

EUROfusion C&S development for IVCs: from ITER to DEMO

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EUROfusion

With contributions from WPMAT and F4E TBM project teams.



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Issues in selecting C&S for Fusion SSCs

- C&S are developed to comply with regulations, but there is **no harmonized regulatory framework** for fusion installations.
- Existing C&S address **SIC components** in fission plants but fusion plants have **different safety challenges** compared to fission.
- **“Mission critical” components** (magnets, IVCs) may not be SIC and exempted from regulation but **must still be designed, manufactured and operated to the highest quality standards (investment protection)**.
- **The wide range of operating conditions of fusion SSCs** (operating temperatures from 4 K to 2000 K, EM loads linked to electrical functionality, strong cyclic operation, effects of 14 MeV neutron irradiation, plasma-wall interactions leading to materials degradation, etc.) **are not covered by any single existing industrial code.**

A multi-code approach was selected from the beginning for ITER SSCs, complemented by specific design rules and Technical Specifications



C&S for mechanical components used in the ITER Project

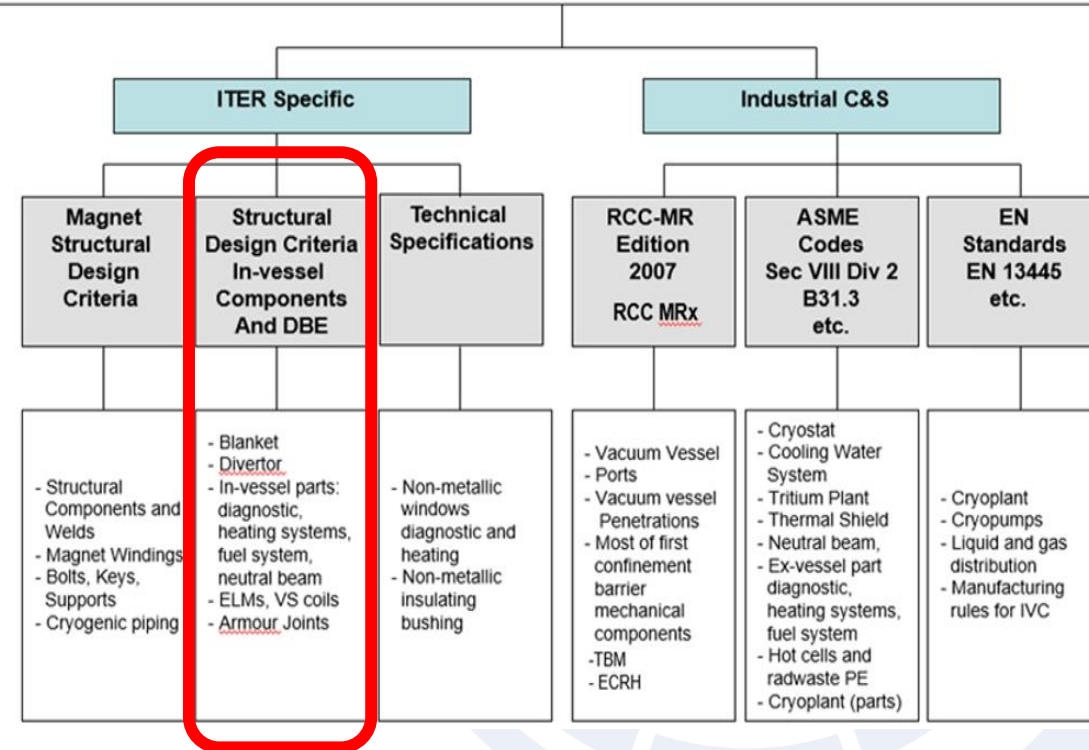
Industrial codes:

- **RCC-MR(x)**: for primary confinement barrier (VV) and **SIC/nuclear** components under **ESPN** regulation (**TBM**).
- **ASME (non-nuclear)**: for piping, valves, pumps, vessels and **SIC classified** under the EU **PED/ESP** regulation (CWS).
- **EN standards**: for selected components, complementary to ASME for **specific EU regulation requirements**.

ITER Specific:

- **SDC-IC**: for IVCs, to take into account **neutron irradiation effects and fusion specific material properties**. Includes **Design By Experiment** for DIV.
- **Magnet-SDC**: for cryogenic temperatures, where **loss of FT and defects acceptability** are the main concern.
- **Technical Specifications**: for non-standard components and ITER (fusion) specific requirements (**Tritium, Vacuum...**).

C&S selection for ITER mechanical components



ITER had to produce additional documentation to justify the coherency and consistency of the different codes



The EUROfusion and F4E strategy: following the ITER approach for IVCs

EUROfusion, in collaboration with F4E, is following a similar approach for IVCs:

We are supporting F4E in the development of RCC-MRx:

- RCC-MRx is the code selected for the EU TBMs (ESPN N2 components).
- We are focusing on the codification of EUROFER97 material properties, both for base metal and joints in irradiated and non-irradiated conditions and the validation of (elastic) design-by-analysis rules.
- These developments, and the corresponding lessons learned will be essential for the development of C&S for DEMO IVCs (not only the BB) .

