Materials Processing Institute

1944 - 2019 75 YEARS OF INNOVATION

Development of High Temperature Materials for Power Generation

Dr Peter Barnard

Cleveland Institution of Engineers - Middlesbrough College 6th Feb 2024

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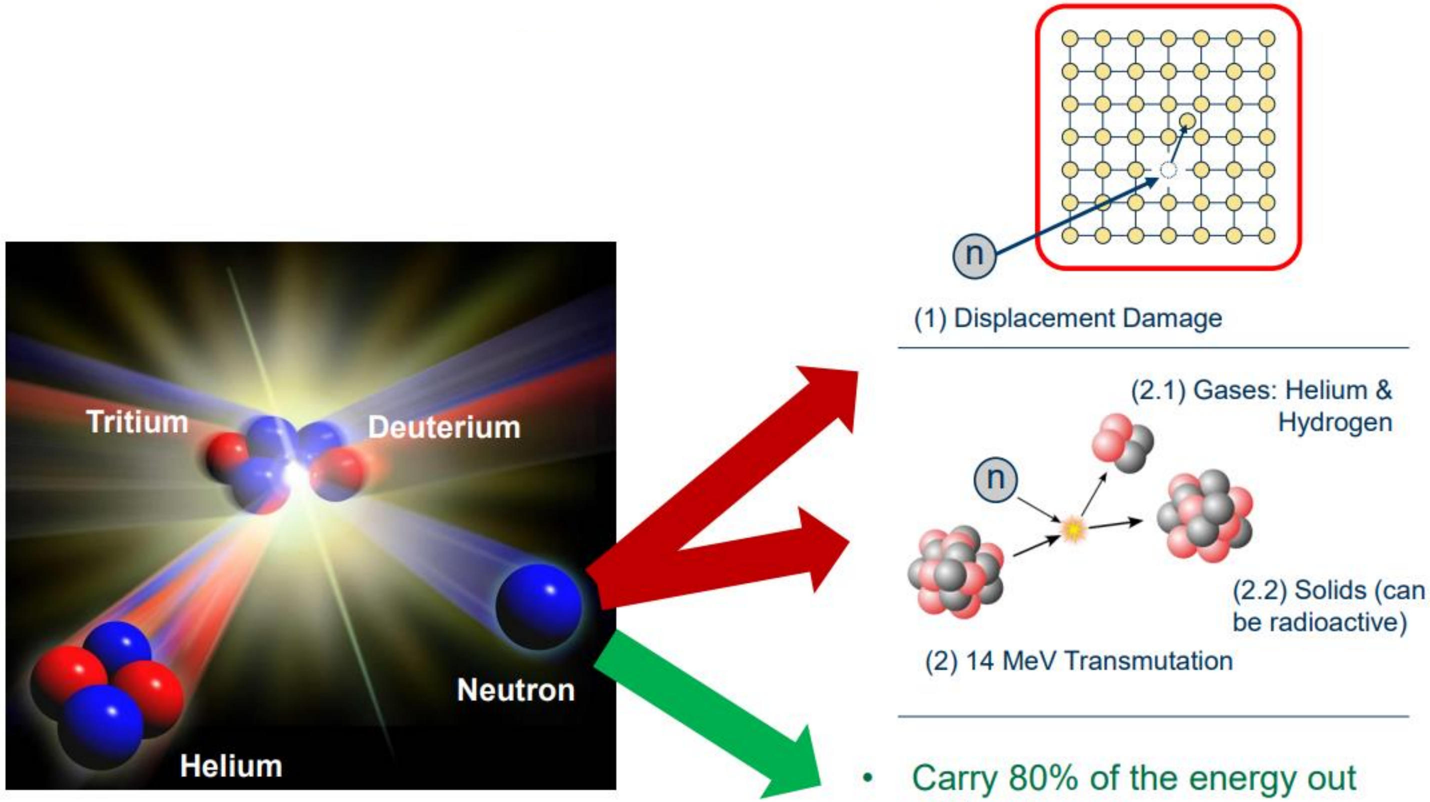
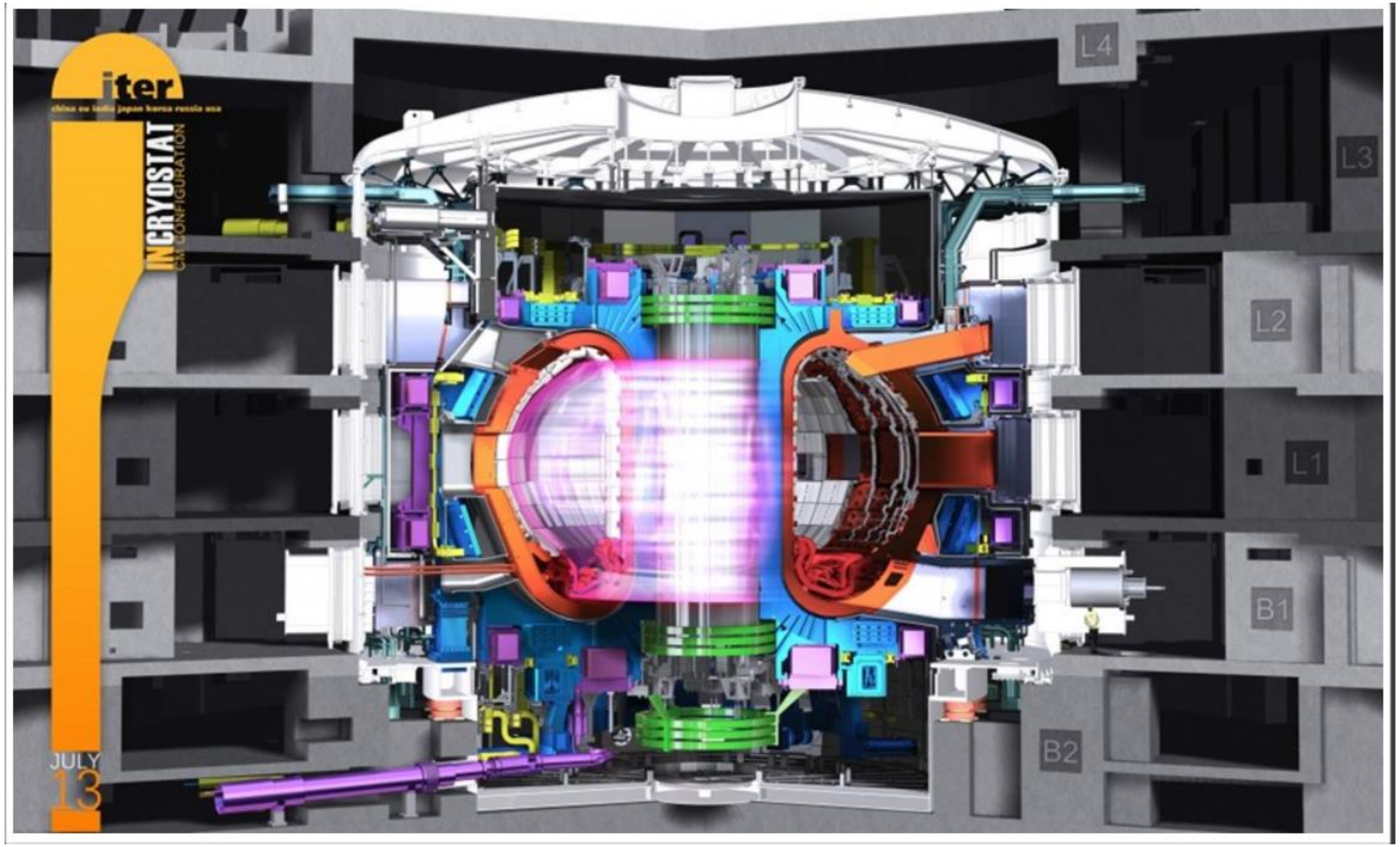
Fusion Plant

