CHARACTERIZATION PROGRAM OF EUROFER97 RAFM STEEL AND IMPLEMENTATION PLAN IN THE RCC-MRx CODE FOR THE DESIGN AND MANUFACTURING OF ITER TBM

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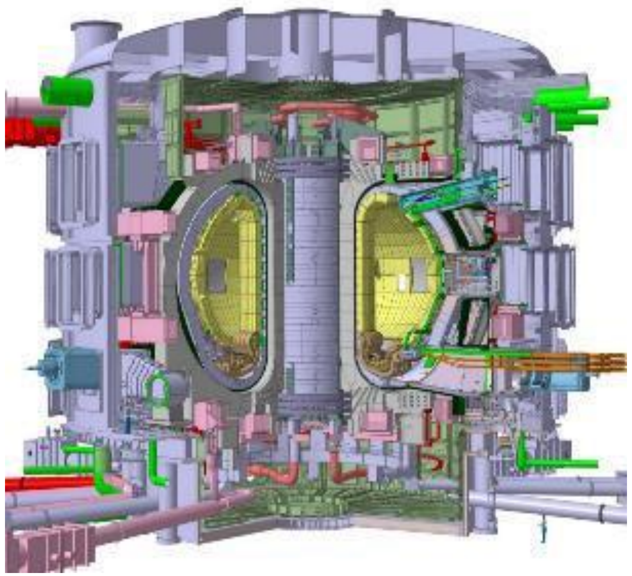
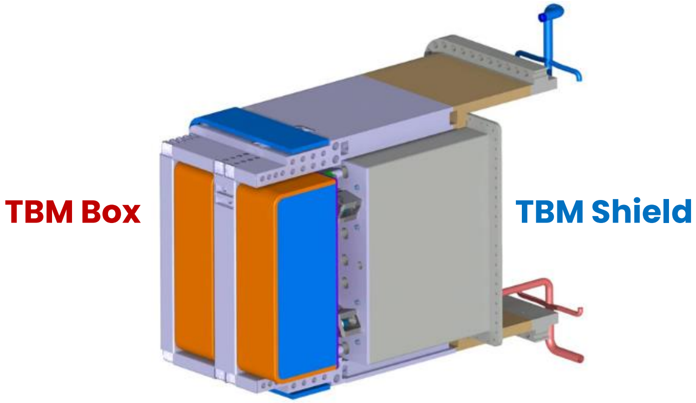
Content

1. Introduction

Overview of EU Test Blanket Modules for ITER





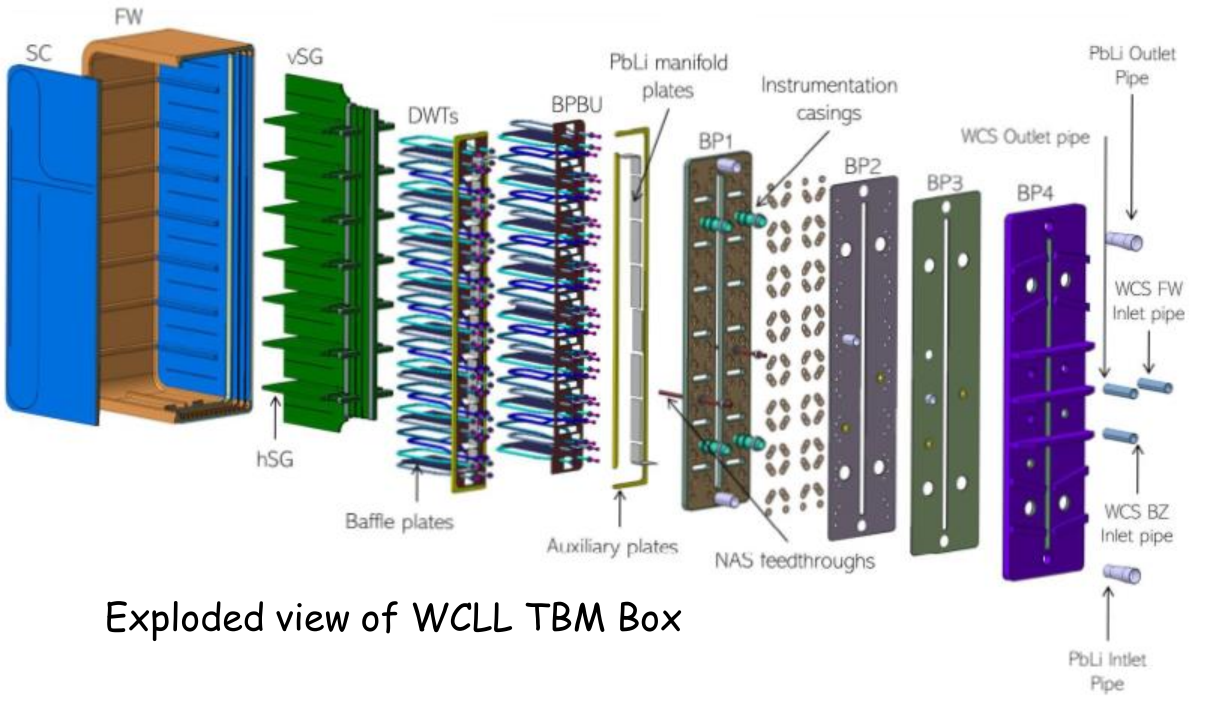
2 TBM sets in Equatorial Port #16

- Objectives of Test Blanket Modules (TBM) for ITER
  - Demonstrate the capability of Tritium Breeding
  - Extract thermal power from the plasma and fusion reactions
  - Contribute to the neutron shielding

WCLL-TBM (proposed by EU): - Pb-16Li liquid metal (multiplier/breeder) - H_2O at 15.5 MPa 280/325°C (coolant) - EUROFER97 RAFM (box structure)	**HCCP-TBM** (proposed jointly by KO/EU): - Li_4SiO_4 (w/ Li_2TiO_3 phase) pebbles (breeder) - Be pebbles (multiplier) - He at 8 MPa 300/500°C (coolant) - EUROFER97 RAFM (box structure)
WCCB-TBM (proposed by JA): - Li_2TiO_3 pebbles (breeder) - Be pebbles (multiplier) - H_2O at 15.5 MPa 280/325°C (coolant) - F82H RAFM (box structure)	**HCCB-TBM** (proposed by CN): - Li_4SiO_4 pebbles (breeder) - Be pebbles (multiplier) - He at 8 MPa 300/500°C (coolant) - CLAM or CLF1 RAFM (box structure)

Overview of EU Test Blanket Modules for ITER

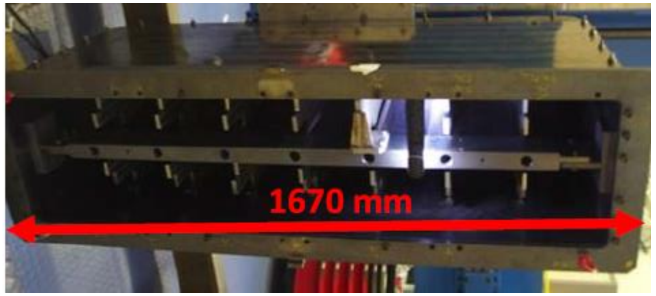
- WCLL (Water Cooled Lead Lithium) TBM:
  - PbLi liquid metal (enriched in ^{6}Li)
  - Water (15.5 MPa, 295/328°C) in Double Wall Tubes
  - RAFM EUROFER97 as structural material
  - GTAW (TIG) and HIP (diffusion) welding
  - Nuclear Pressure Equipment Cat. IV, N2 level
  - Design and construction with RCC-MRx nuclear code



