ORIENT-NM - Organisation of the European Research Community on Nuclear Materials

CROSS-CUTTING ISSUES IN FUSION AND FISSION MATERIALS DEVELOPMENT

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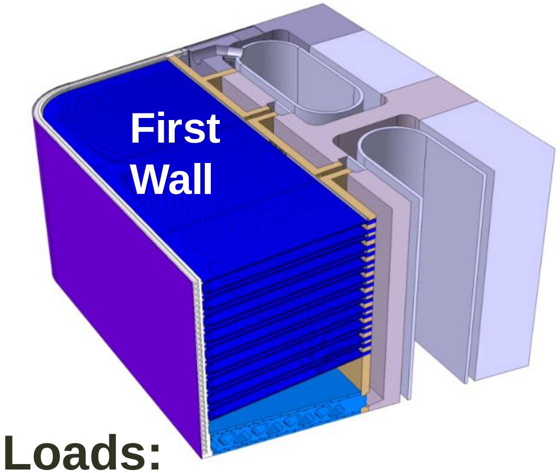
Outline:

- Harsh conditions in fusion, fission and other energy technologies
- F/M steels as intersection materials
    - Cyclic softening/hardening
    - Plastic flow localisation
    - Improvement of creep strength
    - Ion irradiation as screening technique
    - Materials acceleration platforms

Materials for plasma-near DEMO components will need to withstand unprecendented conditions

Blanket



Loads:

≤ 2.5 MW/m²

≤ 25 dpa/fpy

≤ 250 appm He/fpy

Materials

EUROFER

(9Cr RAF/M steel)

350–550°C,

400 appm He*

EUROFER-ODS

400–650°C

Tungsten alloys

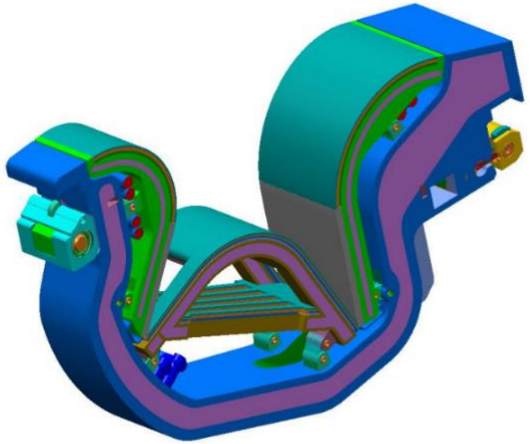
800–1100°C

Cu-1%Cr-0.1%Zr

(heat sink, high conductivity: 350 W/m/K)

fpy ≡ full power year

Divertor



Loads:

≤ 10 (20) MW/m²

≤ 10 dpa/fpy

≤ 100 appm He/fpy

Coolants: **water, helium, (heavy) liquid metals (PbLi), in some designs simultaneously used**

These are extremely high thermo-mechanical, neutron irradiation and environmental loads:
difficult to find equivalent conditions in other technologies

** E. Gaganidze, J. Aktaa, Fus. Eng. Des., 2013*

From J. Aktaa, KIT, FISA workshop

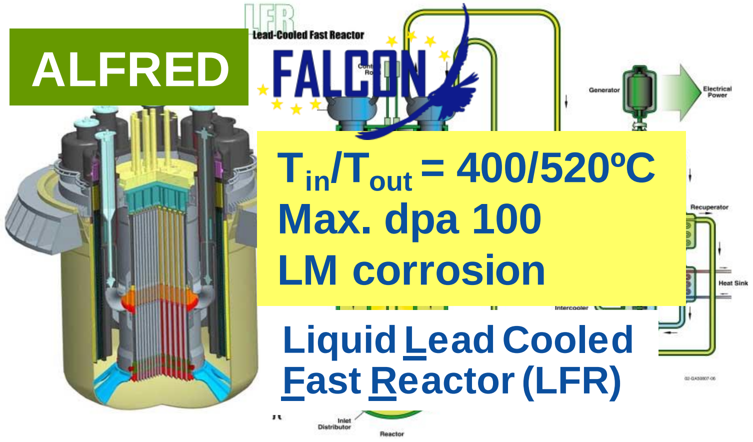
Nuclear fission GenIV systems also envisage largely unprecendent conditions for materials

framatome cea EDF

ASTRID

T_{in}/T_{out} = 350/550ºC
Max. dpa 150
60 yrs lifetime

Liquid Sodium Cooled Fast Reactor (SFR)

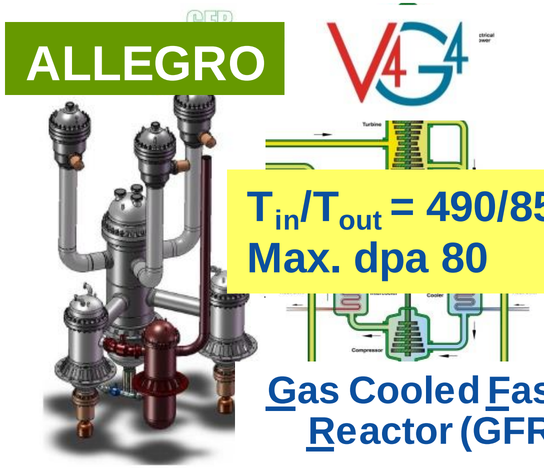


ALFRED

FALCON

T_{in}/T_{out} = 400/520ºC
Max. dpa 100
LM corrosion

Liquid Lead Cooled Fast Reactor (LFR)

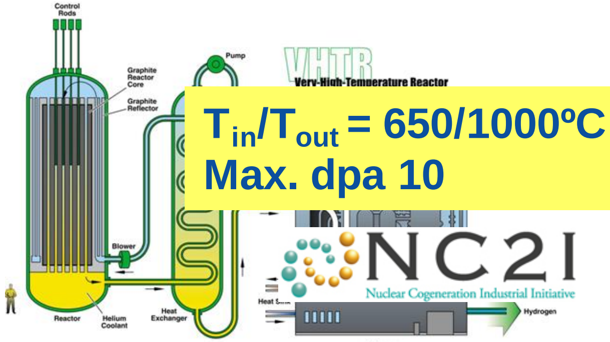


ALLEGRO

V4G4

T_{in}/T_{out} = 490/850ºC
Max. dpa 80

Gas Cooled Fast Reactor (GFR)



T_{in}/T_{out} = 650/1000ºC
Max. dpa 10

NC2I
Nuclear Cogeneration Industrial Initiative

(Very) High Temperature Reactor (HTR)

T_{in}/T_{out} = 280/625ºC
HT SCwater corrosion

NUGENIA
Nuclear Generation II&III Alliance

SuperCritical Water Cooled Reactor (SCWR)

T_{in}/T_{out} = 200/340ºC
LM corrosion

MYRRHA

sck cen
Belgian Nuclear Research Centre

Accelerator Driven System (ADS)

Currently emerging, several startups

T_{in}/T_{out} = 620/<750ºC
Max. dpa 80
MS corrosion

Molten Salt Reactor (MSR)

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GenIV systems according to GenIV Intl. Forum (2001) + ADS

European Sustainable Nuclear Industrial Initiative ESNII concepts

Beyond nuclear energy, also solar, bio and fossil thermal energy expose materials to extreme conditions

