Commonalities between materials development in fission and fusion technologies

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Introduction

- Next generation nuclear systems (Fusion, GEN IV) share the common goal of achieving higher efficiencies, longer lifetimes and better sustainability.

- This translates in requirements for the **(structural) materials**, which must be capable of :
  - **Working at high(er) temperatures**
  - **Resisting high (fast) neutron irradiation doses**
  - **Presenting improved chemical compatibility with a variety of coolants.**

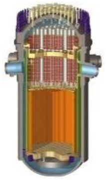
Despite the differences in plant architecture, the underlying technological issues and the investigated solutions in materials' development are very similar in Fission and Fusion R&D

Materials for Innovative Nuclear Systems

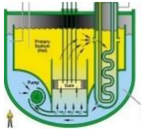
	Gen IV					Fusion		
	SFR	GFR	VHTR	LFR	MSR	DEMO	Power Plant	Advanced Concepts
Coolant T (°C)	Na 300-550	**He** 400-850	**He** 600-1000	**Lead alloys** (Pb-Bi) 550-(800)	Molt. Salt. **FLiBe** 500-720	H_2O 290-315 **He** 300-520	**He** 350-700 **Pb-Li** 480-700	**He** 400-1000 **Pb-Li** 700-1100 **FLiBe**
Core Structures	*Wrapper* **F/M steel** *Cladding* **ODS**	*Fuel+Core* **SiC_f/SiC**	*Core* Graphite *Cont. Rods* CfC - **SiC_f/SiC**	*Target, window clad.* **F/M steels** **ODS**	*Core and cladding* Ni alloys **F/M steels**	**F/M steel** **EUROFER97**	**Adv. EUROFER** **ODS**	**ODS** **V-alloy** **SiC_f/SiC**
Temp. (°C)	390-700	600-1200	600-1600	350-500	700-800	300-550	350-650	(ODS,V) 400-750 (SiC_f-SiC) 700-1100
Dose	*Core* 100 dpa *Cladding* 200 dpa	60-90 dpa	7-25 dpa	*Cladding, Target* 100dpa		20-50 dpa **(14.1 MeV)** **(+10appm He/dpa)**	100-150 dpa **(14.1 MeV)** **(+10appm He/dpa)**	>100 dpa **(14.1 MeV)** **(+10appm He/dpa)**

Past interactions between fusion and fission R&D

FISSION



PWR Internals
SFR Vessel



SFR Steam Generators, Fuel Assemblies

Cladding Materials

Austenitic steels, service experience with water at 300°C, design codes (RCC-MR) →

← Mechanical data after irradiation, design rules for irradiated structures (SDC-IC)

Mod. 9Cr-1Mo steel, compatibility with liquid metals, corrosion, fusion welding →

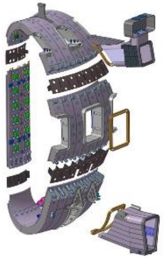
← High dose irradiation data, HIP welding, design rules for HT operation

ODS steels, SiC_f/SiC composites, joining technologies →

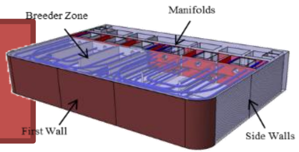
← Powder metallurgy, fibers development alternative fabrication routes

FUSION

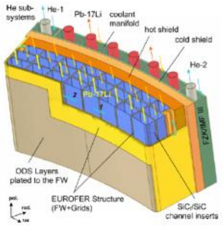
ITER 316LN-IG, Vacuum Vessel, shielding blanket



