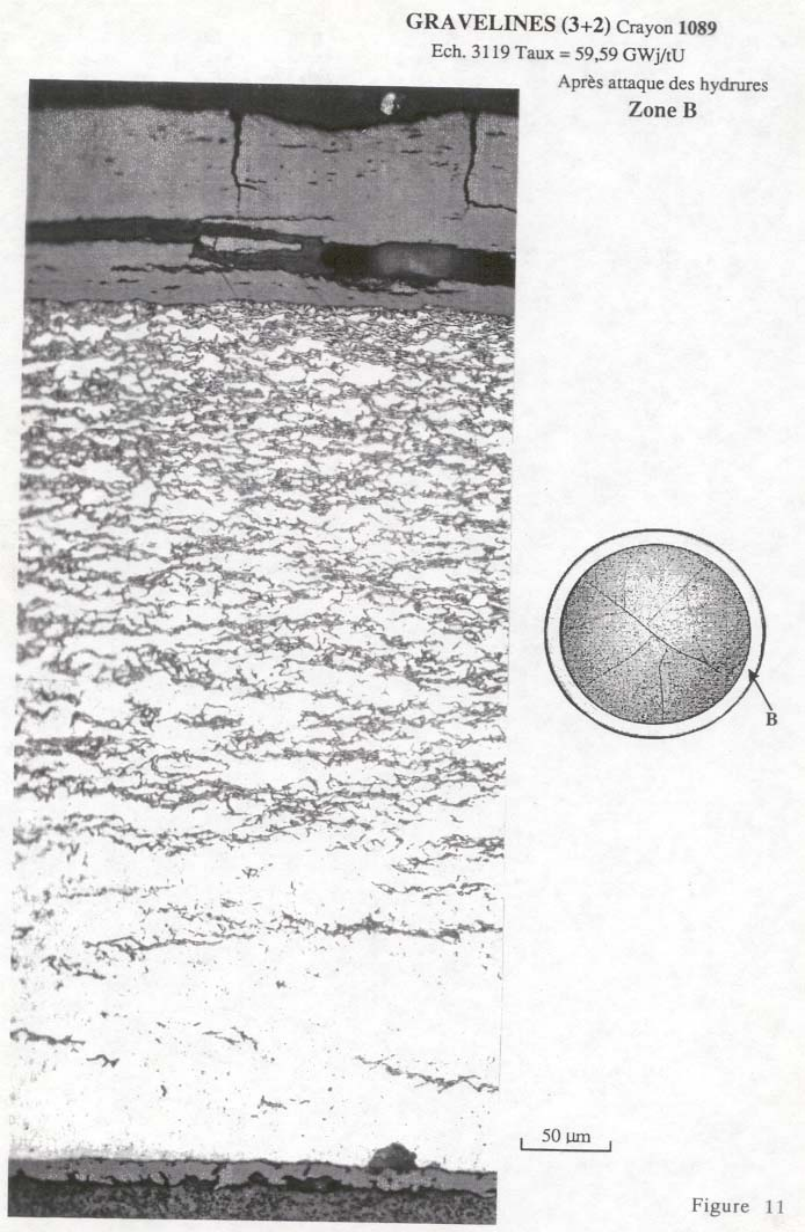
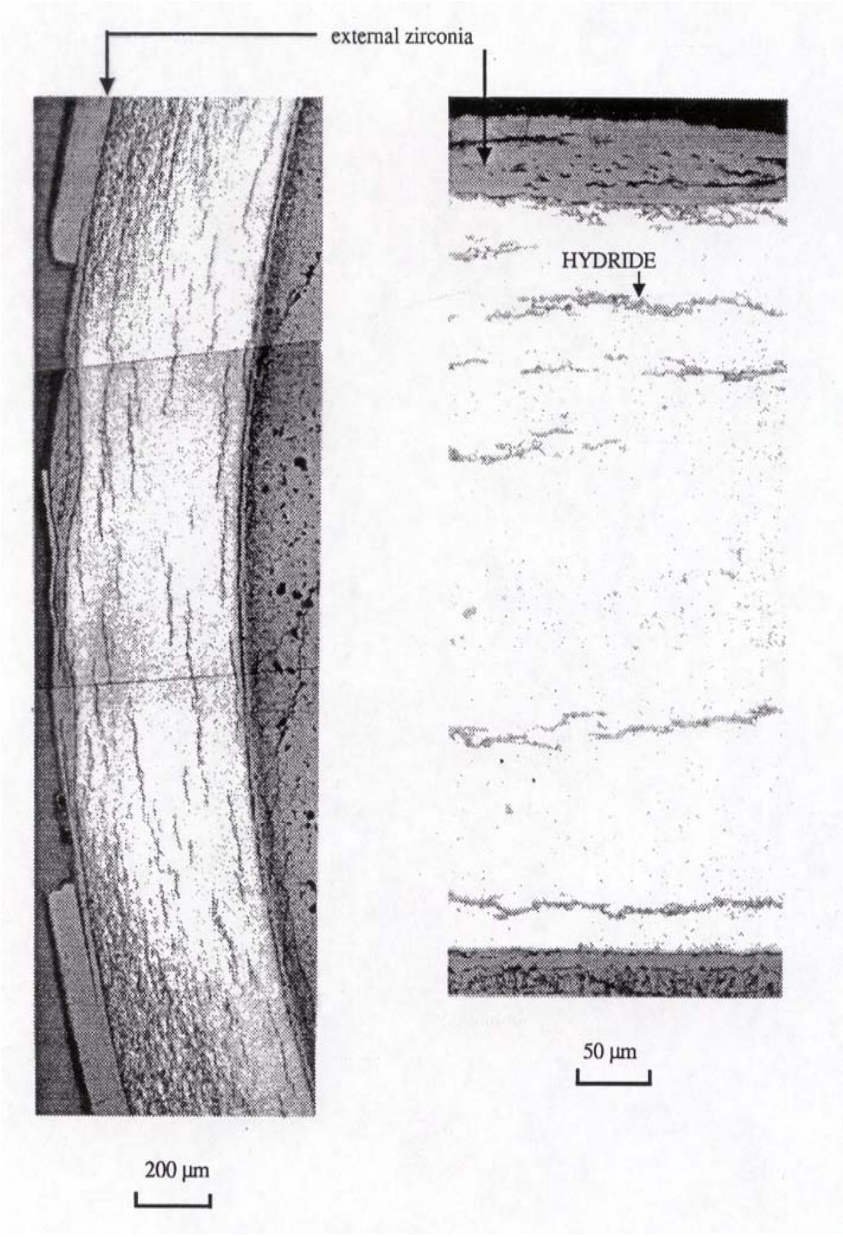
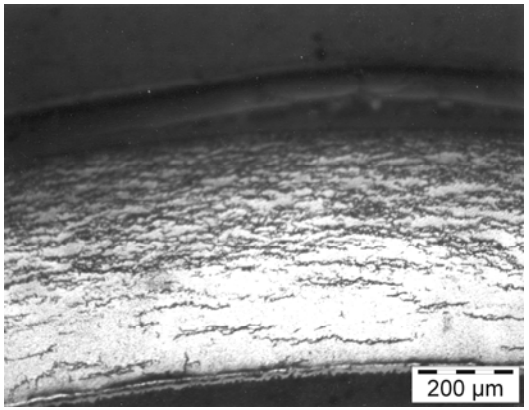
Metallography: Hydride distribution in a spalling area, 5 cycles **Zy4**

