Materials R&D for a Near-Term DEMOnstration Fusion Reactor

G. Federici, and the EFDA PPPT Team

EFDA Power Plant Physics and Technology

- Roadmap toward a Demonstration Fusion Power Plant
- Main Materials Issues/ Challenges for DEMO
- R&D Priorities: Advanced Steels and High Heat Flux Materials

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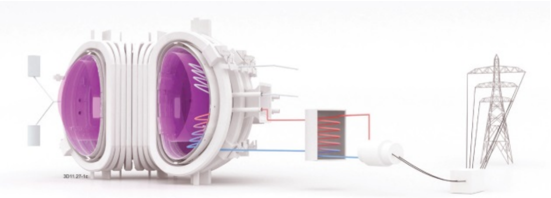
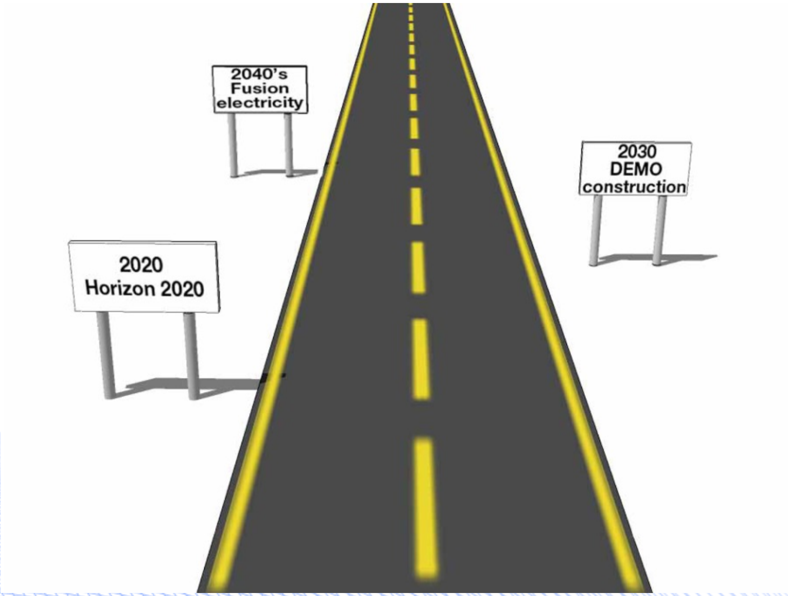
EIROForum Science-Business WAMAS

Workshop on Advanced Materials and Surfaces

CERN, Geneva, Switzerland
19-20 November 2013

Part 1:
EU Roadmap toward a Demonstration Fusion Power Plant



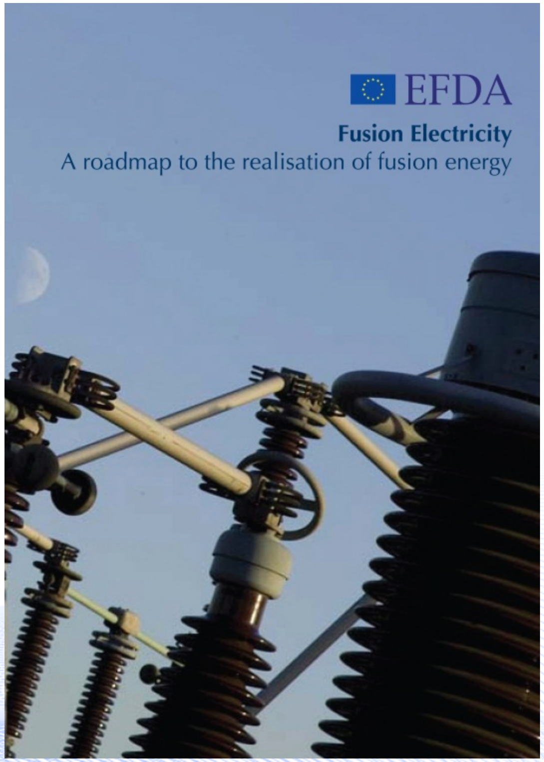


New EU Fusion Roadmap

- An ambitious yet realistic roadmap to fusion electricity by 2050
- Published in November 2012
- 8 Strategic Missions to tackle the critical challenges for Fusion:

http://www.efda.org

1. ***Plasma Operation***
2. ***Heat Exhaust***
3. ***Neutron resistant Materials***
4. ***Tritium-self sufficiency***
5. ***Safety***
6. ***Integrated DEMO Design***
7. ***Competitive Cost of Electricity***
8. ***Stellarator***


EFDA
Fusion Electricity
A roadmap to the realisation of fusion energy

Emphasis on:

- ❖ **Central role of ITER**
- ❖ **14 MeV neutron sources for material qualification**
- ❖ **DEMO as a single step to the commercial power plant**
- ❖ **Pragmatic approach to DEMO foreseen as a project starting construction in early 2030s** (to make electricity and tritium)

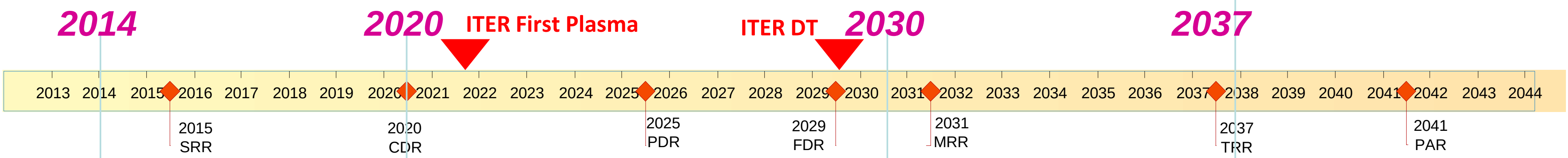
→ It should not be perfect but good enough and must come on time to make an impact.

