DE LA RECHERCHE À L'INDUSTRIE

PARIS-SACLAY

Fontevraud 9

Assesment of potential swelling of Pressurized Water Reactor internals: The GONDOLE experiment in Osiris reactor

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OUTLINE

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   3. Irradiation conditions
   4. Density measurements experiments

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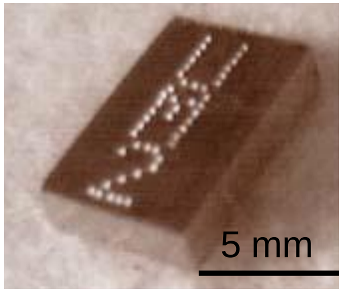
   1. Density measurements
   2. TEM characterizations

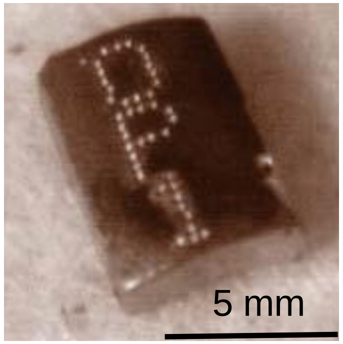
3. Conclusions and prospects

1.1. THE GONDOLE PROGRAM - OBJECTIVES

- Main goal: to evaluate potential swelling of PWR internals
  - by density measurements
  - PWR internals representative materials
  - Irradiation in a mixed spectrum (Osiris MTR) at 360°C
  - 30 cumulated dpa (15 dpa for initial program + 15 dpa for prolongation)

- Density specimens characteristics:
  - Nominally rectangular shape
  - Small size
  - 7.7 × 5 × 1.5 mm^3
  - Specimen reference engraved

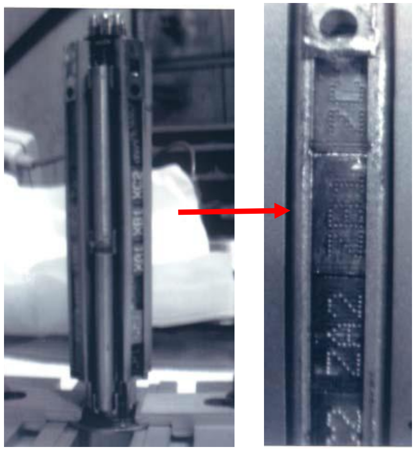




1.2. THE GONDOLE PROGRAM – DENSITY SPECIMENS

- Virgin and pre-irradiated materials (reach higher doses)
- 304 / 316 type materials (metallurgical state and chemical composition), with in particular “PWR reference materials” (304 Solution Annealed and 316 Cold-Worked + 308 welds) – French irradiation programs, PWR core internals materials, archive materials
- Others materials (stabilized steels, “low activation” steel…)

- Specimens inserted in four barrels in two baskets in SEMI/CEA hot cells
- 64 specimens



1.3. THE GONDOLE PROGRAM – IRRADIATION CONDITIONS

- Irradiation program: 2 parts
- 2005-2010: 5 phases (6 cycles each)
- 2011-2015: 3 phases (11, 10 and 9 cycles)
- ~ 1206 Equivalent Full Power Days

- Irradiation in the core of Osiris reactor
- Fast flux ~ 2×10^{14} n/cm²/s
- Thermal flux ~1.4×10^{14} n/cm²/s