We are developing the DEMO Design Criteria for In-vessel Components (DDC-IC), with multiple aims:

- Complement and extend design rules in existing C&S to cover the operational domain of DEMO IVCs (higher doses, higher temperatures, different materials than ITER).
- Act as a guideline for designers, providing references on how to use existing C&S and integrate DDC-IC rules in the design assessment.
- Provide alternative damage classification schemes able to capture the specific failure modes of fusion IVCs and their consequences in terms of functionality.



Collaboration with F4E: introduction of EUROFER in RCC-MRx

EUROfusion WPMAT/MAT-TBM:

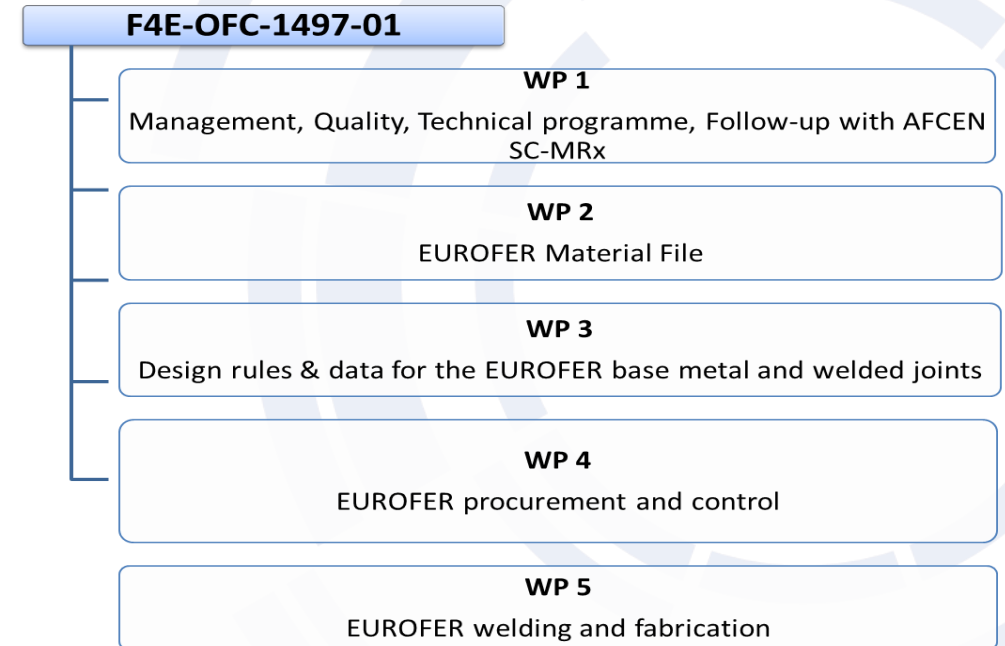
characterization of EUROFER batch 3 and 4 according to AFCEN “Guide for introducing a new material in RCC-MRx”.

Non-irradiated/Base Metal	Test types	Nb tests MAT-TBM	Nb tests done	% achieved
Immediate Plastic Flow	Plain/Notched Tensile	20	20	100%
Localization*	Plain/Notched 4 Points Bending	6	6	100%
Ratcheting	Tension/Torsion Cyclic	44	4	10%
Uniaxial Ratcheting*	Stress-controlled Cyclic Uniaxial	90	133	100%
Creep-Fatigue Interaction	Creep-Fatigue Cyclic Uniaxial	60	55	90%
	Fatigue-Relaxation Cyclic Uniaxial	25	18	70%
Sm after Cyclic Softening	Cyclic + Tensile tests	60	22	40%
Sigma d	CCT	32	0	10%
Fatigue*	Strain-controlled Cyclic Uniaxial	107	104	97%
Fracture Toughness	Compact Tension (CT)	40	27	70%
Creep*	Tensile Creep	72	44	60%
Fatigue Crack Growth	Cyclic CT	16	0	10%
Irradiated/Base Metal	Test types	Nb tests	Nb tests	Achieved (%)
Immediate Plastic Flow Localization	Plain/Notched Tension	20	20	100%
	Plain/Notched 4 Points Bending	9	9	100%
Tensile Properties*	Cylindrical Tensile	149	81	55%
Irradiation Creep*	Creep pipes	34	24	70%
Fracture Toughness*	CT and Disk CT	90	42	50%

EUROfusion is in charge of providing basic material properties and performing dedicated experiments for validation of design rules

F4E- OFC-1497-01:

supply of services for the technical management, codification and justification of the integration of EUROFER steel in the RCC-MRx code for ITER TBMs application.