- December 2011: **Independent Material Assessment Group** to answer Q.: “which Materials for which DEMO?”
  - ❖ **to review EU structural, HHFC materials R&D** programme for a DEMO;
  - ❖ to identify all the major knowledge gaps;
  - ❖ to establish a coherent strategy and road map; and
  - ❖ to define a resource-loaded R&D plan

Final MAG Report - December 2012

DEMO Programme Timeline

EU Fusion Roadmap, emphasising a DEMO concept with a construction decision in the early-2030s allows a sharp focus on issues of materials development.

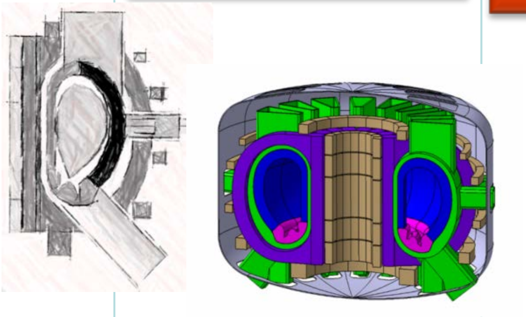


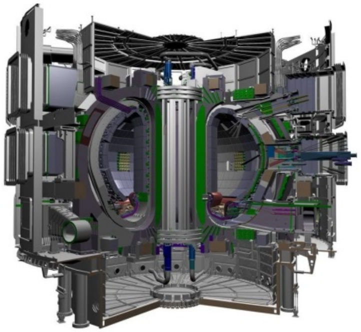
CDA

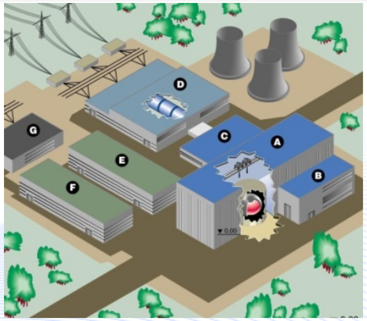
EDA

Construction

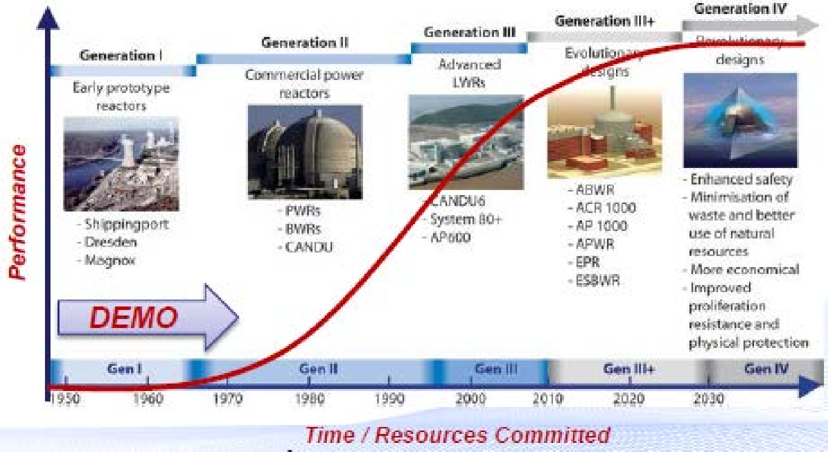
Commissioning/ Operation







Development Paradigm: Fission Power Plants



DEMO must
- **Demonstrate production of electricity**
- **Make its own fuel/ T-self-sufficiency**

Fission: Simple/ well established physics→ evolution thanks mainly to advances in materials and technology (and involvement of industry from the very beginning)

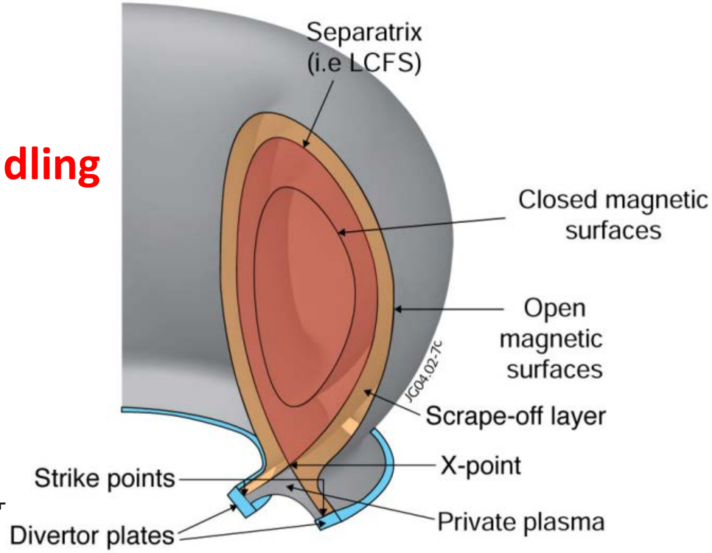
Fusion: Complex physics with many uncertainties - technologies readiness in many areas still quite low. In some areas we are close to physical material limits or even beyond (e.g., divertor).