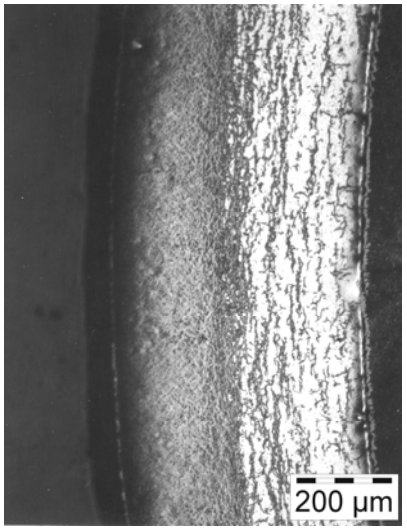


Metallography: Hydride distribution in a spalling area
6 cycles **Zy4**

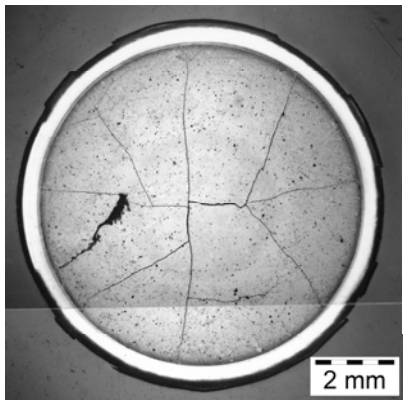


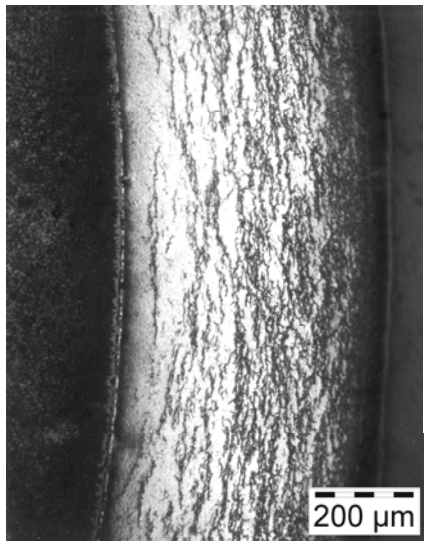
Metallography: Hydride distribution in a spalling area 6 cycles **Zy4**