F4E (with partners CEA and FRAMATOME) is in charge of post-processing the data to derive design allowables and submit corresponding DRMx to AFCEN

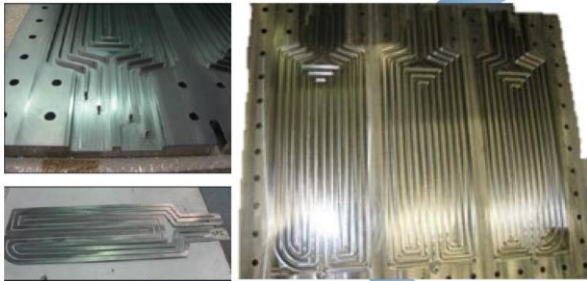
Courtesy of Y. Poitevin (F4E)



Collaboration with F4E: manufacturing techniques for the EU-TBMs

F4E- OMF-1070:

Weldability study and preliminary Welding Procedure Specifications (pWPS) for TBM and sub-components

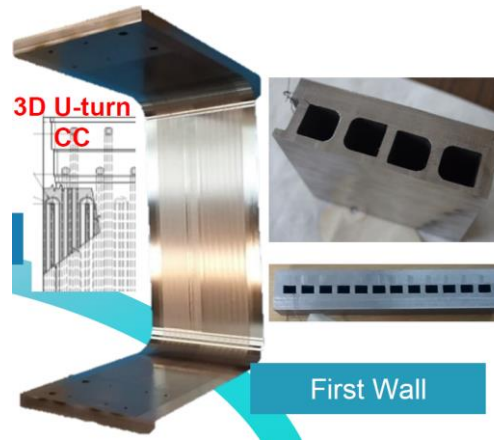


Stiffening Plates

TIG welding robot



14 horizontal SP welding



3D U-turn
CC

First Wall

FW and 2 SC assembly by 2-step HIP process (EUROFER97)



1200 mm

Figure 5: Side Cap

Figure 2: First Wall of the TBM

Figure 9: Canister for FMU

YAG laser welding + Hot Isostatic Pressure (HIP) Diffusion Welding (DW)

- Cooling Plate-reference process (thickness 6.5 mm)
- Stiffening Plates(thickness 11 mm)
- Side Caps / First wall (thickness 30 mm)

Tungsten Inert Gas (TIG) welding with and without filler material

- TBM box assembly (30 mm)

2-step HIP process – low pressure & high pressure HIP

- Cooling Plate – alternative process
- TBM box First Wall – alternative process

Drilling + Spark erosion + Bending



EUROfusion WPMAT/MAT-TBM: characterization of Welding Joint properties

Non-irradiated welded joints	Test/Joint types	Nb of tests	Joint type/Plate
Tensile Properties	Transverse Tensile/HIP	24	HIP/Plate batch 4 thickness 36mm
	Transverse Tensile/TIG	48	TIG single U/Plate batch 4 thickness 45mm
Fatigue	Transverse LCF/HIP	68	HIP/Plate batch 4 thickness 36mm
	Transverse LCF/TIG	68	TIG single U/Plate batch 4 thickness 21mm
Fracture Toughness	CTJ/HIP	33	HIP/Plate batch 4 thickness 36mm
	CTJ/TIG	36	TIG single U/Plate batch 4 thickness 21mm
Irradiated welded joints	Test/Joint types	Nb of tests	
Tensile properties	Transverse Tensile/HIP	48	HIP/Plate batch 4 thickness 36mm
	Transverse Tensile/TIG	48	TIG single U/Plate batch 4 thickness 21mm
Toughness	CTJ/HIP	39	HIP/Plate batch 4 thickness 36mm
	CTJ/TIG	42	TIG single U/Plate batch 4 thickness 21mm



The DEMO Design Criteria for In-Vessel components in EUROfusion

- The DDC-IC will be a **fully integrated guideline adopting inelastic design procedure** supported by advanced FE based assessment approaches to **avoid relying on (over)conservative margins** associated with elastic design methods.
- Is not meant to be a stand-alone code but to provide **links and guidelines to apply existing C&S (ASME, SDC-IC, RCC-MRx)**.
- Provide **complementary or alternative design rules** to cover gaps in existing C&S.
- **Provide design allowables and material properties** for fusion-relevant materials and DEMO loading conditions (in particular neutron irradiation) in parallel with the development of specific **Material Properties Handbook**.
- **Introduce an alternative damage classification methodology tailoring the damage limits for each specific failure mode to the required functionality of the component in the different plant states.**
- **Provide specific sections for selected components to instruct designers on the methodology to follow, i.e. tailored components' Design Specifications**



Development and validation of inelastic constitutive material models

Material : **EUROFER97**

Hardening laws are combined to build material models

Chaboche kinematic hardening

$$\dot{\Omega}_i = \frac{2}{3} C_i \dot{\epsilon}_p - \gamma_i \Omega_i \dot{p}$$

$$\Omega = \sum_i^n \Omega_i$$

Voce law isotropic hardening

$$R = k + R_0 p + R_\infty (1 - e^{-b p})$$

EVH (viscoplastic) model

$$\dot{\epsilon}_p = \sum_{i=0}^n \left(\frac{\sigma_{eq} - R}{K_i} \right)^{1/m_i}$$