Tritium, H3, is a rare and radioactive isotope of hydrogen with a half-life of ~12.3 years. The nucleus one proton and two neutrons, whereas the nucleus of the common isotope H1 (protium) contains one proton and zero neutrons, and that of a non-radioactive H2 (deuterium) contains one proton and one neutron. Deuterium has a natural abundance in Earth's oceans of about one atom of deuterium among every 6,420 atoms of hydrogen.



- Carry 80% of the energy out of the plasma
- Heat = power = electricity

Fusion Plant - International Thermo-nuclear Experimental Reactor (ITER)



The term "tokamak" comes to us from a Russian acronym that stands for "toroidal chamber with magnetic coils" (тороидальная камера с магнитными катушками).

https://www.iter.org/mach/Tokamak

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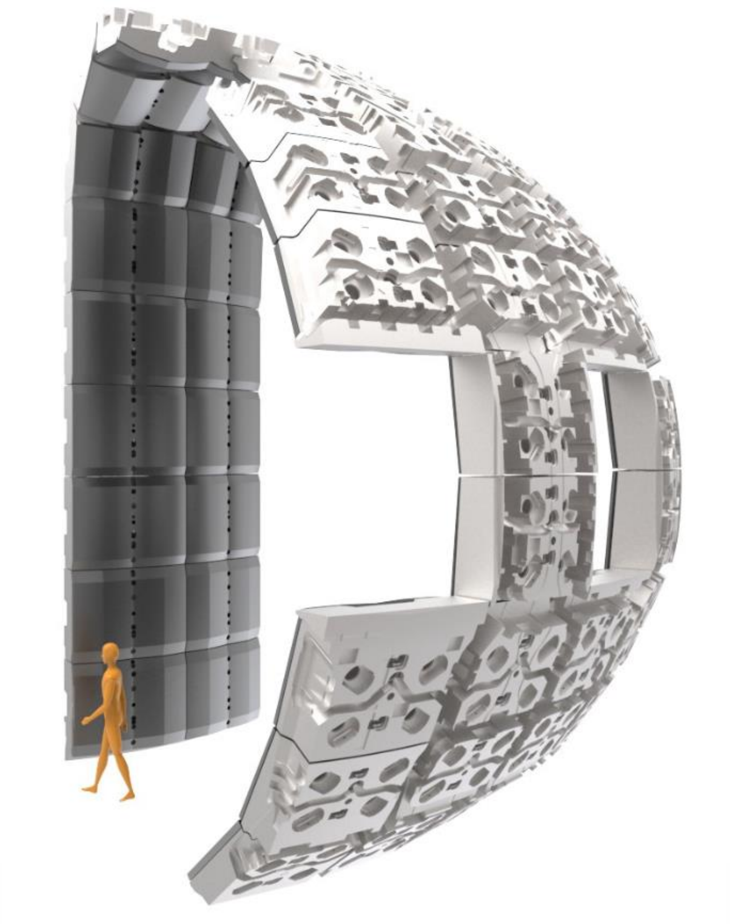
Fusion Plant