Exploded view of WCLL TBM Box

RCC-MRx: Design and construction rules for mechanical components of advanced, experimental and fusion reactors, by afcen

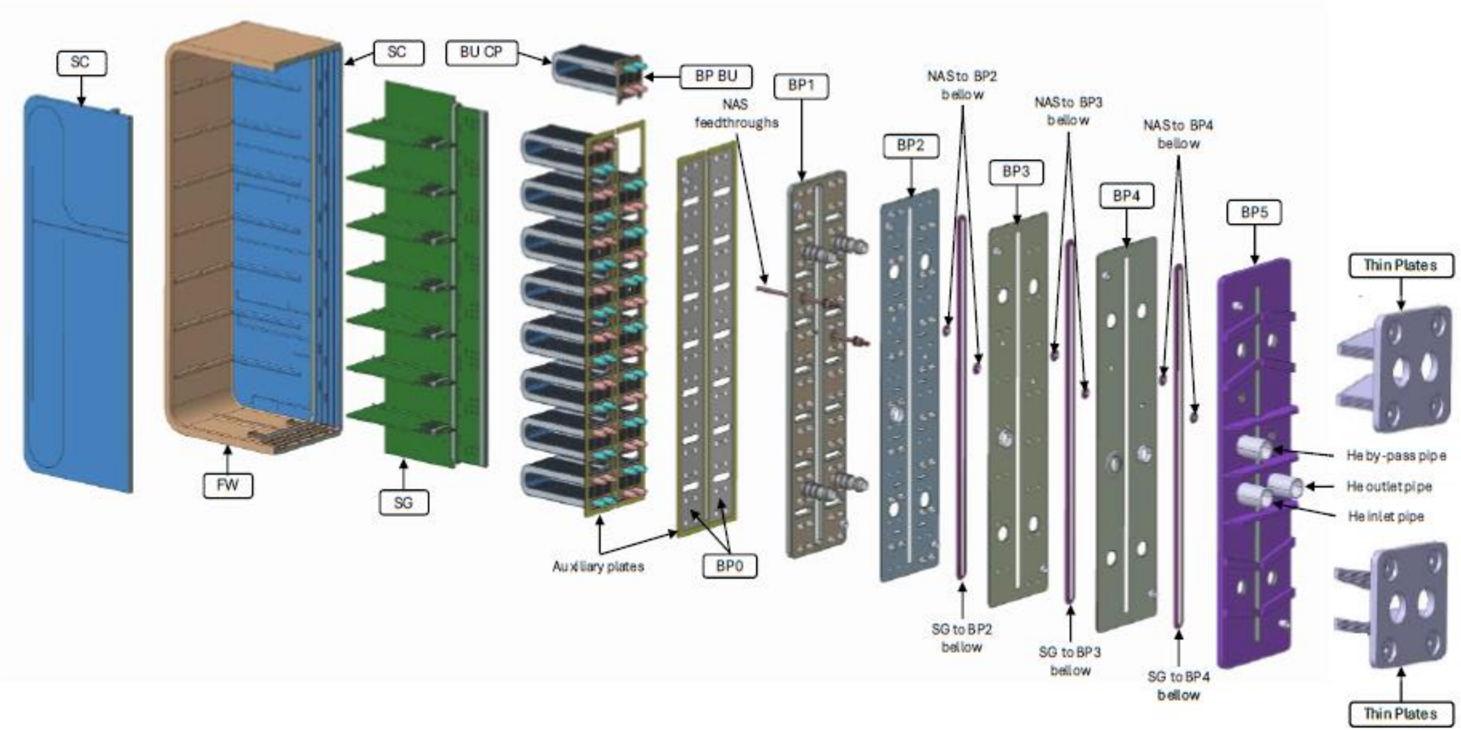
First Wall U bend plate (Zmitko, 2017)



TBM box with Stiffener Plates (Zmitko, 2017)

Overview of EU Test Blanket Modules for ITER

- HCCP (Helium Cooled Ceramic Pebble) TBM:
  - Li_4SiO_4 + Li_2TiO_3 (enriched in ^6Li) breeding ceramic pebbles
  - Be (neutron multiplier) ceramic pebbles
  - Helium (8 MPa , 300/500°C) in cooling zone (0.4 MPa in breeding zone, purge gas)
  - RAFM EUROFER97 as structural material
  - Design and construction with RCC-MRx nuclear code
  - PE Cat. IV

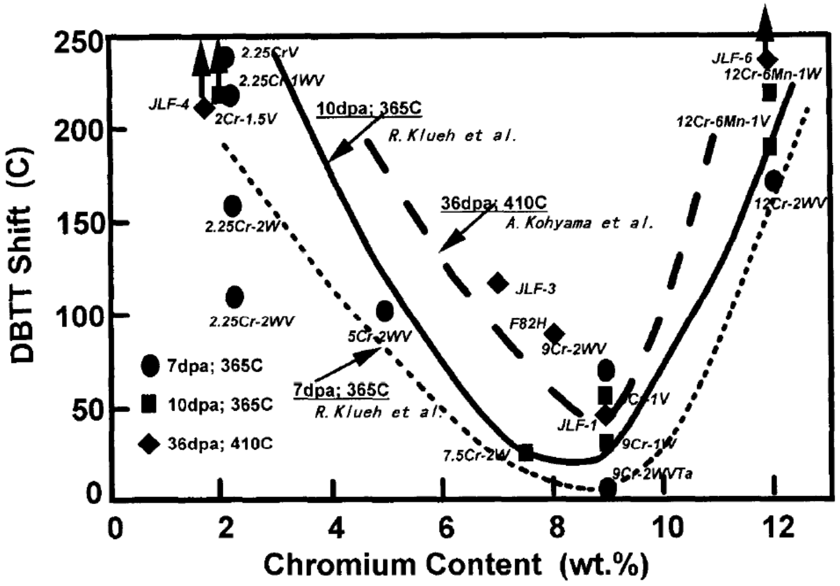


Exploded view of HCCP TBM Box

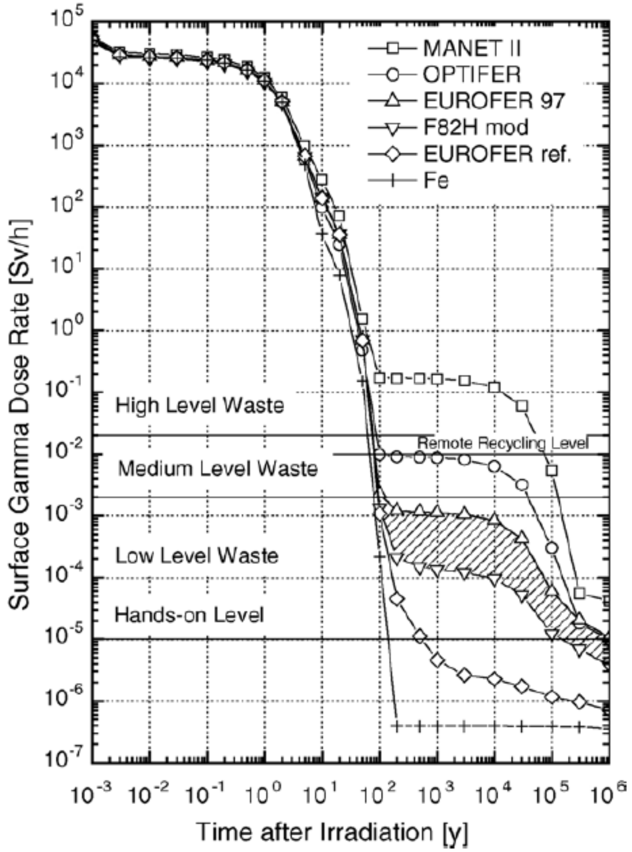
2. EUROFER97

Choice of EUROFER97 as structural material

- EUROFER97 RAFM steel developed in EU for fusion needs:
  - ➢ Avoid irradiation swelling of stainless steels up to high dose (50 dpa)
  - ➢ Reduced irradiation embrittlement at 7-9% Cr
  - ➢ Accelerate decay of radioactivity by replacing Mo and Nb (Grade 91) by W and Ta



