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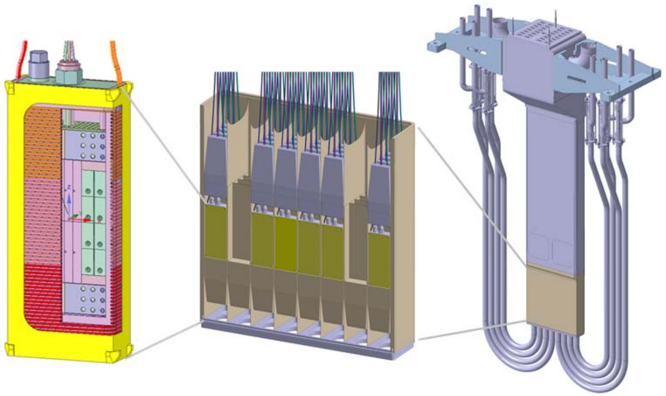
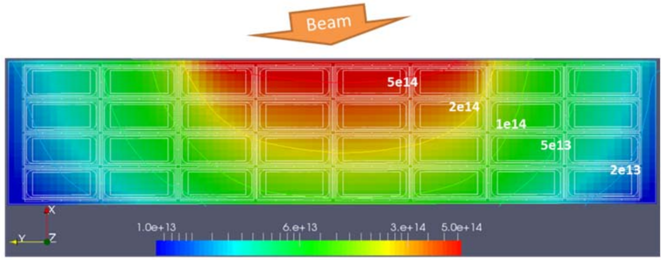
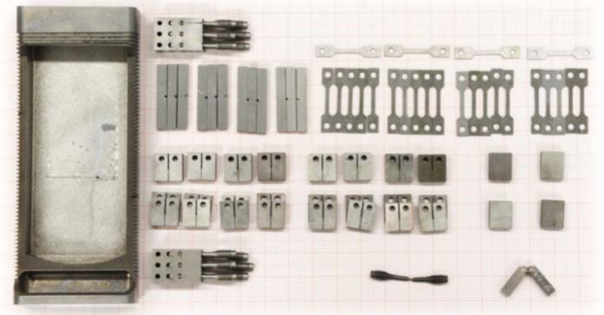
IFMIF-DONES HFTM : design overview and strategy to obtain high-dpa samples

Frederik Arbeiter, Yuefeng Qiu, and the IFMIF-DONES team





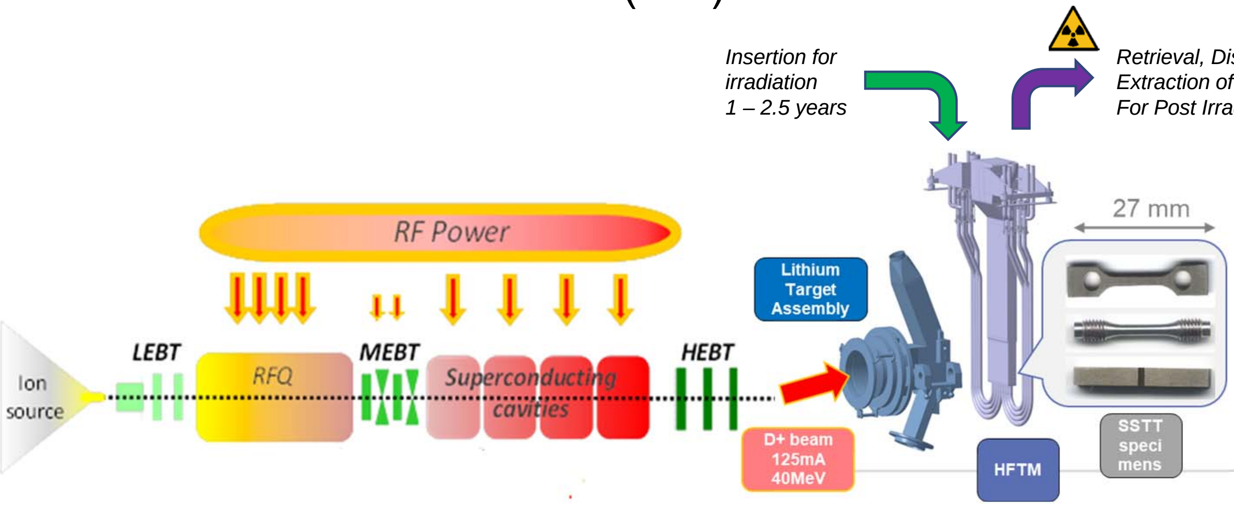


Mission of the DONES HFTM

HFTM = High **F**lux **T**est **M**odule

- Utilization of the **“high flux” region** directly behind the IFMIF-DONES neutron source
- Irradiation of (SSTT) specimens **for PIE**

The current development aims to facilitate the irradiation of SSTT specimens of **RAFM steels** (Eurofer, F82H, …) at conditions of the DEMO **First Wall** (FW)