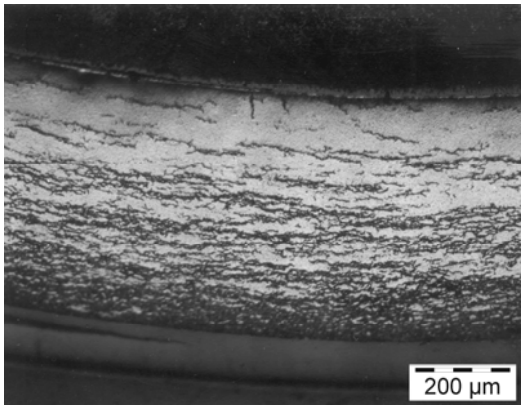




Blister

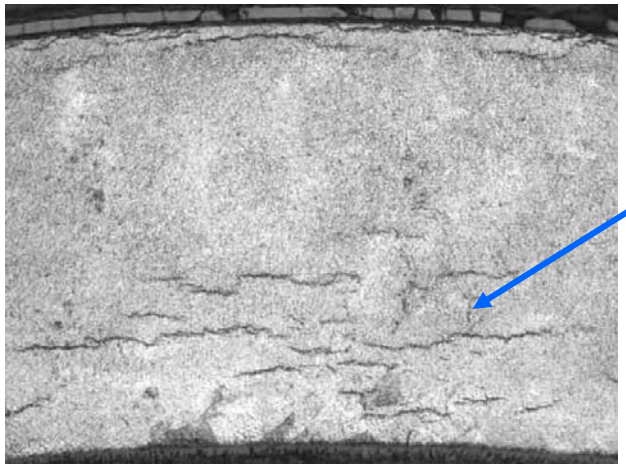






Metallography: hydrides on a 6-cycle **M5 clad**

200 µm

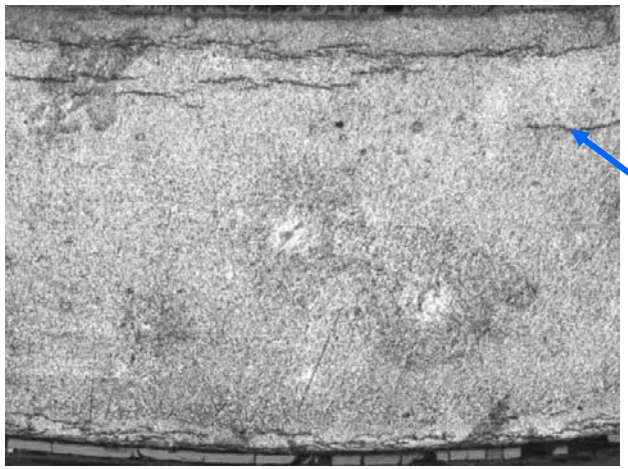


Few radial hydrides

Span 6,
72,6 GWd/tU

Azimuth 90°

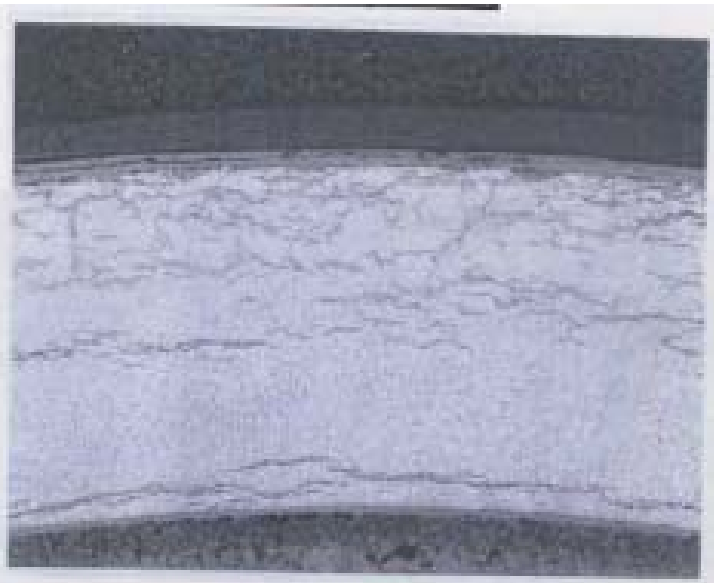
Azimuth 270°



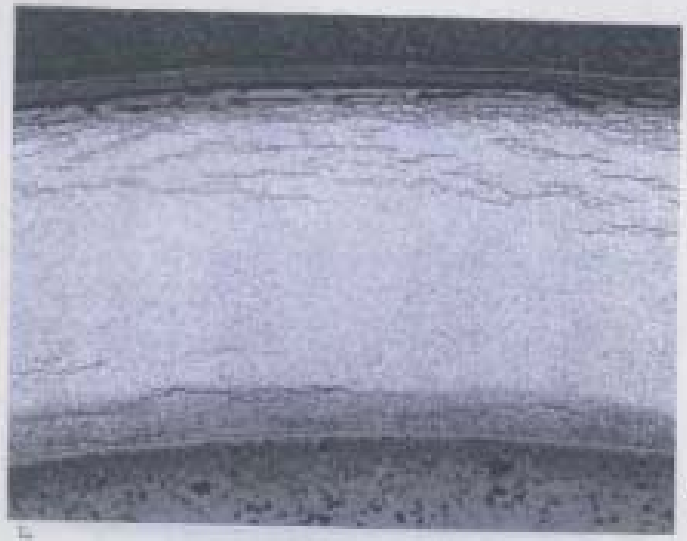
Circumferential hydrides

Homogeneous distribution through the wall.
No hydride accumulation at metal oxide interface (as in high burn up Zy4)

Generatrix 90°

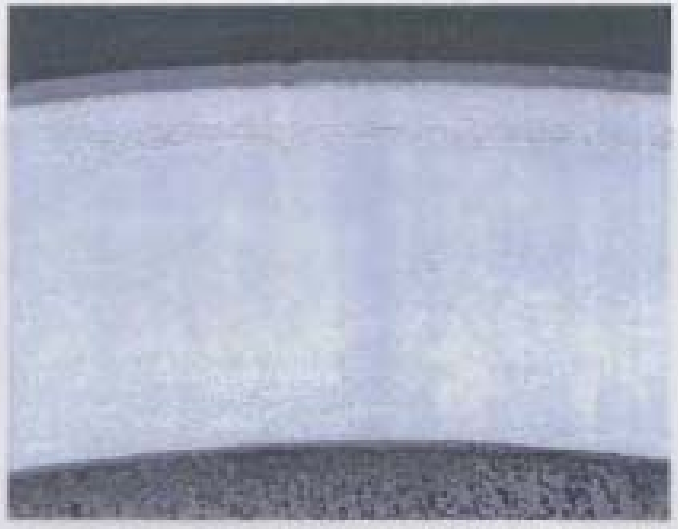


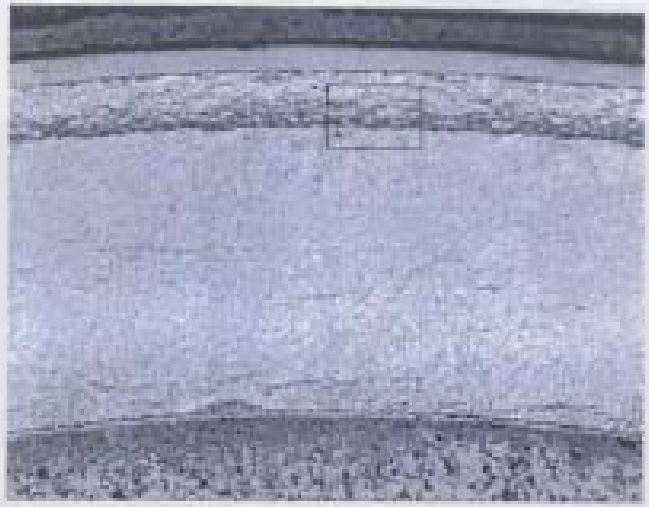
Generatrix 180°



Generatrix 270°

Metallography: Hydrides on a 5-cycle **4R clad** (Zr,Sn,Fe,V,O alloy) 54 GWd/tU





Before etching

Metallography:

Hydrides on a duplex **7.1** clad (Zr,Sn,Fe,Cr,O alloy outer layer on Zy4)
5 cycles
53 GWd/tU

After etching

100 µm

Hot cells:

3) Mechanical properties :

After chemical dissolution of the fuel pellets, claddings are submitted to standard tests, such as:

- Tensile testing at 350°C, 3.10^{-4} s^{-1}
- Burst testing at 350°C, 3.10^{-4} s^{-1}
- Creep testing 400°C, 130 MPa, 240 h

=> Performing the same tests on different materials (alloy, burn-up, span level) enables to compare performances.