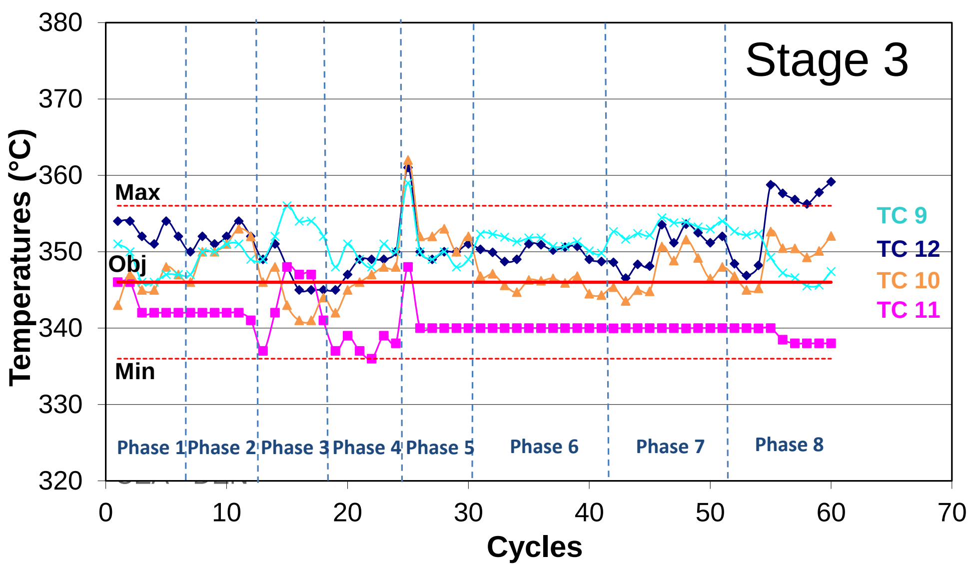
- Doses

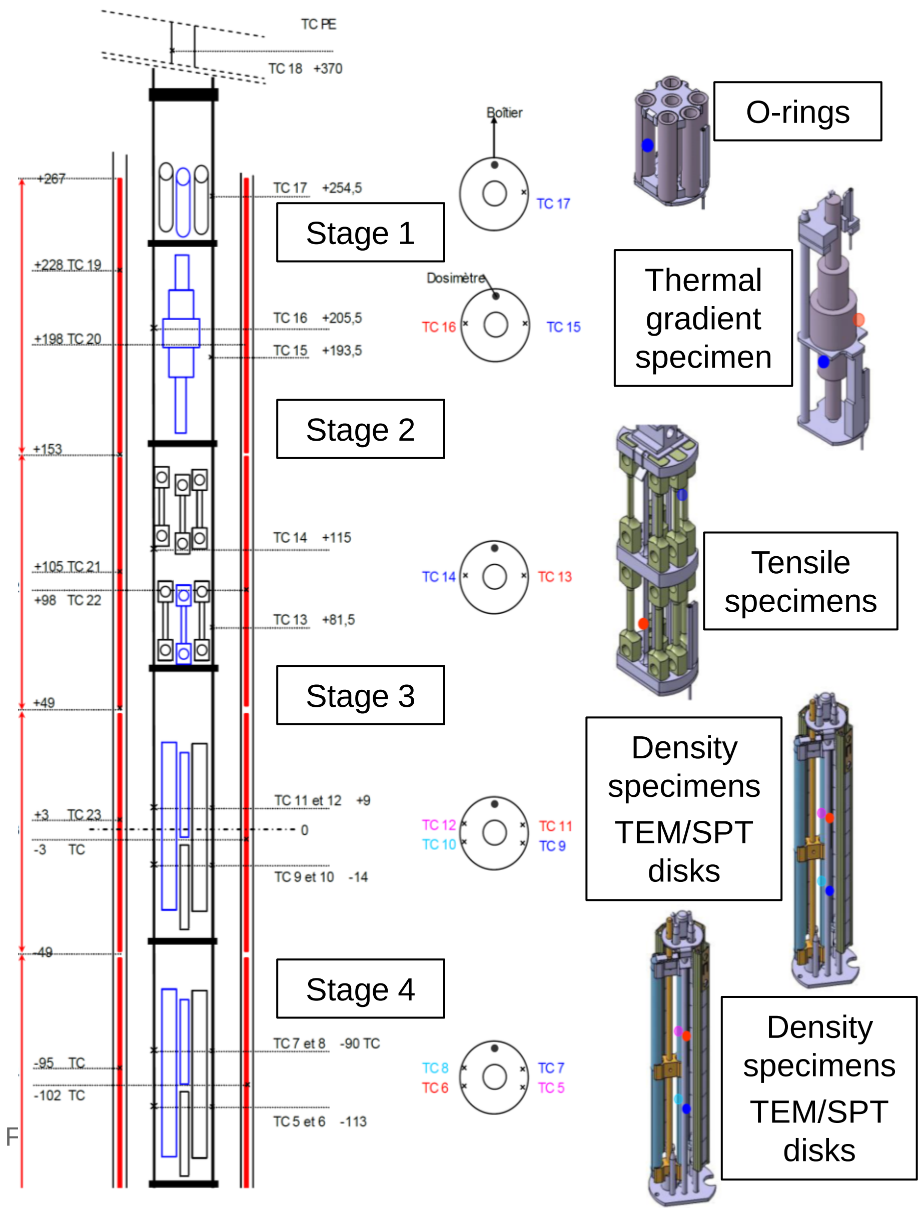
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Cumulated dose (dpa)
Dose (dpa Fe)	2.50	2.41	3.25	3.05	2.82	5.75	5.13	4.65	29.56

