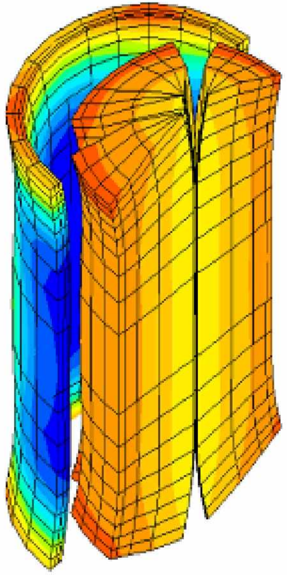
Exploratory research project:



Development of a manufacturing process for a simulating fuel for the study of fine fragmentation in LOCA

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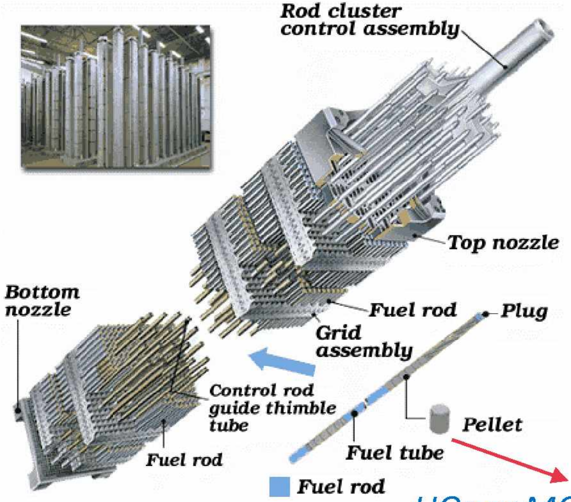
Context of the study – fuel fragmentation

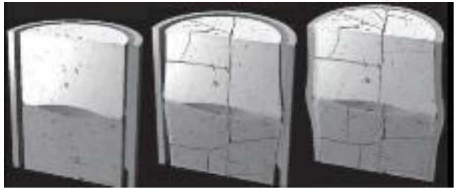
Fuel pellets undergo significant changes during their life in the reactor. Their condition is also potentially degraded during an incident or accident.

Fabrication → Base Irradiation → Incident/Accident

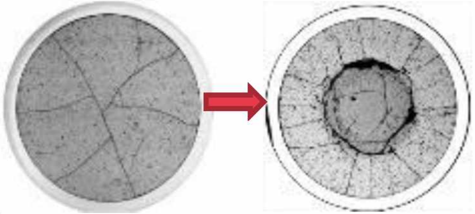


UO$_2$ or MOX sintered ceramic

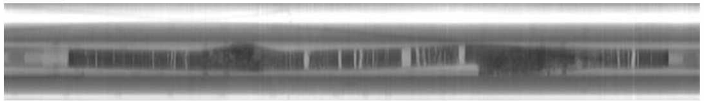
$P_{lin} \uparrow$



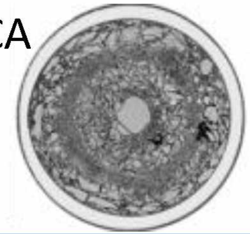
- Power ramp



- RIA



- LOCA



Study Objectives – Simulating fuel

A few programs exist for the study of fragmentation on irradiated fuels:

- Many influential parameters: burnup, irradiation history, test conditions (temperature, pressure and quantity of gas in the rod, dT/dt)
- Few tests (expensive, material consuming)

The objective of the study is to develop a pre-fragmented fuel fabrication process to various degrees:

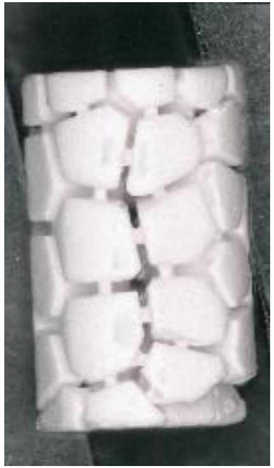
- Ability to have several pellets with various characteristics of fragmentation
- Use outside the hot cell and possibility of studying fragmentation, relocation and dispersion/ejection under many conditions (crushing of rod section, impact, 4-point bending, semi-integral tests)…