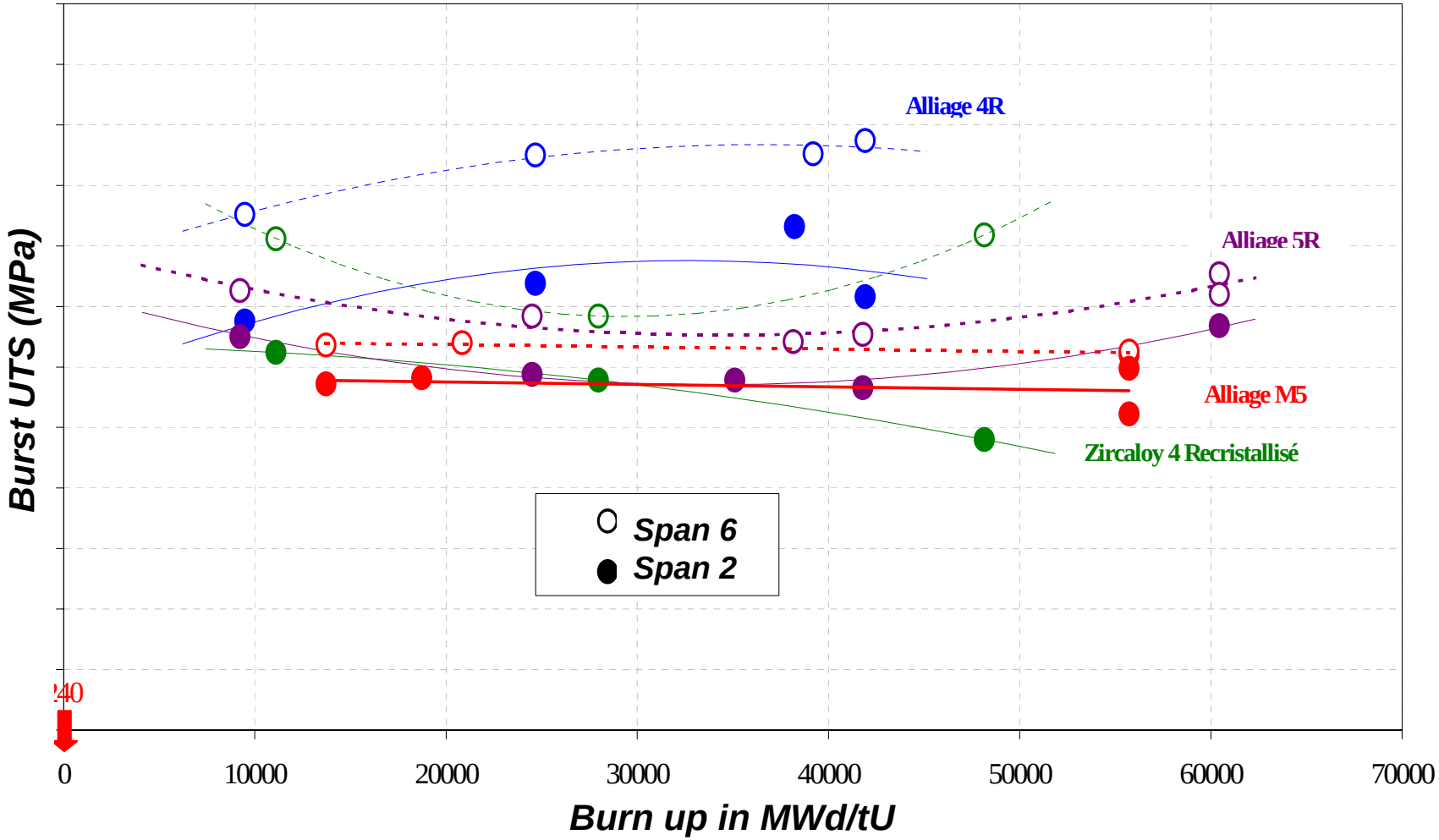
Mechanical testing machines for irradiated materials

Tensile ↑

← Creep

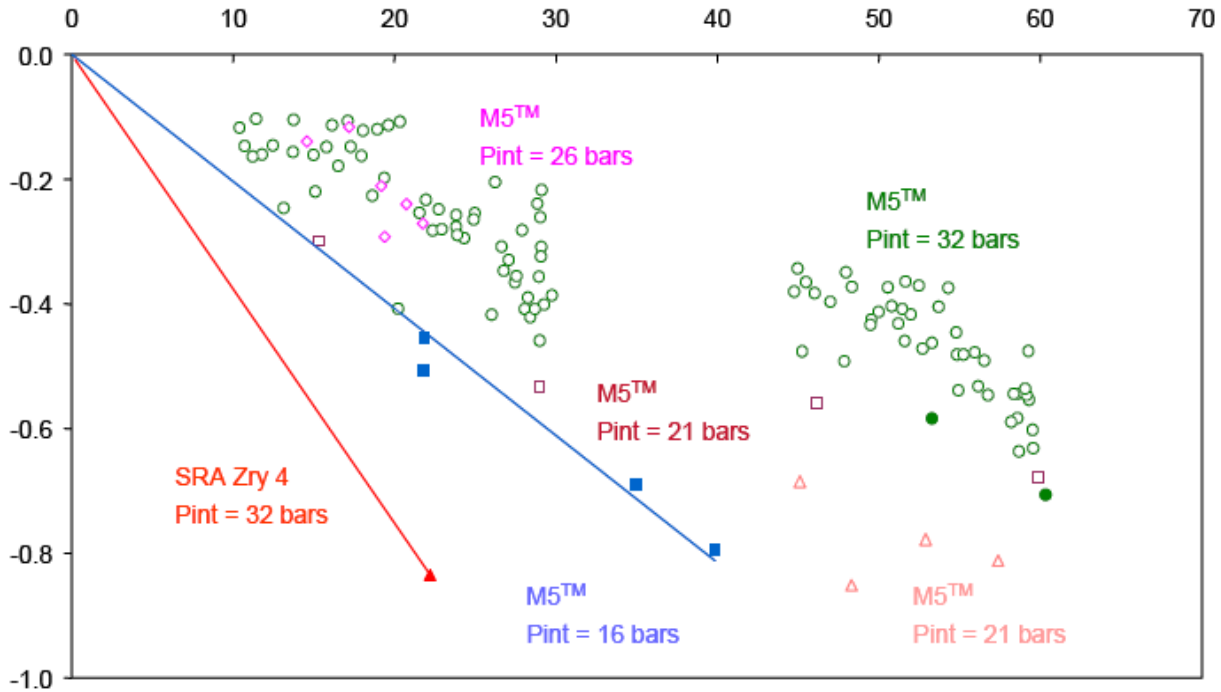
Tensile samples →

Mechanical properties: burst tests
Comparison between recrystallized Zy4, alloys 4R, 5R and M5™



Diametric creep for M5® fuel rods is much smaller than for stress-relieved Zy4 rods with identical internal pre-pressurization and stay lower even with pre-pressurizations two times lower.

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



Diameter deformation, in %

Providing fuel samples to other programmes :

Surveillance programmes are the usual mean to provide irradiated fuel for special tests:

- Specific mechanical properties,
- Power ramps (short rod manufacturing),
- RIA tests and support programmes (ex.: ring tests),
- Studies on failed rods, SCC,
- Instrumented in-pile tests, analytical tests on fission gas release (ex.: Verdon).
- Dissolution process for irradiated fuel treatment (ex. High burn up MOX), validation of neutronics codes (reprocessed U)
- Studies on long term storage,
- …

Non standard hot cell examinations:

– Burn up determination (^{148}Nd) & isotopic values (U, Pu, Nd, Am, Cm) by mass spectrometry,

– Specific mechanical tests: ring testing, dynamic tensile testing, fatigue,..

– Non-destructive measurement of the internal pressure by 85Kr,

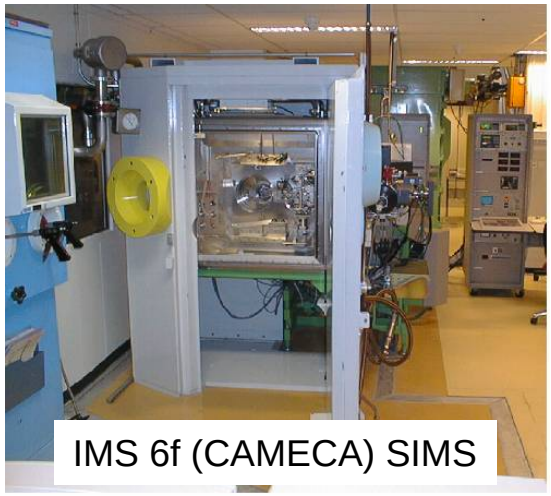
– X-ray diffractometry (ex. O/M on MOX).