Mod. Time Hardening (Primary)

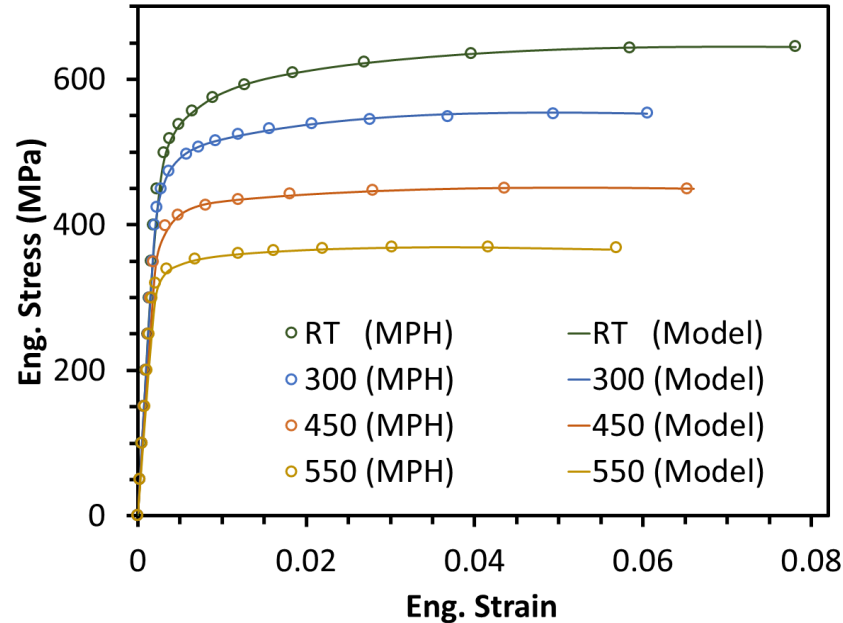
$$\epsilon_{cr} = \frac{C_1}{C_3+1} \sigma^{C_2} t^{C_3+1} e^{-C_4/T}$$

Monotonic

Cyclic

Cyclic, creep and hold time

Monotonic load



Loaded till UTS

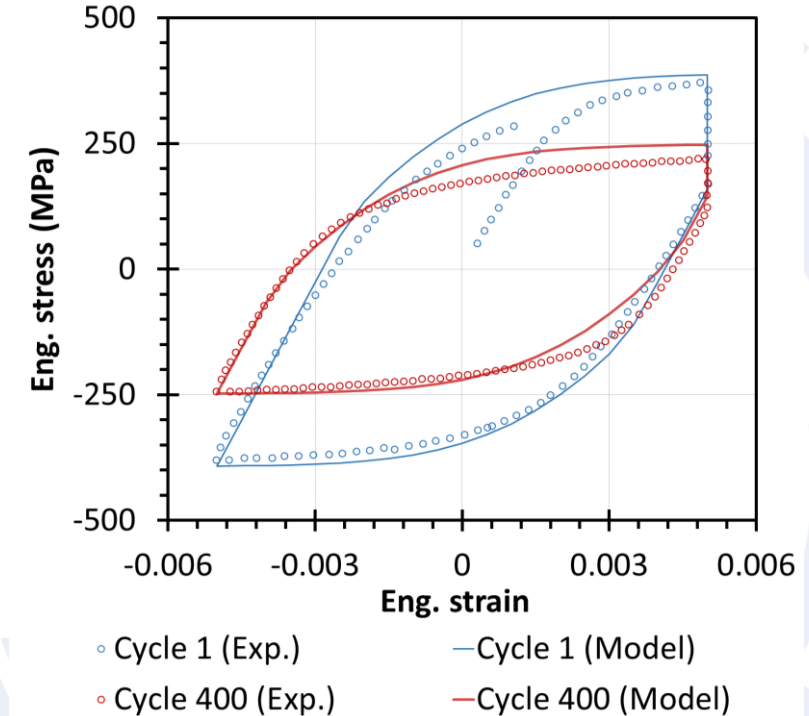
$$@T_{test} = RT - 550 \text{ } ^\circ\text{C}$$

Material Property Handbook – Eurofer97 (2023)

Next steps:

- Experimental tests for validation on CuCrZr
- Extension to irradiated conditions

Cyclic load with hold time



$\Delta\epsilon = 1.0\%$ Hold time = 10 mins

$$@ T_{test} = 550 \text{ } ^\circ\text{C}$$

J. Aktaa and R. Schmitt, FED (2006)

ANSYS



Development and validation of design rules for *inelastic analysis*

• Exhaustion of ductility

- Determination of the actual failure envelope by non-standard test at different triaxialities
- Validated on CuCrZr and EUROFER97 at different T