Effect of Cr content on DBTT shift (Charpy) after fast neutron irradiation in FFTF (from Kohyama et al., 1996)



Decay of dose rate after exposure in FW impact on waste management (from Lindau et al., 2005)

Choice of EUROFER97 as structural material

- EUROFER97 RAFM steel developed in EU for fusion needs:
  - 9%Cr - 1%W - TaV
  - Other elements As Low As Possible (Nb, Mo, Ni, Co, Cu, …) by VIM/VAR or VIM/ESR

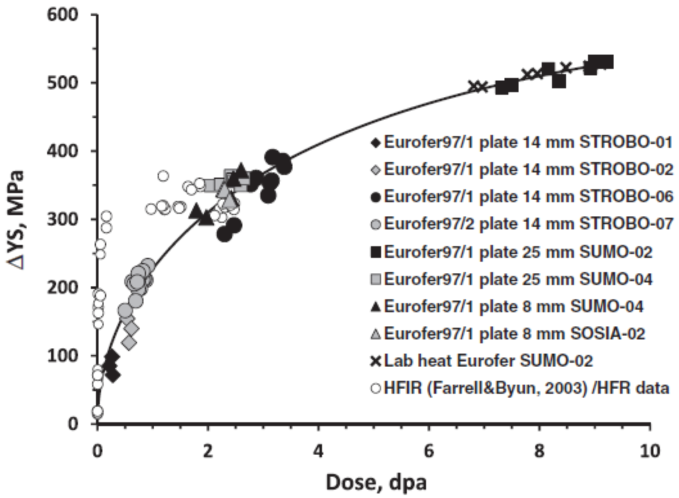
		C	Si	Mn	P	S	Ni	Cr	Mo	V	Ta	W	Ti	Cu	Nb	Al	N_2
EUROFER97	min.	**0.09**		**0.2**				**8.5**		**0.15**	**0.1**	**1.0**					**0.015**
	max.	**0.12**	0.05	**0.6**	0.005	0.005	0.01	**9.5**	0.005	**0.25**	**0.14**	**1.2**	0.02	0.01	0.005	0.01	**0.045**

  - From laboratory to industrial heats: 4 batches of EUROFER97 produced in EU (3.5, 7.5, 11 and 24 tons at Boehler, Austria and Saarschmiede, Germany)
  - Plates (from 1 mm to 50 mm thick) and bars (100 x 100 mm^2)
  - Normalizing (940/980°C) and Tempering (740/760°C) heat treatment leading to tempered martensite
  - RT tensile properties at least equal to Grade 91

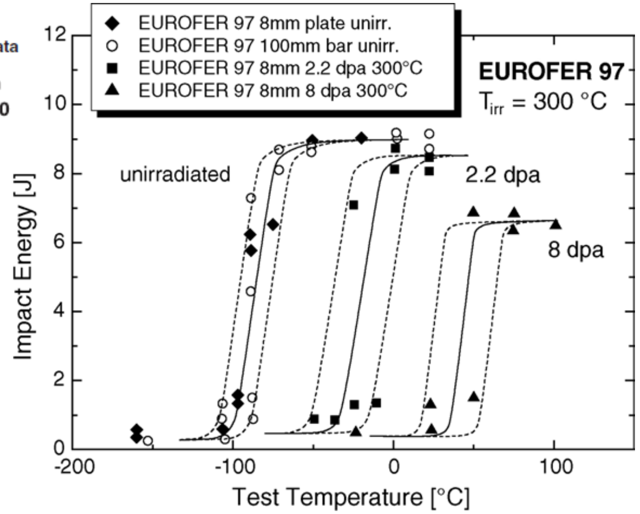
	GRADE 91	EUROFER97
$R_{p0.2}$ (MPa)	445	520
R_m (MPa)	580-760	640-760
A (%)	20	15
$R_{p0.2}$ (MPa) 550° C	260	316

Choice of EUROFER97 as structural material

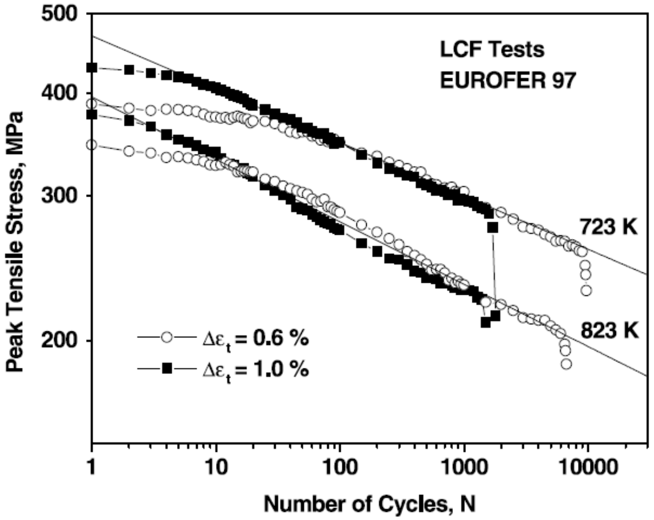
- EUROFER97 RAFM steel developed in EU for fusion needs:
  - Good mechanical properties in non-irradiated state (tensile, creep)
  - Good fatigue properties but cyclic softening
  - Irradiation hardening with loss of ductility and increase in DBTT (irr. temp. ≤ 300°C)



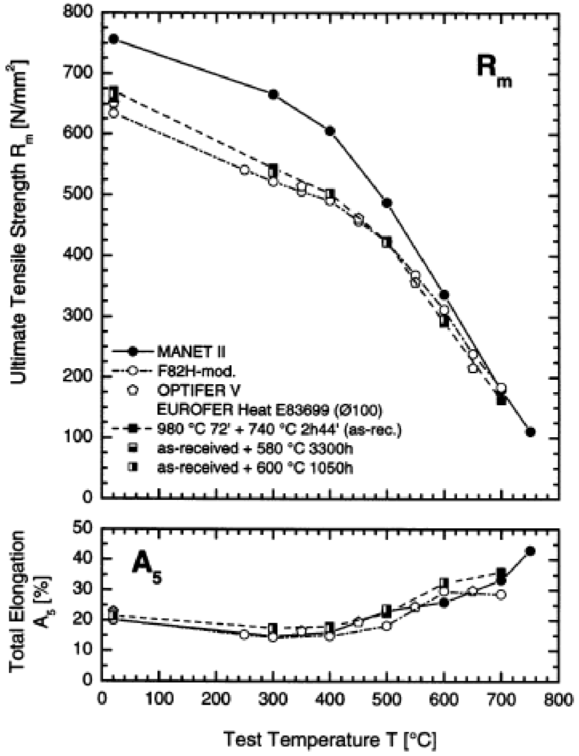
Irr. Hardening of E97
(Luzginova et al., 2014)



Impact energy (KLST) of E97
(Lindau et al., 2005)