- Gradient along the sample holder: results at max flux plane
- Final cumulated dose ~29.6 dpa
- Specimen changes at phase 1 and 2: only a part of the specimens cumulated the whole dose, but from phase 3 specimens were not changed (except one) (~24.7 dpa at the max flux plane)

1.3. THE GONDOLE PROGRAM – IRRADIATION CONDITIONS

- Sample holder immersed in NaK
- 4 stages:
  - Density specimens (stages 3 and 4)
  - Other specimens (stages 1 to 4)
- Heaters and thermocouples for temperature regulation
  - ~ 346°C on thermocouples for 360°C mean temperature on density specimens
- Activation foils for dosimetry measurements





1.4. THE GONDOLE PROGRAM – DENSITY MEASUREMENT EXPERIMENTS

- Density measurement principle
- Immersion density method by double wheighing in air and phenyl bromide

Mass in air

$$\rho = \frac{(M1 - m1)}{(M1 - m1) - (M2 - m2)} \times \left(d_{PhenylBromide} - d_{air}\right) + d_{air}$$

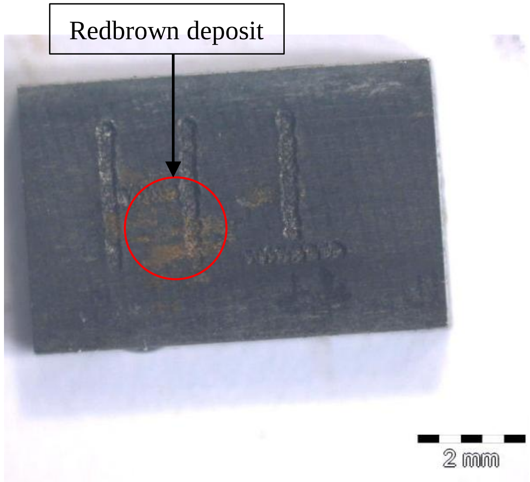
Mass in liquid

- Immersion density measurements performed before GONDOLE irradiation and after each irradiation phase in hot cells
- Possibility to determine density evolution between phase ‘j’ and former phase ‘i’

$$\Delta d(\%) = \frac{\rho_j - \rho_i}{\rho_i} \times 100$$

1.4. THE GONDOLE PROGRAM – DENSITY MEASUREMENT EXPERIMENTS

- Choice of the density specimen geometry is a compromise:
- Size/mass of the specimens
- Common geometry for pre-irradiated material machining in hot cells
- Placing many specimens in the sample holder for material comparison
- ➢ Reduced weight of specimens (between 0.2 and 0.5 g) not optimal for density measurements (strong impact on uncertainty)



- Specimens were initially not checked
- Surface checked after phase 6
- Deposit confirmed on density specimens

- ➢ Enhancement of the density measurement protocol during the program
- ➢ Work to define the uncertainty as precisely as possible

1.4. THE GONDOLE PROGRAM – DENSITY MEASUREMENT EXPERIMENTS

- Density measurement procedure

➢ Phase 0 to phase 4:

Specimen cleaning in US bath (alcohol, 5 min)
2 double weighings (taking account of $T_{phenylbromide}$ and P_{air})
If the two densities differ of > 0.02 g/cm^3 the measure is repeated
Scales precision: 0.1 mg

➢ Phase 5:

Similar protocol to that of phase 4 but with **4 double weighings** and a new set of scales (**precision: 0.01 mg**) to improve accuracy

➢ Phase 6:

Specimen cleaning in US bath (alcohol, increased time 20 min), optical observation and weighing
Cleaning steps are repeated until mass stabilization
4 double weighings (30 specimens measured)

➢ Phase 7:

Similar protocol to that of phase 6
Daily calibration of the scales and increased cleaning efforts

➢ Phase 8:

Similar protocol to that of phase 7
5 double weighings

1.4. THE GONDOLE PROGRAM – DENSITY MEASUREMENT EXPERIMENTS

- Uncertainty determination

1 - Theoretical measurement uncertainty (precision of each measurement)

Accuracy limit on small samples (0.2 g)

Phase 1 - 4: +/- 0.40% (97.5% due to mass uncertainty)

Phase 5 - 7 : +/- 0.05% (80% due to mass uncertainty) – new scales

2 – Measurement scatter

Limited numbers of measurements : Student-Law approach

$$\mu = \pm t_{1-\frac{\alpha}{2}}^{n-1} \times \frac{\sigma}{\sqrt{n}}$$

n: number of measurements ($n_{phases\ 1\text{-}4}=2$, $n_{phases\ 5\text{-}7}=4$, $n_{phase\ 8}=5$)

α: risk of error, taken equal to 5 %

σ: standard deviation for the n measurements

$\boldsymbol{t_{1-\frac{\alpha}{2}}^{n-1}}$: Student law quantile for n-1 level of freedoms and with an error risk of α/2

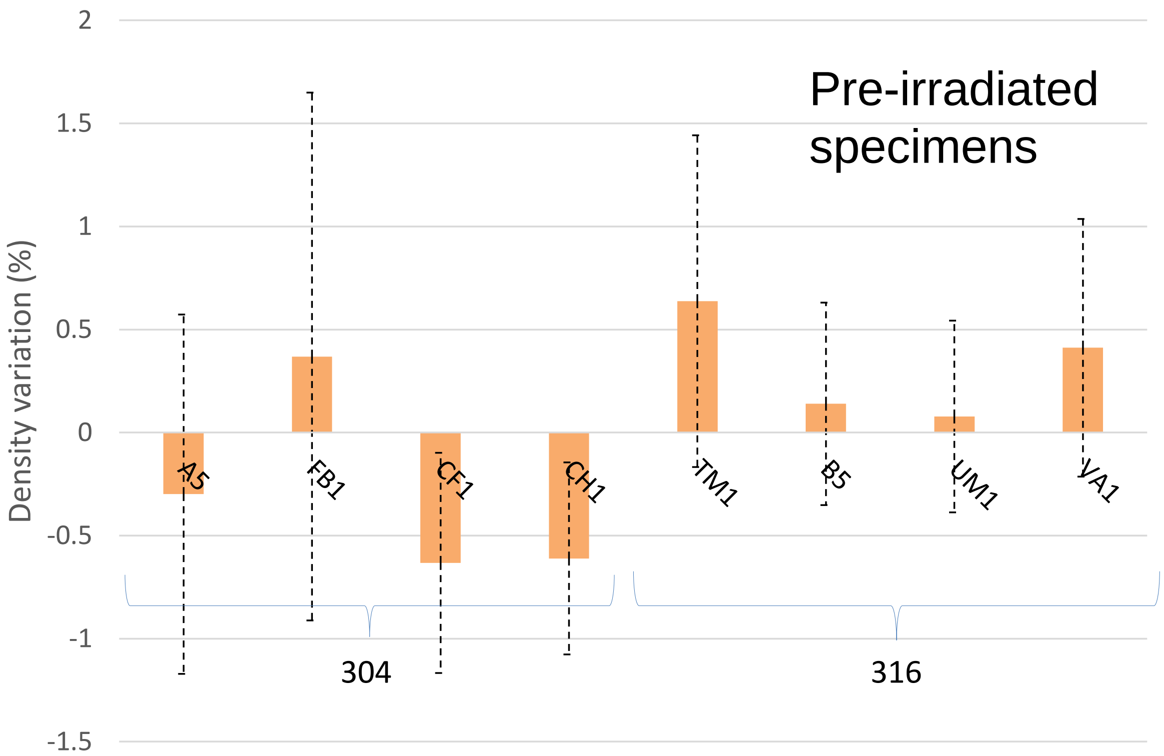
$t_{phases\ 1\text{-}4} = 12.71$, $t_{phases\ 5\text{-}7} = 3.182$, $t_{phase\ 8} = 2.776$

- Overall confidence interval = Precision + Student-Law interval
- Confidence interval reduced for last phases
- Δd confidence interval = $(\text{Precision + Student-Law})_{Pi}$ + $(\text{Precision + Student-Law})_{Pj}$