• Multiaxial fatigue

- To reduce conservatism on the fatigue design curve ($N/20$ or $\varepsilon/2$)
- Validation for EUROFER97 on going

• Creep-fatigue interaction

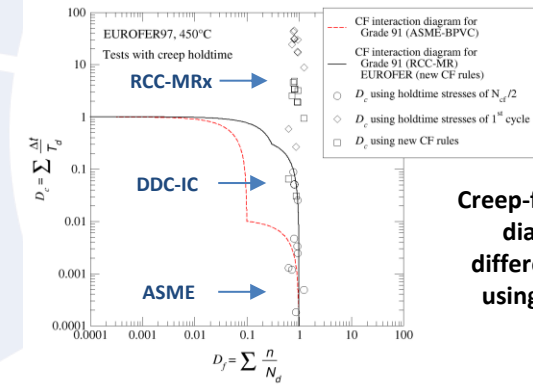
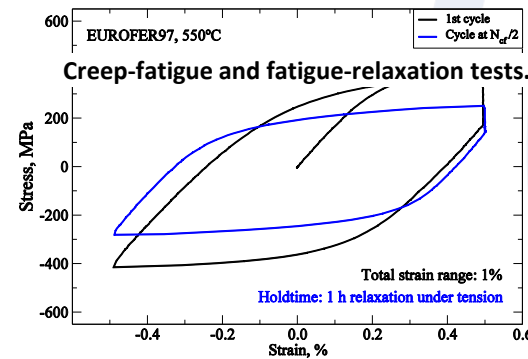
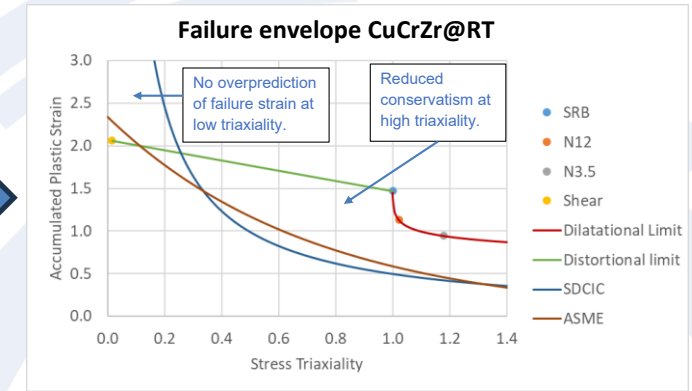
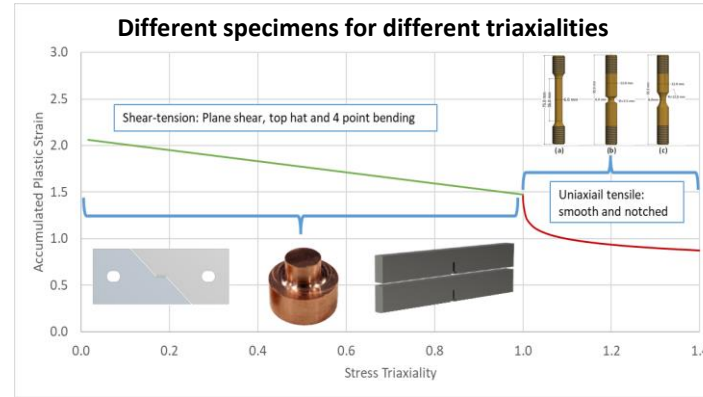
- To account for cyclic softening, between ASME (overconservative) and RCC-MRx (not conservative)
- Validated on EUROFER97, CuCrZr on-going

• Fast fracture

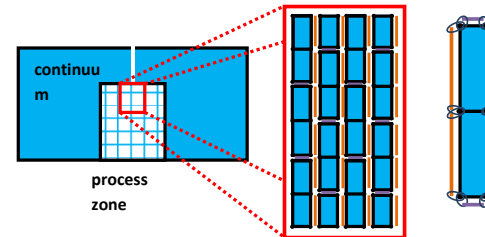
- To define a master curve for W based on Weibull model and the Cohesive Zone Elements method
- Validated in un-irradiated conditions, on-going for irradiated conditions

• Fatigue crack growth

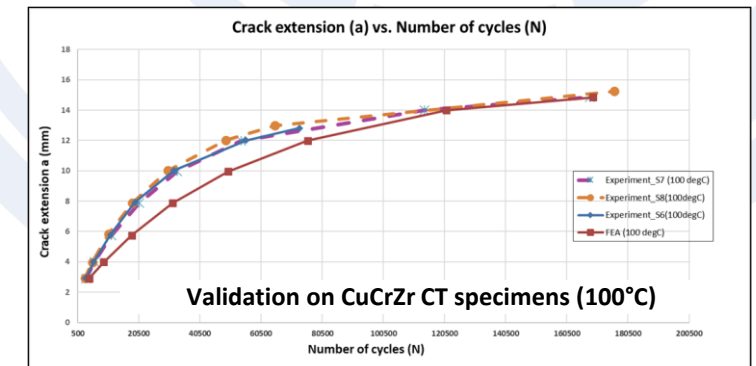
- Alternative method to calculate the J-integral in elasto-plastic materials
- Validated on CuCrZr, validation for EUROFER97 on-going