Project structure

PRE-FRAGMENTED PELLET DESIGN

FABRICATION BY 3D PRINTING

EVALUATION OF THE MECHANICAL BEHAVIOR OF PELLETS

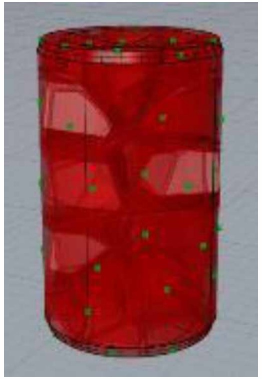


Main characteristics of model pellets

- CAD software used: Rhino7/Grasshopper

- Pellet geometry:
  - Modeling of dish and chamfers
  - External diameter: ~ 8.2 mm
  - Height ~ 13.5 mm

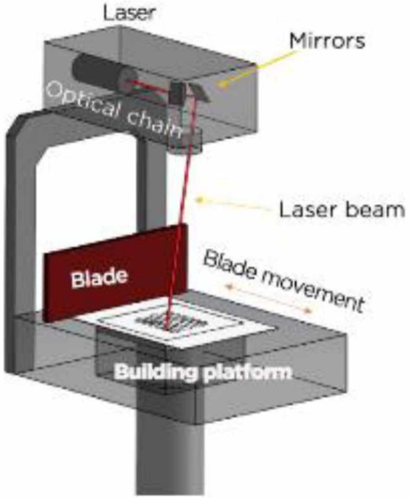
- Fragments: Points generation inside the pellet



- IFZ (Inter-Fragments zone): “Brittle" but facilitating handling

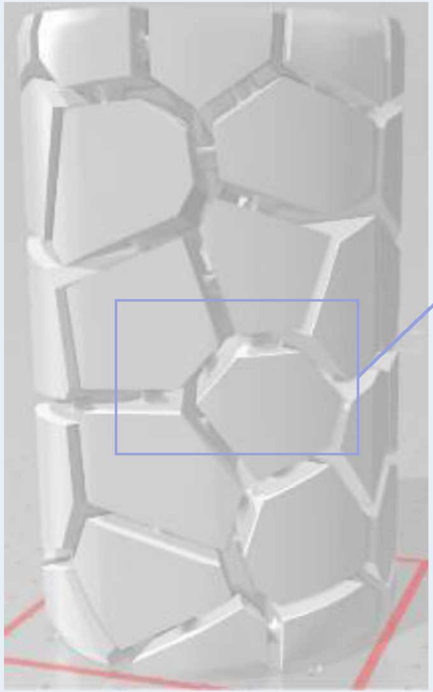
Direct printing by stereolithography

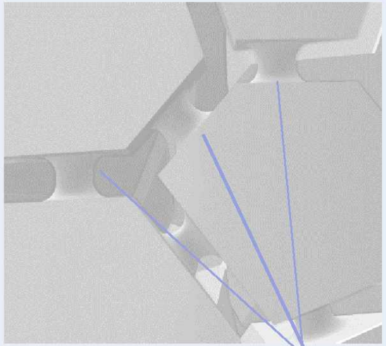
- Direct printing by stereolithography
  - 3D CERAM C900 from Novadditive
  - Resolution: ~ 0.035mm
  - Fabrication without supports
  - Material: Alumina Al_2O_3
  - Light-curing reaction of ceramic resin
  - Debinding in air: removal of organic additives (1°C/min up to 600°C for 2 hours)
  - Sintering: partial melting of the ceramic powder for densification (1700°C for 2 hours for maximum mechanical properties)