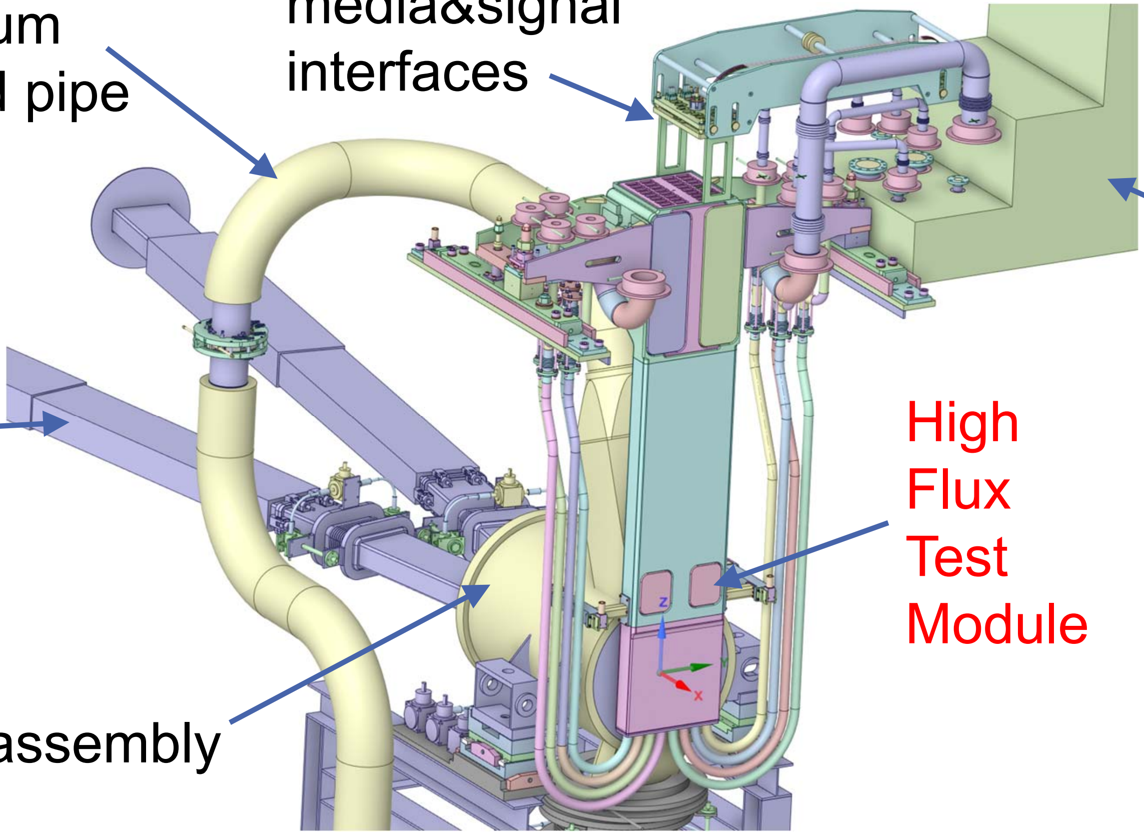


Insertion for irradiation 1 – 2.5 years

Retrieval, Dismantling, Extraction of specimens For Post Irradiation Examination

Neutron flux ~5×10^{14} #/cm²/s

HFTM installed behind DONES Li-Target



Liquid Lithium Feed pipe

HFTM media&signal interfaces

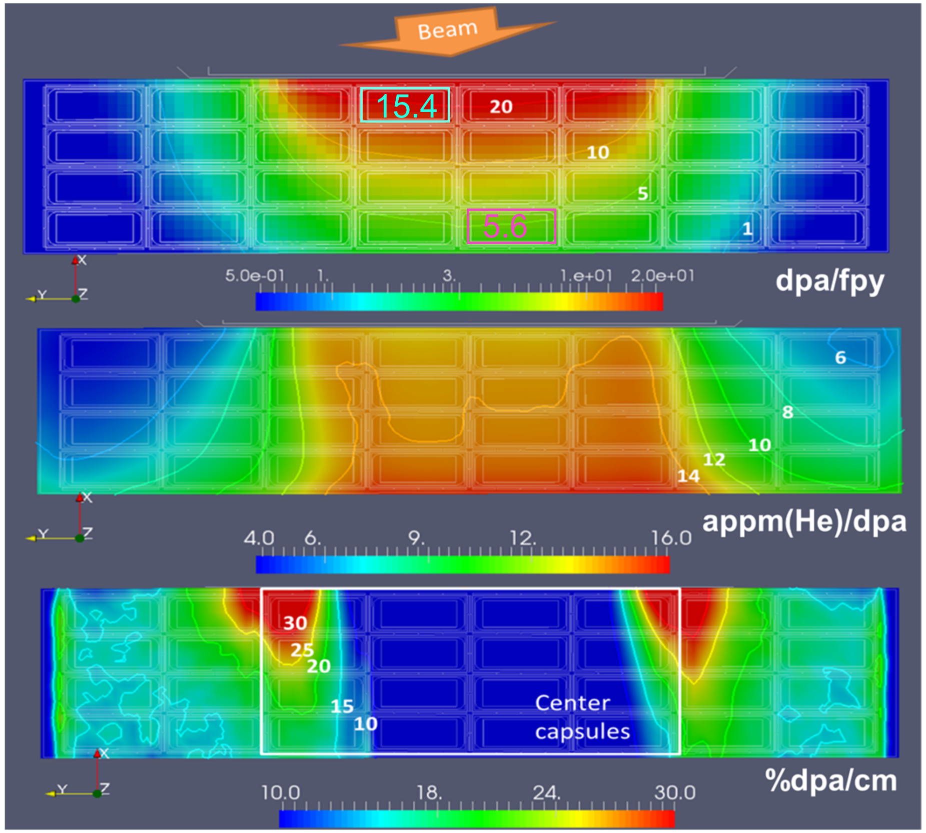
Accelerator Beam tube (125mA x 40 MeV Deuterons)