Cyclic softening of E97
(Armas et al., 2011)



Tensile properties of E97 with temperature (Lindau et al., 2001)

Gaps for codification of EUROFER97

- EUROFER97 was introduced in RCC-MRx as Probationary Phase Rules in 2012:

RCC-MR 2007
- EUROFER was not codified

RCC-MR 2012
- Introduction of Eurofer (RPS for plate and A3.19AS)
- Physical properties, Basic data

RCC-MR 2015
- Properties group A3.19AS was updated
- Creep data, fracture mechanics data

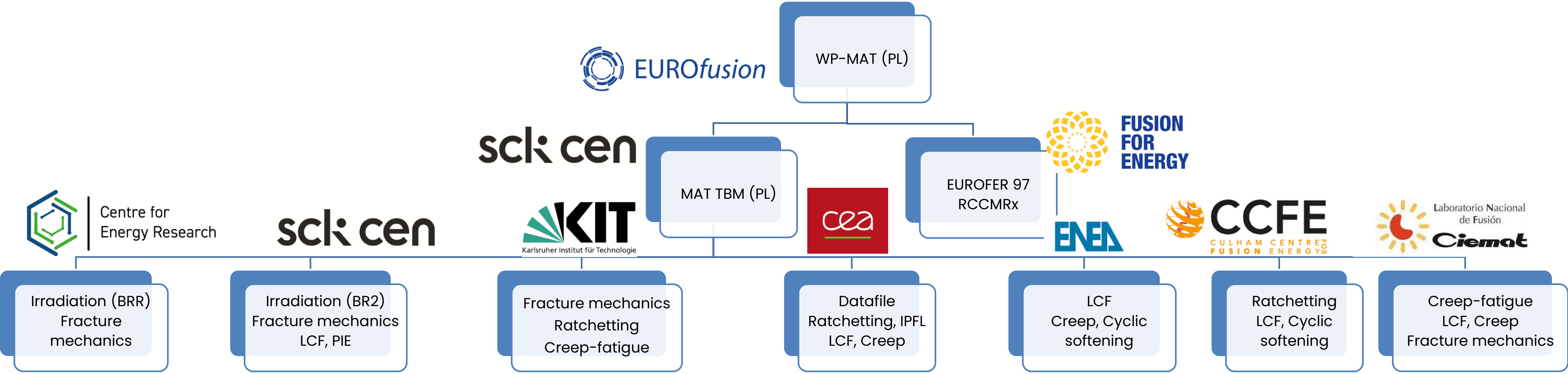
RCC-MR 2018
- Irradiated data

- Some gaps are identified to fully implement the EUROFER97 in the RCC-MRx code:
  - Complete the Material File with:
    - Industrial experience for procurement, manufacturing and welding
    - Justification of the applicability of the RCC-MRs Design Rules
    - RoX on In-service behaviour (ageing, corrosion, irradiation, …)
  - Consolidate and Complete Procurement Specification (RPS)for plates, bars and tubes
  - Update or complete the Properties Group (A3.19 AS for base metal, A9.19AS for welds):
    - Update basic mechanical properties from tests on more batches (application of AFCEN Technical Publication)
    - Introduce a negligible creep curve, irradiation boundary curves and an efficiency diagram for ratcheting
    - Update S_{em} and S_{et} allowable stresses for validated design rules in significant irradiation
    - Welding coefficients for TIG and HIP joints (J_m, J_t, J_r, J_f) …

3. Progress On The Characterization Program

Progress On The Characterization Program

- EUROFER97 Experimental Qualification Program within EUROfusion project (MAT-TBM) **2021-2025 (2027)**



- Tests on base metal for validation of design rules (racheting, IPFL, creep-fatigue, cyclic softening, σ_d)
- Tests on base metal to complete the database (creep behaviour and negligible creep, fracture toughness, FCG)
- Tests after irradiation (2-3 dpa @ 300-550°C) to evaluate irradiation hardening (tensile, IPLF, fracture toughness, irradiation creep)
- Tests on welded joints (TIG, HIP) to determine the weld coefficients (J_m, J_f, J_{1c}) before and after irradiation

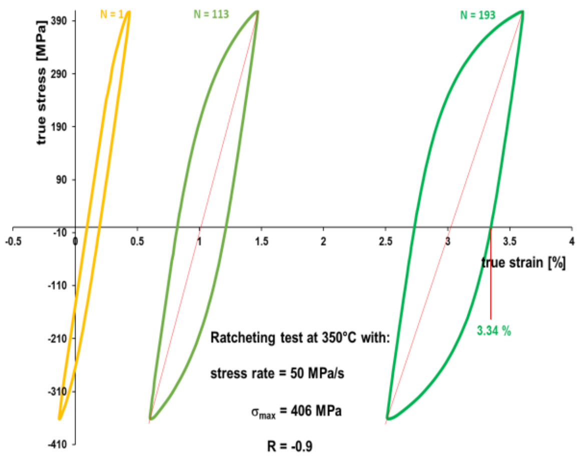
Progress On The Characterization Program

- EUROFER97 Experimental Qualification Program within EUROfusion project (MAT-TBM) **2021-2025 (2027)**

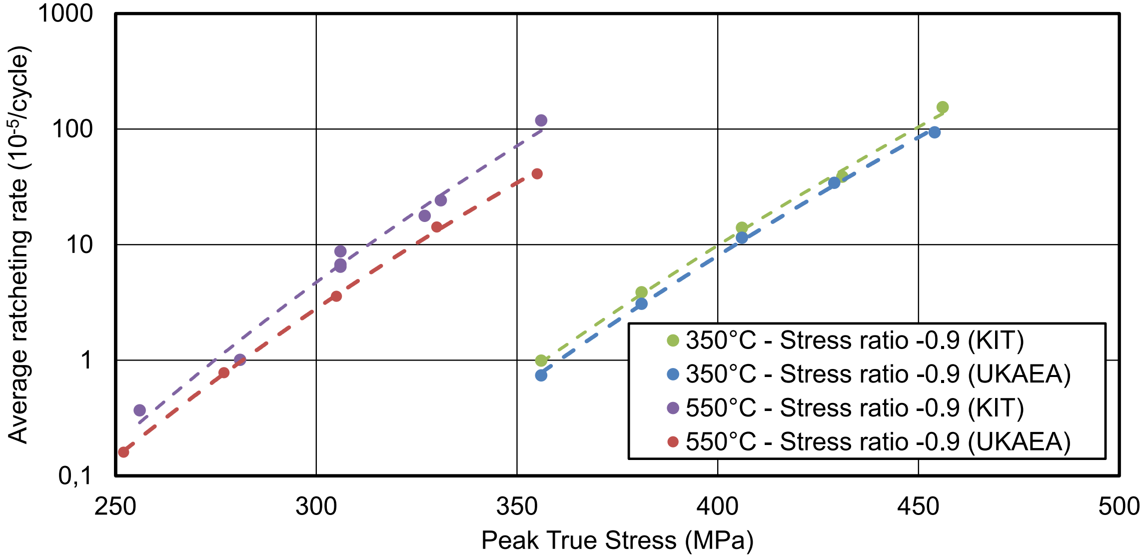
Non-irradiated/Base Metal	Test types	2020	2021	2022	2023	2024	2025	…
Immediate Plastic Flow Localization	Plain/Notched Tensile	■	■	■	■			
	Plain/Notched 4 Points Bending		■					
Ratcheting	Tension/Torsion Cyclic		■	■	■	■	■	
Uniaxial Ratcheting	Stress-controlled Cyclic Uniaxial	■	■	■	■	■		
Creep-Fatigue Interaction	Creep-Fatigue/Fatigue-Relaxation		■	■	■	■	■	
Sm after Cyclic Softening	Cyclic + Tensile tests					■	■	
Sigma d	CCT						■	■
Fatigue	Strain-controlled Cyclic Uniaxial	■	■	■	■			
Fracture Toughness	Compact Tension (CT)		■	■	■	■	■	
Creep	Tensile Creep	■	■	■	■	■	■	■
Fatigue Crack Growth	Cyclic CT					■	■	
Irradiated/Base Metal	**Test types**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**…**
Immediate Plastic Flow Localization	Plain/Notched Tension		■	■	■	■		
	Plain/Notched 4 Points Bending		■	■	■	■		
Tensile Properties	Cylindrical Tensile	■	■	■	■	■	■	■
Irradiation Creep	Creep pipes	■	■	■	■	■	■	
Fracture Toughness	CT and Disk CT	■	■	■	■	■	■	■
Welded Joints	**Test/Joint types**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**…**
Non-Irradiated Tensile Properties	Transverse Tensile/HIP							■
	Transverse Tensile/TIG						■	■
Non-Irradiated Fatigue	Transverse LCF/HIP							■
	Transverse LCF/TIG						■	■
Non-Irradiated Fracture Toughness	CTJ/HIP							■
	CTJ/TIG						■	■
Irradiated Tensile properties	Transverse Tensile/HIP							■
	Transverse Tensile/TIG						■	■
Irradiated Toughness	CTJ/HIP							■
	CTJ/TIG						■	■