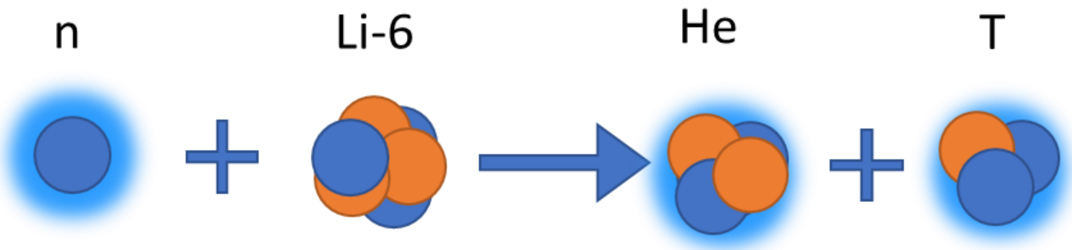
https://www.iter.org/mach/Divertor

Fusion Plant – Breeder Blanket

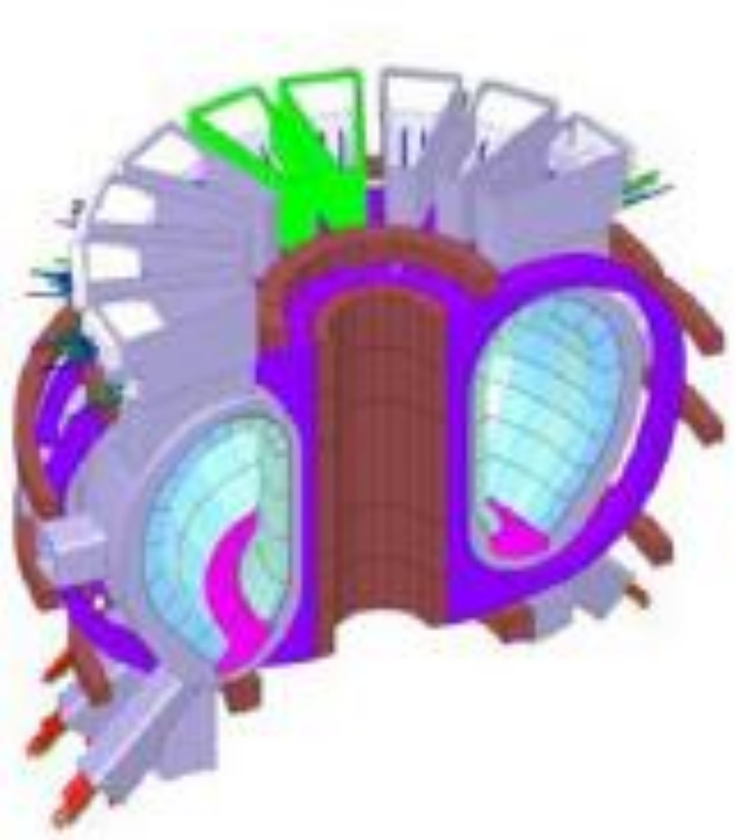


https://www.iter.org/mach/Blanket

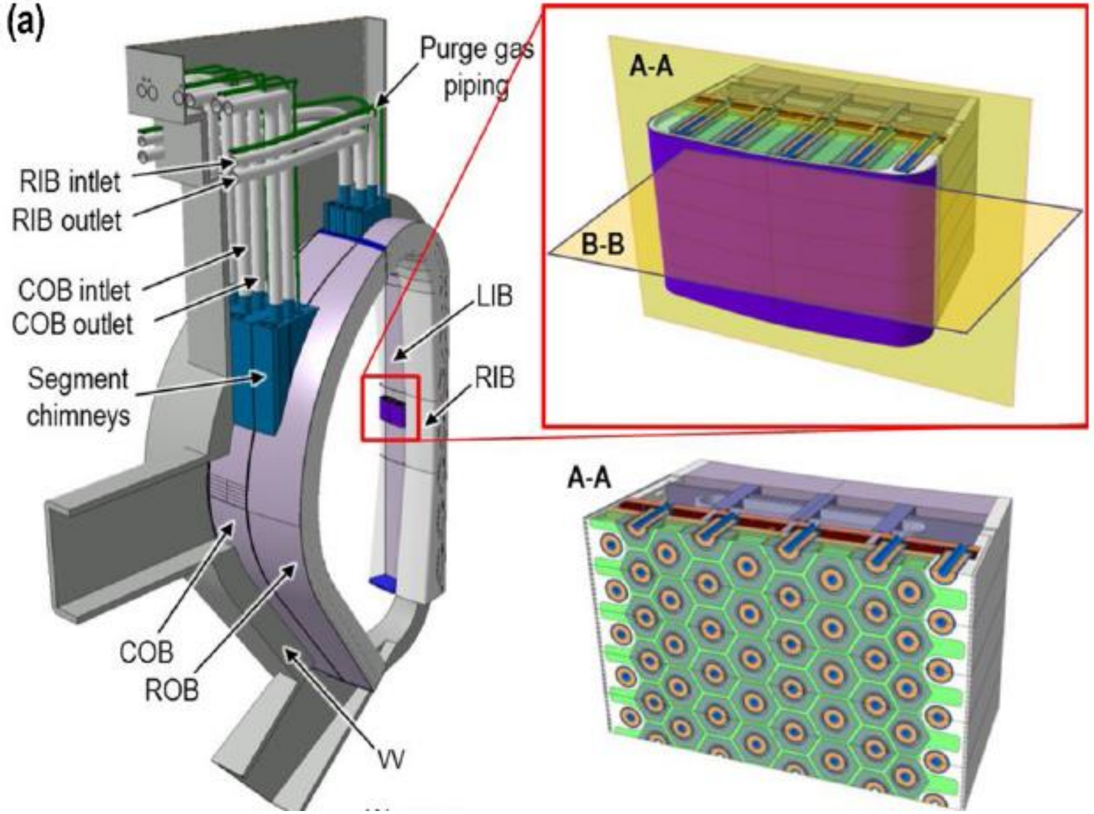
The breeding of tritium occurs through the reaction Li6 + neutron becomes He4 + tritium.