– Electron Probe Micro Analyses.

– SEM: examination of fracture surfaces after ramp testing,

– SIMS.

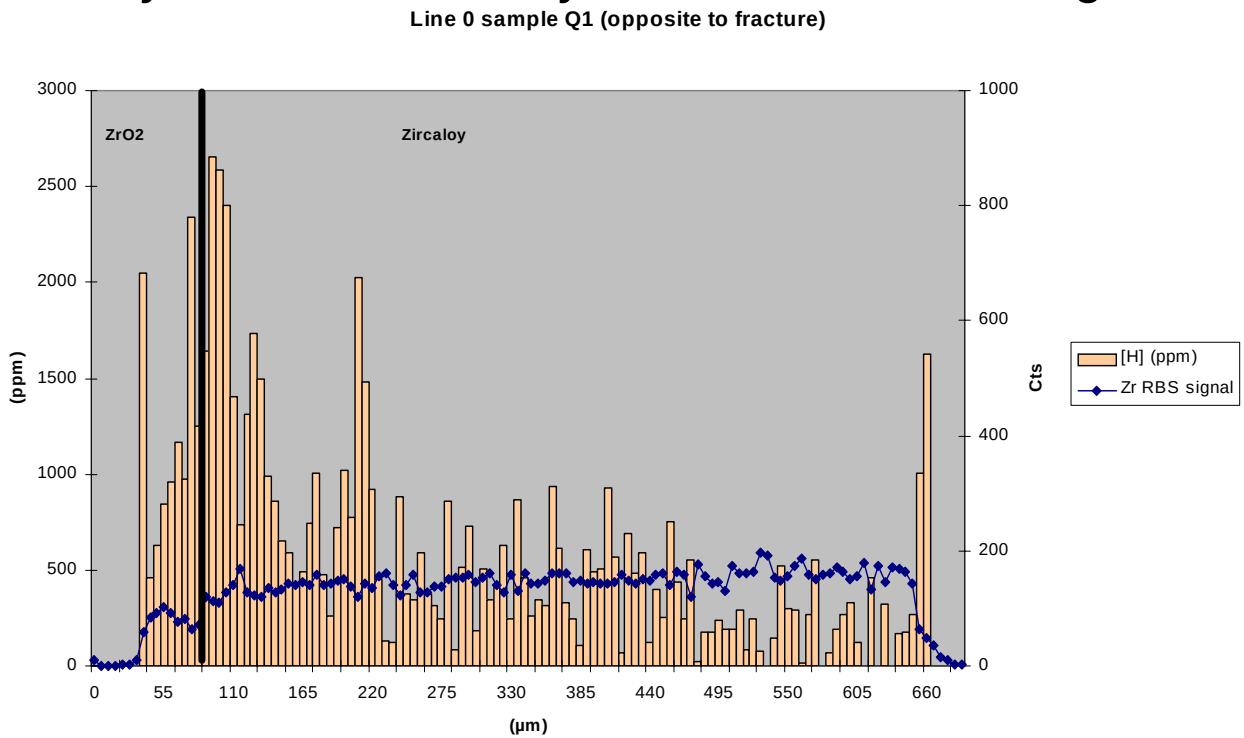
– Etc..



IMS 6f (CAMECA) SIMS

Example of detailed analyses: measurement of hydrogen content by ERDA (Elastic Recoil Depth Analysis) at LPS, Saclay.

Hydrogen in the clad can be distinguished from hydrogen in the zirconia layer, here on a 5-cycle irradiated cladding.



Surveillance programme results: an illustration.

20 ALLOYS

Autoclave and mechanical tests ⇒ knowledge of parametrical effects of alloying elements

How Framatome-ANP (now Areva-NP) selected a new alloy : 20 → 6 → 4 → 2 → M5™

Definition of 6 alloy compositions:

M1	Zr - Sn0,5 - Fe0,2 - Cr0,1 - O 0,12
M2	Zr - Sn0,5 - Fe0,2 - Cr0,1 - O 0,18
M3	Zr - Sn0,5 - Nb0,5 - Fe0,25 - O 0,12
M4	Zr - Sn0,5 - Fe0,6 - V0,4 - O 0,12
M5	Zr - Nb1 - O 0,12
M6	Zr - Fe0,25 - V 0,25

Selection de 4 alloys according to conception criteria (based on out-of-pile creep and long time corrosion tests.

4 ALLOYS M2, M3, M4, M5

Verification of **irradiation behaviour** in 15 power plants (5 countries) under a very wide range of PWR operating conditions

2 ALLOYS M5 & M4

The best margins for future PWR operating conditions.

M5™

Depending on power plant operations, surveillance programme conditions are more or less detrimental.