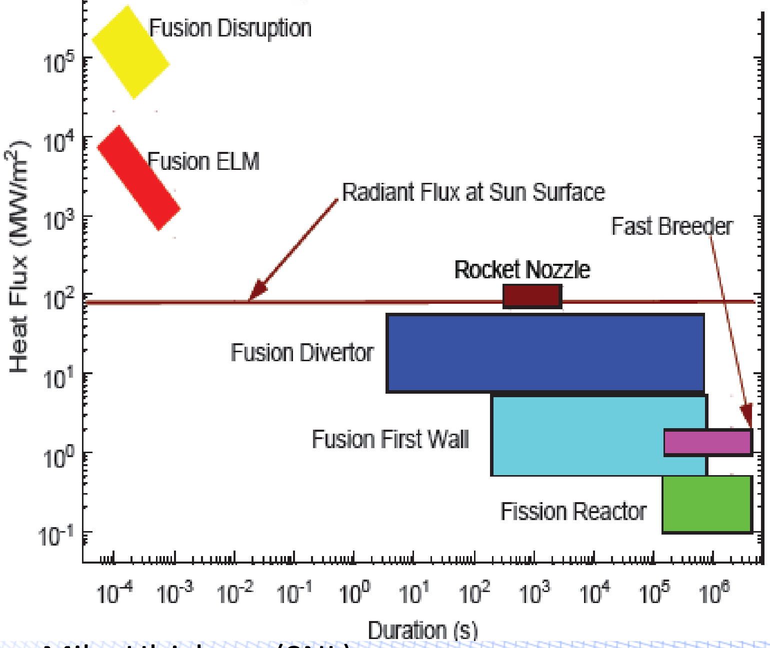
Part 2:

Main Materials Issues/ Challenges for DEMO

Main Materials/ Design Issues
Neutrons and Heat

Power handling

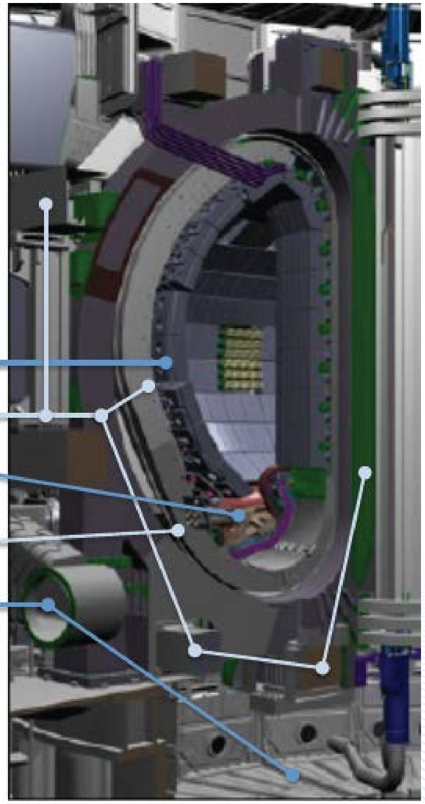




Mike Ulrickson (SNL)

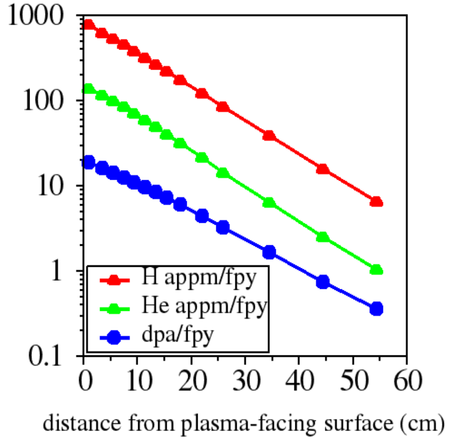
Radiation damage

ITER Lifetime Fast Neutron Fluence (n/m2; E>0.1 MeV)	Fusion Power Reactor Annual Fast Neutron Fluence (n/m2, E>0.1 MeV)	Compon-ent
3.7e21	5e22	Blanket
5.1e14	7e15	Magnet
1.9e21	2.6e22	Divertor
1.1e19	1.5e20	Vacuum Vessel
3.4e11	4.5e12	Cryostat