EUROFER 97, TBM, DEMO Breeding Blanket



Advanced blanket concepts



F/M steels as structural materials for Fusion IVC

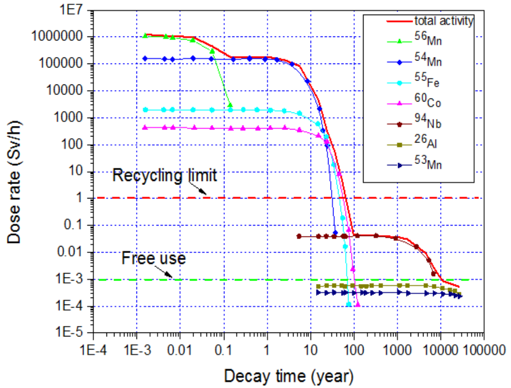
- **EUROFER97 is a Reduced Activation Ferritic Martensitic (RAFM) steel**, with high activation elements (Mo, Cu, Nb, Ni) replaced by their low activation equivalents (e.g. W, V and Ta) and reduced impurity content. **The objective was to achieve a Low Level Waste classification after ~100y**

- **EUROFER97 shows better properties after irradiation than conventional 9Cr steels** (shift of DBTT, decrease of USE) . It is the reference material for TBM in ITER and the DEMO blanket.

- For use in an FPP however, **the temperature window of operation is limited** by low temperature irradiation embrittlement and creep lifetime.

EUROfusion is currently investigating advanced RAFM steels with improved properties at higher temperature (EUROFER-HT)

EUROFER 97 - Chem. Comp. wt%			
	min	max	Comments
Cr%	8.5	9.5	Target 9
C%	0.09	0.12	Target 0.11
Mn%	0.2	0.6	Target 0.4
P%	-	0.005	
S%	-	0.005	
V%	0.15	0.25	
N_2%	0.015	0.045	Target 0.030
W%	1	1.2	Target 1.1
Ta%	0.1	0.14	Target 0.12
Ti%	-	0.02	
Nb%	-	0.005	ALAP
Mo%	-	0.005	ALAP
Ni%	-	0.01	ALAP
Cu%	-	0.01	ALAP
Al%	-	0.01	ALAP
Si%	-	0.05	
Co%	-	0.01	ALAP
B%	-	0.002	ALAP
As+Sn+Sb+Zr%	0	0.05	
Fe%-	Balance	Balance-	

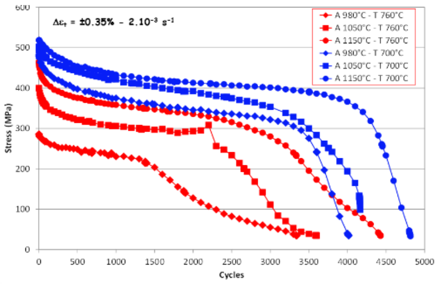


Advanced (RA)FM steels for high temperature operation

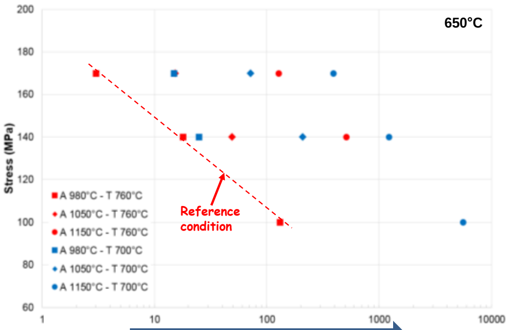
Strategy 1 – alternative TT/TMT ← (not specific to fusion) → **Strategy 2 modification of Chem. Comp.**

- Alternative TT can significantly improve the strength, fatigue and creep properties.
- TMT seem less effective in this sense
- All alloys present reduced impact properties w.r.t. as received conditions.