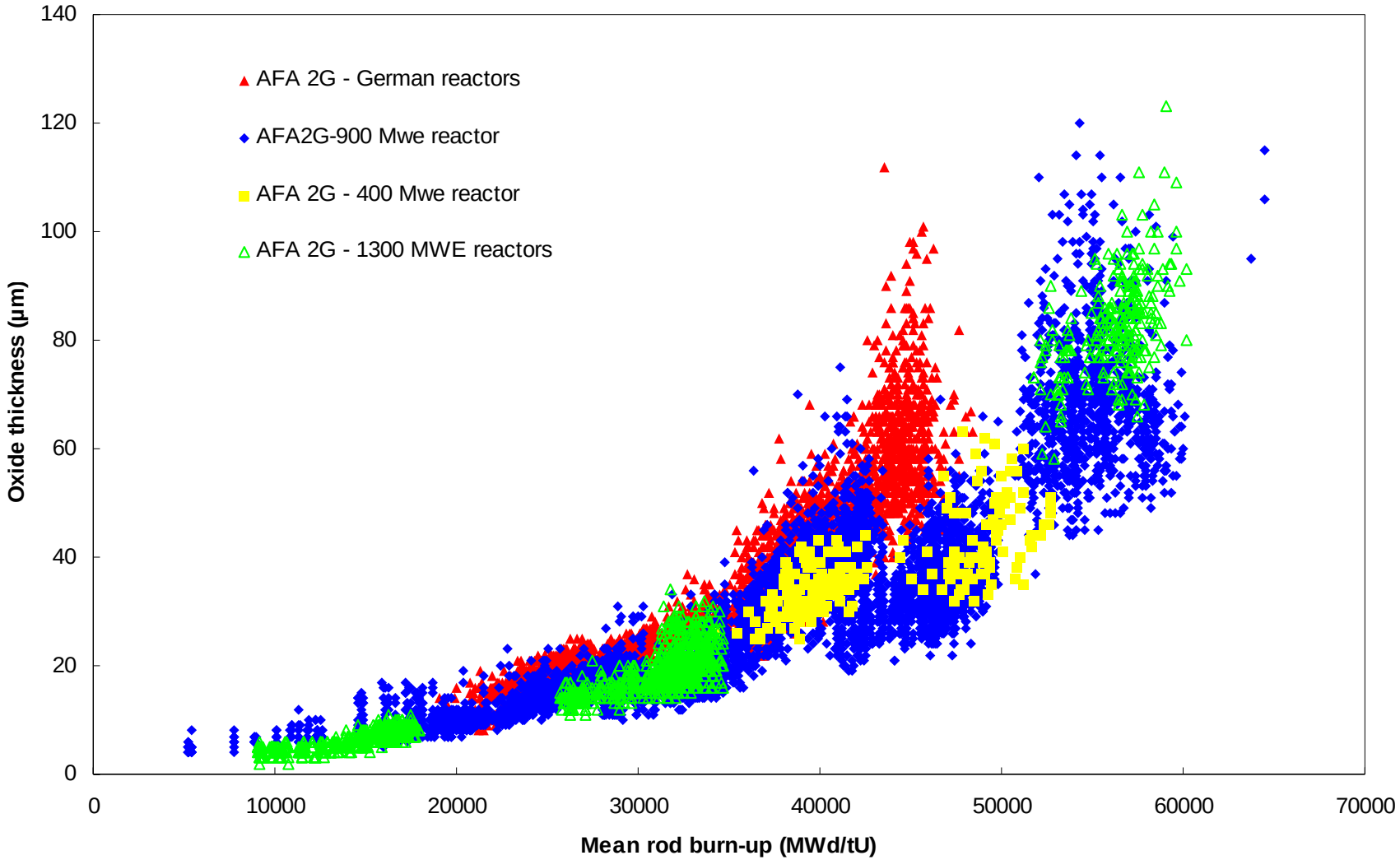
Plant	Core power (MWt)	Inlet T° (°C)	Outlet T° (°C)	Linear power (W/cm)
PWR 900 17x17	2775	287,7	321,5	178,3
PWR 1300 17x17	3800	289,9	323,1	170,2
PWR 400 14x14	1192	285,2	314,0	219,8
Pre-Convoy 16x16	3850	291,8	326,5	211,1
Convoy 18x18	3850	291,7	325,4	166,1

Summary of corrosion results

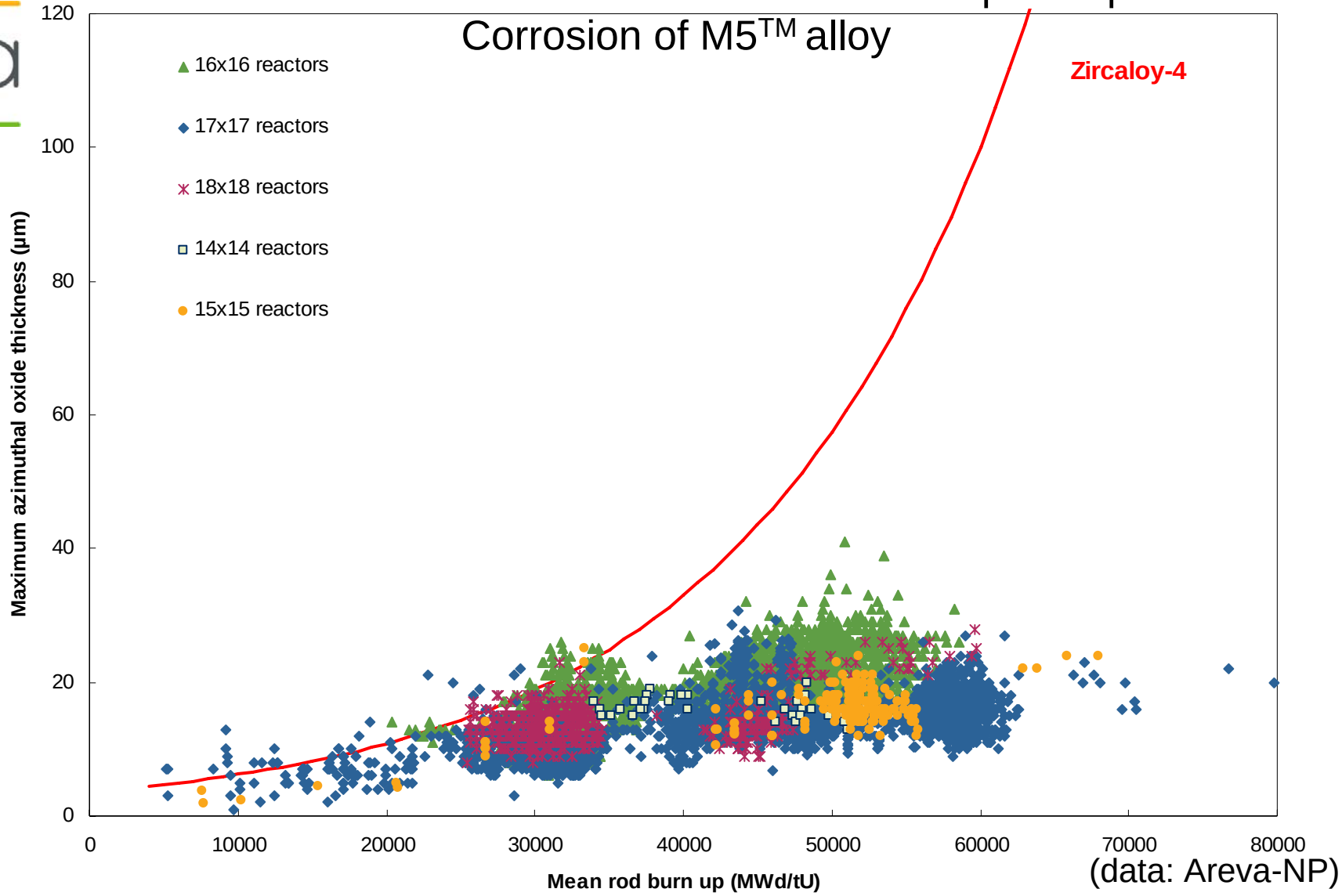
	900 MWe PWR		1300 MWe PWR		GERMAN PLANTS		400 MWe PLANT	
Alloy	B.U. in GWd/tU	Oxide thickness (μm)	B.U. in GWj/tU	Oxide thickness (μm)	B.U. en GWd/tU	Oxide thickness (μm)	B.U. en GWd/tU	Oxide thickness (μm)
AFA 2G	65	124	60	123	48	112	53	63
2	60	47	-	-	47	40	53	26
4	63	40	60	45	51	49	-	-
M5™	80	31	60	27	59	41	53	20

(data Areva-NP)