1. CAD model and validation in stereolithography printing

CAD modeling with interconnected fragments





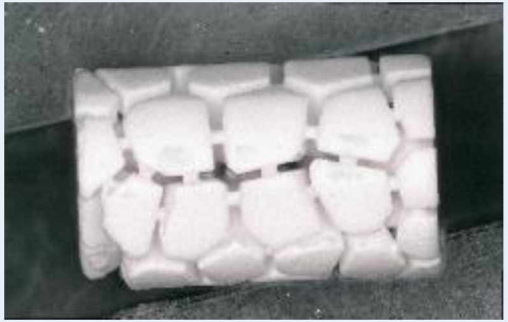
Fillets between fragments

Pellet characteristics:

- 50 fragments of an average size of ~ 2 mm
- Distance between fragments: 0.4 mm
- Diameter of the bridges: 0.4 mm
- 0.2 mm fillets on bridges to prevent crack formation

Feasibility test with Novadditive

Fabrication of two pellets



2. Lateral compression test

Hertz model:

- Maximum stress is at the center of the disc and corresponds to a tensile stress along the x axis.

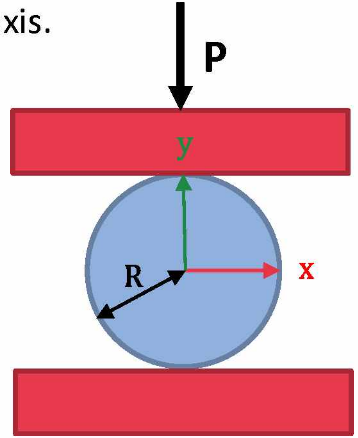
$$\sigma_x = \frac{-2P}{\pi L}\left\{\frac{x^2(R-y)}{\beta_1^4} + \frac{x^2(R+y)}{\beta_2^4} - \frac{1}{2R}\right\} \quad (1)$$

$$\sigma_y = \frac{-2P}{\pi L}\left\{\frac{(R-y)^3}{\beta_1^4} + \frac{(R+y)^3}{\beta_2^4} - \frac{1}{2R}\right\} \quad (2)$$

$$\sigma_{xy} = \frac{2P}{\pi L}\left\{\frac{x(R-y)^2}{\beta_1^4} + \frac{x(R+y)^2}{\beta_2^4}\right\} \quad (3)$$