Selection of TT supported by ThermoCalc calculations

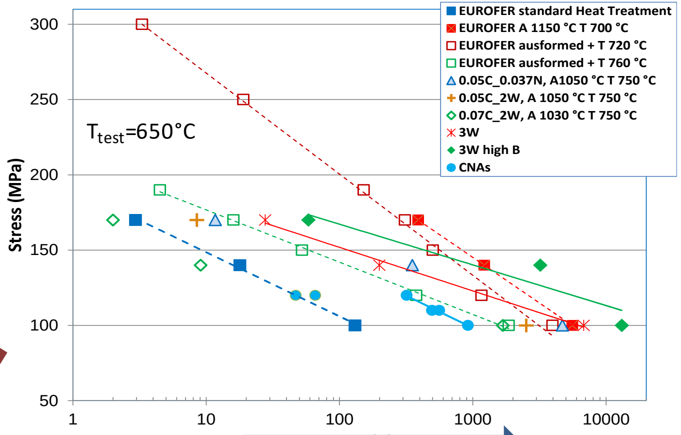


Number of cycles



Time to rupture

- Modification of C of N content does not yield significate improvements
- Addition of W and B significantly improves creep strength
- Impact properties are preserved



Time to rupture

Next : investigate effects of advanced TT on modified compositions.

Development of ODS steels

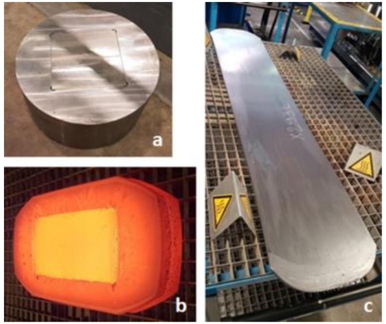
- The EU Fusion Roadmap includes **development of 9-14%Cr ODS steels** for advanced blanket concepts because:
  - They present higher thermal **creep resistance** w.r.t. conventional FM steels.
  - They exhibit **less radiation-induced hardening** than conventional RAFM steels, as oxides act as effective point defects sinks.
  - **Oxides act as precipitate sites to 'fix' the helium gas bubbles generated by high-energy fusion neutrons preventing movement to grain boundaries and enhanced embrittlement.**

- **Upscaling to industrial scale production (at a reasonable cost) is still needed.** EUROfusion is following two different approaches:
  - **Fabrication of a large ODS batches following the classical route (Mechanical Alloying – MA) in close collaboration with industry.**
  - **Development of an alternative (i.e. without MA), low cost, ODS production route.**

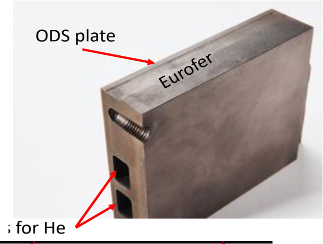
Development of ODS steels – MA route

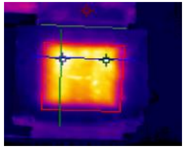
- **Upscaling in collaboration with industry:**
  - atomization of pre-alloyed powders NANOVAL Powderful Solutions
  - Mechanical alloying of the powder with Y_2O_3 powders PLANSEE
  - vacuum canning (by Aubert & Duval) AUBERT&DUVAL
  - consolidation by hot isostatic pressing (HIP; by Bodycote) Bodycote
  - hot-cross rolling and final cold rolling (by OCAS). ocas

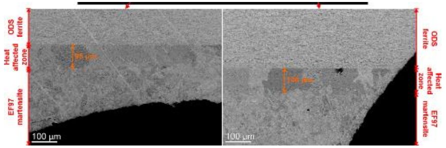
a) ODS blocks after HIPing
b) subsequent machining



a) ODS block with protective cladding; b) block during hot cross-rolling; c) plate after hot-rolling

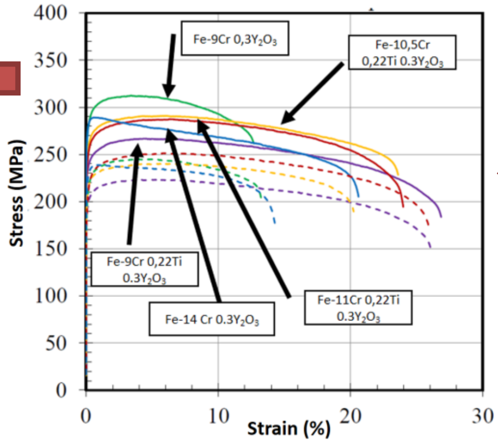






EUROFER+ODS mockup welded by HIP

High Heat Flux testing at 650°C in HELOKA facility at KIT + post-mortem examination