Creep-fatigue interaction diagram (0.3,0.3) different conservatism using different rules.



$$J = \frac{1}{B} \frac{dUe}{da}$$





Alternative damage classification scheme (*limit state/inelastic analysis*)

**Present
approach
used in
nuclear C&S**

Criteria Level	Failure modes	Damage limit	Meaning
Level A/B	Failure mode 1	No damage	Component can be operated indefinitely
	Failure mode 2		
	Failure mode 3		
Level C	Failure mode 1	Limited Damage	Component can be repaired or changed, operation can be continued
	Failure mode 2		
	Failure mode 3		
Level D	Failure mode 1	Ultimate damage	Component must be changed, or continuation of operation may not be possible
	Failure mode 2		
	Failure mode 3		



**Alternative
approach
proposed
for DDC-IC**

Criteria Level	Failure modes	Damage limit	Meaning
Level A/B	Failure mode 1	No damage	Design is expected to resist the onset of this failure mode with a wide margin (over the design life).
	Failure mode 2	Limited damage	Design is expected to resist the onset of this failure mode with a reduced margin (over the design life).
	Failure mode 3	Ultimate damage	The design is expected to meet (or exceed) the conditions for onset of this failure mode (over the design life)

The DDC-IC approach is specific to each component



Introduction of component-level “Design Specification”

Objective:

- To have a **clear picture** of the current practice of structural analysis of each component’s design process to be able to draft a “design specification” (“**state of the art**”)
- To **ensure coherency** (“harmonization”) of design rules used for analyses
- **Not limited to design analyses:** component classification, operating conditions, loads, materials and manufacturing shall at term be included

IDM Reference	EFDA_D_IMSUID	Version/Dates: see IDM
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ABC-D.01.02-E052-F001

Divertor Design Specification

Work Package*	WPMAT
WP Leader*	Pintsuk, Gerald

References (IMS): Task Specifications (TS), Task Coordinator, Deliverable Owner	
Deliverable Owner*	Lebarbé, Thierry
Benef(s) involved in Deliverable*	CEA

Deliverable Review & Approval (IDM Roles & Names)		
IDM Role	Scope	Name(s)
Author/Signatory*	Author	Lebarbé, Thierry

1 Short Introduction and Objectives of Work

The present document is the detailed “design specification” (including materials, loadings, operating conditions, rules to be applied) for the DEMO divertor, that will lead to identify needs to go through the design process. These “design specification” could be introduced as an appendix of DDC-IC document. It is a draft written from a survey sent to the designers (Appendix 1 : the table is divided in seven sections: *basic data, codes/standards/set of rules, loadings and/or operating conditions and others, materials, specified criteria, calculation and analysis, conclusion.*).

For this first year of work regarding this task, the idea is to have a clear picture of the current practice and current analysis of the divertor design process to be able to point out where things are missing or not.

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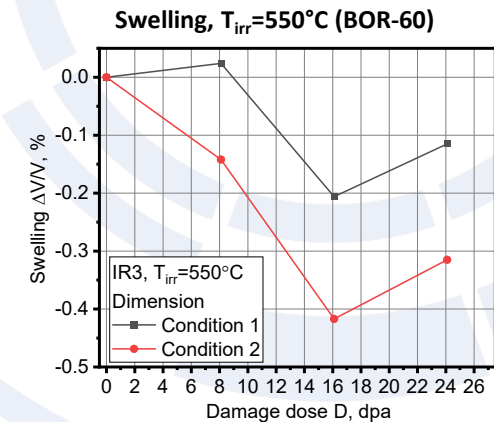
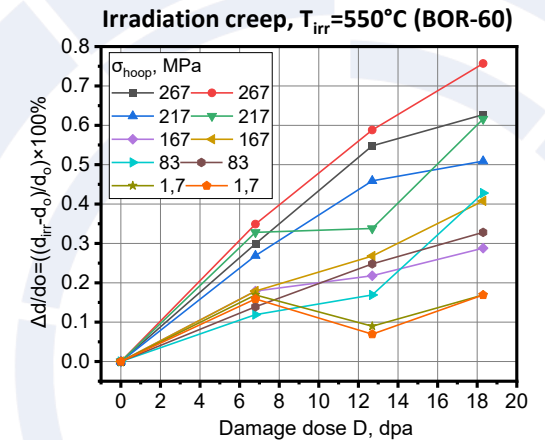


Extending the domain of applicability to DEMO operating conditions

- There is a lack of data on the effects of neutron irradiation at **high dpa levels (20-50 dpa for EU-DEMO)** and **high neutron energy (14 MeV)**: change in physical properties (thermal conductivity, electrical resistivity), hardening, shift of DBTT, irradiation induced creep and swelling.
- Applicability of design rules for neutron irradiated materials must be proven.
- Irradiation campaigns to fill these gaps are part of the EUROfusion program:

Courtesy of D. Terentyev, SCK-CEN.