$$\beta_1^2 = (R-y)^2 + x^2$$

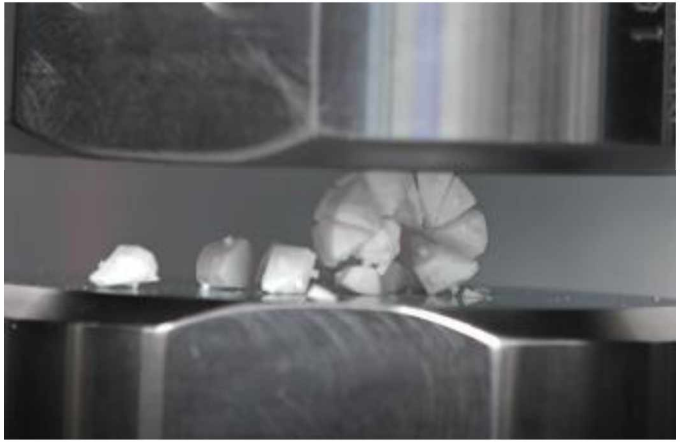
$$\beta_2^2 = (R+y)^2 + x^2$$

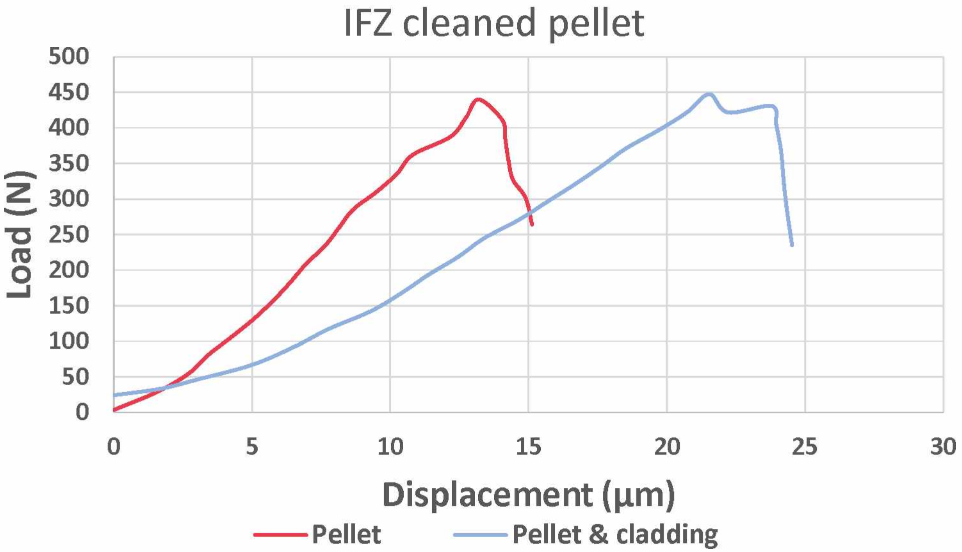


- Assuming that the tensile stress along the x axis is responsible for the sample failure, the tensile strength σ_f is obtained by substituting x=y=0 into equation 1 to obtain :

$$\sigma_f = \frac{2P}{\pi DL} = \frac{P}{\pi RL}$$

3. Results : Tests on fragmented and pellet





	Force (N)	σf (MPa)
Pellet	439	2.5
Pellet & cladding	447	2.6

→ Same fracture strength
→ Brittle pellets
→ Need to change the nature of IFZ for higher strength

3. Results : New strategy of fabrication

- Following fabrication, no IFZ cleaning.

- Goal: exploiting the densification difference between the polymerized fragments and the unpolymerized IFZ.

- IFZ thickness reduced to 200 µm for higher mechanical properties.

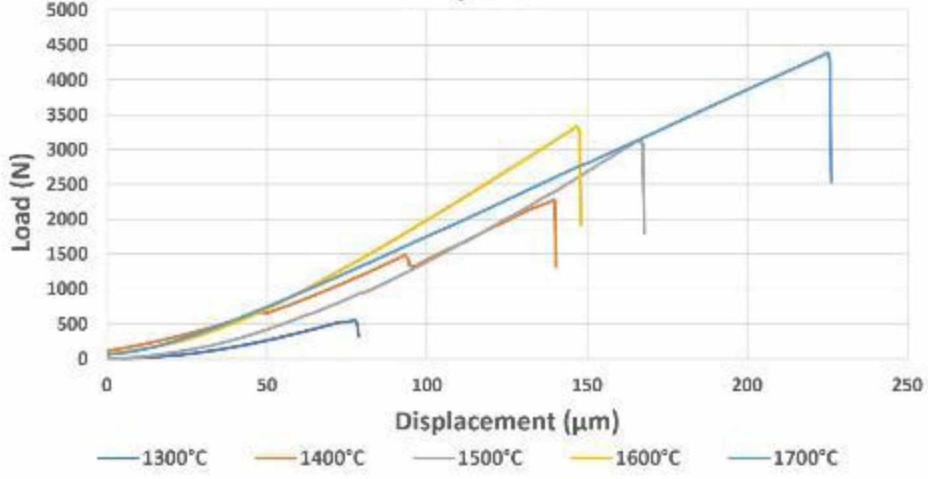
- Several sintering temperatures tested to ensure a good fragmentation and sufficient mechanical properties.

- Fabrication of reference bulk pellets.