Test Cell Piping&Cabling Plug

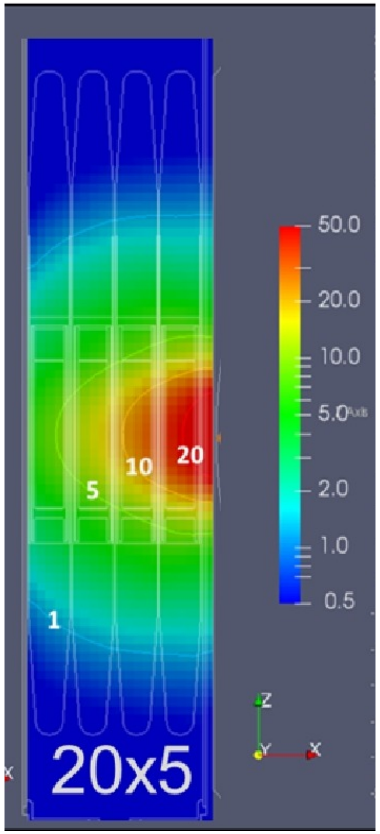
High Flux Test Module

Target assembly

Neutron irradiation conditions



Nuclear responses in horizontal cut on beam (20x5cm²) level



Vertical cut

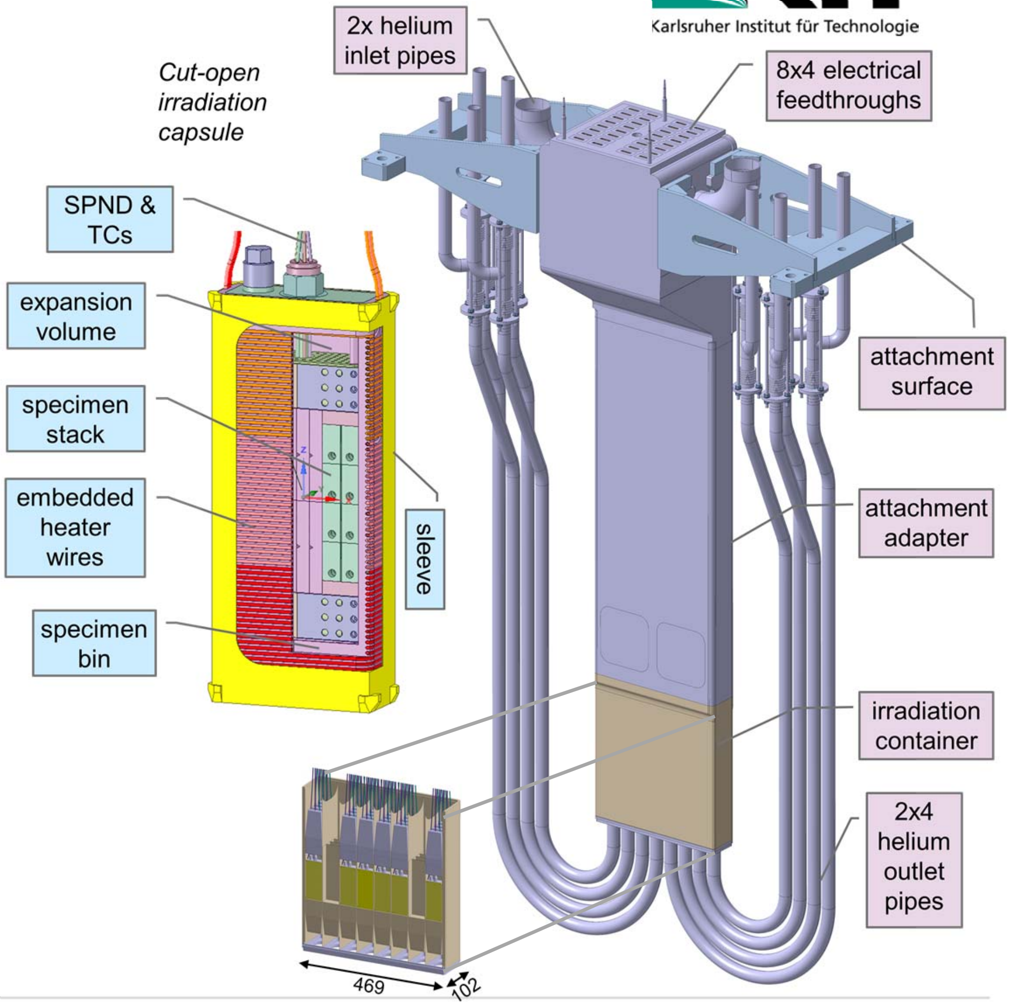
- Incident neutron flux: 5×10^{14} n/cm²/s
- 12 – 25 dpa/fpy are reached in a volume of 306 cm³ (~850 specimens)
- **The HFTM structure receives up to 25 dpa/fpy**
- 13-15 appm(He)/dpa,
- 50-60 appm(H)/dpa

➔ Good match to DEMO conditions at First Wall

- Significant gradients at beam edges !

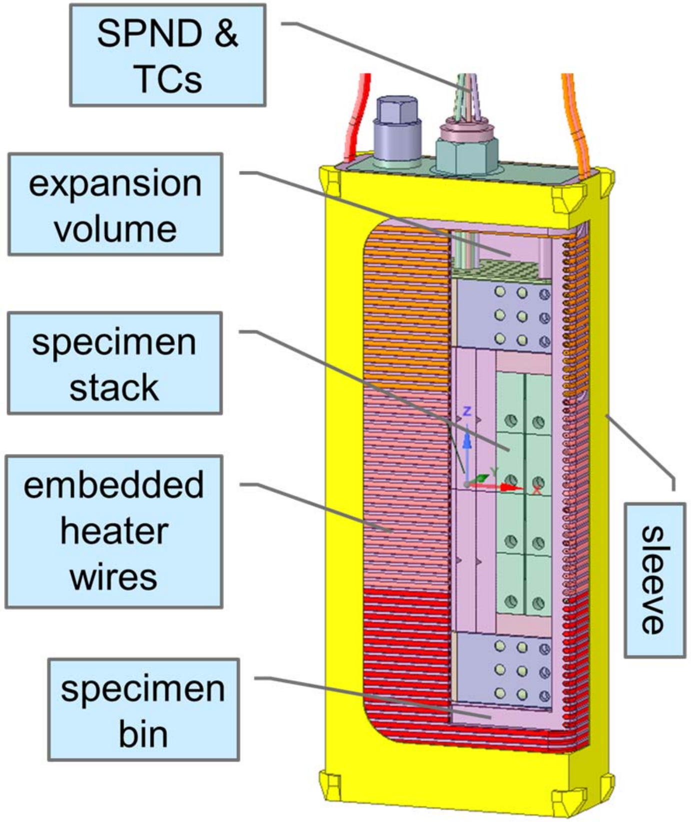
The HFTM overall design

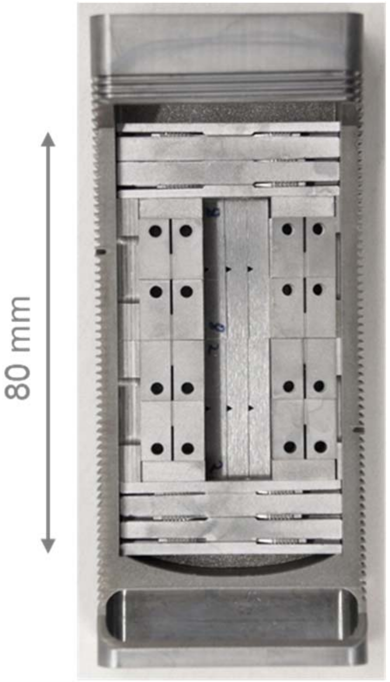
- 2.6m high stainless steel body
- 16.9 kW complete nuclear heating
- Cooled by 180 g/s Helium at 3.5 bara, 50 °C
- Interfaces on the the top end
- Irradiation container on beam level
- Slots for 8x4 irradiation capsules
- Neutron reflectors (axial, lateral) are provided



HFTM irradiation capsule

- Specimen payload 15x39x80 mm³ O(100) SSTT specimens per capsule
- Instrumentation by
  - 3x2 thermocouples
  - 1 central SPND
  - distributed activation samples
- 3 controlled **electrical heater** sections (up to 575W each)
- Body made by high temperature brazing from EDM-manufactrured **Eurofer** parts
- Filled with Sodium & **evacuated**





Design driving requirements

- Compatibility with high neutron flux / fluences
  ➔ required lifetime to **50 dpa, 3years**

- Irradiation temperatures **250 – 550 °C**

- Allowing **well-controlled experiments** & analyses
  ➔ sufficient monitoring (temperature, fluxes, fluences)
  ➔ low temperature spread (+/-3 %)
  ➔ temperature control independent of neutron source

- **Maximization of irradiation payload** (neutron economy)
  ➔Shape compatibility with DONES neutron source & test cell
  ➔Minimization of parasitic volumes

Antagonism of lifetime vs. irradiation payload !