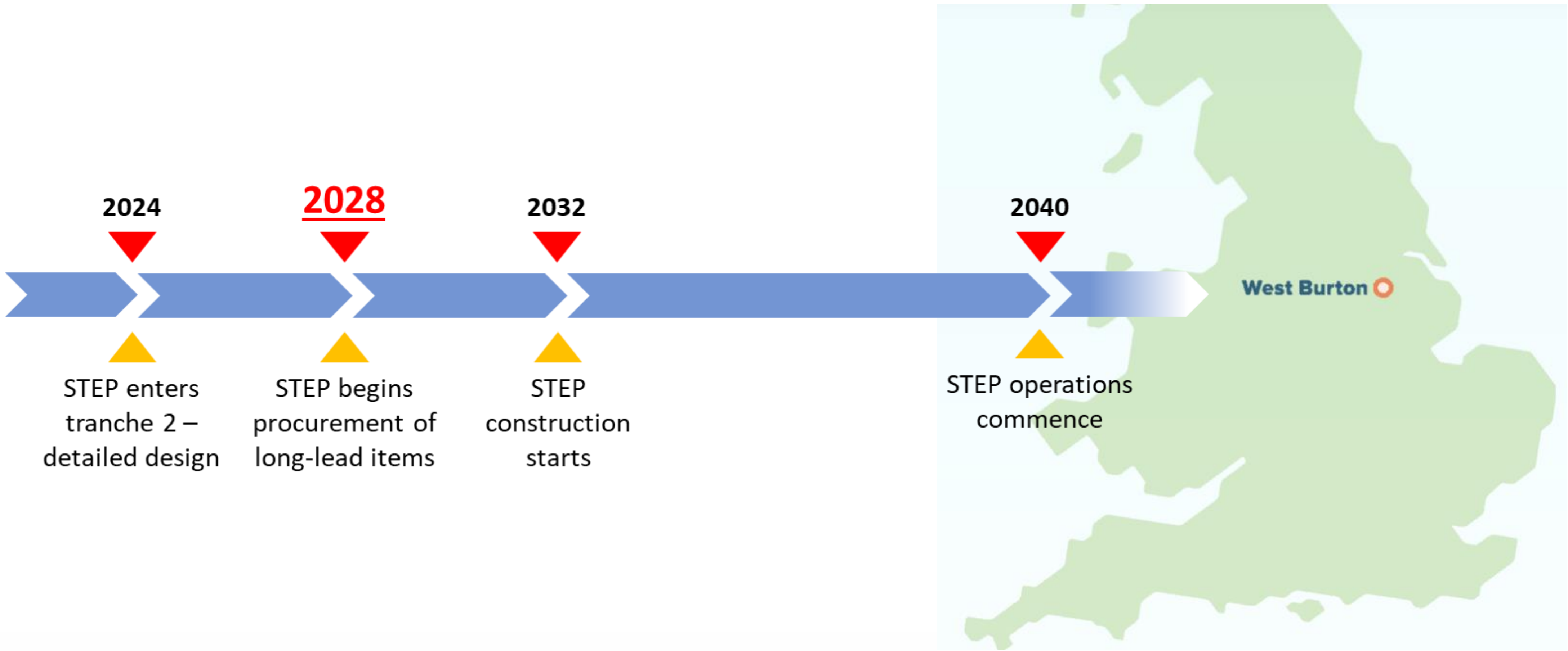
Fusion Plant – STEP (Spheroidal Tokamak for Energy Production)



UKAEA Fusion reactor



Fusion Plant – STEP



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Why Do We Need New Materials

Currently across Europe, Americas and Asia the main high temperature alloy developments are focussed upon Nuclear and in particular Fusion.