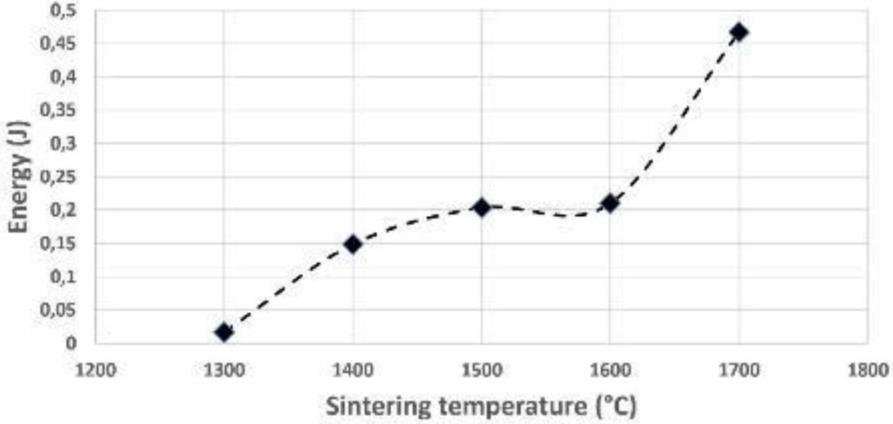
IFZ

3. Results : Bulk pellets

a)



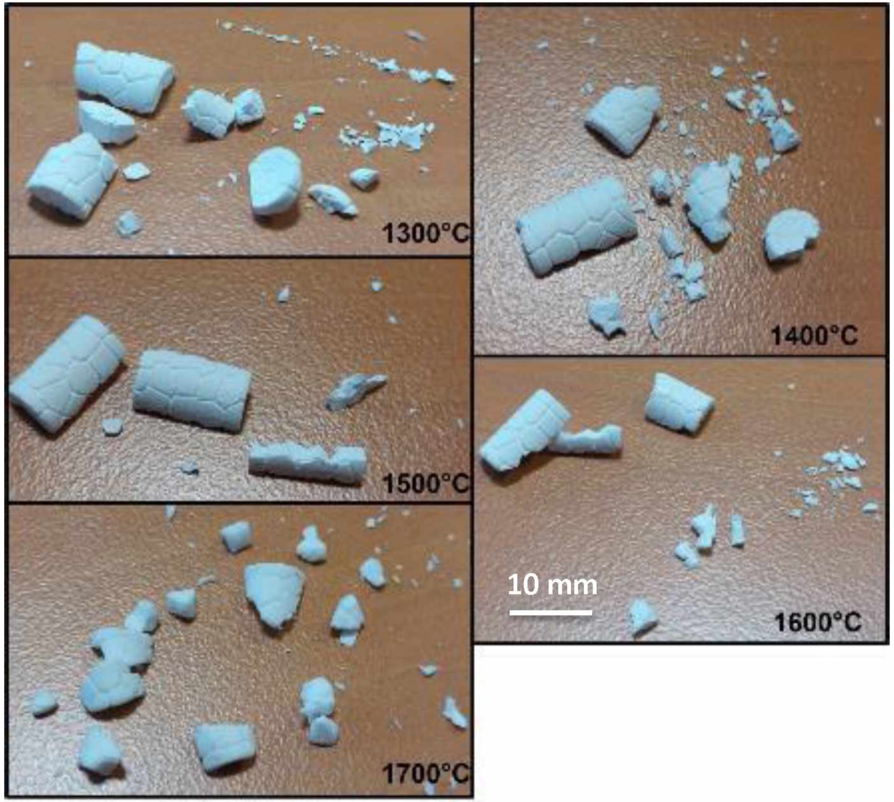
b)



Temperature (°C)	Force (kN)	Energy (J)	σ_f (MPa)
1300	0.6	0.02	4.3
1400	2.3	0.14	12.3
1500	3.1	0.2	34
1600	3.3	0.21	54.5
1700	4.4	0.47	107

- Higher resistance with higher sintering temperature.