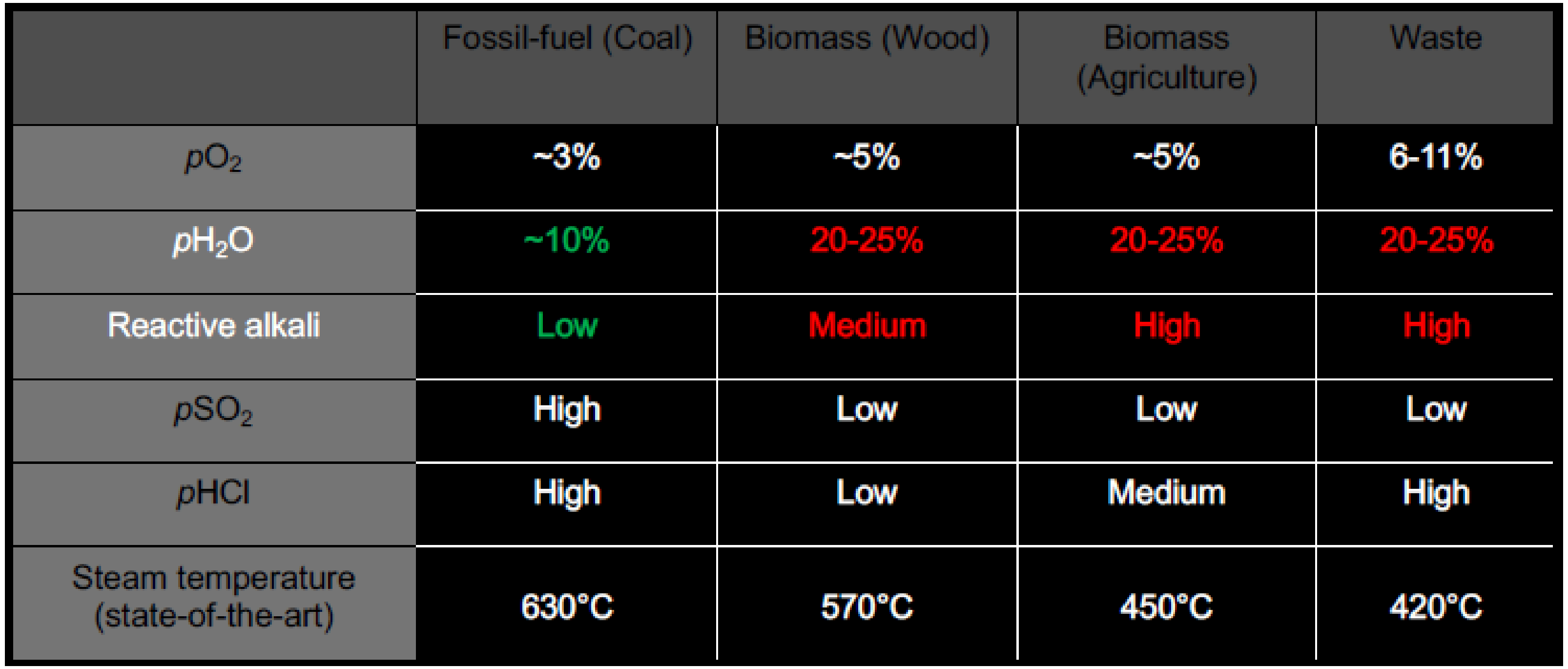
P. Heller, DLR

Point Focus Systems

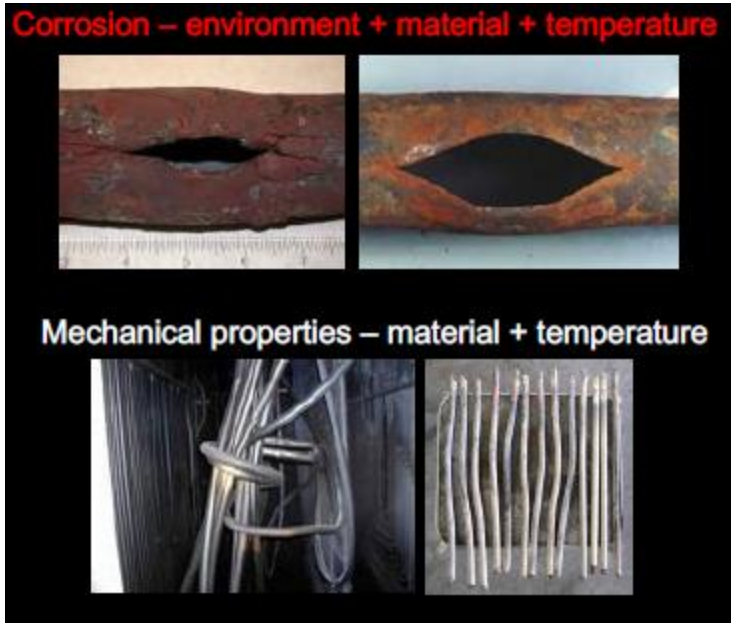
- Steam: 560°C
- Molten Salt: 560°C
- Air/Helium: 700-1000°C
- Liquid Metals: 560°C
- Heat flux: up to 6 MW/m^2

Line Focus Systems

- Synthetic Oil: 390°C
- Steam: 560°C
- Molten Salt: 560°C



	Fossil-fuel (Coal)	Biomass (Wood)	Biomass (Agriculture)	Waste
pO_2	~3%	~5%	~5%	6-11%
pH_2O	~10%	20-25%	20-25%	20-25%
Reactive alkali	Low	Medium	High	High
pSO_2	High	Low	Low	Low
$pHCl$	High	Low	Medium	High
Steam temperature (state-of-the-art)	630°C	570°C	450°C	420°C



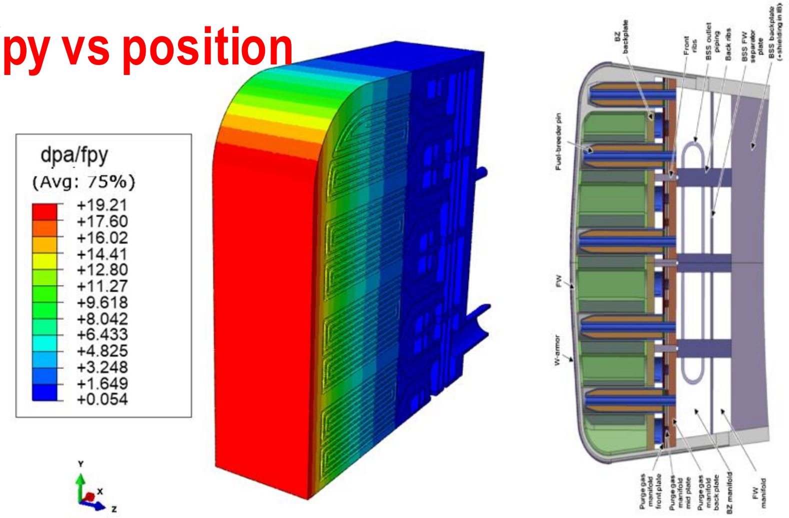
T. Jonsson, Chalmers

Four specificities of fusion: high helium production, high thermal shocks, activation of large quantities of structural materials, tritium

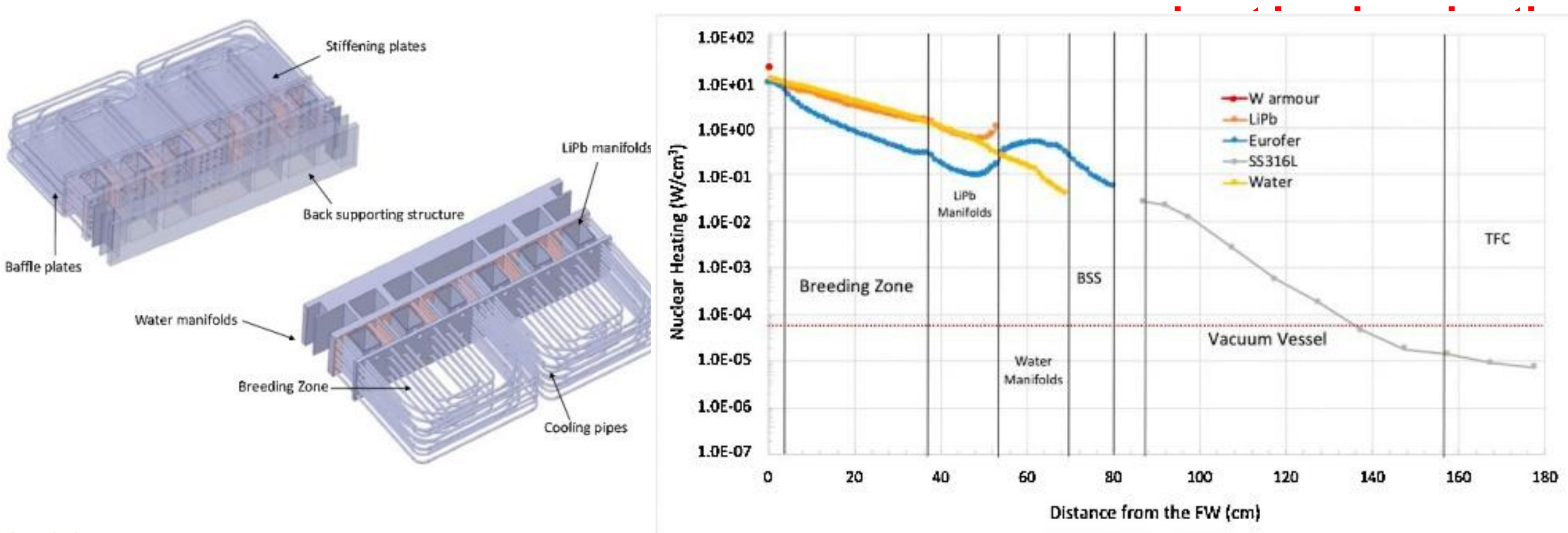
HCPB DEMO breeding blanket

WCLL DEMO breeding blanket

dpa/fpy vs position



Fusion Engineering and Design 169 (2021) 112428



Fusion Engineering and Design 168 (2021) 112514

- ❑ A few centimeters make a big difference as they suffer from:
  - ❖ High He/dpa ratio: *~10 He appm/dpa in the steel (fusion) >> 0.1 He appm/dpa (GenIV)*
    - ⇒ Fission reactor irradiation is relevant for most structures except for these “few cm”
  - ❖ High heat flux: ~ *1 MW/m^2* – *no equivalent in fission, comparable with solar applications*
  - ❖ High heat load: ~ *1-10 W/cm^3 in the steel and even more in tungsten*
    - ▪ Special heat flux protection solutions are needed