2.1. RESULTS – DENSITY MEASUREMENTS

- Evolution of density after GONDOLE irradiation program (comparison of density before GONDOLE irradiation and after the 8 phases of irradiation)

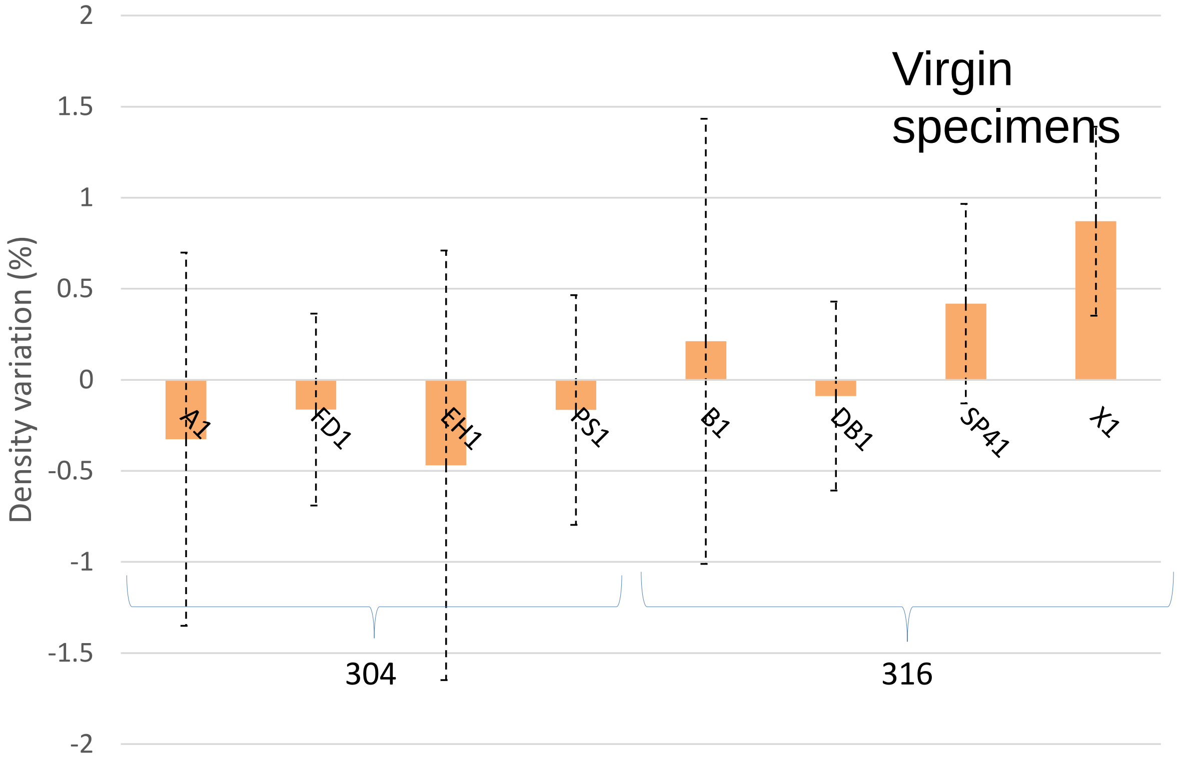
- Positive values = densification
- Negatives values = swelling