Campaign	Irradiation facility	Materials & parameters
PIE of EUROFER97 (tensile)	HFIR, ORNL	EUROFER97/2 20 dpa @ 220 / 250 / 300 / 350 °C
High-dose irradiation in BOR60 and PIE	BOR 60, RIAR	EUROFER97/3 and welds, F82H, adv. steels 20 / 40 dpa @ 330 / 550 °C
Irradiation and PIE of isotopic tailored EUROFER	HFIR, ORNL	⁵⁴ Fe and ^{58/60} Ni doped EUROFER97 12-15 / 25-35 dpa @ 300 / 400 / 500 °C
Irradiation of PFMs with thermal neutron shielding (0.5%Re/dpa)	BR2, SCK CEN	Commercial W, Tohoku-W & K-doped W, self-passivating W, W-ZrC 1 dpa @ 400 / 800 / 1100 °C
PIE of CuCrZr	LVR-15, REZ PIE: VTT	CuCrZr 0.7-1.3 dpa, 150 / 250 °C
Low temperature irradiation of divertor materials	BR2, SCK CEN	CuCrZr, OFHC-Cu, EUROFER97 1 / 3 / 6-9 dpa @ 50 / 150 / 250 / 350 / 450 °C
Design rule validation and RCC-MRx data (fracture toughness)	BR2, SCK CEN	EUROFER97/3&4 0.5, 1, 2 dpa @ 300, 350, 450, 500 °C



A 14 MeV irradiation facility (DONES) is required to complete the database

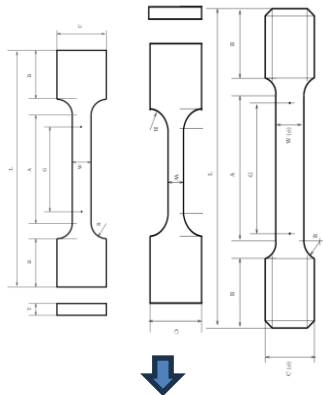


Standardization Small Specimen Test Techniques (SSTT)

Need to ensure “Code-qualified” data for irradiated material properties

- **OBJECTIVES:** propose SSTT for tensile, fatigue, FT and FCG testing, and respective sample geometries → *Support for IAEA CRP on SSTT for fusion → Prepare the guidelines (for ISO/ASTM review/approval)*

Tensile properties

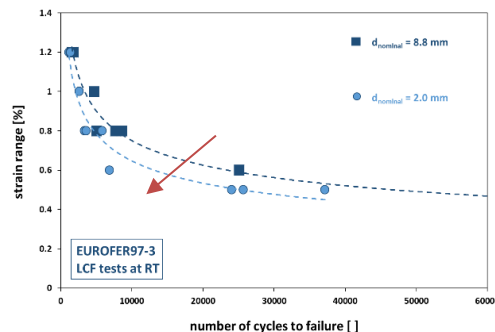


• Pilot Run (PL), according to ASTM guidelines completed by EU labs at RT, 300°C and 550°C

• Next step: Interlaboratory Study (ILS), open to international partners (JA, CN).

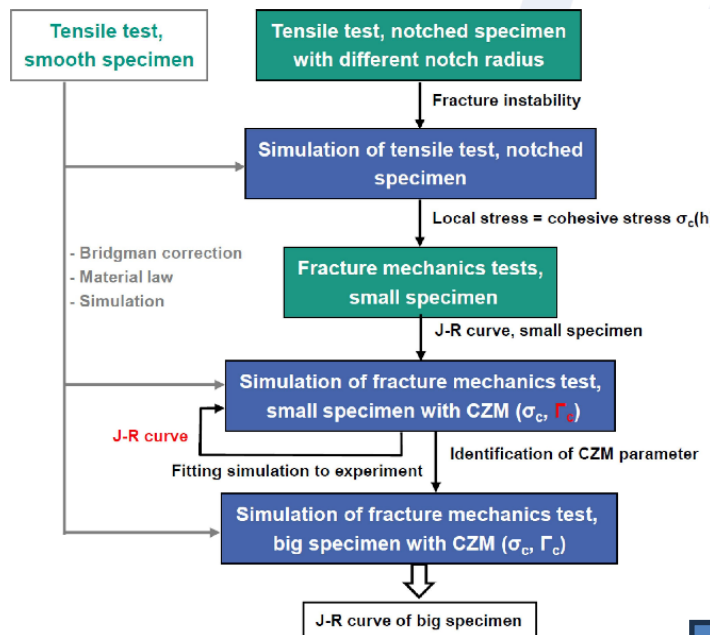
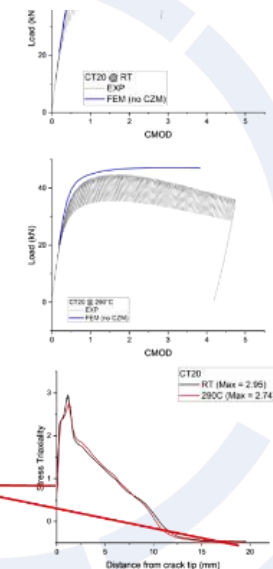
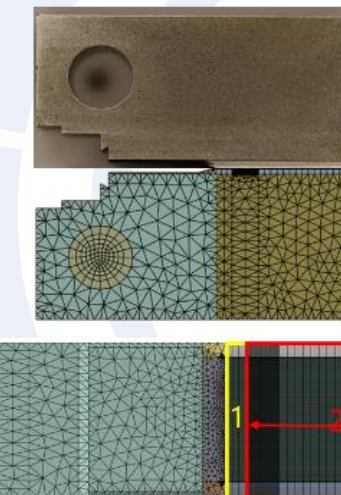
• Contribution to ASTM E8/E8M by end of 2025.