Progress On The Characterization Program

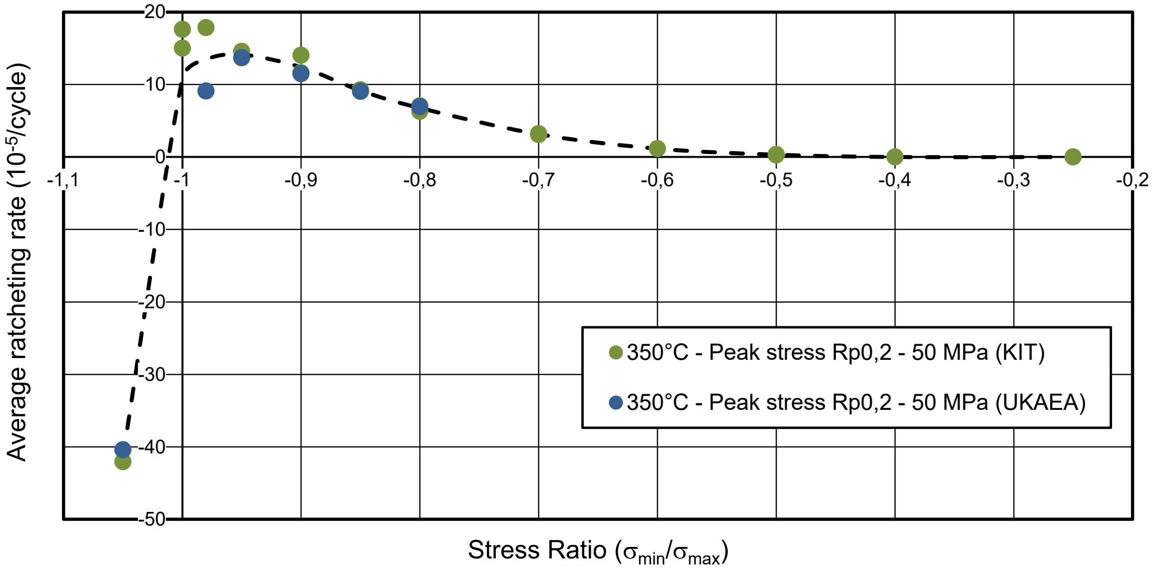
- EUROFER97 Ratcheting behaviour: KIT Karlsruher Institut für Technologie, CCFE Culham Centre for Fusion Energy, cea
  - ➢ Cyclic tensile tests at imposed true stress from 350 to 550°C:
    - Effect of peak stress, stress ratio and stress rate on the average ratcheting rate



True stress-strain loops at 350°C
σ_{max} = 406MPa ($R_{p0.2}$ – 50) / R = -0.9



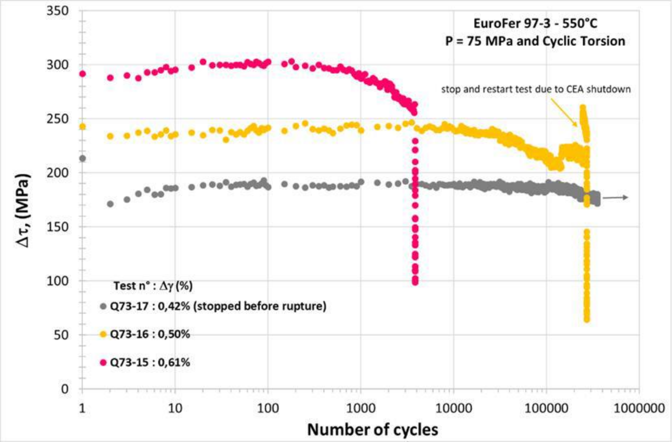
Effect of peak stress on the ratcheting rate
R = -0.9



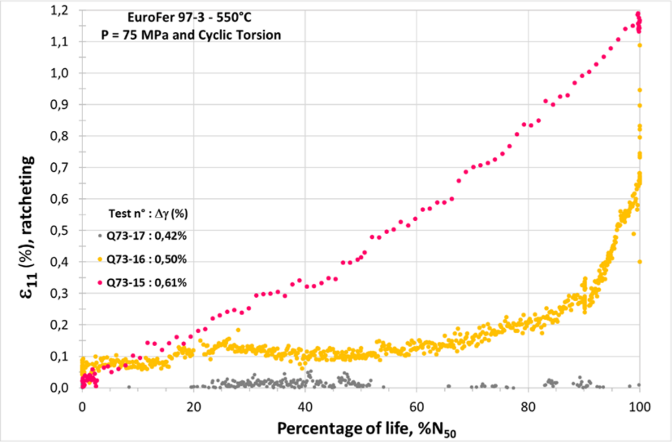
Effect of stress ratio at 350°C
σ_{max} = 406MPa ($R_{p0.2}$ – 50)