- Positive and negative variations

- Limited variations in the uncertainty range
- Small variations on CF1 and CH1

2.1. RESULTS – DENSITY MEASUREMENTS



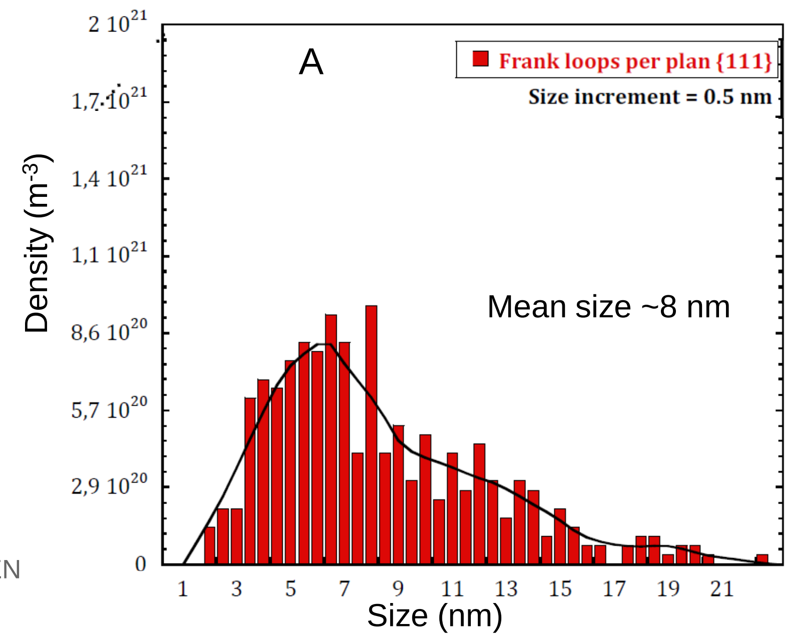
- ➢ Same results as pre-irradiated specimens
- Positive and negative variations
- Limited variations in the uncertainty range
- Small variations on X1

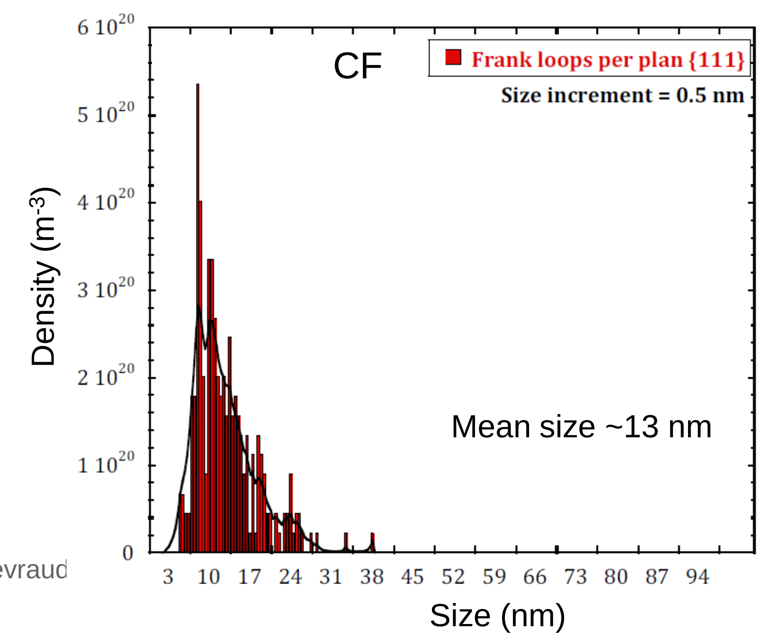
- Density measurements revealed that the density evolution are small and in the uncertainty range (virgin and pre-irradiated specimens)

2.2. RESULTS – TEM CHARACTERIZATIONS

- At stages 3 and 4, specimens were also introduced as TEM disks in tubes
- TEM disks removed after part 1 for TEM characterizations:
- A (pre-irradiated) specimen – 24 dpa – 375°C
- CF (pre-irradiated) specimen – 44 dpa – 375°C

- Irradiated microstructure (both materials):
- Frank loops
- Segments of perfect dislocations
- Precipitates
- Cavities