S. Zinkle, ORNL ICFRM 16

M. Gilbert, CCFE

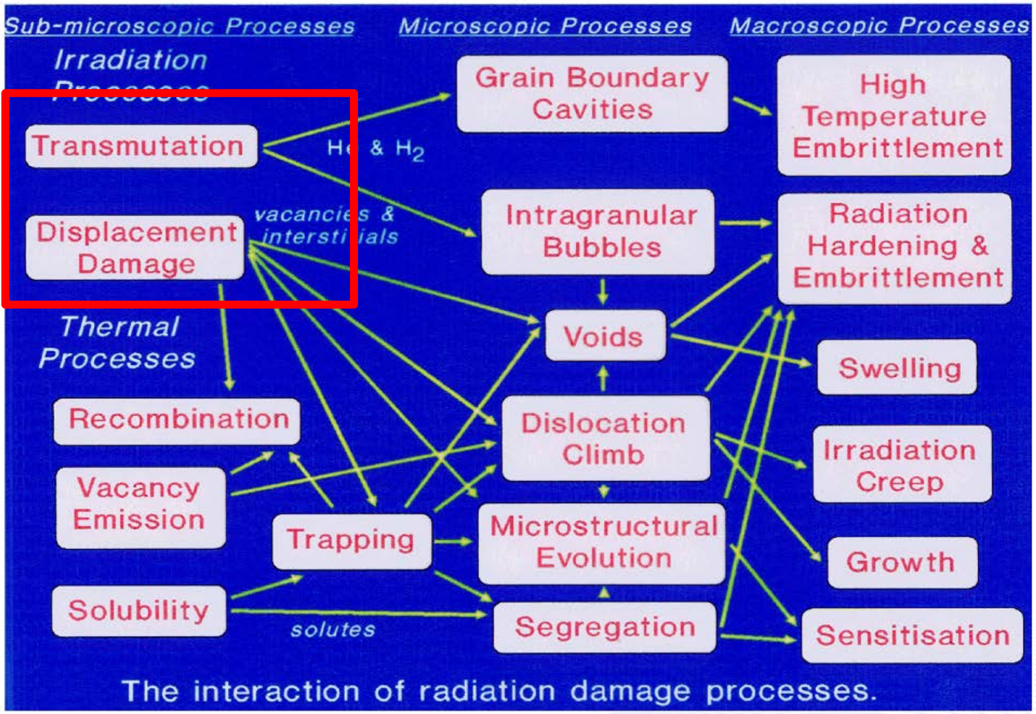


Strong thermal and stress gradients!!

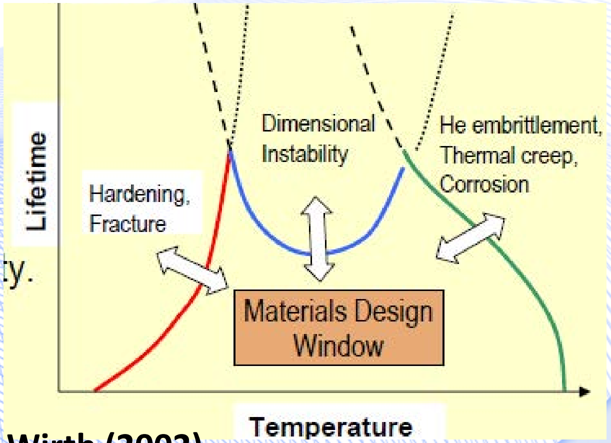
Effects of Neutron Irradiation on Materials

	Fission (Gen. I)	Fission (Gen. IV)	Fusion (ITER)	Fusion (EU DEMO)
Structural alloy T_{max}	<300˚C	600-850˚C (~1000˚C GFRs)	300˚C	290-500˚C
Max dose (core intern)	~1 dpa	~30-100 dpa	<3 dpa	~10 dpa/fpy
Max He conc.	~0.1 appm	~3-10 appm	~30-60 appm	~300-1000 appm
He/dpa H/ dpa	~1 ~10	~1 ~10	> 10 > 40	> 10 > 40
Coolants	H_2O	He, H_2O, Pb-Bi, Na	H_2O	H_2O, He, PbLi
Structural materials	Zircaloy, stainless steel	Ferritic steel, St steel, Superalloys, C-comp.	Austenitic 316 LN-IG	Reduced Activation FM steel

C. English (2011)



The interaction of radiation damage processes.



Ghoniem & Wirth (2002)

- **Narrow design temperature operation window**
- **High He concentrations may narrow design window**

Typical DEMO Materials

- **Internal Components**
  - **Divertor**: W (armour), Cu-alloy (heat sink), Eurofer
  - **Breeding Blanket**: Li_4SiO_4, Li_2TiO_3, Be, $Be_{12}Ti$ (high melting point and good chemical stability), LiPb Eutectic, EUROFER, Coatings (Al_2O_3 etc.)
- **Magnets**
  - **Conductor**: Nb_3Sn, NbTi (LTSC), ReBCO, YBCO (HTSC),
  - **Coil Case**: Stainless Steel….
- **Heating & Current Drive Systems**:
  - **NBI:** Cs, Cu-alloy, steels, insulators, Nb_3Sn
  - **ECH**: CVD diamonds, Cu-alloys, steels, Cryogen-free magnets YBCO (HTSC)
  - Others…
- **Diagnostics**
  - Ceramics, insulators, wires and cables, mirror and reflectors, window, optical fibres, etc, (e.g., silica glasses KU-1, KS-4V)
- **Vacuum systems**
  - Cryogenic pumps: Charcoals, liquid metals, e.g, Hg (continuous pumps), V, steels. Insulators…
- **Remote Maintenance**
  - Cables, fibre-optics, etc….
- **BoP**