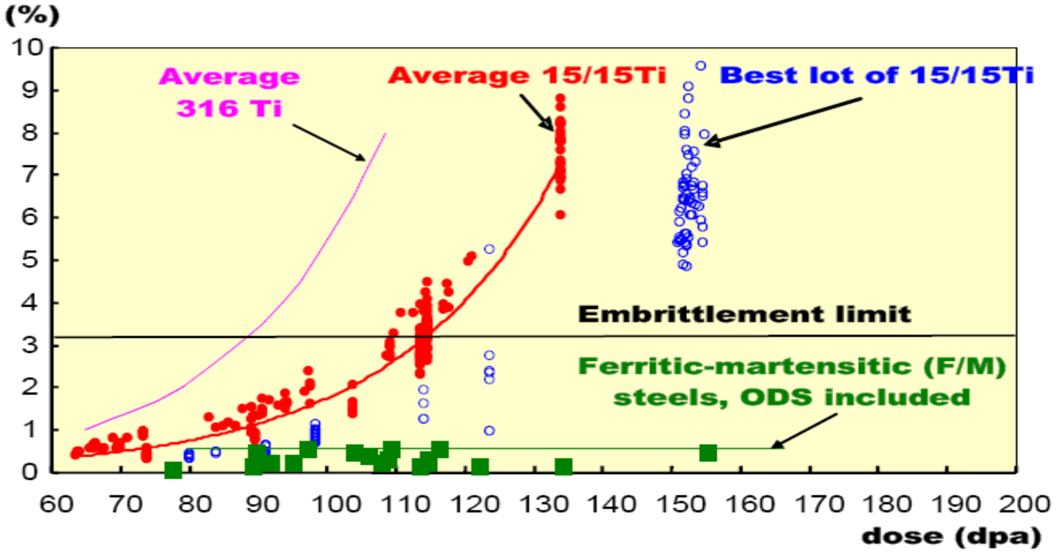
- ❑ In addition,
  - ❖ Large quantities of material will become activated - *no equivalent quantities in fission*
    - ⇒ Reduced activation materials to facilitate decommissioning
  - ❖ Tritium production and extraction
    - ⇒ Tritium permeation barriers

Common structural materials for fission and fusion applications

Fission Materials	System
Low alloy steels (e.g. SA-508)	(V)HTR, SCWR, current LWR
Zr-alloys (cladding)	LWR
Ni-based alloys (Hastelloy X, Inconel 617, Haynes 230, …)	(V)HTR, SCWR, MSR, GFR, (SFR)
F/M steels (grade 91,92 (T91, EM10, …), grade 122 (HT9), grade 22, (future) FeCrAl)	(V)HTR, SFR, future ADS, future LFR, SCWR, LWR (ATF)
F/M ODS steels (9 or 14 or even 20 %Cr)	future (V)HTR, SFR, ADS, LFR, SCWR, GFR
Austenitic steels (AISI 316L(N), 15-15Ti, 800H, advanced versions (AIM1, AIM2, AFA, …))	(V)HTR, SFR, ADS, LFR, SCWR, GFR
SiC/SiC composites, (SiC in other forms)	(V)HTR, GFR, LWR(ATF)?, (SFR, LFR)
C/C composites and graphite	(V)HTR, *(old GenI/GenII reactors)*
Other and perspective materials (V, Mo alloys, Mo-ODS, High Entropy Alloys, Max phases)	(V)HTR, GFR, LFR, ADS, MSR

Fusion Materials	Component
Tungsten alloys	Plasma facing components, divertor
Cu alloys (CuCrZr)	Divertor, heat transfer components
Reduced activation F/M steels (grade 91,92 (Eurofer, F82H, CLAM, …)	All structural components in first wall, blanket, divertor
RAF/M ODS steels (9 %Cr)	Plasma facing components or right below plasma facing components
Austenitic steels (AISI 316L(N), Mn Auss, …)	Vacuum vessel and other parts
SiC/SiC composites, (SiC in other forms)	Perspective material for first wall and blanket
C/C composites, Beryllium and other PFC possibilities	PFC for ITER or previous tokamaks
Other and perspective materials (V alloys, refractory High Entropy Alloys)	Perspective materials for first wall, blanket and also divertor

Main intersection between fission and fusion materials are F/M steels. Why?



Main reason for using F/M steels in components exposed to high neutron-flux:

low swelling

(one or two orders of magnitude less than in austenitic steels … with the caveat of He effects …)

In addition …	F/M steel	Austenitic steel
Thermal conductivity (W/mK)	26-30 **>>**	16-21
Thermal expansion (10^{-6}/K)	10-12 **<**	15-20
He production by transmutation	About the same or lower in F/M (with less swelling to start with)	
Price	About the same or lower in F/M (until 2010 Ni was >> expensive than Fe)	
Years for hands-on handling after irradiation	**About 100**	**A few thousands**

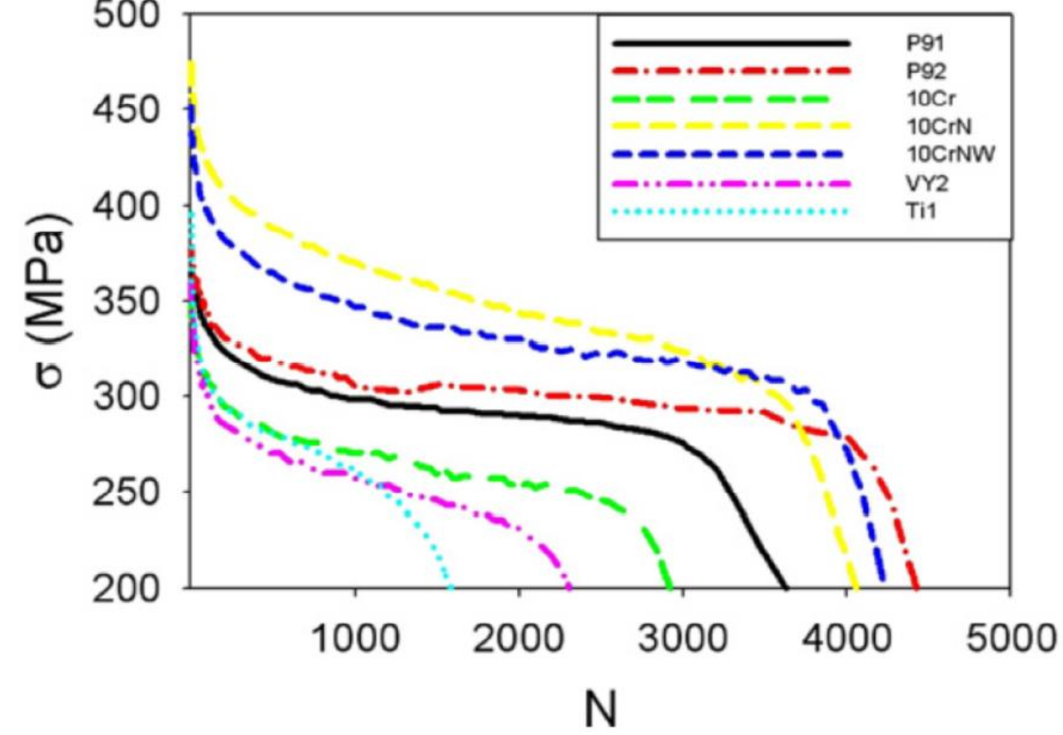
There are several examples of materials (F/M steel) issues that can be/ are being addressed jointly by fission and fusion

- Compatibility of structural materials with heavy liquid metals in terms of corrosion and also liquid metal embrittlement (applies to solar thermal energy, too);
- Barriers protecting structural materials from liquid metal corrosion, also investigated as hydrogen isotope barriers in fusion, to avoid tritium permeation;
- Design code rules whenever F/M steels behave differently from e.g. austenitic steels
- …

Some are going to be discussed in other presentations – here the focus is on "less discussed" issues of interest for fission and fusion