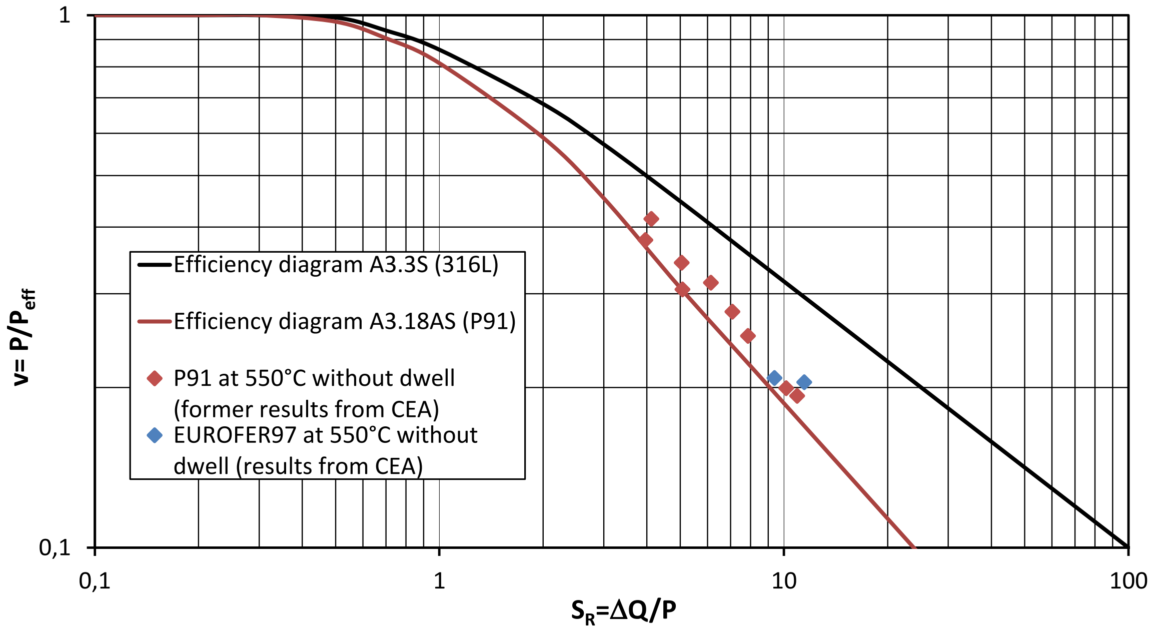
Progress On The Characterization Program

- EUROFER97 Ratcheting behaviour:
  - Tension-Cyclic torsion tests at 550°C:
    - Evaluation of the efficiency diagram and limits for ratcheting (first results)



First tension-torsion tests at 550°C





First ratcheting tests results at 550°C reported in Efficiency Diagram

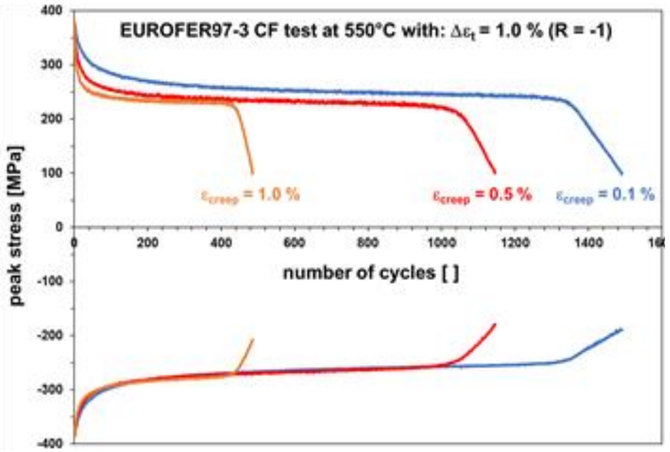
Progress On The Characterization Program

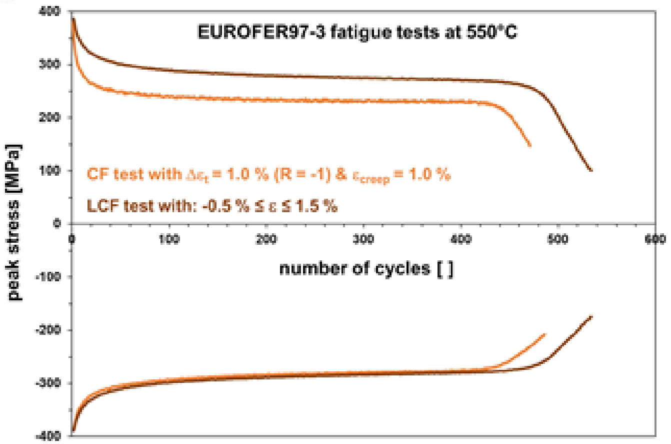
- EUROFER97 Creep-Fatigue Interaction:

Karlsruher Institut für Technologie

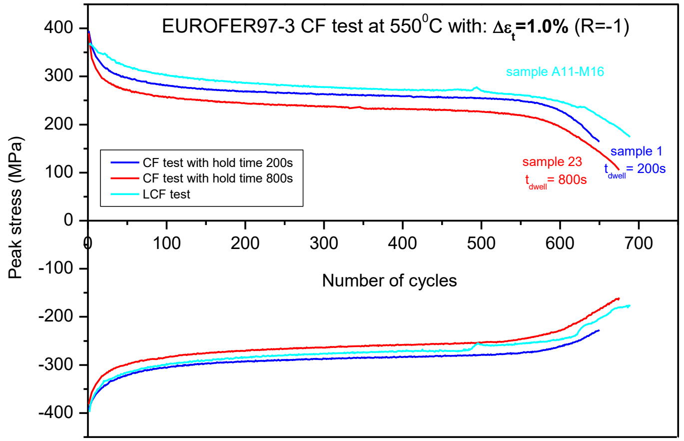
Laboratorio Nacional de Fusión Ciemat

  - Creep-Fatigue behaviour:
    - Comparison with non-symmetrical LCF tests ➔ No significant effect of creep damage on lifetime (dwell in tension)
    - Evaluation of the effect of creep during dwell in tension and/or compression (450 to 650°C)

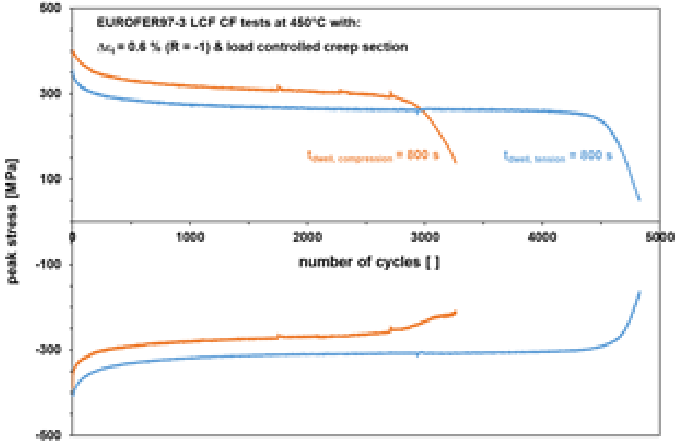




Creep-Fatigue and LCF tests at 550°C



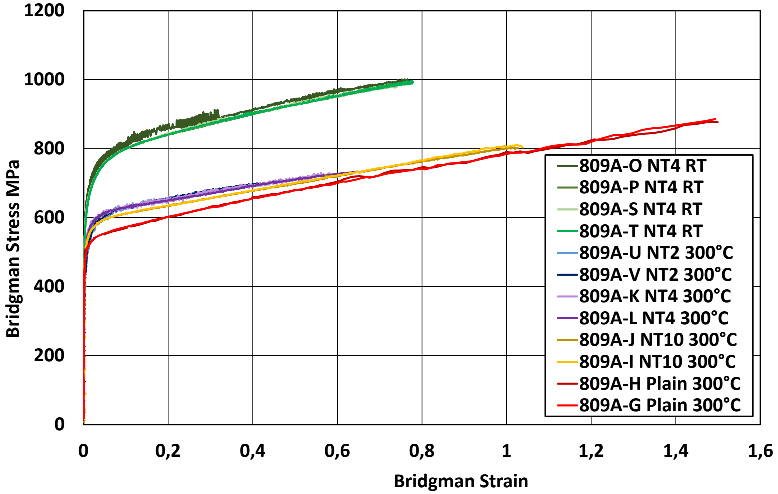
Fatigue-Relaxation and LCF tests at 550°C