Corrosion of ZIRCALOY-4 AFA2G in commercial power plants

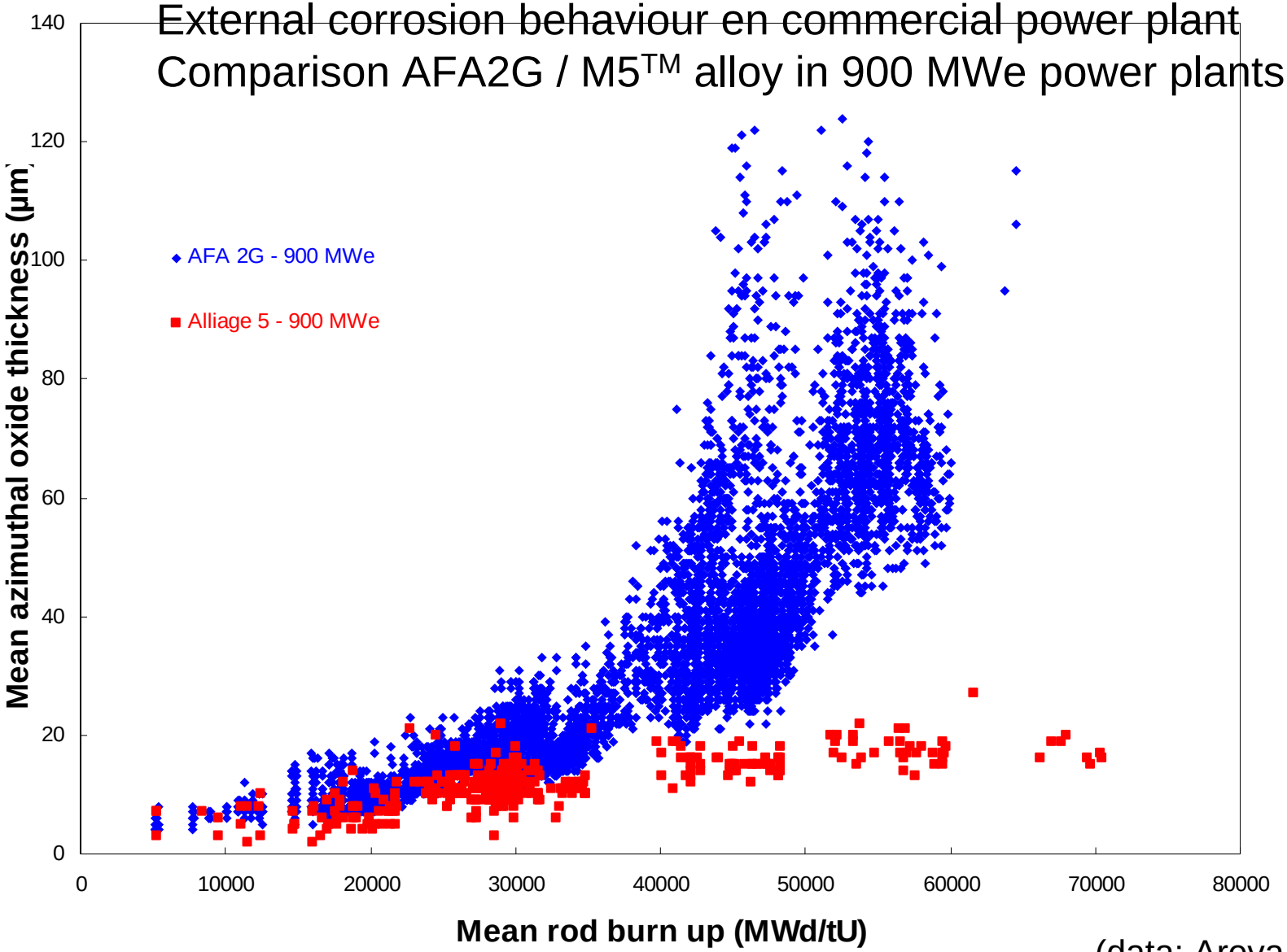


External corrosion behaviour en commercial power plant



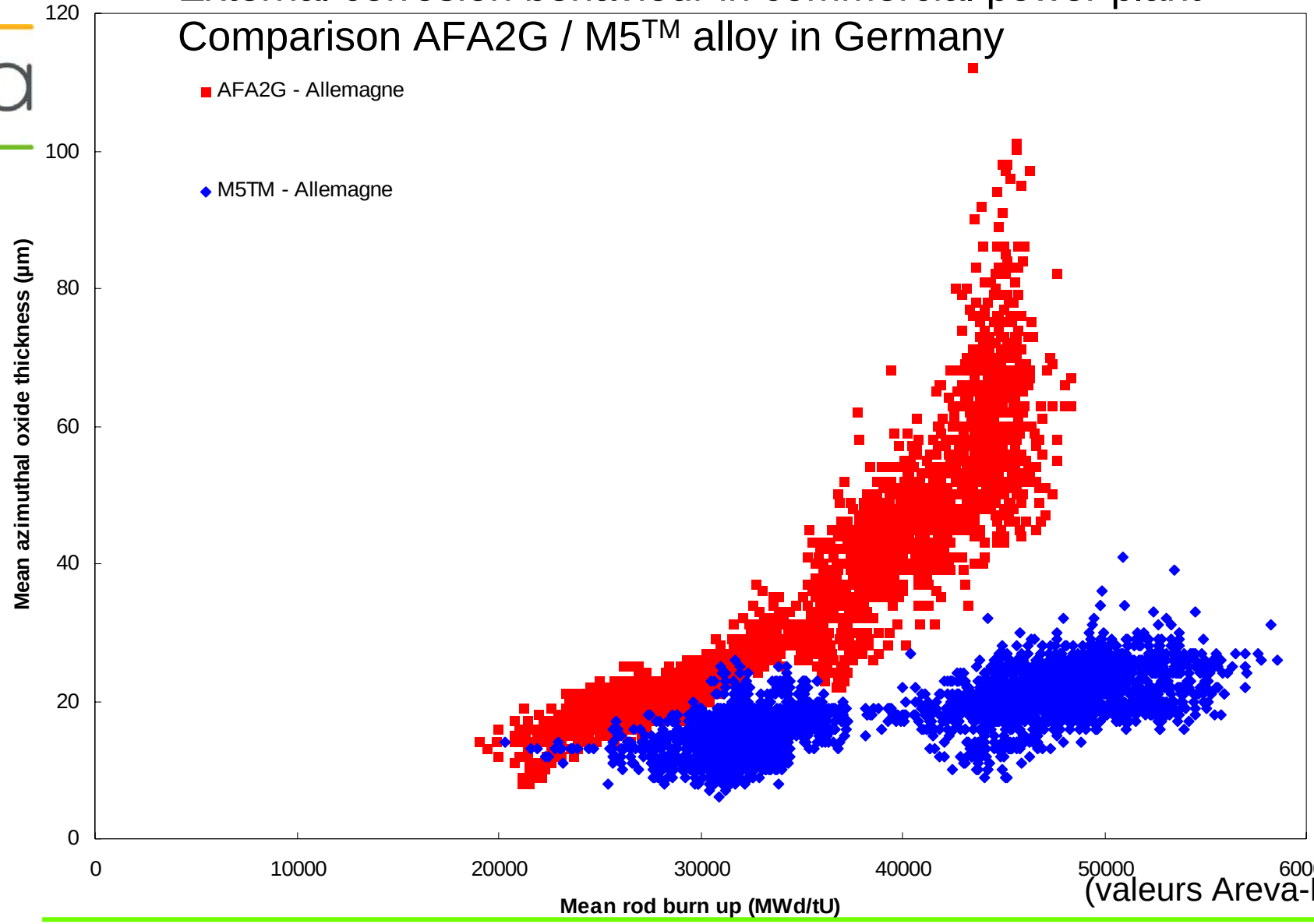
(data: Areva-NP)