HFTM materials strategy

The HFTM is the first-ever pressure-bearing component to endure high doses of fusion-like neutrons

- The HFTM **body** (PS = 4 MPa, TS = 200 °C)
  - must withstand significant primary stresses (membrane + bending)
  - Is a large welded structure (hermetic)
  - Can be operated at selectable temperature (by designing the cooling)
  - Only loaded with moderate safety functions (SIC-2)

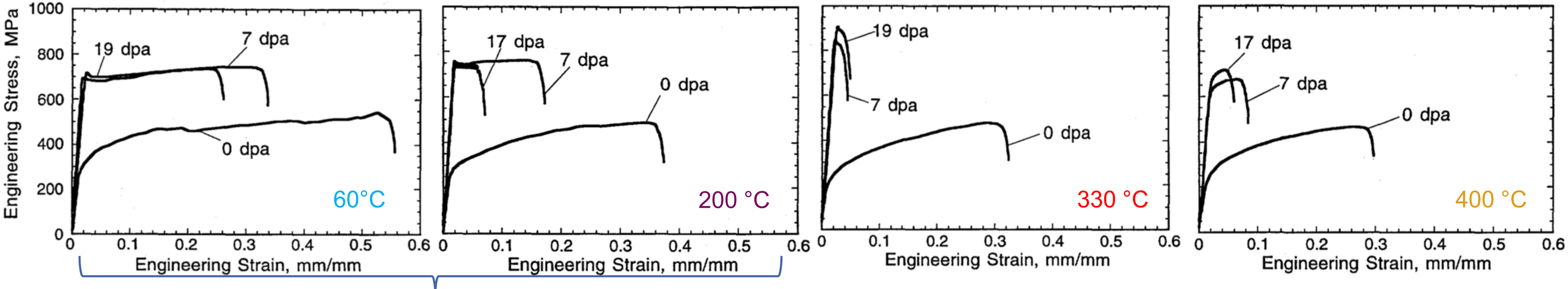
  ➔ Is made of **X2 CrNiMo 17-12-2 (N)** austenitic steel as in RCC-MRx

- HFTM **specimen-capsules**
  - Must operate at temperatures 250 – 550 °C as emerging from irradiation mission
  - Contain (9%Cr steel) specimens immersed in liquid sodium
  - Can be relieved of pressure loads by design
  - Not loaded with safety functions (non-SIC)

  ➔ Body is made of same material as specimens, **Eurofer 97**

  ➔ Mineral-insulated metal-shielded heaters (and thermocouples) are brazed on (!)

HFTM body irradiation limits



***HFTM body operation conditions: 50-160 °C**, 25 dpa/1fpy*

Solution annealed 316 steel, ORR+HFIR irradiation, 10-12 appm(He)/dpa, [Robertson 1997] :

RCC-MRx (A3.1S) X2 CrNiMo 17-12-2 (N) sol.ann. :

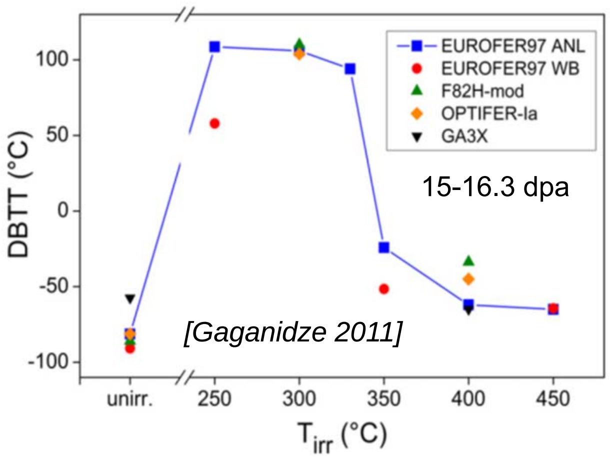
- "For temperatures ≤ 400°C and irradiation damages < 24 dpa, the swelling is negligible."
- Maximum allowable irradiation damage at 20 – 375 °C is **53 dpa**.
- Between 20 – 350 °C, saturated values of Rp and Rm are reached at 7 dpa
- Between 20 – 250 °C, minimum total elongation at maximum force saturates at Agt = 1.8%

Formula by **[Kalchenko 2013] for 18Cr 10Ni Ti** steel : incubation phase **46-52 dpa** @ 150 °C

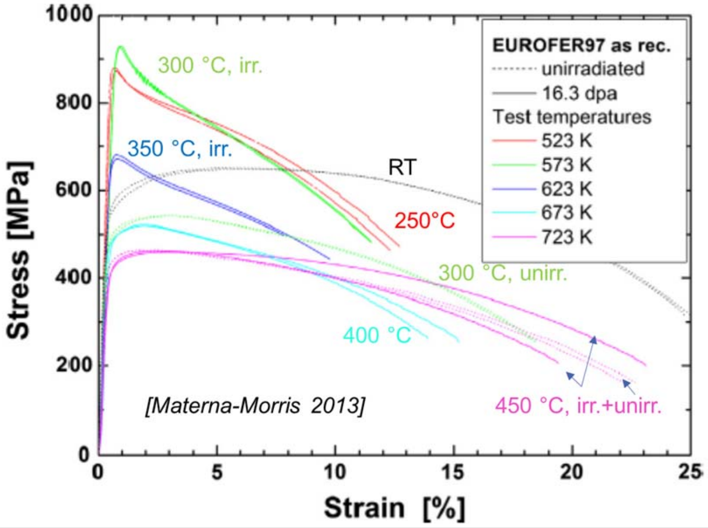
➔ Survival of HFTM body (≤150 °C), to ~50 dpa expected acc. to fission neutron experiences