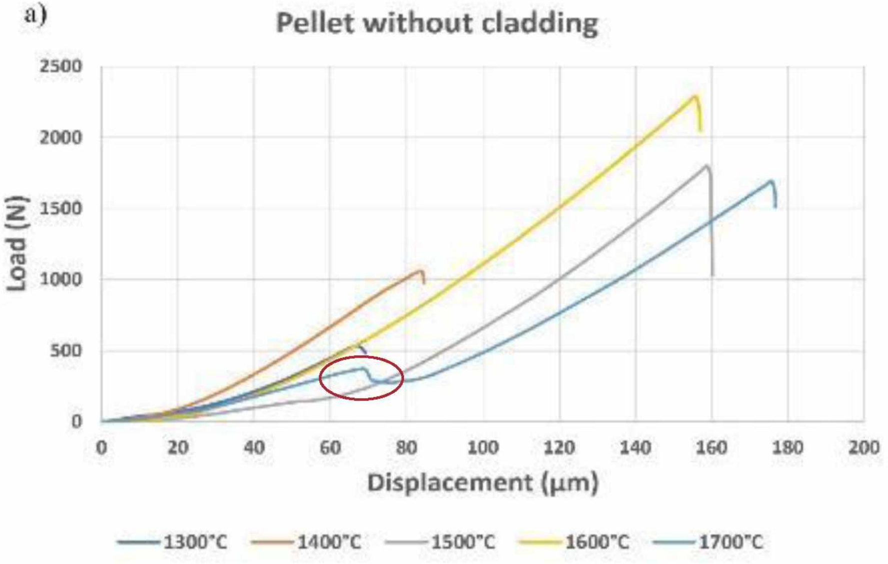
3. Results : Test on pre-fragmented and uncleaned pellets



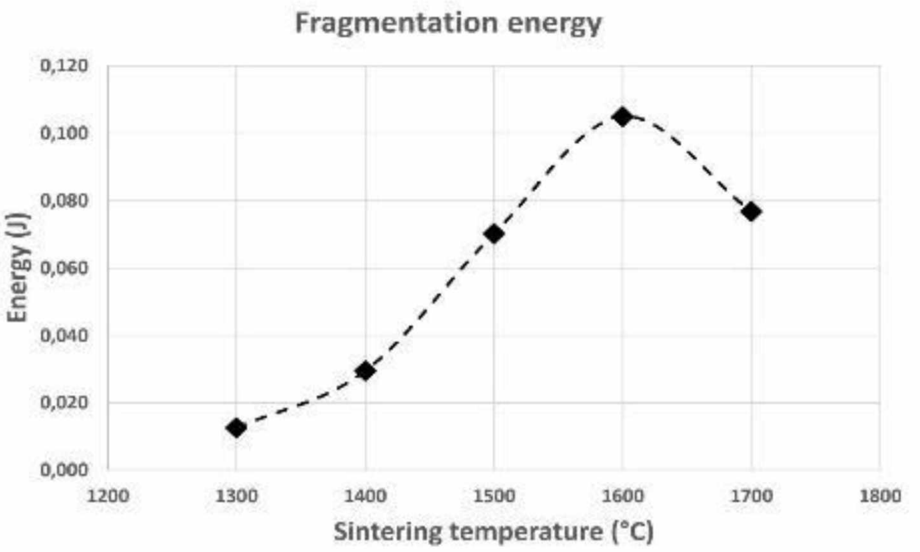
- Fragmentation occurs mainly in the IFZ.
- IFZ-controled fragmentation for the pellet sintered at 1700°C, as there is more individual and smaller fragments.