EU DEMO In-vessel Components

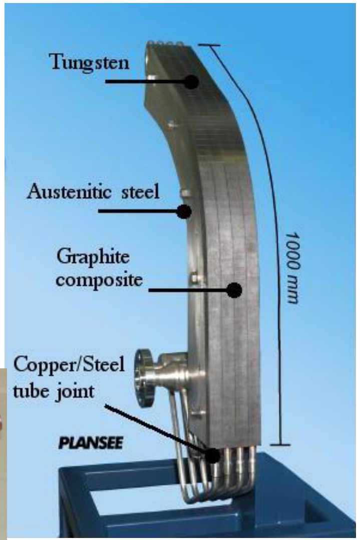
Divertor

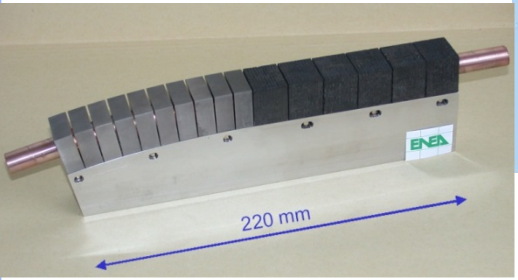
Armour: Tungsten

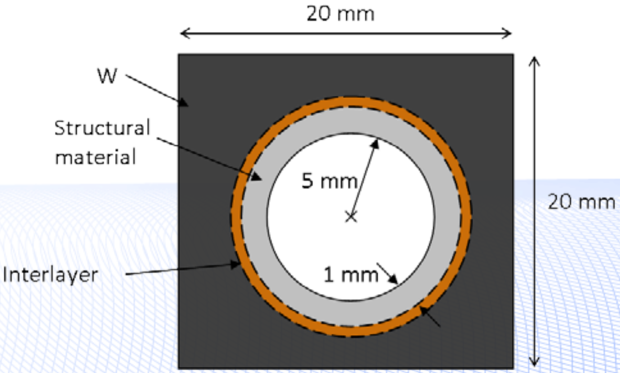
Structural: CuCrZr

<10 dpa, 200-350°C

Coolant: Water







Timmis, CCFE

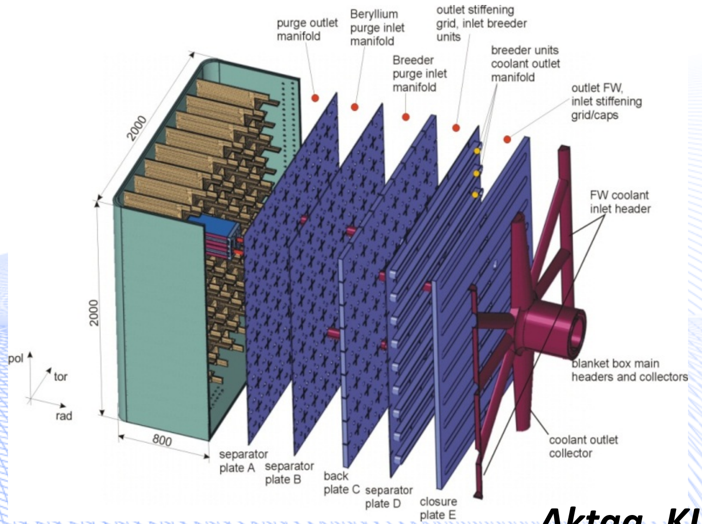
Blanket

Armour: Tungsten

Structural: EUROFER97

~20 dpa, 300-500°C, ≤12 appm/dpa

Coolant: Helium or Water

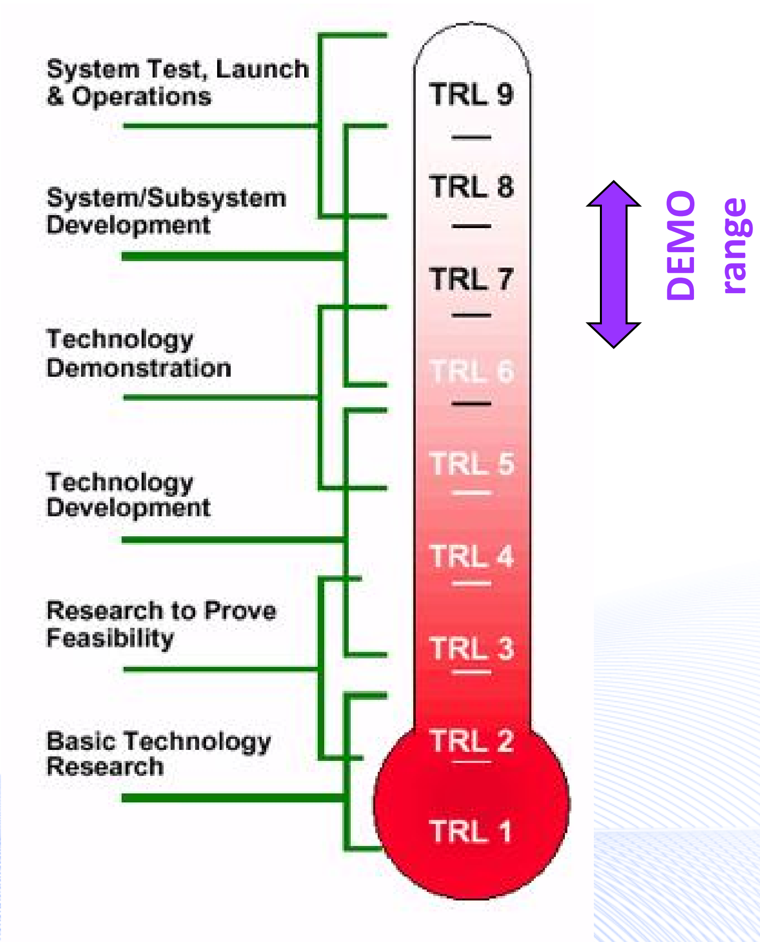


Aktaa, KIT

W-Cu laminates
ODS EUROFER
W & W-base alloys

Zr-base alloys
Al-base alloys

Part 3:
R&D Priorities: Advanced Steels and High Heat Flux Materials



Materials versions of this NASA meter are in development

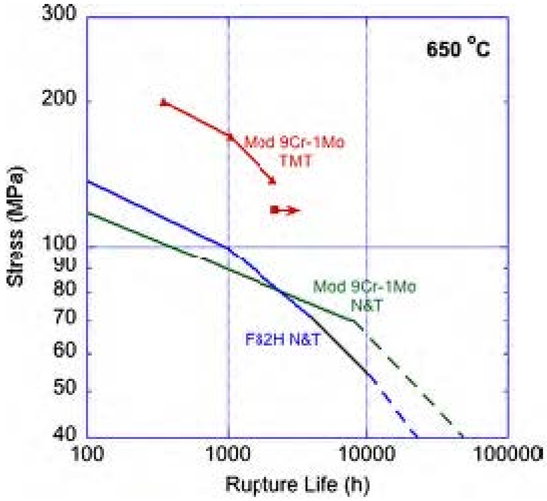
Blanket Structural Steels
Baseline and Risk-log

EUROFER (8-9%Cr Reduced Activation Ferritic Martensitic –RAFM - Steel) is confirmed by the MAG as Baseline structural steel (TRL4/5)

- Good overall mechanical properties required (strength ductility, fracture toughness, creep resistance, fatigue resistance);
- broad industrial experience in fabrication;
- sufficient corrosion resistance to LiPb for interface temp. at least ~475C;
- compatibility with He-gas cooling;
- good neutron-irradiation stability of a BCC material (low swelling, more resistant to DBTT and radiation-hardening
- Low-activation – ‘hands-on’ recycling of waste after ~ 100 y.

In current form, narrow operational temperature range of EUROFER (350°C – 500°C) poses high-impact risks for the DEMO mission

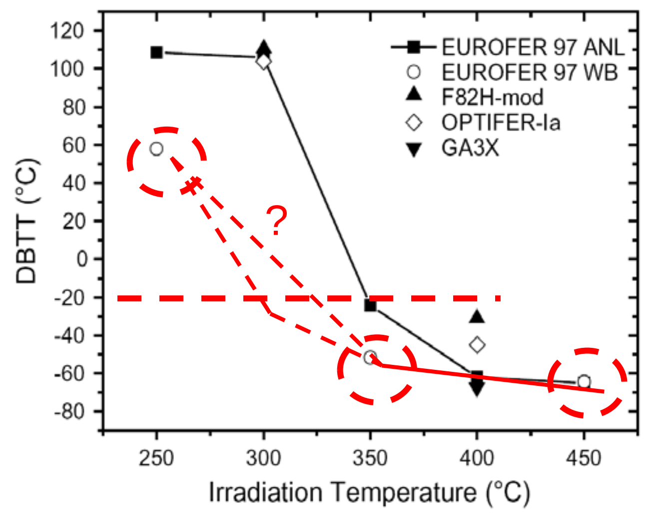
- Low temperature radiation embrittlement
- Unknown effect of helium embrittlement
- Decline in strength above 550°C
- Creep-rupture limits operation to <550°C for >12 10^3h
- Lack of Design-code development
- Incompatibility with Water-cooled blanket/PWR BoP