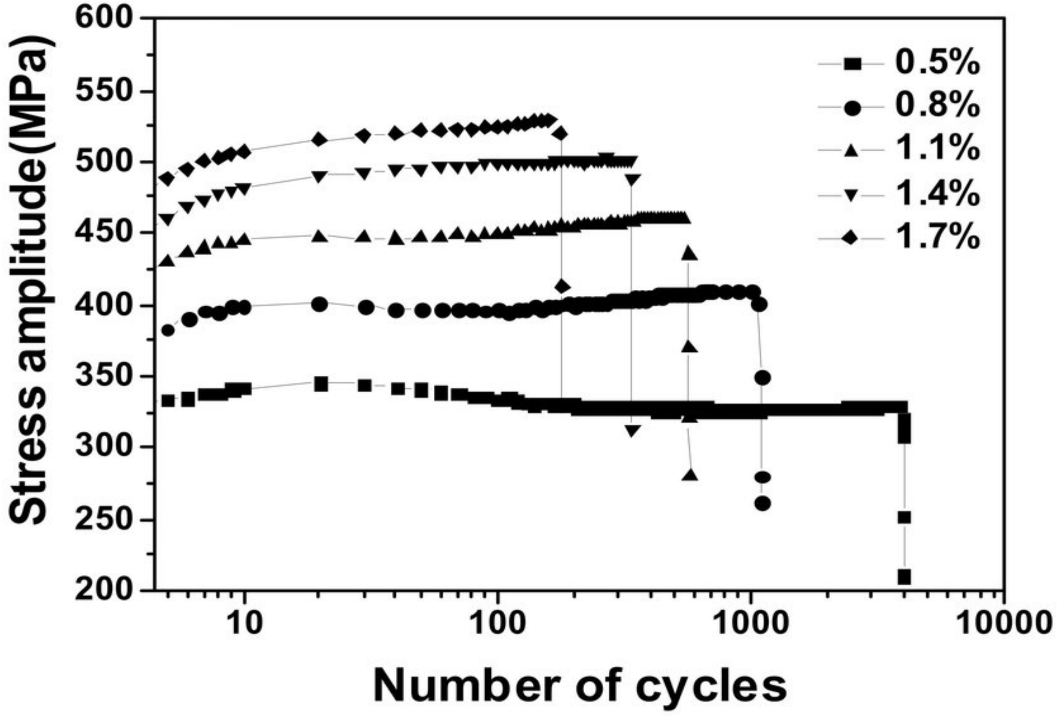
Cyclic softening (F/M) vs cyclic hardening (AuSS)

F/M steels, $\Delta\varepsilon_t$=0.7%, T=550ºC – cyclic softening



Cabet et al. JNM (2019)
https://doi.org/10.1016/j.jnucmat.2019.05.058

316L stainless steel – cyclic hardening



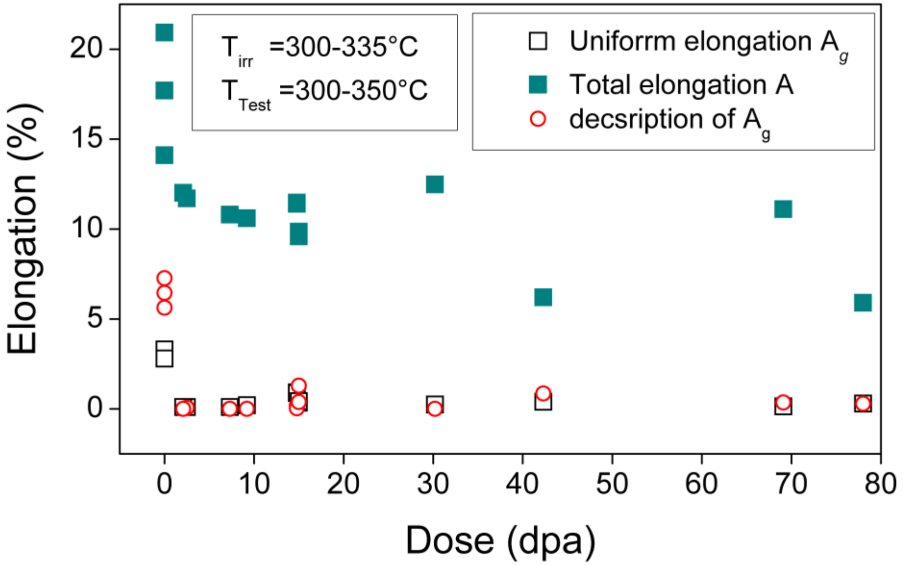
Chungseok, Metals (2017) 8. 14.
10.3390/met8010014

The behaviour under fatigue conditions is **qualitatively different** between F/M and austenitic steels.

Design rules for austenitic steels are *not* extendable to F/M steels: need to understand, collect data and elaborate different criteria and rules

Localisation of deformation: problem and results

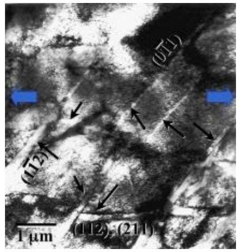
E. Gaganidze, J. Aktaa, Fusion Eng. Des. 88 (2013)



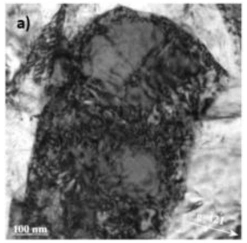
Problem:

Current design rules consider the elongation as only indicator of ductility → F/M steels are unusable according to this criterion!

S. Zinkle, B.N. Singh, J. Nucl. Mater. 351 (2006)



Traditionally loss of elongation is attributed to creation of clear bands free of defects, removed by moving dislocations, observed in Fe

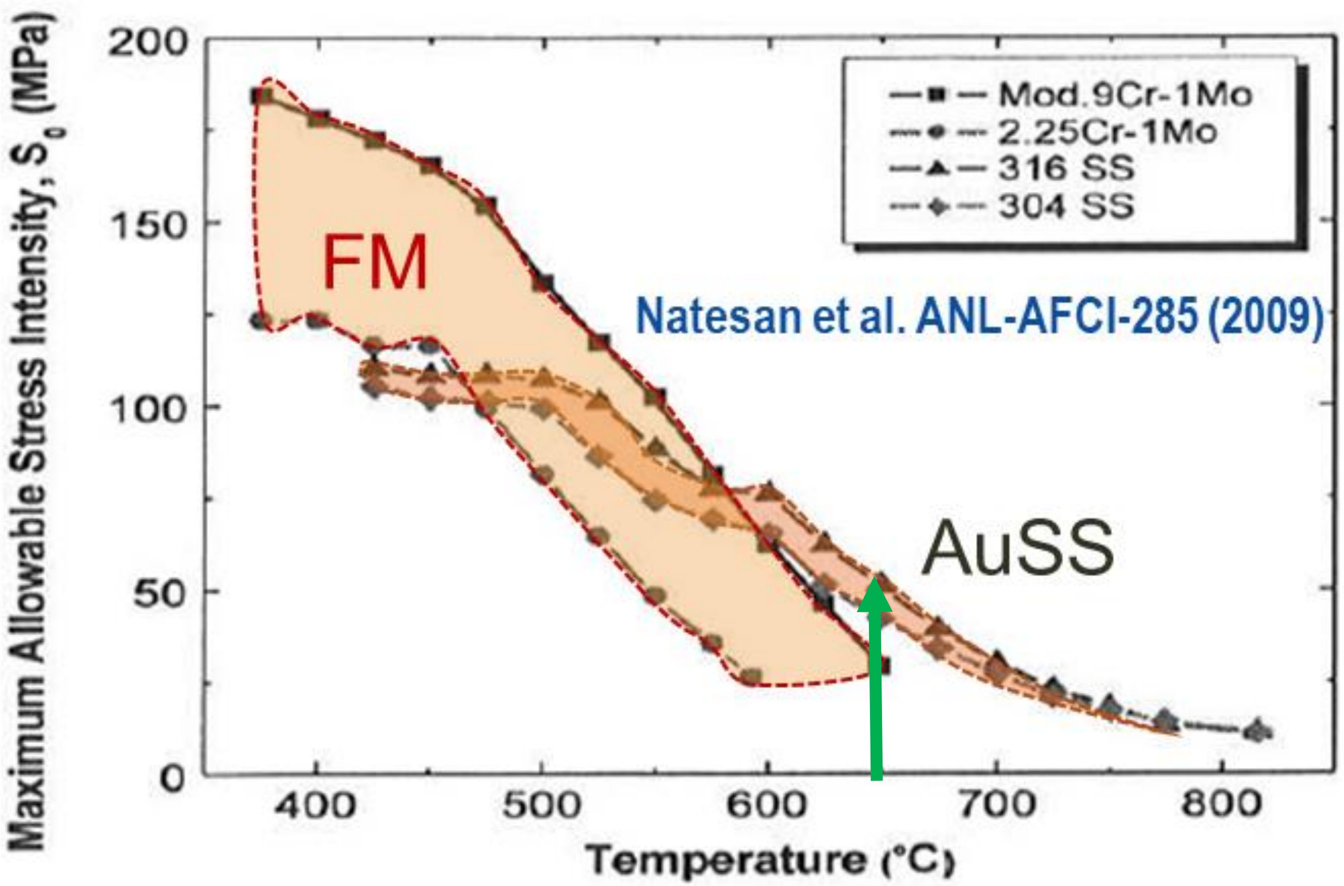


Electron microscopy on Eurofer97 in M4F suggests that in some grains loops are absorbed with dislocation wall formation
→ preferential channels for plastic deformation causing softening