HFTM capsule

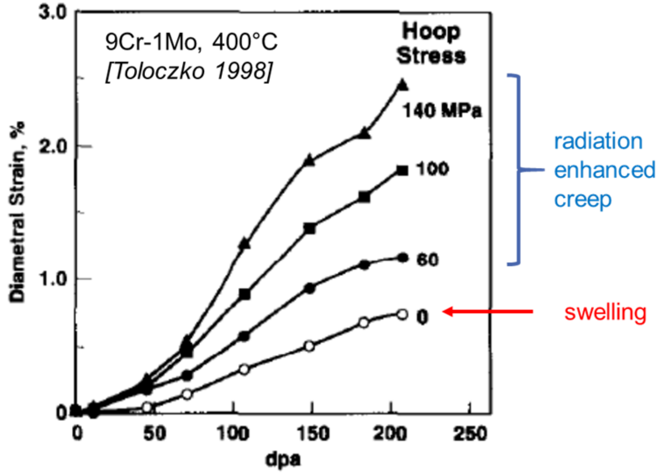
- Requested temperature range 250 – 550 °C spans (intentionally!) several regimes of irradiation behaviour of RAFM steels
  - Loss of plasticity, hardening, embrittlement for T < 350 °C
  - Softening (small effect) for T > 400 °C
- Very favourable swelling properties of bcc lattice



[Gaganidze 2011]



[Materna-Morris 2013]



9Cr-1Mo, 400°C [Toloczko 1998]

Design approach towards radiation resistant design of the specimen capsules

- The temperatures are **fixed by the mission**: 250 / 350 / 450 / 550 °C
  ➔ embrittlement at 250 °C
  ➔ creep at 550 °C
- After specimens insertion: no heat treatment allowed.
  ➔ **no post-weld heat treatment possible** !

Approaches:

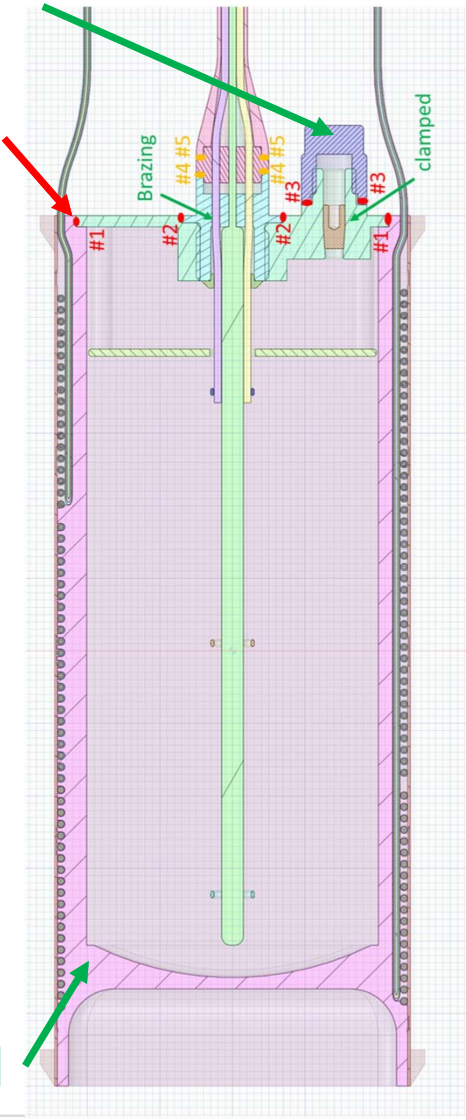
- IFMIF/EVEDA: inert gas filling, up to 6 bar int. pressure at 550 °C

➔ new design : **Evacuation** after filling to avoid stresses (➔ creep), replacement of NaK by Na to avoid Argon gas production

- IFMIF/EVEDA: prismatic body with welded bottom plug

➔ new design: **Avoidance of welds where possible** (die sink erosion)

- Theoretically, different grades / thermomechanical treatments are possible, optimized for each temperature level (not yet studied)



no PWHT possible !

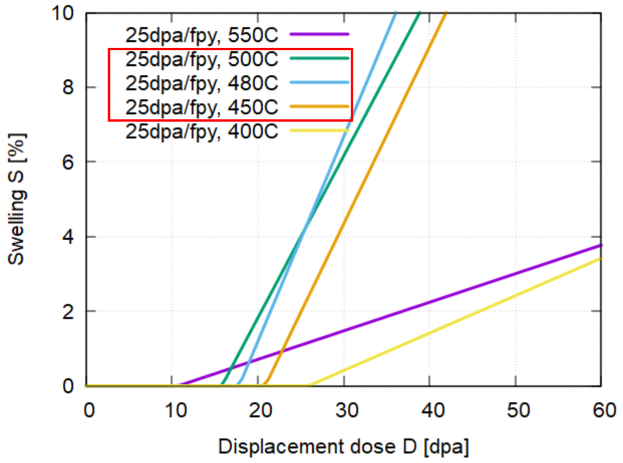
weld avoided

Capsule heater wires

- Capsule heaters are NiCr8020 resistive wire, embedded in compressed MgO/Al_2O_3 within a cladding.