S. Zinkle (ORNL) J. Nucl. Mat. 417 (2011) 2

Blanket Structural Steels
Risk Mitigation

- Needs a risk mitigation programme on blanket advanced steels.
- MAG recommends (candidates identified at TRL~3 or above):
  - EUROFER development to lower T. Evidence of some EUROFER heats with superior low temp performance + new JA F82H mod3 data (Shiba, Tanigawa et al)
  - High temperature FM steels from the non-Fusion programme
  - Oxide Dispersion Strengthened (ODS) RAFM or Ferritic Steels (Fusion programme)
- Good physical metallurgy reasons to expect these latter two steels to be more resilient against He-embrittlement:
  - ODS RAFM steels incorporate Y_2O_3 particles (by fine ball-milling into a RAFM alloy powder) - yttria is expected to provide a defect location to fix Helium migration – prevent accumulation at grain boundaries and resultant fracture.
  - the high precipitate density in the HT FM steels should do the same job, and improve the low temperature embrittlement.



D. Stork (CCFE), ICFRM 16 (2013)

- **Note: each 'back-up' already on its 10-15 years of development**

High-Heat-Flux Materials

Divertor HHFC materials choice is cooling concept dependent

Baseline and Risk-log

- **Baseline water-cooled divertor with W and Cu-based alloys for heat sinks.**
  → High W's erosion resistance and low tritium take-up → low inventory

- **Highest impact risks for Cu-alloys:**
  → Most serious Cu-alloy risks are rapid loss of ductility under irradiation at temperatures < 180°C (operating temp. should be kept above 200-250°C) → may necessitate composite material development.
  → There are activation issues with most promising alloy (Glidcop) but not serious after 100 year cool-down – worse than W but much better than Mo.