Q. Why?

A. Money

Current fission plant structural materials run at around 450ºC and using similar materials the fusion plant could potentially operate at around 550ºC.
(The deuterium-tritium fusion reactions are in excess of 100 million degrees, but the containment materials operate well below that)

Operating at 650ºC the financial benefit from the increased efficiency is around £3.5B over the lifetime of the plant and at 850ºC this raises to around £10.35B.

Q. Why aren't existing materials capable of being used since many conventional power plant operates at 650ºC and aerospace materials well over 850ºC?

A. Activation

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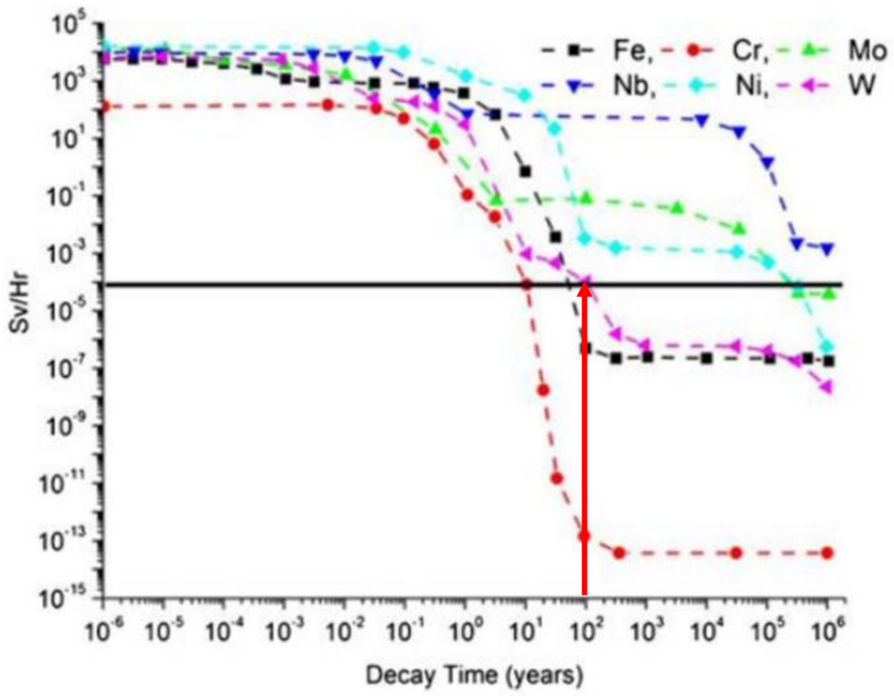
Why Do We Need New Materials

Each country will have its own requirements, for many countries including the UK this requires that after plant decommissioning all materials need to be recyclable in mainstream recycling systems within 100 years.