3. Results : Test on pre-fragmented and uncleaned pellets without cladding

a)



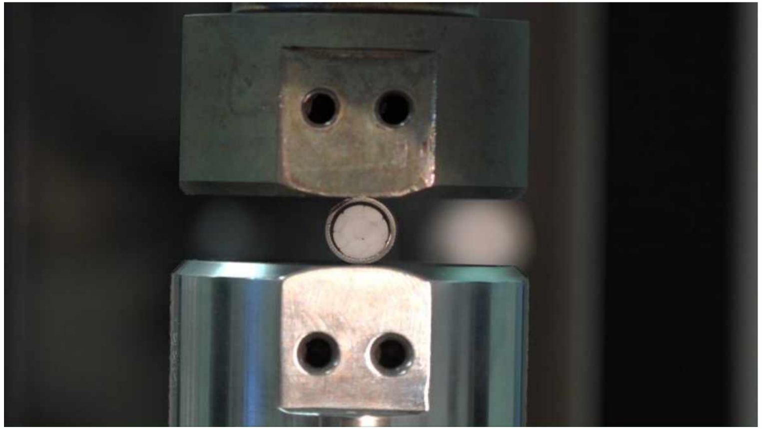
b)



Temperature (°C)	Force (N)	Energy (J)	σf (MPa)	σf (MPa) Bulk
1300	527	0.01	2.9	4.3
1400	1054	0.03	6.1	12.3
1500	1797	0.07	11.2	34
1600	2287	0.11	15.2	54.5
1700	1692	0.08	10.8	107

- Same behavior as the bulk pellet.
- Higher resistance with higher sintering temperature, except for 1700°C.
- A drop at 350 N indicating a cracking which could induce a drop in the overall resistance of the pellet

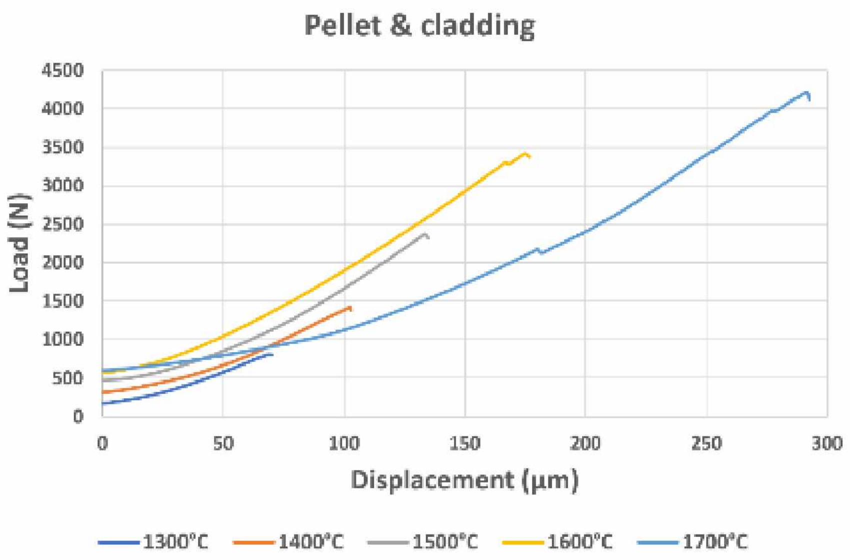
3. Results : Test on pre-fragmented and uncleaned pellets with cladding