LCF



- Tests on:
 - lab-specific sub-sized specimens ($D = 2 \text{ mm}$ & 5 mm)
 - standard sized specimens ($D = 8.8 \text{ mm}$)
- Strain controlled LCF tests in air at RT & 550°C
- Underestimation of fatigue life w.r.t standard specimens → correction factor needed.

Fracture toughness



Combined procedure of experimental tests on small size specimens and FEM simulation to reconstruct the J-R curve of “standard-size” specimens.



Conclusions: extending existing C&S to DEMO IVCs

- **ITER has already provided a significant contribution to the development of C&S for IVCs:**
 - By implementing specific evolutions in industrial C&S (RCC-MRx).
 - By developing a set of criteria and related material properties for the specific damage modes of ITER IVCs (SDC-IC).
- **EUROfusion, in collaboration with F4E, is following a similar approach:**
 - We are supporting F4E in the development of RCC-MRx for the Test Blanket Modules.
 - We are developing DDC-IC to extend the domain of applicability of existing C&S to DEMO relevant materials and operating conditions.
- **In parallel, we are also investigating innovative approaches:**
 - Proposing an alternative damage classification scheme, based on inelastic assessment route and limit state notion for component's functionality.
 - Developing dedicated "Design Specifications", for selected, critical IVCs collecting the lessons learned in design, building and operating similar components in existing Tokamaks.



Conclusions: towards a collaboration with ITER

- **Identification of SIC and essential safety functions in the different plant states.**
- **Correspondence between ESR and selected C&S (under agreement with safety authorities).**
- **Identification of “mission critical” components and functionalities.**
- **Ensure consistency in design when different C&S are used for interfacing components.**
- **Feedback from manufacturing and qualification of components (and later from operation).**





The DDC-IC structure

Part A – General Provisions

- Driving objectives and strategic challenges for development of DDC-IC.
- Background on key principles of fusion plasma and their implications in component design context.
- Overview of the major DEMO in-vessel components covering the current technological developments.

Part B – Design Criteria and Analysis Procedures

- DDC-IC scope, methodology and approach.
- Failure mechanisms considered and respective design factors.
- Outline of the operating conditions classification, damage classification criteria level definitions and limits.
- Material properties and load case formulations.

Part CA – Analysis Examples

- Step-by-step example analyses for small scale cases such as test specimens as well as full scale DEMO components.
- Microscopic examination of some salient aspects and challenges underlying inelastic design by analysis methods (such as application of non-standard loads, mesh topology and element type selection).

Part CB – Justification of design criteria

- Design rule validation considering strain rate/ range, temperature and irradiation dose (targeting DEMO requirements).
- Validation of the material models and adequacy of material properties for design rule validation.
- Clarity of theoretical basis/ approximations underpinning each design rule, the damage classification approach and the corresponding limits of applicability.



Use of R6 failure assessment curve for setting damage limits

Basic rationale

- The R6 failure assessment procedure indicates that the plastic damage accumulation has an influence on the margin against fast fracture.
- This can be used for design assessment considering crack growth and plastic strain accumulation (in the remaining ligament).



Proposed approach

- Predetermining “design limits” against brittle fracture and plastic damage by considering the R6 failure assessment curve boundary.
- These limits may be suitably modified further considering component quality class/ limit state requirements.



Envisioned advantages

- Provides a theoretical basis to justify the adopted margins against brittle and ductile failure considering the synergistic effects.
- Preferable to assessment against each failure mode in isolation (which may be non-conservative).

The overall aim of this approach is to provide a higher level of granularity in the structural integrity assessment of DEMO in-vessel components with clear justification for design limits against different failure modes.