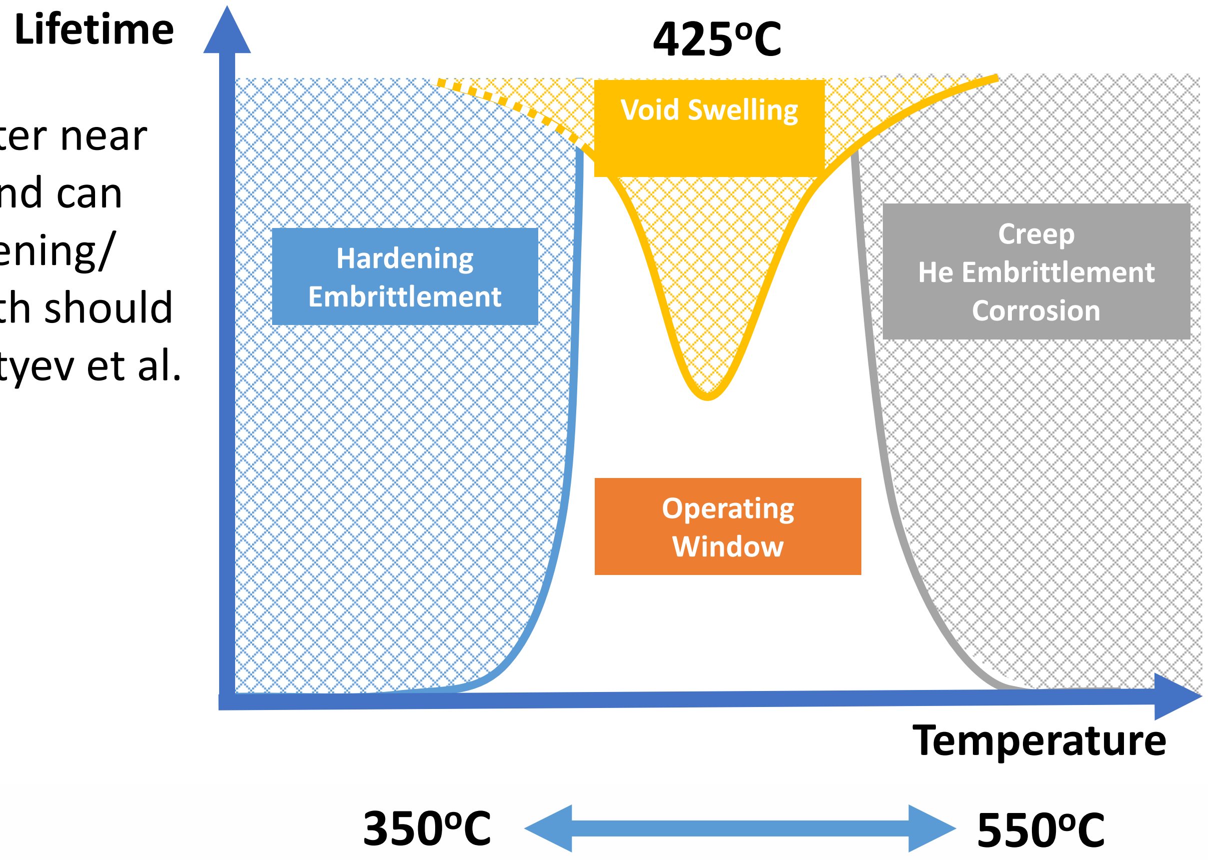
Irradiation levels of common steel alloying elements following exposure to blanket front end irradiation doses. The black line represents the ITER administrative safe irradiation level for hands-on maintenance

Taylor, N., Ciattaglia, S., Cortes, P., Iseli, M., Rosanvallon, S. and Topilski, L., 2012. ITER safety and licensing update. Fusion Engineering and Design, 87(5), pp.476-481.

Why Do We Need New Materials – Breeder Blanket

Helium can cause swelling, hardening and DBTT-shift

Mn and Si can cluster near dislocation loops and can contribute to hardening/ embrittlement. Both should be kept low (Terentyev et al. 2021)



Broadly - creep rupture occurs due to excessive growth of $Cr_{23}C_6$ and subsequent recovery of martensite sub structure

Graphic Courtesy Jim Pickles, UKAEA

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Why Do We Need New Materials – Breeder Blanket