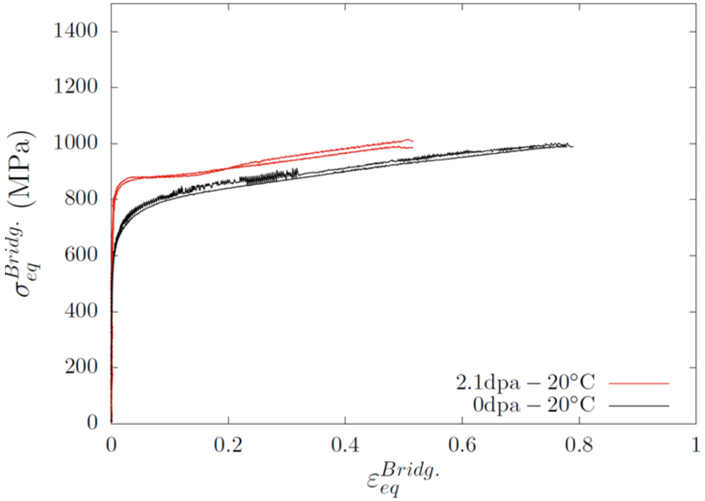
Effect of dwell position at 450°C

Progress On The Characterization Program

- Effect of irradiation on the Plastic Instability (IPFL) and Ductility exhaustion:
  - For validation of S_{em} and S_{et} RCC-MRx design rules
  - Tensile tests on cyl. plain and notched specimens before and after irradiation:
    - Evaluation of the effect of triaxiality and irradiation on the plastic behaviour beyond necking
    - After 2.1 dpa @ 300°C, constant hardening with strain range, reduction of strain at rupture

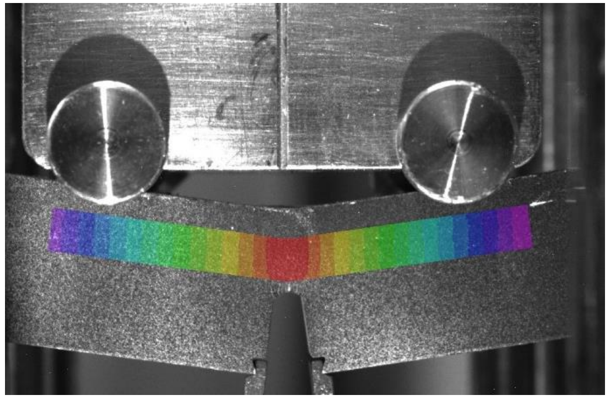


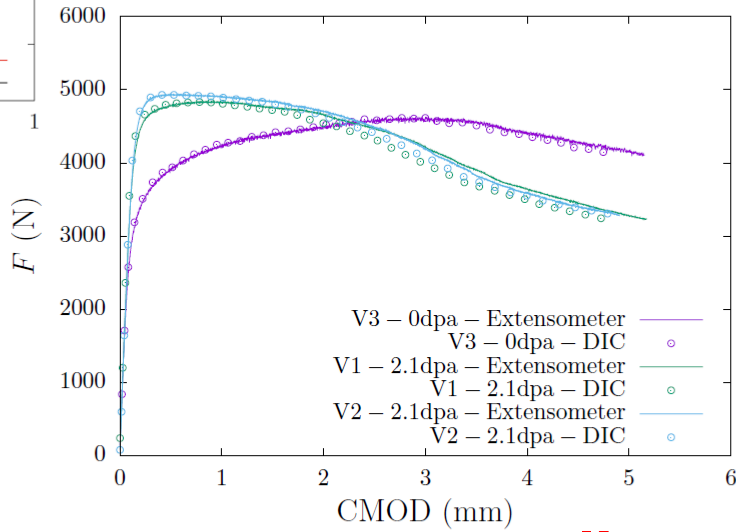
Tensile tests on notched specimens at RT and 300°C



Effect of irradiation on the plastic flow and ductility

4-pts bending tests on notched bars after irradiation

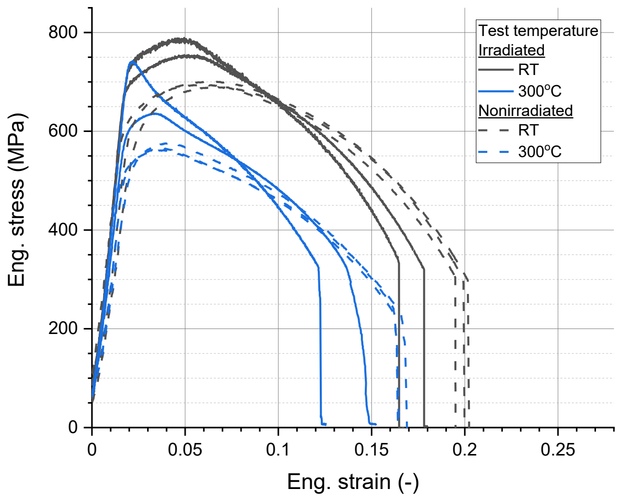




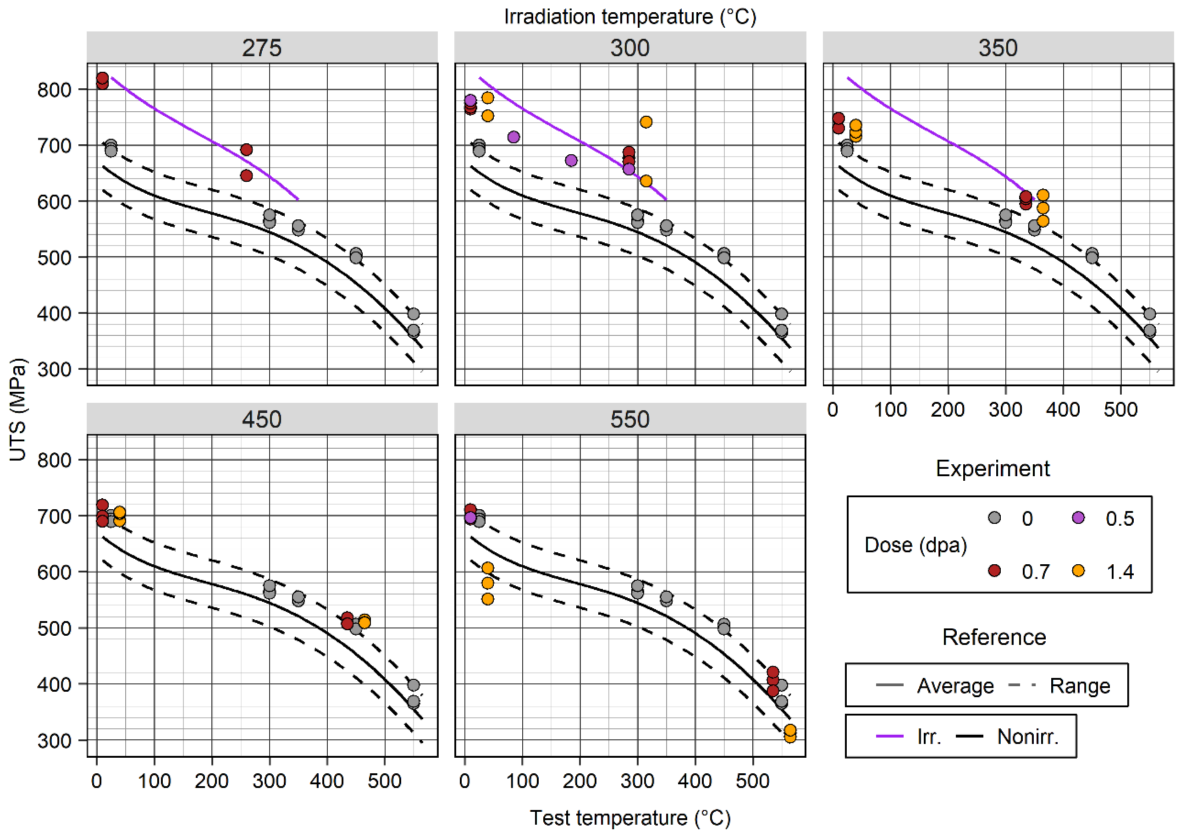
- 4-pts bending tests on plain and notched bars before and after irradiation:
  - Strong reduction of the flexure at instability after irradiation

Progress On The Characterization Program

- Effect of irradiation on the tensile properties of EUROFER97: sck cen
  - Tensile tests after irradiation in BR2 reactor from 275 to 550°C at 0.7 and 1.4 dpa:
    - Tensile strength (YS, UTS) of batch 4 higher then batch 3 before irradiation
    - Irradiation hardening after irradiation at 300°C in agreement with former results
    - Irradiation hardening vanishes above 350°C
    - No clear difference between 0.7 and 1.4 dpa
    - Softening after irradiation at 550°C to 1.4 dpa to be clarified (overheating?)