- **Three models were developed in M4F to address the problem of the effect of dislocation channel formation on mechanical behaviour in 9%Cr Fe alloys :**
  - **Mean field continuum model at aggregate level**
  - **Full field continuum model, also at aggregate level**
  - **Constitutive equations enabling FEM at component level**
- **Dose dependent formation of shear bands was correctly predicted**

Tools to assess the effect of plastic flow localisation at the component level were produced, which are of use to produce design rules for both fission and fusion

Creep strength of F/M steels is somewhat worse than austenitic steels: improvement is needed



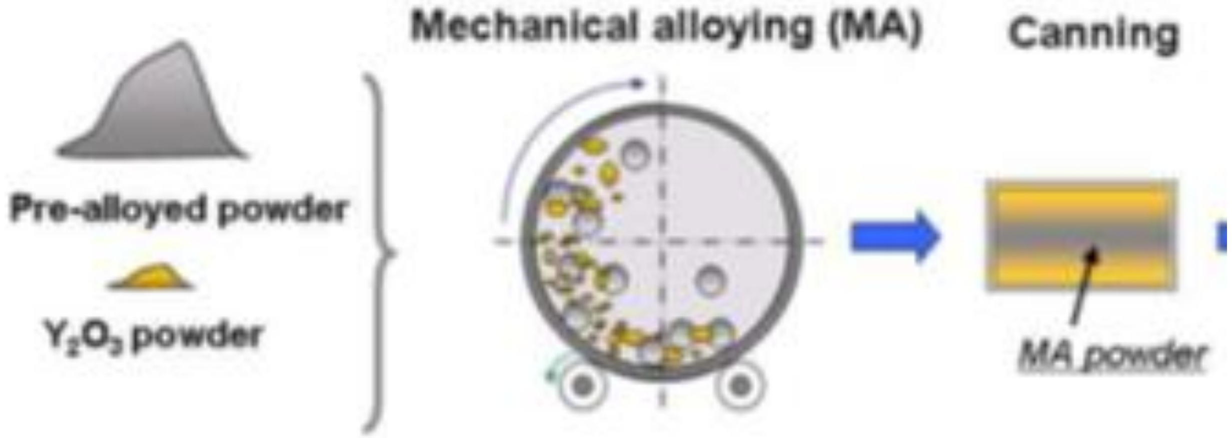
Natesan et al. ANL-AFCI-285 (2009)

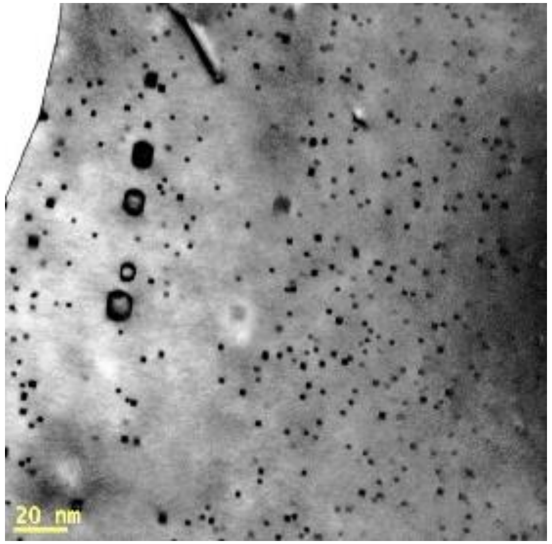
Increase of creep strength is beneficial for ANY high temperature application

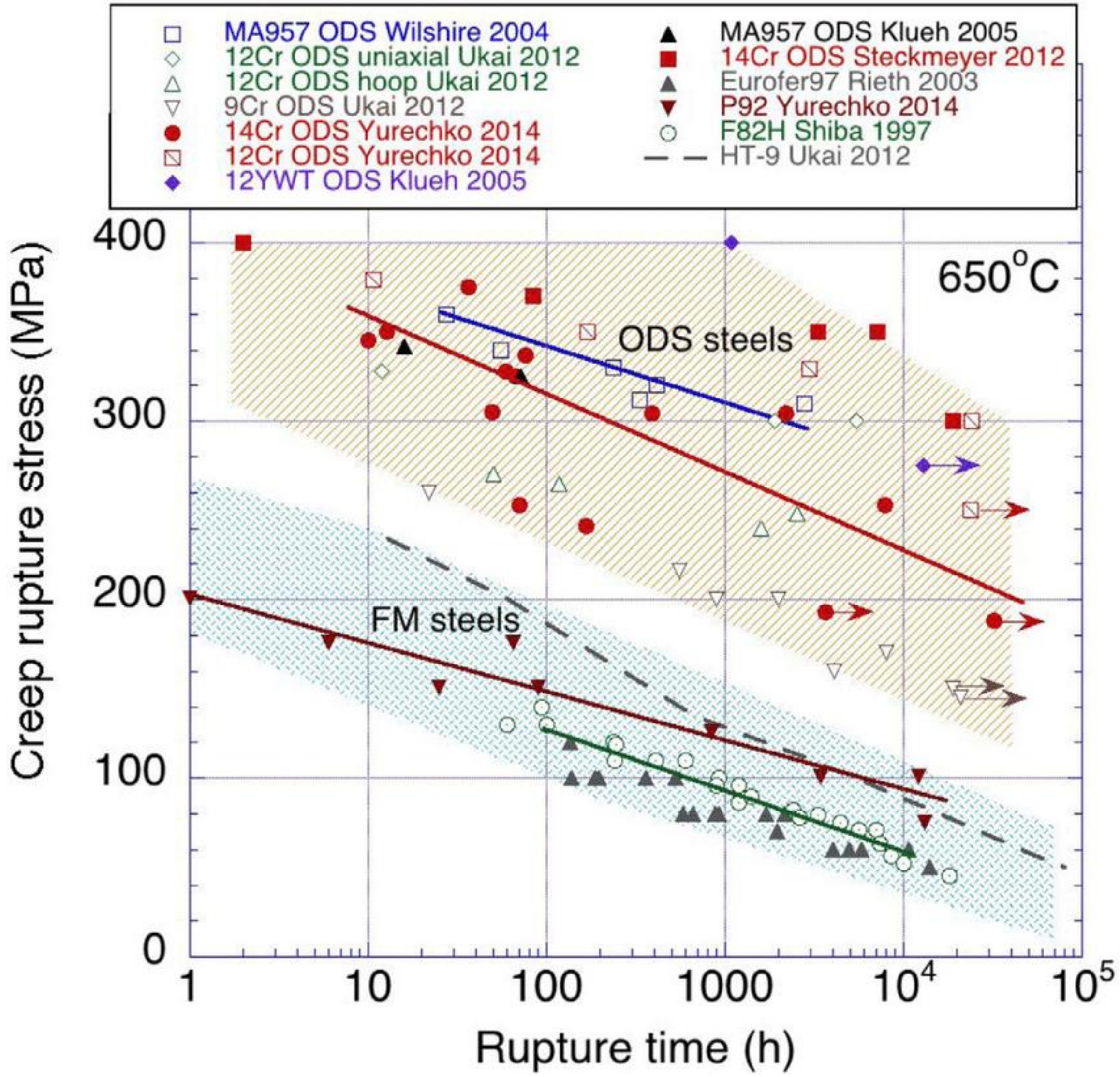
Two routes:

- **Oxide dispersion strengthened steels**
- **Creep-strength enhanced steels**

Oxide dispersion strengthened steels

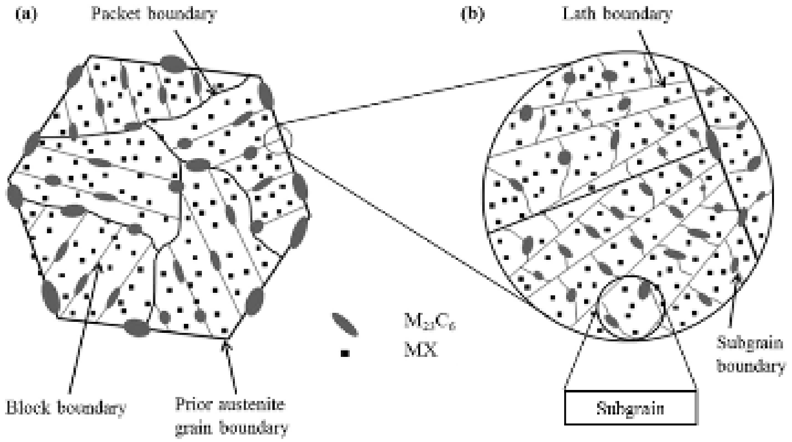




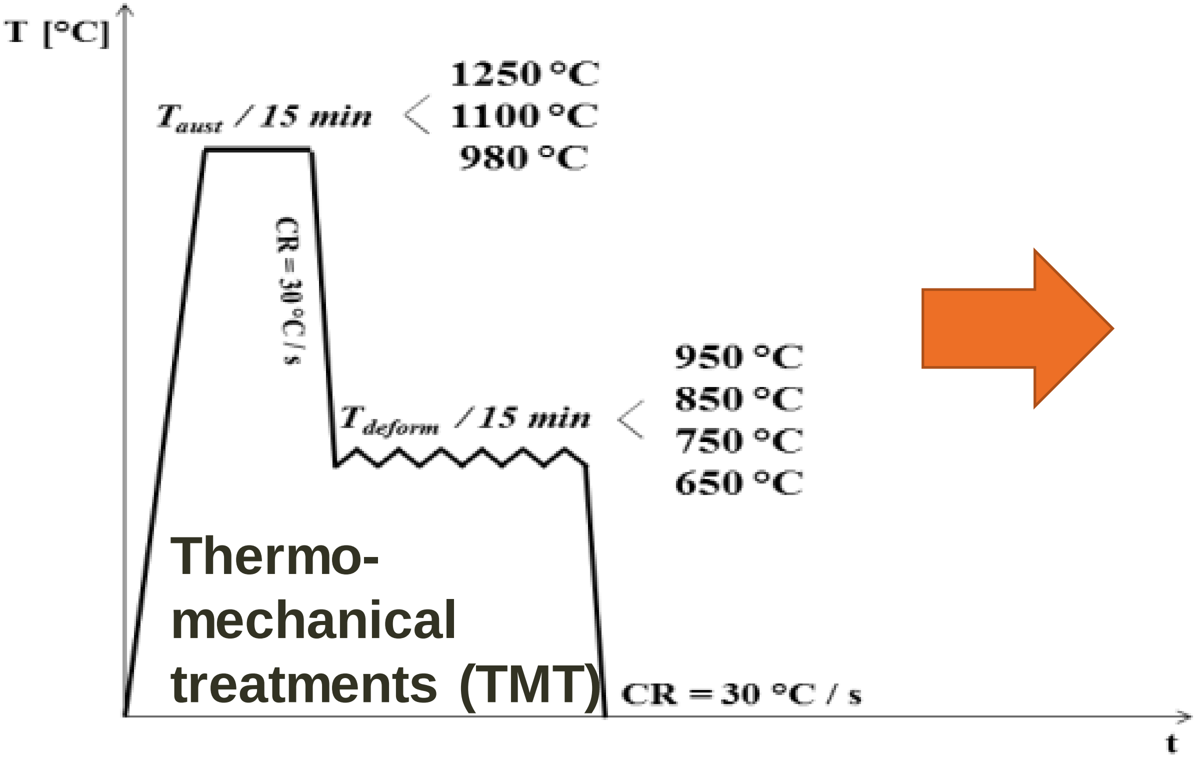


Zinkle et al.Nucl. Fusion 57 (2017) 092005

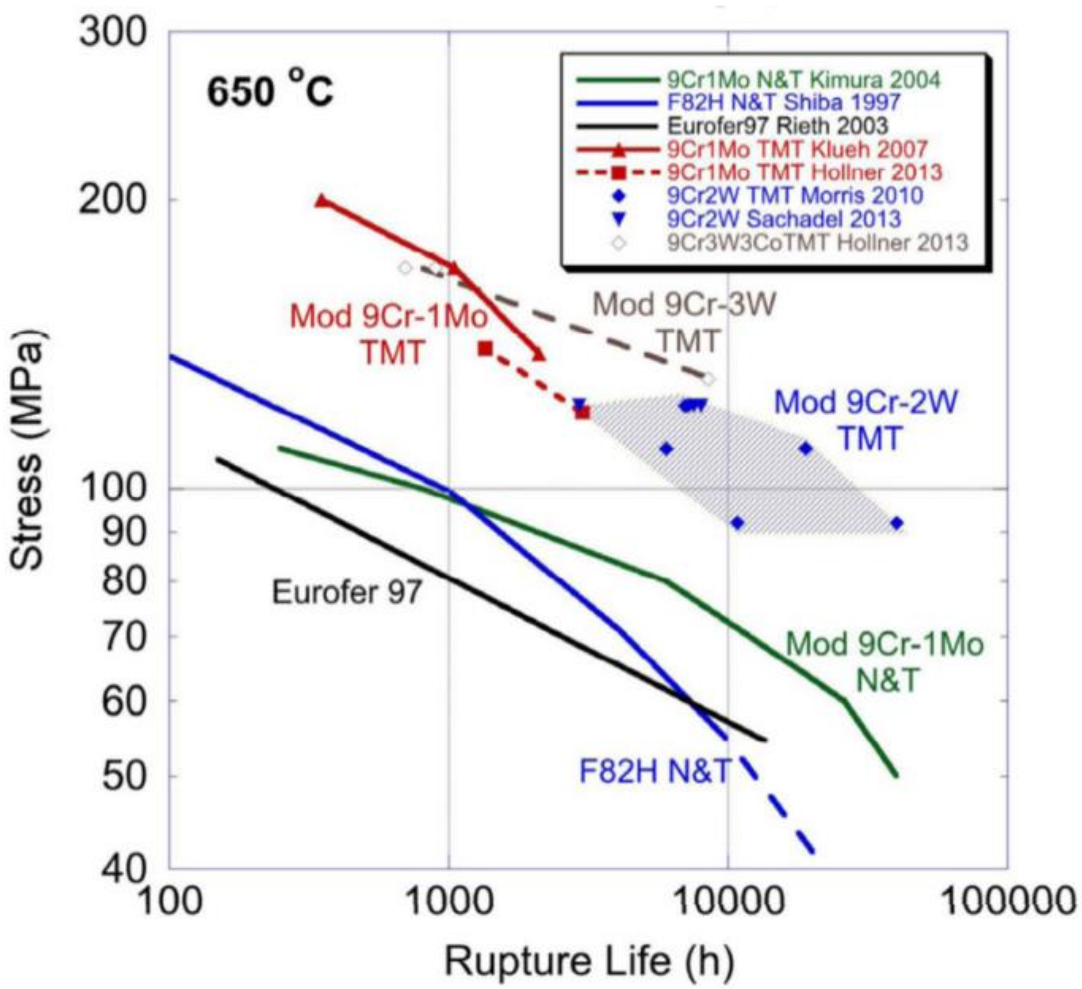
Creep-strength enhanced steels



Composition tuning



Thermo-mechanical treatments (TMT)



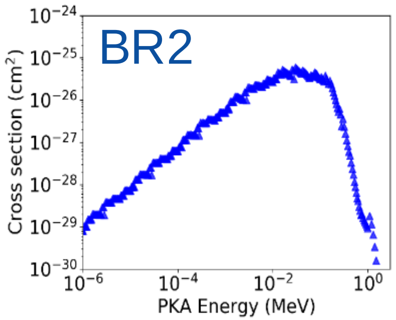
Zinkle et al.Nucl. Fusion 57 (2017) 092005

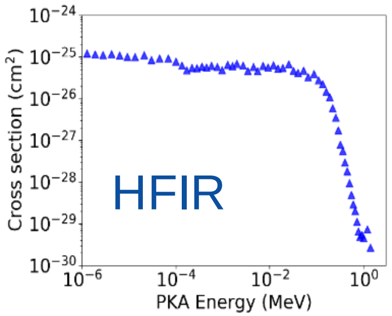
These developments can be accelerated using modern, digital tool-based, techniques

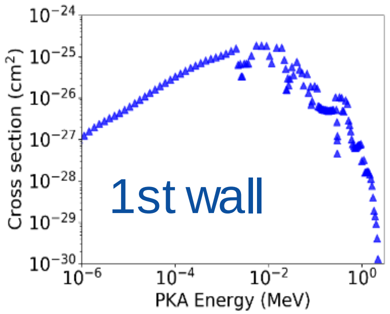
Ions as nuclear materials screening tools: transferability issues