External corrosion behaviour en commercial power plant
Comparison AFA2G / M5™ alloy in 900 MWe power plants



(data: Areva-NP)

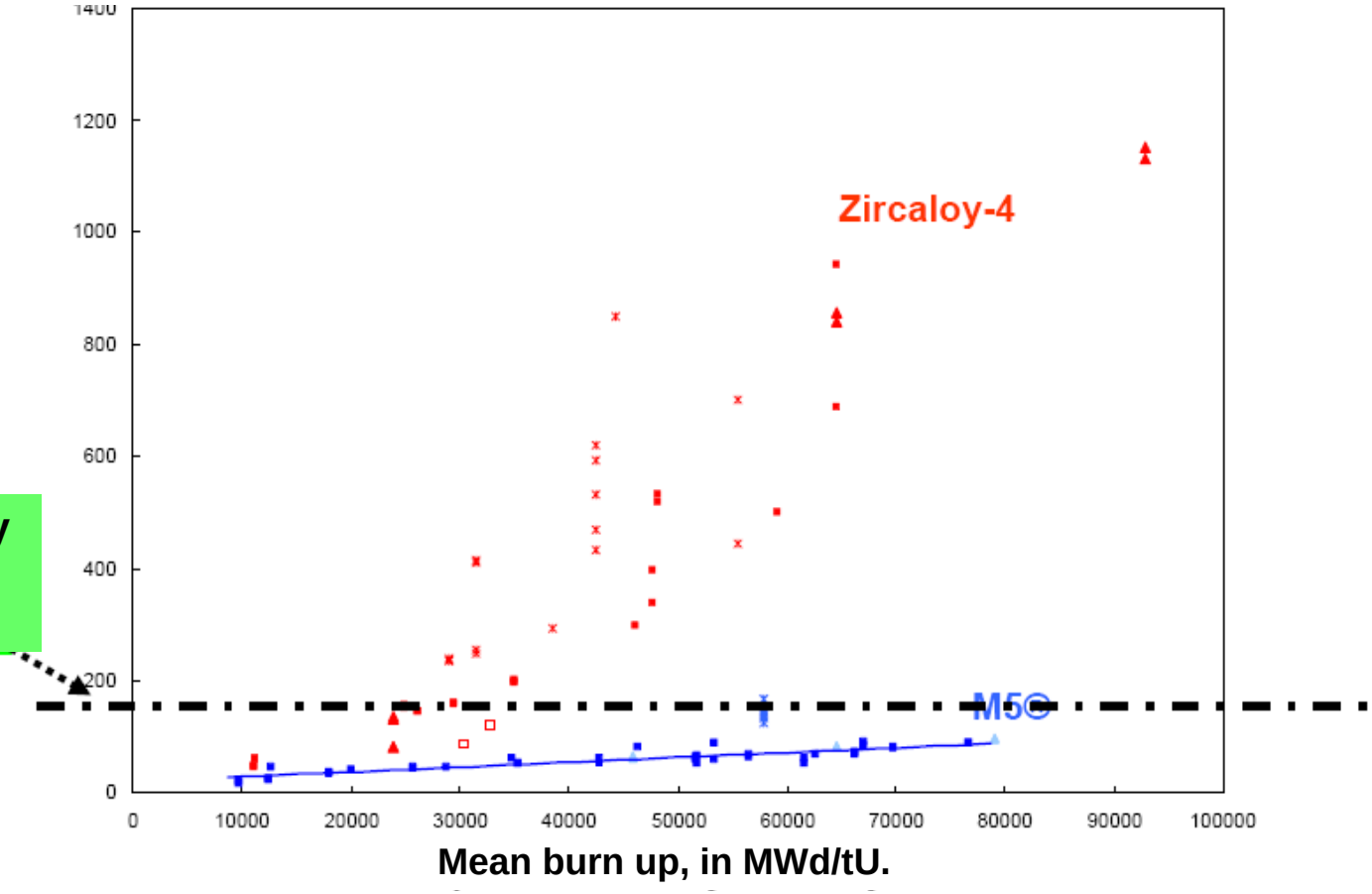
External corrosion behaviour in commercial power plant
Comparison AFA2G / M5TM alloy in Germany



(valeurs Areva-NP)

In service hydrogen pickup for M5® fuel rods is very small compared to low tin Zy4.

Hydrogen content, in ppm.



Hydrogen pickup for high burn-up M5® is lower than 100 ppm and than the in-service solubility limit for claddings.

The DUO experiment.

4 characterised assemblies were loaded:

- in GOL-1 (Li < 2,2 ppm),
- in CAT-2 (Li < 3,5 ppm).

These assemblies included Zircaloy-4 AFA2G, M5, et M4 alloys issued from the same clad batches (and a few rods in advanced cladding materials M5+ and Zy4+ in CAT-2).

- Corrosion measurements were performed by Areva-NP after each irradiation cycle.

- 5 cycles of irradiation were obtained for 5 rods in Cattenom 2 (maximum burn-up = 69 GWd/tU). PIE are nearly completed.

- As power histories were different, comparison is only possible at the same burn up..

- No corrosion acceleration was detected on the 3 alloys under study.

- Good behaviour of alloys + and M5.

Conclusions:

Surveillance programmes are necessary to validate the design of new fuels (new claddings, MOX, higher burn up,…).

Post Irradiation Examinations in hot cells are a lengthy and costly process. Trends are as follows:

– No more examinations on a whole assembly, but only on a few carefully selected rods,

– Augmentation of on-site examinations,

– Limit the number of extracted and examined rods,

– PIE are indispensable for providing raw data to fuel designers and provide samples to other programmes,

– Indispensable for specific examinations : clad mechanical properties, H_2 content, metallographies, surface analyses, fuel burn up determination, pellet structure,...

– Also interesting for expertises, wear traces, irradiated grids or guide tubes…

Thanks for your attention.