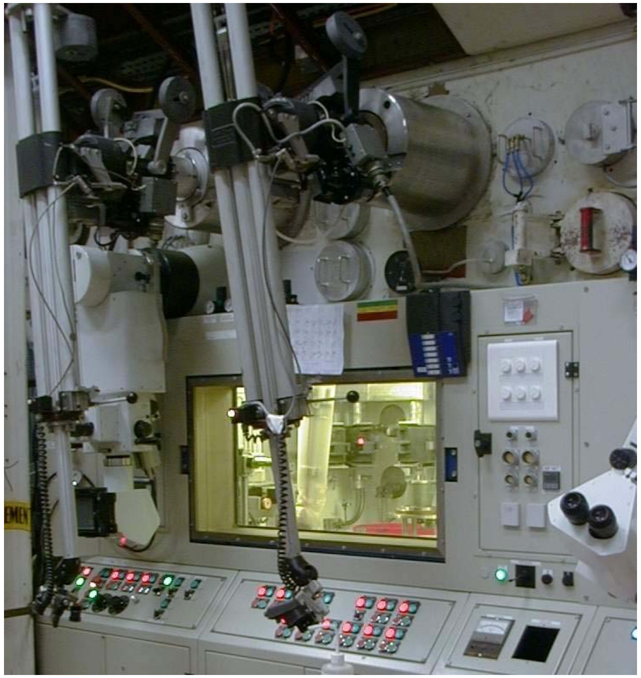


Hot cells:

2) Destructive PIE :



Puncturing: fission gas release (F%), free volume determination, end-of-life pressure, fission gas analyses (by mass spectrometry de masse or GPC),



Cutting.

Metallography.

H_2 content in the cladding.

Fuel density.

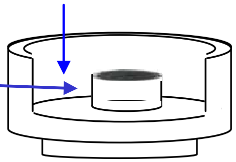
Metallography in hot cell:

Metallographic preparation

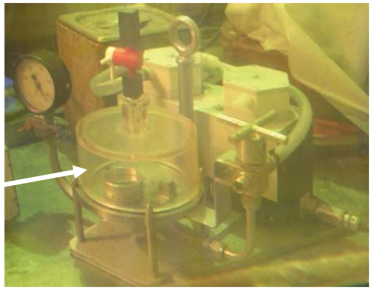
1. Rod segment

2. Vacuum embedding

Epoxy or embedding alloys



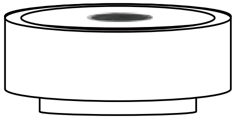
Embedding form



Cloche à vide

3. Grinding

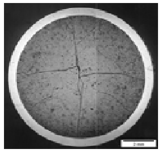
With paper or grids



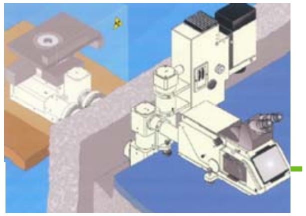
Polishing machine

4. Polishing

With felt + diamond powder suspensions



→ Optical microscope observations



Metallography: Hydride distribution in a 5 cycles **Zy4** cladding