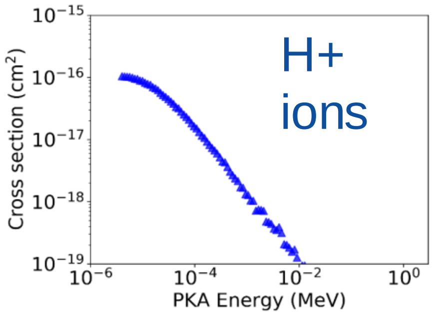
Different PKA spectrum and thus different damage

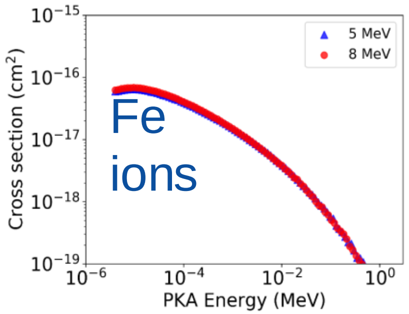
Different dpa rate





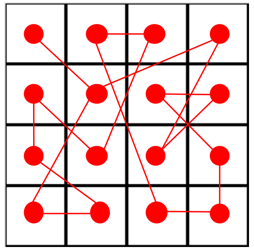




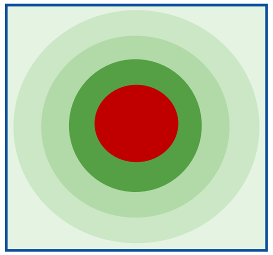


Rastering versus defocusing

Rastering (pulsed irradiation)



Focused ion beam (continuous irradiation)

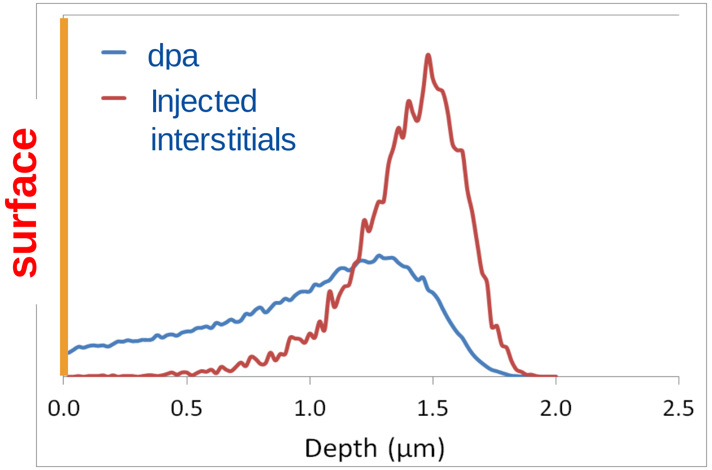


Is it possible to minimise these effects?

Limited penetration, closeness of surface

Damage profile, damage gradient

Injected interstitials



1) Microstructure evolution models for "transfer function"

2) Explore conditions through chracterization

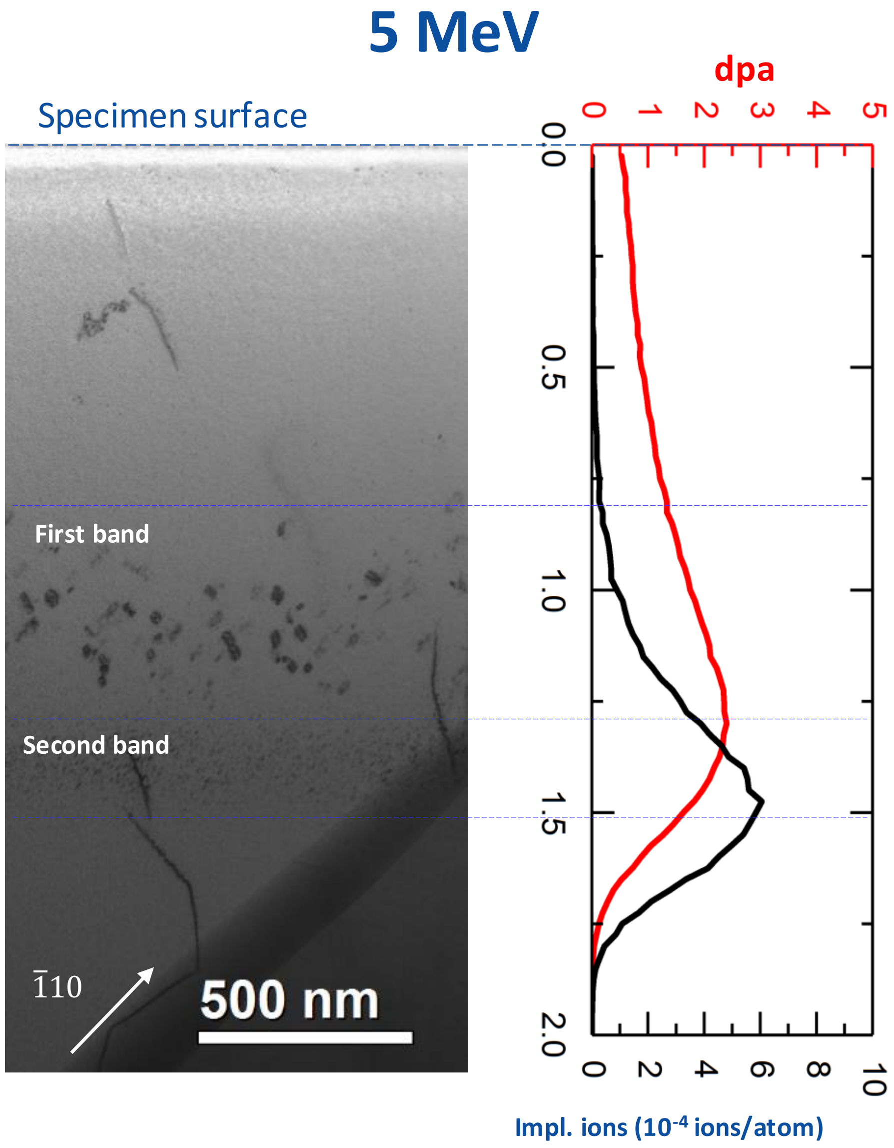
Towards good practices for ion irradiation

- **Ion irradiations were performed applying different parameters**
  - Different ion energy, focused beam versus rastering, different doses and temperatures, but same materials
  - Most difficult variable to control: C contamination

This clarified several effects and suggested good practices to mimick neutron irradiation

- **Three new different microstructure evolution models have been developed, each offering new modelling opportunities, not available before**
  - Simulation of the whole ion penetration thickness
  - Simulation of Cr concentrated alloys including precipitation
  - Simulation of the effect of minor solutes

- **Good practices to assess the mechanical properties of ion irradiated materials using nanoindentation** have been drafted
  - Standards for testing have reached the level of a **CEN workshop** and relevant publication



Materials acceleration platforms

MATERIALS ACCELERATION PLATFORM

Accelerating Advanced Energy Materials Discovery by Integrating High-Throughput Methods with Artificial Intelligence