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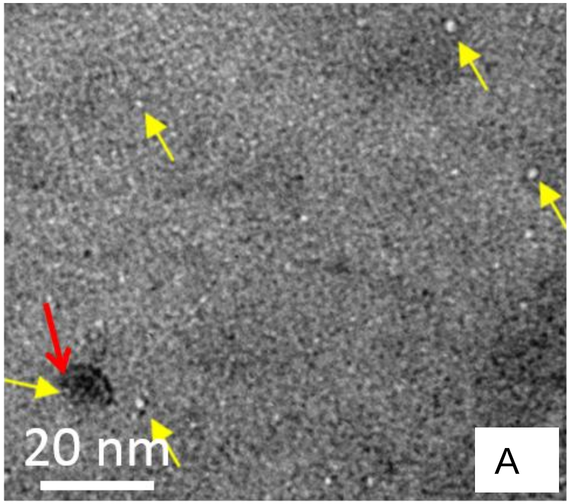
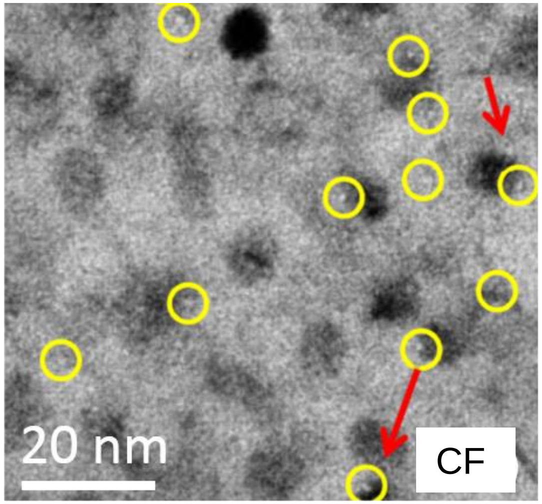
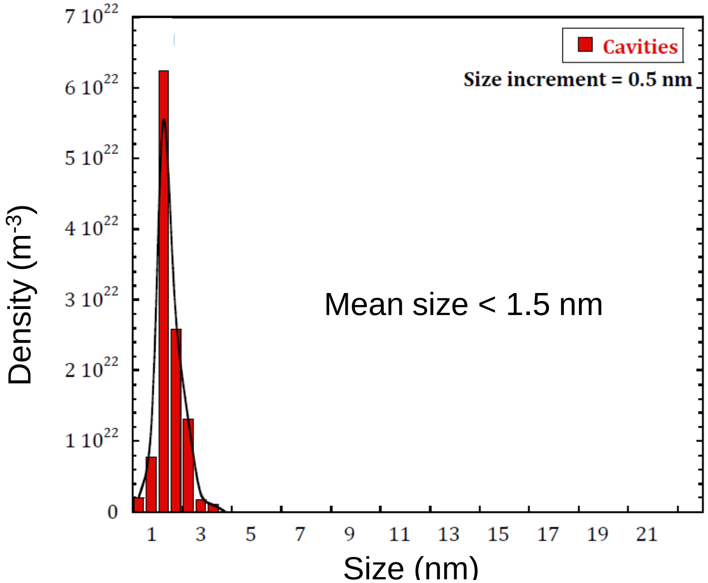
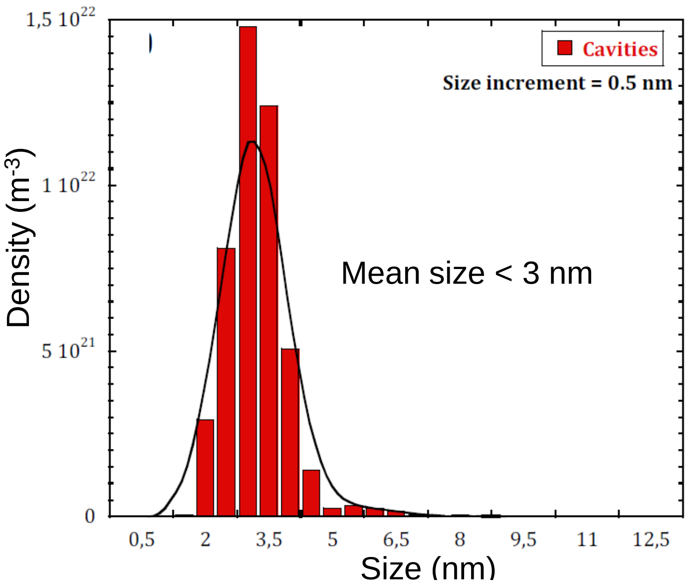
2.2. RESULTS – TEM CHARACTERIZATIONS

Cavities









- Small and numerous cavities
- Volume fraction limited (~0.04 and ~0.07%)

3. CONCLUSIONS AND PROSPECTS

CONCLUSIONS

- Description of the GONDOLE irradiation program
- Assessment of potential swelling by density measurements
- ➢ Description of the protocol and uncertainty measurements improvements
- ➢ Limited density variation, below the uncertainty limit
- ➢ TEM characterizations of pre-irradiated materials: cavities identification, limited associated swelling

Prospects

- To improve density measurements uncertainty (new measurements of the ‘before GONDOLE irradiation state’ - virgin specimens and some pre-irradiated archive specimens)
- To perform TEM characterizations of specimens available after phase 8

Thank you for your attention

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