Tensile curves measured at 700°C (dotted lines) and at 650°C for 5 ODS grades with various Cr contents

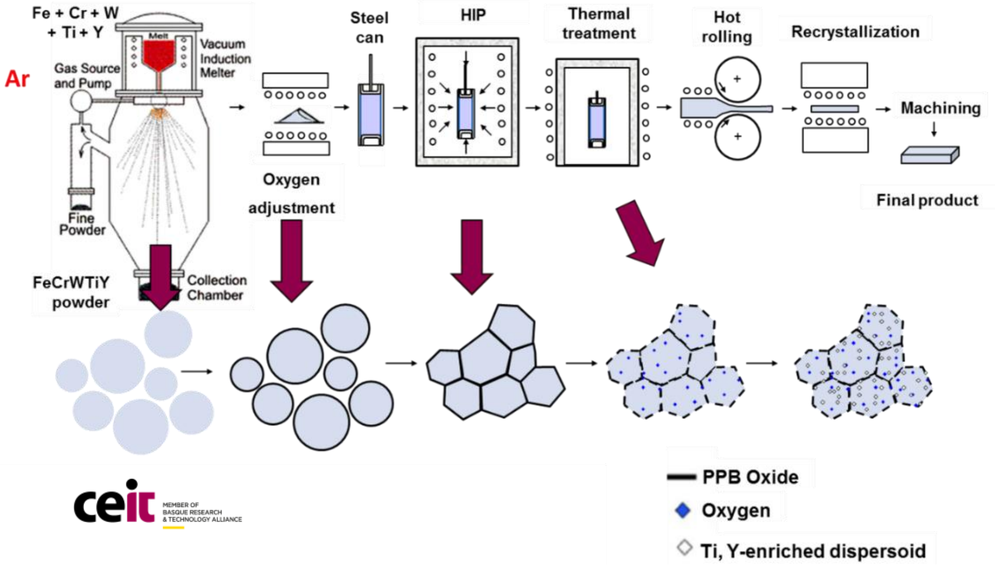
Following the successful fabrication of thin ODS plates, five additional 9-14%Cr ODS grades have been produced. The obtained results will be the base for the selection of the most suitable grade for the fabrication of thick First Wall mock-ups

Development of ODS steels – STARS route

STARS = Surface Treatment of gas Atomized powder followed by Reactive Synthesis

1. powder atomization (VIM)
2. powder oxidation (Cr-rich oxide layer)
3. consolidation by HIP followed by high temperature thermal treatments (oxygen reacts with Ti and Y forming the desired nano-oxides)

Development at lab-scale has reached a level where powder batches whose chemical compositions are within specifications are routinely produced. The method is robust, leads to reproducible results and can be implemented in the industry



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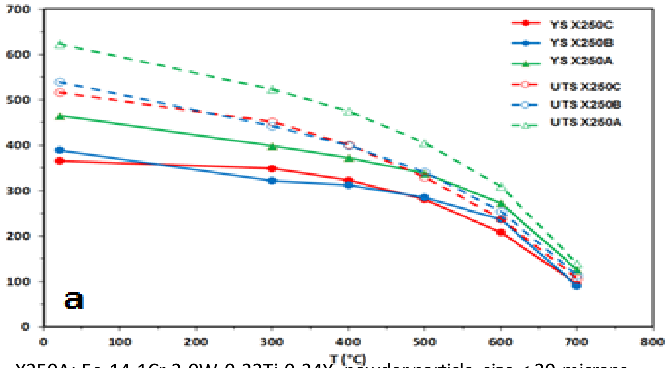


X250A: Fe-14.1Cr-2.0W-0.32Ti-0.34Y, powder particle size < 20 microns.
X250B: Fe-14.2Cr-2.0W-0.30Ti-0.18Y, powder particle size < 20 microns.
X250C: : Fe-14.2Cr-2.0W-0.30Ti-0.18Y, powder particle size 20-45 microns.