Mission Innovation

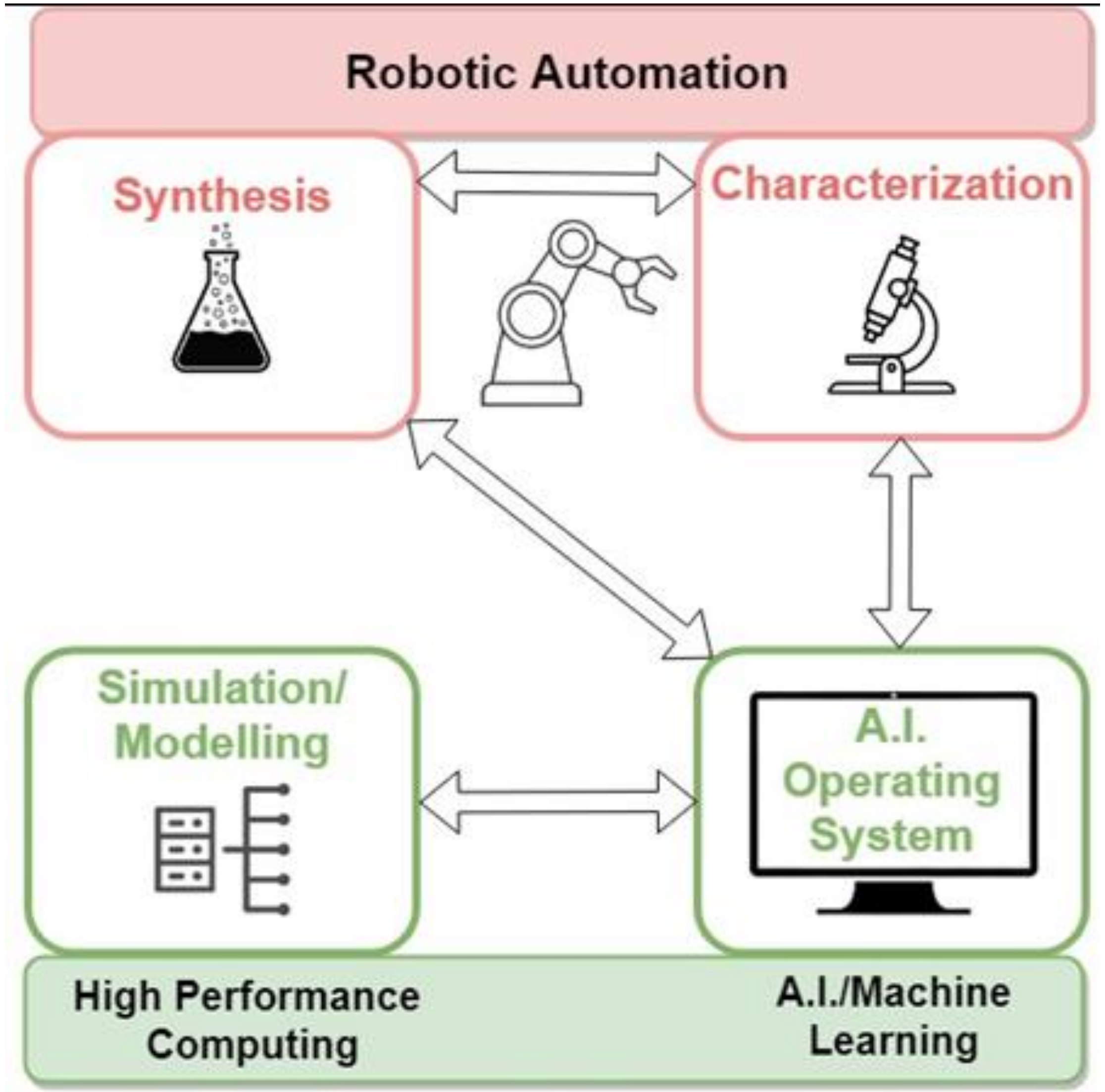
January 2018

REPORT OF THE CLEAN ENERGY MATERIALS INNOVATION CHALLENGE EXPERT WORKSHOP

SENER

U.S. DEPARTMENT OF ENERGY

CIFAR CANADIAN INSTITUTE FOR ADVANCED RESEARCH



- Closed-loop coupling of synthesis, characterization and computation
- Robotic automation
- Accelerated experimental planning and simulation/ modeling through AI machine learning algorithms
- Develop novel materials and devices

Mark S. Kozdras, NRCan, Canada - Özlem Özcan, BAM, Germany

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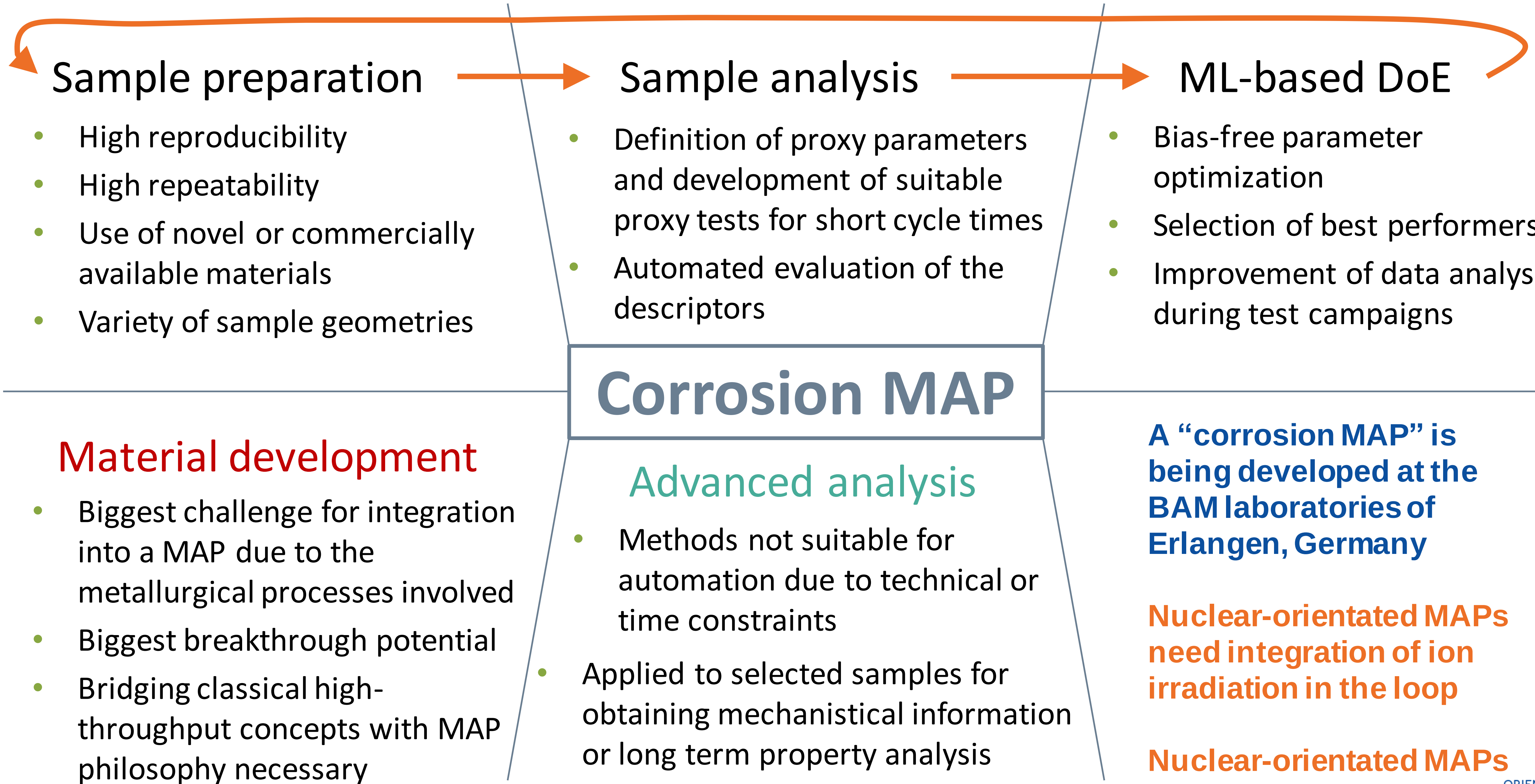
MISSION INNOVATION



Sample preparation

- High reproducibility
- High repeatability
- Use of novel or commercially available materials
- Variety of sample geometries

Sample analysis

- Definition of proxy parameters and development of suitable proxy tests for short cycle times
- Automated evaluation of the descriptors

ML-based DoE

- Bias-free parameter optimization
- Selection of best performers
- Improvement of data analysis during test campaigns

Corrosion MAP

Material development

- Biggest challenge for integration into a MAP due to the metallurgical processes involved
- Biggest breakthrough potential
- Bridging classical high-throughput concepts with MAP philosophy necessary

Advanced analysis

- Methods not suitable for automation due to technical or time constraints
- Applied to selected samples for obtaining mechanistical information or long term property analysis

A "corrosion MAP" is being developed at the BAM laboratories of Erlangen, Germany

Nuclear-orientated MAPs need integration of ion irradiation in the loop

Nuclear-orientated MAPs are of equal benefit for fission and fusion

Natural Resources Canada Ressources naturelles Canada

BAM

ORIENT NM

Summary and Concluding Remarks

Materials will be subjected to unprecedentedly harsh conditions in both fusion and GenIV fission reactors

Some non-nuclear technologies (e.g. CSP, geothermal energy, bioenergy, …) also expose materials to comparably harsh conditions (except irradiation)

Fusion specificities: high He production, skyrocketing thermal shocks, tritium permeation and need for low activation materials

Both GenIV and fusion require materials resistant to irradiation, temperature and fluid attack

F/M steels are the main intersection between fusion and fission materials: future for GenIV, only choice for fusion, due to low swelling, thermal stability, possibility to reduce activation, maybe price and He as well

F/M steels require:

❖Bespoke design rules to be developed, to account for: cyclic softening, creep-fatigue, low T embrittlement and loss of elongation, liquid metal corrosion/embrittlement

❖Improvement of creep strength and compatibility with fluids

These two points define a common research agenda, part of which has been or is being addressed in GenIV, fusion and cross-cutting projects (Matter, Eurofusion, M4F, ...)

The second point will benefit from the development of nuclear-oriented MAPs that should include ion irradiation in the loop, provided that suitable good practices are agreed upon to perform unbiased irradiation experiments

ORIENT NM

Thank you!

www.eera-jpnm.eu/orient-nm

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