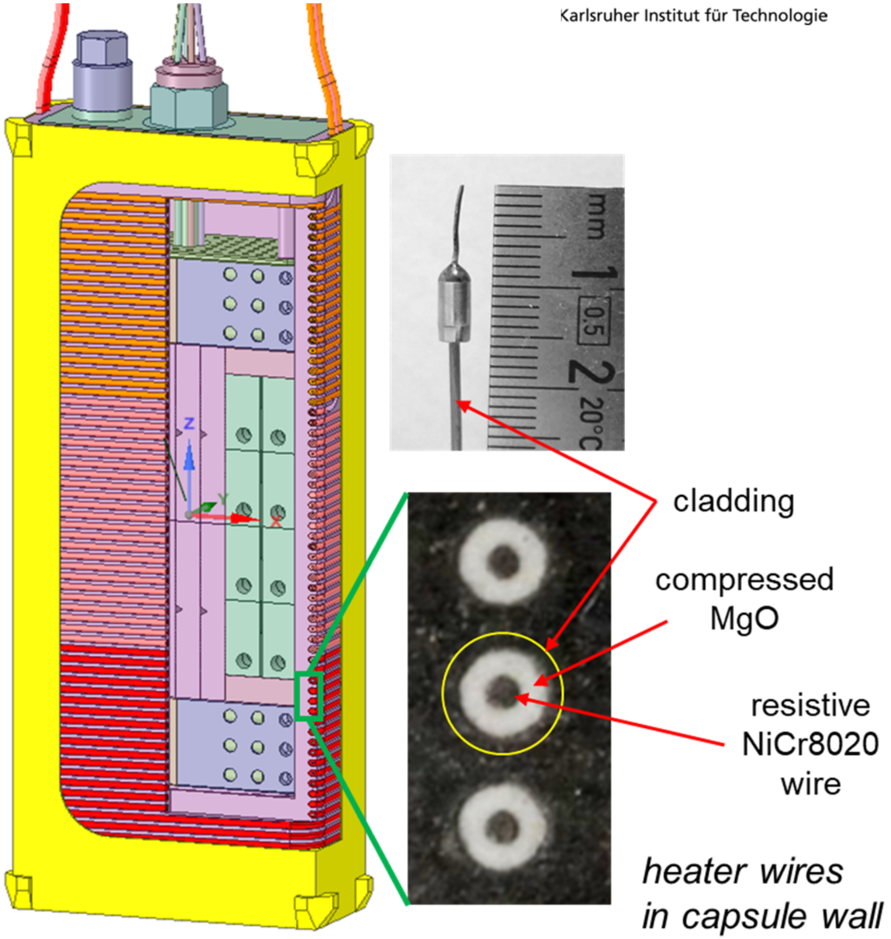
Issues: {316L, 321, Inconel, Nimonic}

1. The cladding and wire may experience swelling. Peak swelling for 18Cr10NiTi (example) is at 440 – 480 °C
2. The ceramic insulation may suffer of RIC & RIED loss of insulation properties (see next page)



➔ Problems for > ~1year/30dpa. Inconel alloys could be a solution In the critical temperature range.

[Powell 1981]: <2.4% swelling at 87 dpa, 400 – 650 °C for Inconel X750 and 718

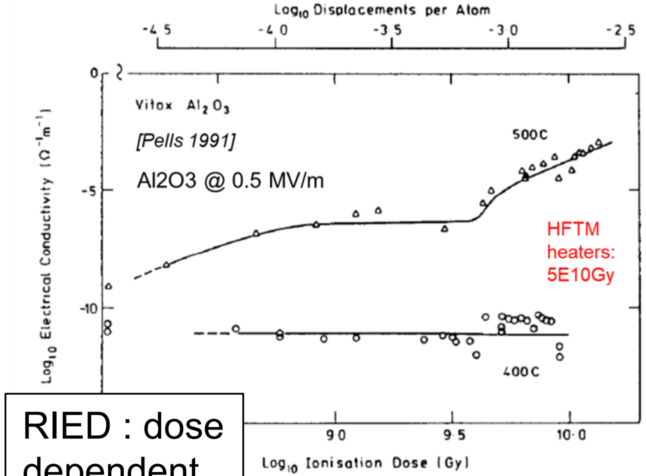


Loss of insulation resistance

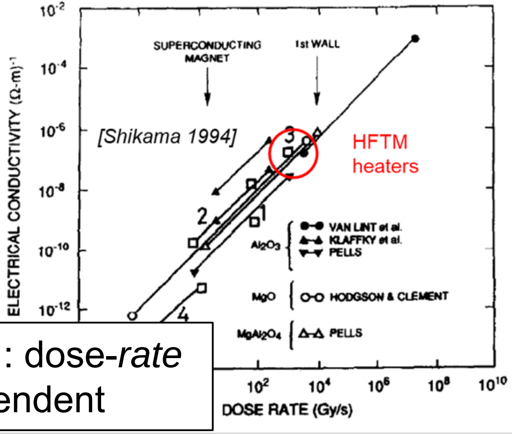
- Initial resistances of heaters are > 10 GΩ ($>1\times10^{14}$ Ω m)
- Semiconductor behaviour: resistivity drops factor 10^8 from RT to 600 °C
- [Shikama 1994] RIC at $O(10^3$ Gy/s) ~ factor 10^6
- RIED f(dose, temp., E-field)
  - Most loaded heater parameters in HFTM: 140V (0.76 MV/m), 550 °C, estim. 5×10^{10} Gy
  - [Pells 1991] : (10^{10} Gy @ 500°C for Al_2O_3) resistivity dropped factor ~10^8

➔ Heaters (insulators) are at/beyond the expected limits of their operation regime at 1 fpy and may prove to be lifetime-limiting

➔ MARIA irradiation for testing

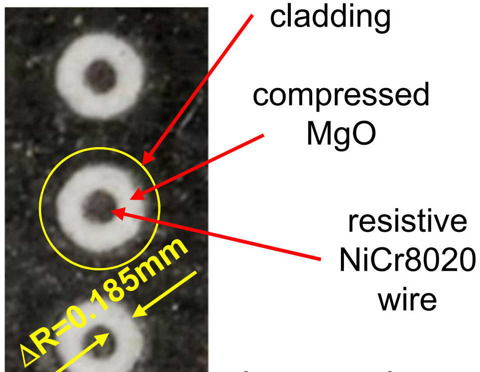


RIED : dose dependent



RIC : dose-*rate* dependent

$$\sigma = \sigma_0 + k \cdot DR^\delta$$



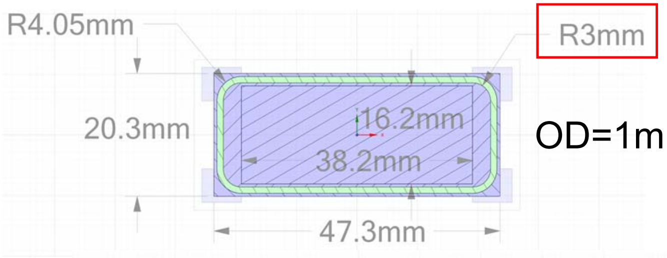
heater wires in capsule wall

Design option for heater lifetime extension

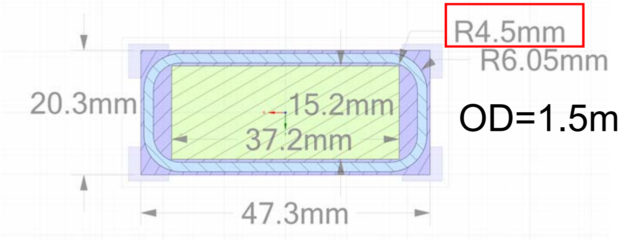
- **Increasing heater wire thickness**:
  - Increase start-value of insulation resistance
  - Increase insulation thickness, decrease required voltage ➔ decrease E
- Geometry variation: keep outer capsule dimension, t thicker heater wires → 1.5mm / 2.0mm OD
- Bending radius R=3*OD must be conformed