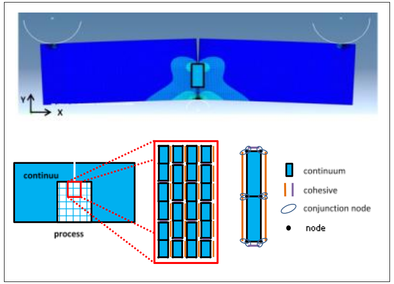
Strength is still low (~70-80%) compared to ODS produced with the MA route: microstructure needs further optimization

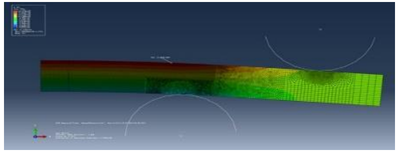
Development of C&S

- **The combination of new materials and new applications must be supported by extension of existing C&S**

- **The DEMO Design Criteria (DDC)** are being developed to complement existing C&S :
  - Rules for cyclic-softening, multi-axial fatigue, creep-fatigue interaction, fast fracture (ductile or brittle)
  - Deterministic and probabilistic approach (*partial safety factors*).

- Other long term activities cover **statistical methods** for analysis of data to **improve confidence interval** with scarce data as well as **optimize test matrixes** for future characterization activities (in particular w.r.t irradiation)



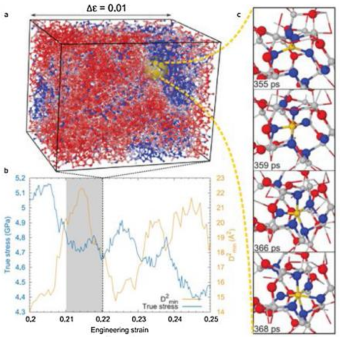


Local approach for brittle fracture

DDC is being developed to complement existing C&S, not to replace them.
The rules developed in DDC-IC could in the future be included in existing C&S.

Compatibility with coolants / breeder materials

- **Al-based (Al_2O_3) coatings** are considered as **corrosion (and T permeation) barriers in PbLi** – upscaling of fabrication techniques:
  - **PLD – Pulsed Laser Deposition**: Ductile Amorphous Ceramic showing plastic behavior at room temperature. Excellent stability and permeation reduction. Only on external surfaces.
  - **ECX – Electro Chemical deposition:** High deposition rates, self-healing. Need for heat treatment.
  - **ALD – Atomic Layer Deposition:** CVD process, low temperature. Sensitive to surface cleanliness.

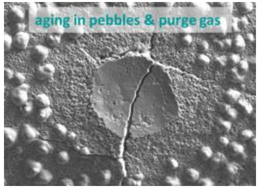


Atomistic mechanism of room temperature plastic deformation in α-Al_2O_3

- Modeling **of corrosion phenomena in water/RAFM/316LN system** (+joints)
  - Optimization of Water chemistry, IASCC
  - **Development of ACP codes** (PACTOLE, TRACT, PACTITER, **OSCAR-Fusion**) – **inclusion of (RA)FM steels**