- **Highest impact risks for tungsten concern the degradation by irradiation :**
  - uncertainty in erosion and T-retention effects of neutron irradiated tungsten.
  - For tungsten as a Blanket PFC, require self-passivating tungsten alloys to avoid oxidation/deflagration in Loss Of Vacuum Accident – **DEMO licencing!**

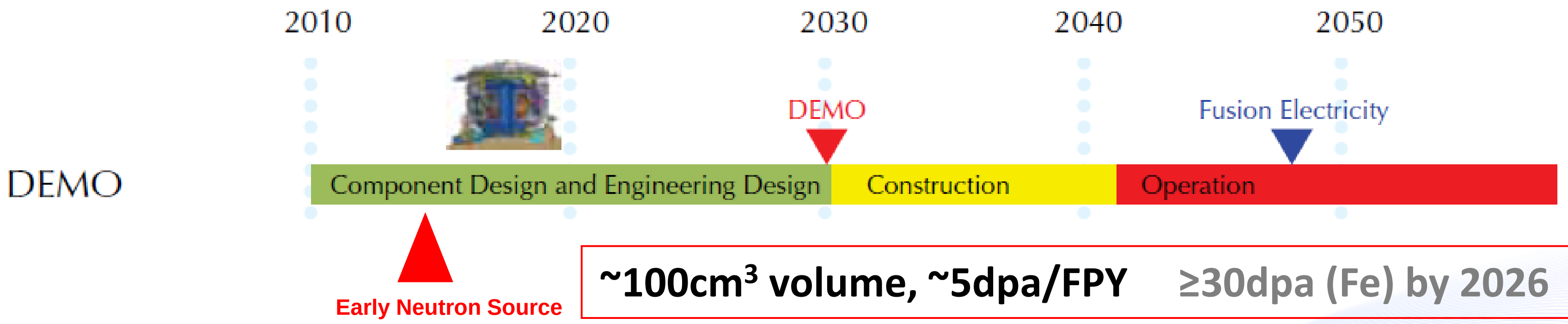
Risk Mitigation

Four promising materials are identified (composites) (all TRL 1-2) :

- W-fibre reinforced materials – most promising avenue for ductilisation of tungsten;
- Fibre and foil reinforced copper and tungsten
- W-Cu laminates (these are currently under irradiation test);
- Developing functionally-graded materials (tungsten-copper composites) for Divertor

Materials testing with a fusion neutron spectrum is a high priority.

- 14 MeV ‘spectrum’ n-test is essential to qualify the effect of He and H embrittlement – correct He/dpa ratio required. → must be timely (≥30dpa steels by 2026).
- IFMIF remains the long-term goal of the Materials testing programme, but deployment of full IFMIF before 2026 appears unlikely
- Roadmap favours testing using an ‘Early Light-ion accelerator-driven 14MeV neutron source’ operational early 2020s



~100cm^3 volume, ~5dpa/FPY ≥30dpa (Fe) by 2026

- Several options:
  - ENS/ DONES - D-Li : based on IFMIF EVEDA
  - FAFNIR (D-C)/ SORGENTINA DT-Ti: (based on technology outside fusion)

- → need assessment by dedicated Experts Group

- **However, fusion needs to exploit all applicable, available irradiation infrastructure (i.e., Fission reactors, spallation n-sources, etc.) to address the urgent material challenges of DEMO.**

Conclusions

- EU Fusion Roadmap, emphasising a DEMO concept with a construction decision in the early-2030s allows a sharp focus on issues of materials development.
- Adoption of a project-based methodology with risk analysis prioritises the R&D programme needed to produce materials to maximise the DEMO mission success.
- Systems engineering analysis, and applying lessons learnt in the fission programme, especially in the development of safety cases, codes and standards all help this process.
- ***Baseline Materials*** are identified for blanket structural applications (RAFM steels), PFC (W), and high-heat flux uses (W &Cu-alloys).
- ***Risk Mitigation Materials*** has also been identified for initial parallel development:
  → high temperature FM and ODS steels for the structure, and composite tungsten and copper materials (laminate, fibre-reinforced materials and functionally-graded materials) for the PF and HHF applications.
- Materials testing with a fusion neutron spectrum is a high priority.
- Acceleration and optimisation of a fusion spectrum test programme is needed via the early deployment of a less powerful 14 MeV neutron source compared to IFMIF, and by the pursuit of precursor programmes with isotopically- and chemically-tailored steels and helium ion implantation.