Heater OD [mm]	Bending R [mm]	Specimen %	LHT @ h [mm]	R/L [Ohm/m]	R [Ohm]	U(P, R) [V]	I(P, R) [A]	E~U/OD [%]
1	3	100	2195.9	12.5	27.4	125.6	4.58	100.0
1.5	4.5	91	1588.7	5.5	8.7	70.9	8.11	37.6
2	6	78	1183.9	3.1	3.7	45.9	12.52	18.3

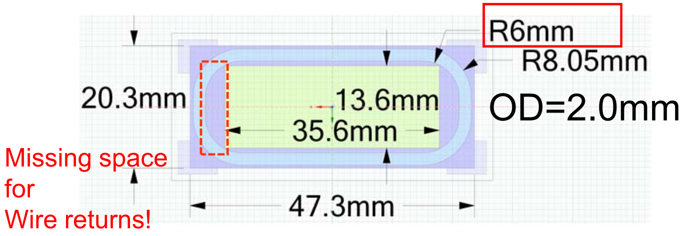
➔ Approach is very effective! E-field is reduced by factor 5.5 by increasing OD from 1mm to 2mm. But : payload reduced by 22 %



OD=1mm

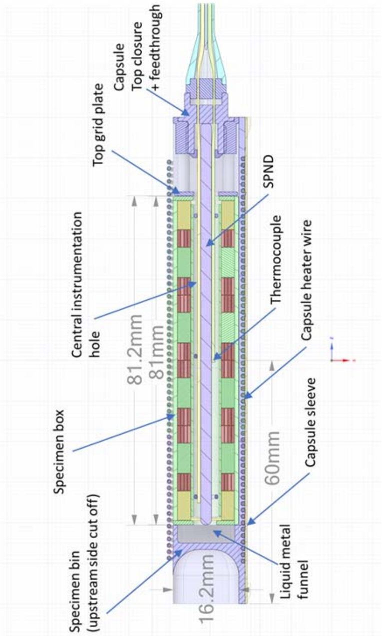


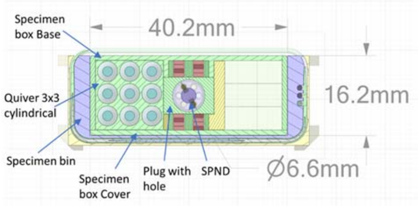
OD=1.5mm



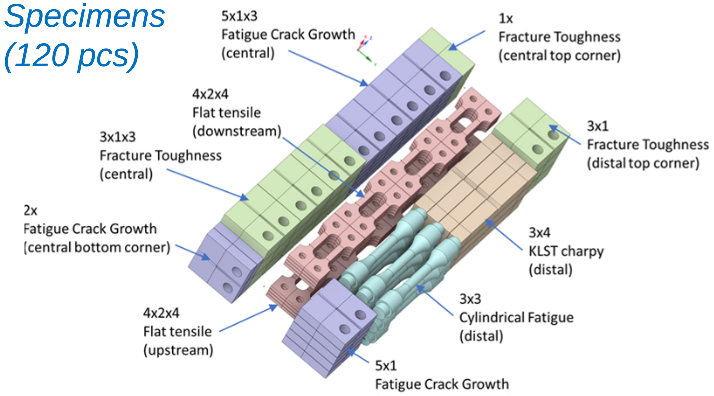
OD=2.0mm

Capsule loading configuration

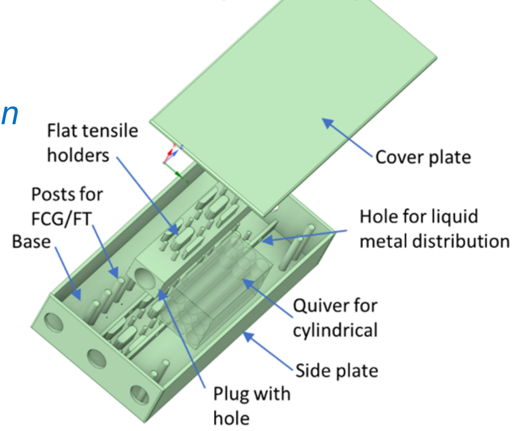




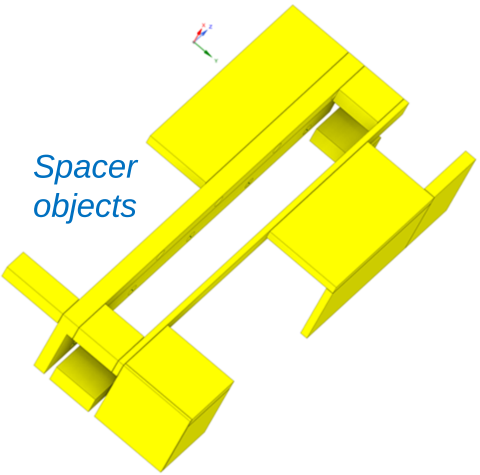
Material Specimens (120 pcs)



Box and specimen holders



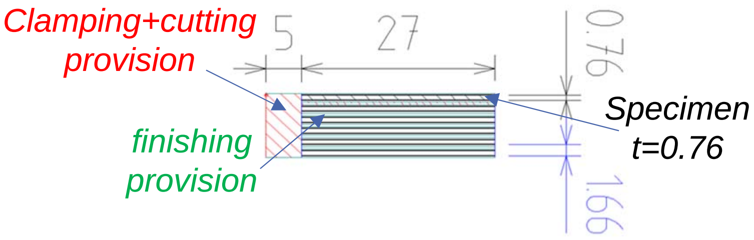
Spacer objects



Component / entity	Volume [mm³]
Enclosing capsule volume 81.2x41.2x16.2	54'169
Solid volume of specimen box parts + quiver	15'266
Solid volume of spacer objects	6'482
Solid volume of specimen payload w/o quiver	20'842
Remaining = liquid metal + instrumentation rod	11'579
Approx. instrumentation rod 1SPND, 6TC, 3 ring	825
Effective void = liquid metal	10'753

➔ 38% of volume Inside capsule are Specimens !

Backup-strategy to capsule : solid slab



Example: cutting losses
For flat tensile specimens

“ What if ” …

- the capsule failure rate is too high
- liquid metal corrosion effects need to be excluded.

The capsule with pre-fabricated specimens can be replaced by a **solid slab** (wound-on heaters, drillings for thermocouples), with **specimen fabrication in PIE**.