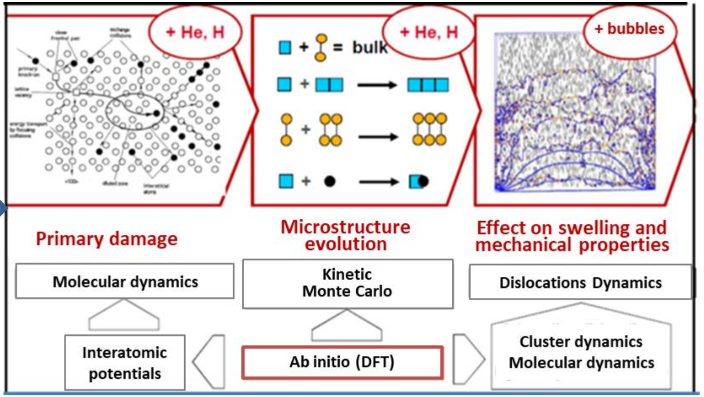
HTHP loop in ENEA/RINA

- Compatibility with **He coolant at high temperatures** (impurities)
  - Effects of H_2 addition (H induced embrittlement)
  - Effects of oxygen impurities + pebble beds
  - Tests are foreseen in the HELOKA facility in KIT.

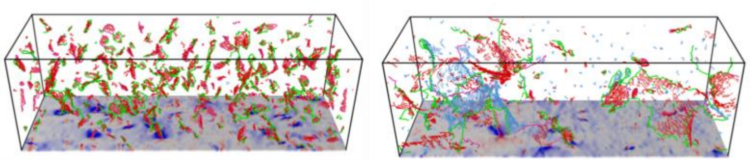


Multi-scale material modeling

- **Underlying theories and calculation tools are the same in Fission and Fusion**
  - emphasis on linking atomistic simulations with the dislocation-based representation of microstructure, supported by experimental observations.
  - In fusion, particular attention is given to **swelling and He production, i.e. effects of 14.1MeV neutrons.**

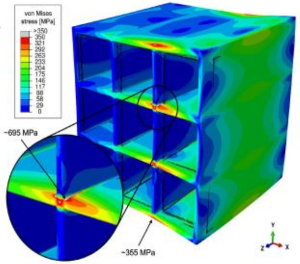


- The recently developed **Creation-Relaxation Algorithm (CRA)** has enabled simulation of high dose (tens of dpa) defect and dislocation structures on a million-atom scale.



Representative Frenkel pair insertion simulations at 0.05 (left) and 0.3(right) dpa

- **Microscopic modelling of swelling has been linked with FEM simulations** of blanket structures exposed to similar level of dpa as fuel claddings in fission
  - In fission, deformations are caused by the crystal anisotropy and texture of the cladding material. In fusion, stress and deformation result from the spatial heterogeneity of neutron exposure



Irradiation programs and SSTT

- EUROFER97 irradiation (up to 20 dpa, 1rst DEMO phase):
  - HFIR – ORNL: T=200, 300 , 350°C, tensile and ductility properties, static toughness ➔**achieved, PIE on-going**
  - BR2 - SCK-CEN: (T=300, 550°C, tensile and ductility properties, fatigue, creep, swelling, impact properties and static toughness) ➔ **Planned**

- Screening irradiations for advanced materials (BR2, SCK-CEN):
  - For advanced materials (FM steels, ODS)
  - For coatings
  - To support material modeling.

} “Low” dose 5-10 dpa
Planned (2020-2027)

- A common requirement is the availability of “standardized” data on irradiated properties determined on small size specimens:
  - **EUROfusion is co-funding participation to the AIEA CRP “Towards the Standardization of Small Specimen Test Techniques For Fusion Applications” in collaboration with CIEMAT, KIT, UKAEA and SCK-CEN.**

Summary: Fission-Fusion synergies

- Common topics of interest in Fission and Fusion:
  - Development of heat and radiation resistant materials (F/M steels, ODS)
  - Upscaling of manufacturing and welding/joining techniques.
  - Understanding of effects of irradiation (microstructure stability, He embrittlement, irradiation creep and swelling)
  - Compatibility with coolants (He, H_2O), development of corrosion barriers (Pb alloys)

- Possible areas of cooperation:
  - Sharing of facilities for component mock-ups testing
  - Common irradiations and PIEs of materials
  - Development of simulation tools (material modeling, but also neutronics, thermo-hydraulics, ACP codes…)
  - Development of (nuclear) C&S

THANK YOU FOR YOUR ATTENTION

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