Tensile tests ar RT and 300°C after irradiation @300°C - 1.4 dpa



UTS vs Temperature and irradiation dose batch 4 ID79

4. Implementation of EUROFER97 in the RCC-MRx

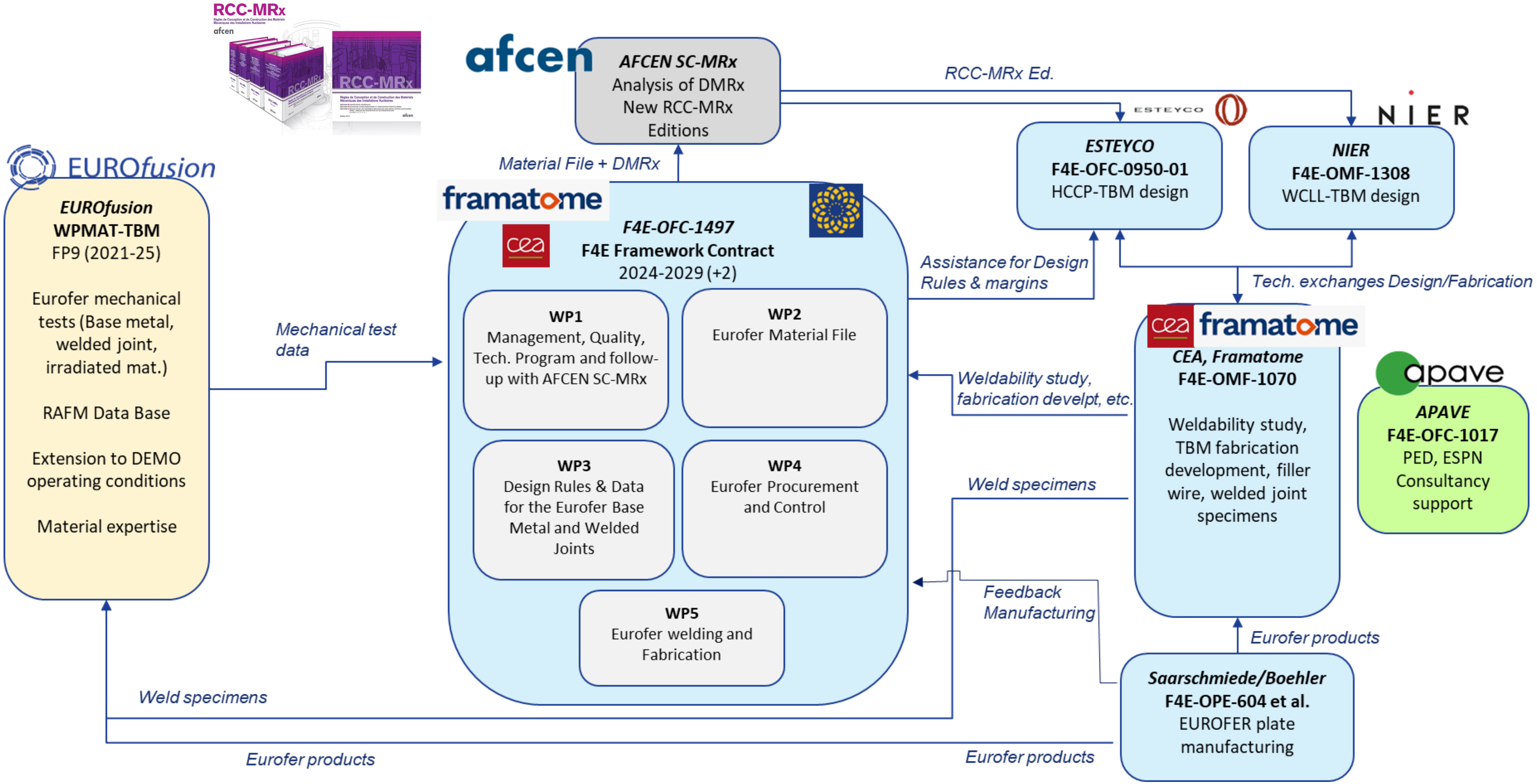
Plan for the codification of EUROFER97 in the RCC-MRx

- A framework contract 2024-2029(+2) is driven by FUSION FOR ENERGY for codification of E97 in the RCC-MRx
- A consortium between framatome and cea was chosen
- Objectives of the contract:
  - Analyse the results from the experimental program to prepare Modification Requests of the RCC-MRx (Tome 1)
  - Update and complete Procurement Specification from industrial experience of 4 EUROFER97 batches (Tome 2)
  - Consolidate the manufacting (welding) and control requirements for TBM with feedback from fabrication activities (Tomes 3 to 5)
  - Update the Material File requested to justify the design and manufacturing requirements and demonstrate the consistency of EUROFER97
- Organization in 5 Work Packages:

WP 1	WP 2	WP 3	WP 4	WP 5
Management, Quality Technical Program	**Material File**	**Design Rules and Data**	**Procurement, Control**	**Welding, Manufacturing**

Plan for the codification of EUROFER97 in the RCC-MRx

- European Organization for the qualification and codification of EUROFER97 in the RCC-MRx:



5. Conclusions and Perspectives

Conclusions and Perspectives

- RAFM steel EUROFER97 has been chosen by EU for WCLL and HCCP TBM in ITER
- EUROFER97 is implemented as Probationary Phase Rules in the RCC-MRx
- An experimental program is ongoing to fill the gaps and complete the data for EUROFER97 base metal and welded joints:
  - Tests on base metal to validate the design rules (racheting, IPFL, creep-fatigue, cyclic softening, σ_d) and complete the database (creep behaviour and negligible creep, fracture toughness, FCG) will end in 2025
  - Tests after irradiation (2-3 dpa @ 300-550°C) to evaluate irradiation hardening (tensile, IPLF, fracture toughness, irradiation creep) are in progress with some PIE and final irradiation dose and temperature to be done
  - Tests on welded joints (TIG, HIP) to determine the weld coefficients (J_m, J_f, J_{1c}) before and after irradiation are starting
- A framework contract driven by F4E started in 2025 to complete the codification of EUROFER97:
  - Validate the design rules and update the properties (Tome 1)
  - Update and complete Procurement Specification for plates, bars and tubes(Tome 2)
  - Consolidate the manufacting (Welding Procedure Qualification for TIG and HIP) and control requirements for TBM with feedback from fabrication activities (Tomes 3 to 5)
  - Update of the Material File.

Thank you