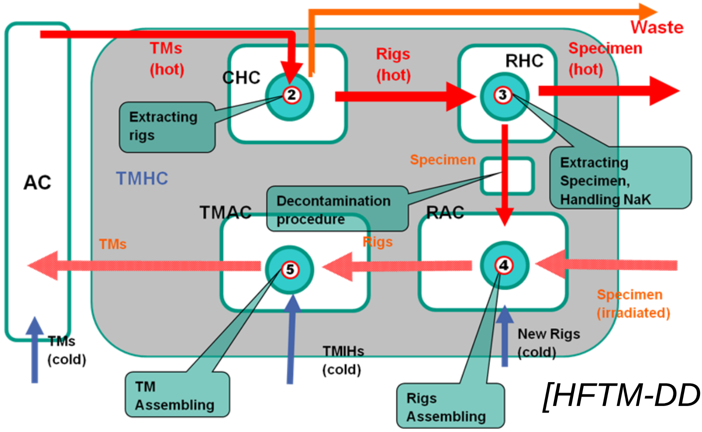
➔Allowances for clamping, cutting, and finishing are estimated (based on specific cutting plans) to reduce the available specimens to **33 – 50%**

➔Post-irradiation fabrication bears risks of damaging/annealing/inducing surface stresses

➔Hot cells need to be equipped with relatively complex tools. Feasibility is supported by SCK-CEN experiences.

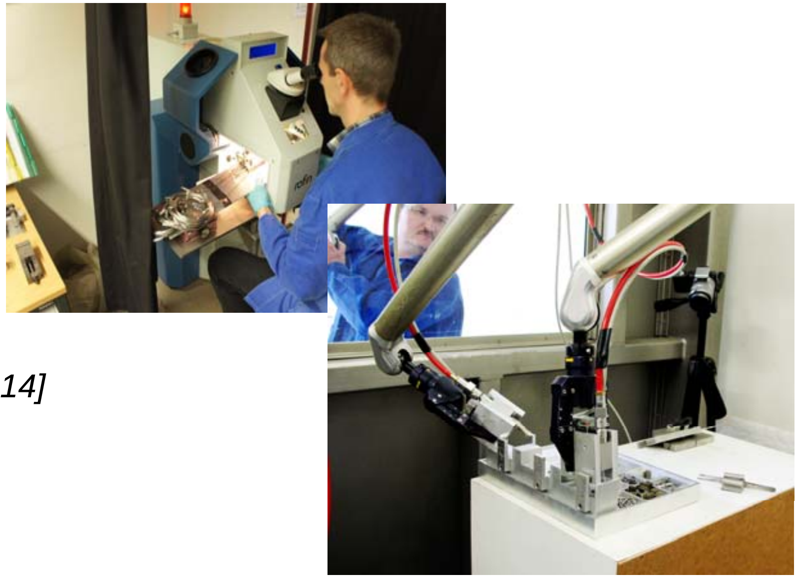
Re-loading capability

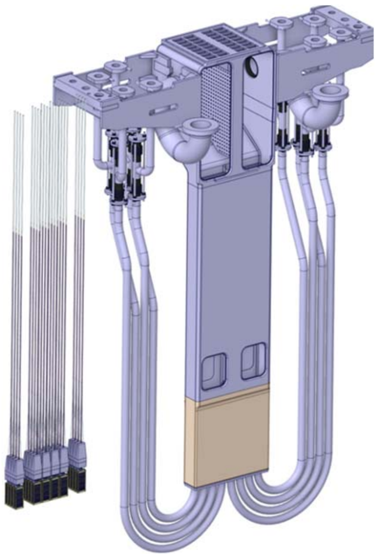
- Lifetime limitations of the HFTM can be “bypassed” if it is possible to re-insert already irradiated specimens into a new HFTM for the next irradiation period
  - This is not the baseline for the WPENS HFTM (2023)
  - It was a requirement to the IFMIF/EVEDA HFTM (2014) : R&D pursued, but no fully validated procedure



[HFTM-DDD 2014]

- “RAC”, a hot cell to
  - Insert specimens into capsule
  - Fill Na, weld close capsule, do QA (leak tightness, electrical, …)
- “TMAC”, a hot cell to
  - Insert capsules/rigs into the HFTM body
  - Hermetically weld close HFTM body, do QA (leak tightness, pressure test, …)





Relatively delicate / fine mechanical tasks need to be “translated” to become hot-cell compatible !

Lifetime limiting conditions in high flux irradiation

- Pressure bearing shell “container” made from RCC-MRx X2 CrNiMo 17-12-2 (N) stainless steel
  - Allowed by code up to 53 dpa (fission neutrons!)
  - Temperatures 50 – 160 °C ➔ low swelling regime
- Specimen capsules made from 9%Cr steels (Eurofer97)
  - No irradiated data in code ➔ no safety function
  - Temperatures 250 – 550 °C ➔ embrittlement .. creep
- Capsule heaters are mineral insulated metal sheated (MIMS) wires (NiCr resistive alloy, MgO insulation)
  - Dose rate near O(10^3 Gy/s) , significant RIC expected
  - Dose limit for RIED (10^{10} Gy @ 500°C for Al2O3) may limit lifetime

Conclusions

- The top-level lifetime requirements aims at **50 dpa, 3 years**.

- Based on fission neutron experiences :
  - The HFTM container (316L(N), 150°C) lifetime is predicted to 46 … 53 dpa
  - The capsule body (Eurofer, 250…550°C) is not limited by swelling or creep, failure effect of top-weld without PWHT is uncritical for successful operation
  - Capsule heater claddings (austenitic, 250 … 550 °C) when operated at 450…500 °C may experience failure due to swelling > 10% after 30dpa / >1year . Option of Inconel claddings tbd.
  - Heater insulations (MgO, 250 – 550 °C) may fail by RIED after ~1 year in the front row. MARIA irradiation ongoing.

➔Irradiation for 1 year / 25 dpa is supported by current design & experiences.
➔Prospect of improving heater lifetime by electric field reduction
➔Option of re-irradiation of specimens would enable irradiation beyond HFTM lifetime

To be reflected by the DONES user commuunity

- The design has to balance
  - Lifetime in irradiation
  - Usable specimen payload
  - Thermal requirements

- Ongoing PI activity : balancing the “lifetime” vs. “specimen payload” requirements. Discussed options:
  a) Priority for “lifetime”, best-effort as lower constraint on specimen payload
  b) Prescription of “minimum payload” (i.e. “69 specimens”)
  c) Maximization of product “dpa x specimen-volume”

➔Input by users to properly set and weight the requirements are welcome!