Thank you for your attention

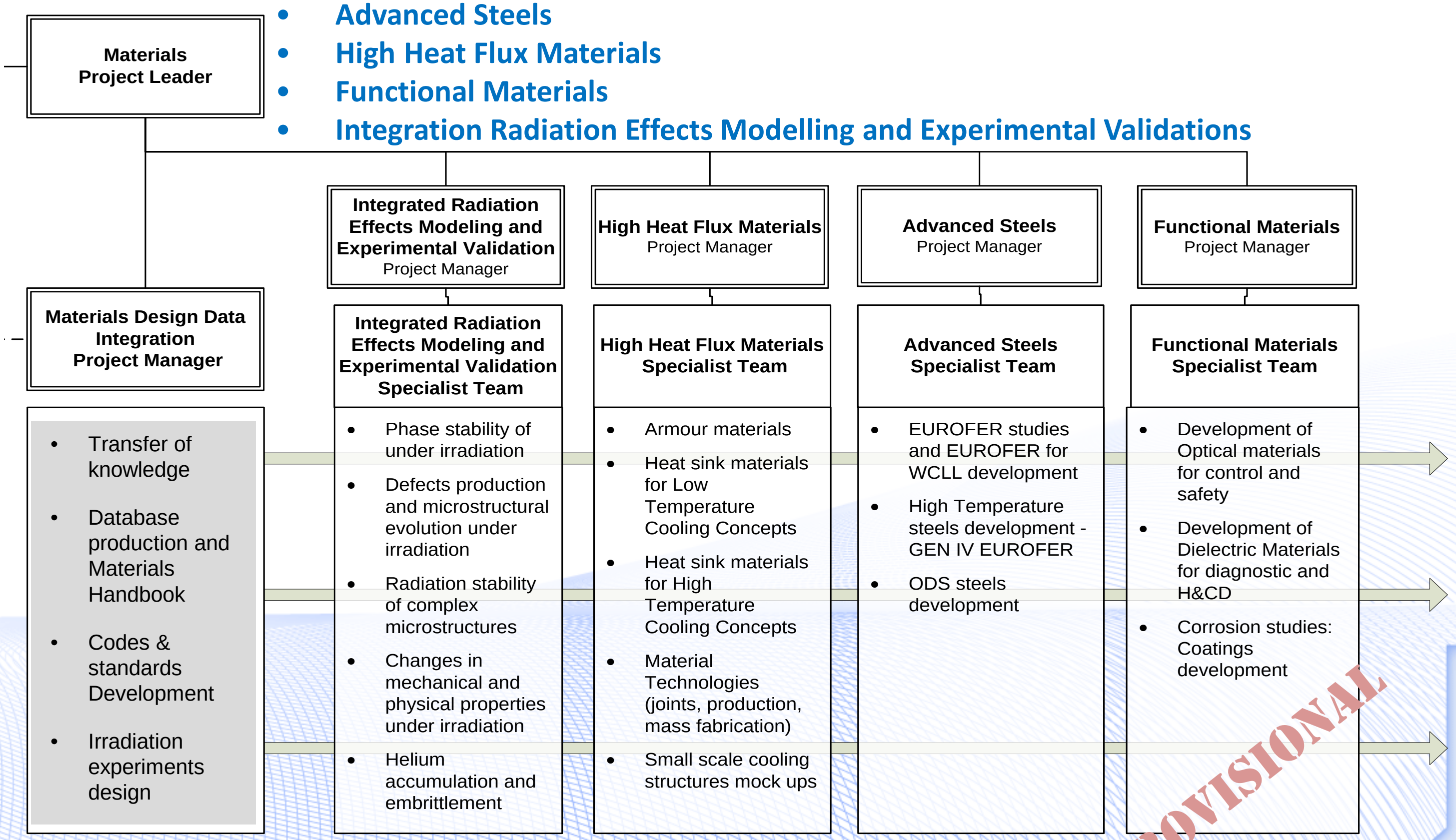
Organisation for 2014 and beyond…
Project Materials

- EFDA shall expire on 31st December 2013
- EFDA will be replaced by a **European Fusion Consortium** made up of all EU Associations with a coordinating association, to provide financial, legal and administrative functions

5 Activities

- Material Design Data Integration
- Advanced Steels
- High Heat Flux Materials
- Functional Materials
- Integration Radiation Effects Modelling and Experimental Validations

- The roadmap (CDA phase) will be implemented by a number of projects to be executed in the period 2014 to 2020.



Materials
Project Leader

Materials Design Data Integration
Project Manager

- Transfer of knowledge
- Database production and Materials Handbook
- Codes & standards Development
- Irradiation experiments design

Integrated Radiation Effects Modeling and Experimental Validation
Project Manager

Integrated Radiation Effects Modeling and Experimental Validation Specialist Team

- Phase stability of under irradiation
- Defects production and microstructural evolution under irradiation
- Radiation stability of complex microstructures
- Changes in mechanical and physical properties under irradiation
- Helium accumulation and embrittlement

High Heat Flux Materials
Project Manager

High Heat Flux Materials Specialist Team

- Armour materials
- Heat sink materials for Low Temperature Cooling Concepts
- Heat sink materials for High Temperature Cooling Concepts
- Material Technologies (joints, production, mass fabrication)
- Small scale cooling structures mock ups

Advanced Steels
Project Manager

Advanced Steels Specialist Team

- EUROFER studies and EUROFER for WCLL development
- High Temperature steels development - GEN IV EUROFER
- ODS steels development

Functional Materials
Project Manager

Functional Materials Specialist Team

- Development of Optical materials for control and safety
- Development of Dielectric Materials for diagnostic and H&CD
- Corrosion studies: Coatings development