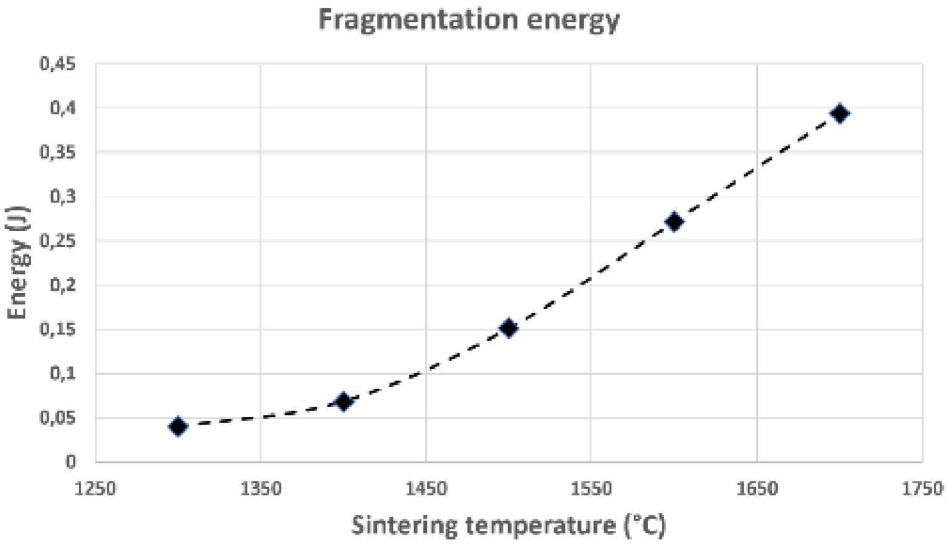
- Mostly powder for 1300 and 1400°C as the fragments are not consolidated enough.
- As before, IFZ-controlled fragmentation at 1700°C as there is more individual and smaller fragments.

3. Results : Test on pre-fragmented and uncleaned pellets with cladding

a)



b)



Temperature (°C)	Force (kN)	Energy (J)	σf (MPa)	σf (MPa) NO cladding
1300	1.5	0.15	8.2	2.9
1400	1.4	0.07	8.4	6.1
1500	2.4	0.15	14.9	11.2
1600	3.4	0.27	22.9	15.2
1700	4.2	0.39	30.3	10.8

- Same behavior as the full pellet.
- Higher resistance with higher sintering temperature

➢ Sintering at 1700°C seems to offer a good fragmentation in the IFZ, with individual fragments and high mechanical properties.

4. Conclusions and prospects

- Excessive embrittlement for IFZ cleaned pellet

- Uncleaned pellets still offer a good fragmentation with higher mechanical properties.

- Chosen sintering temperature: 1700°C.

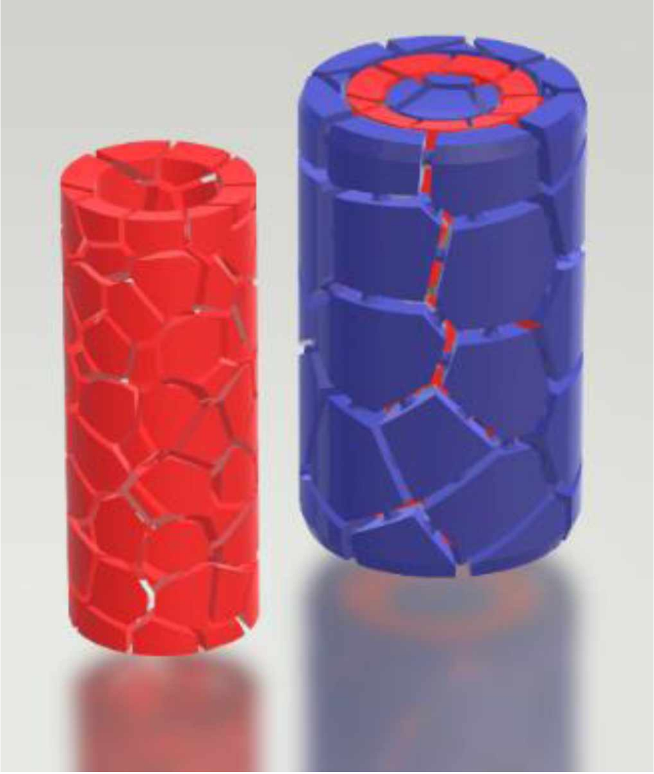
- Future work:

  - Fabrication of 40 pre-fragmented pellets at 1700°C to perform a Weibull’s statistics

  - Performing a semi-integral test on the pre-fragmented pellets

  - Fabrication and mechanical characterization of new pellets with different sizes of fragments

  - Towards DEM modeling to support experimental data



Thank you for your attention