A summary of the fusion materials requirements are

1) Reduced activation potential

2) High creep strength – target life is 60 years of operation

3) Liquid metal corrosion

4) Low potential for swelling and embrittlement

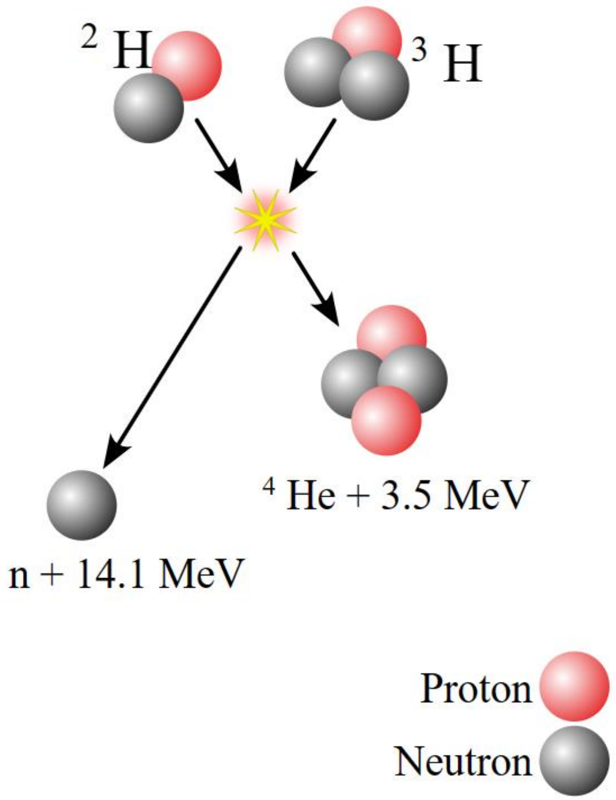
Essential

Desirable

5) Scalable to full production

6) Fabricable

7) For strategic purposes – low rare earth content



$${}^{27}_{13}Al + {}^{4}_{2}He \rightarrow {}^{30}_{15}P + {}^{1}_{0}n$$

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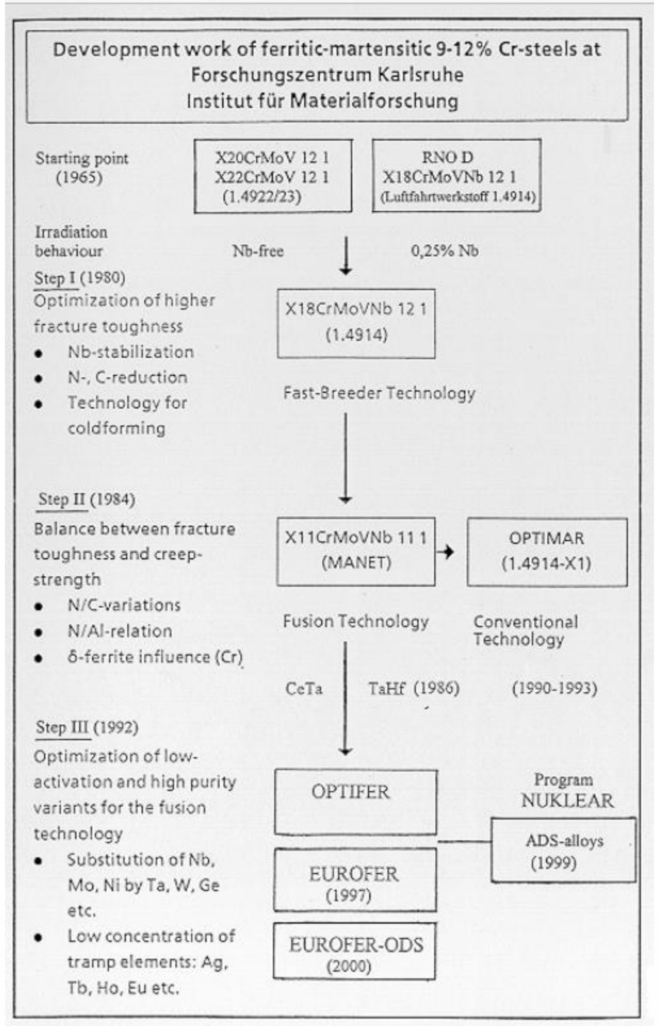
Current Status – Breeder Blanket

Development of low activation fusion steels really kicked off in 1965, from the high temperature 9-12%Cr power plant steels. Leading to the development of EUROFER as a European reference material for future DEMO reactors.

Under the EUROFER umbrella there were many international and national programmes feeding into this collective programme, including the Japanese OPTIFER (Optimized Ferrite) project leading to their own RAFM (Reduced Activation Ferritic Martensitic) steel F82H-mod.

EUROFER released for demonstrator service in 1997 commonly known as EUROFER 97



Eurofer 97 – Tensile, Charpy, Creep and Structural Tests, M. Reith et.al, Forchungszentrum Karlsruhe, FZKA 6911, Oct 2003.

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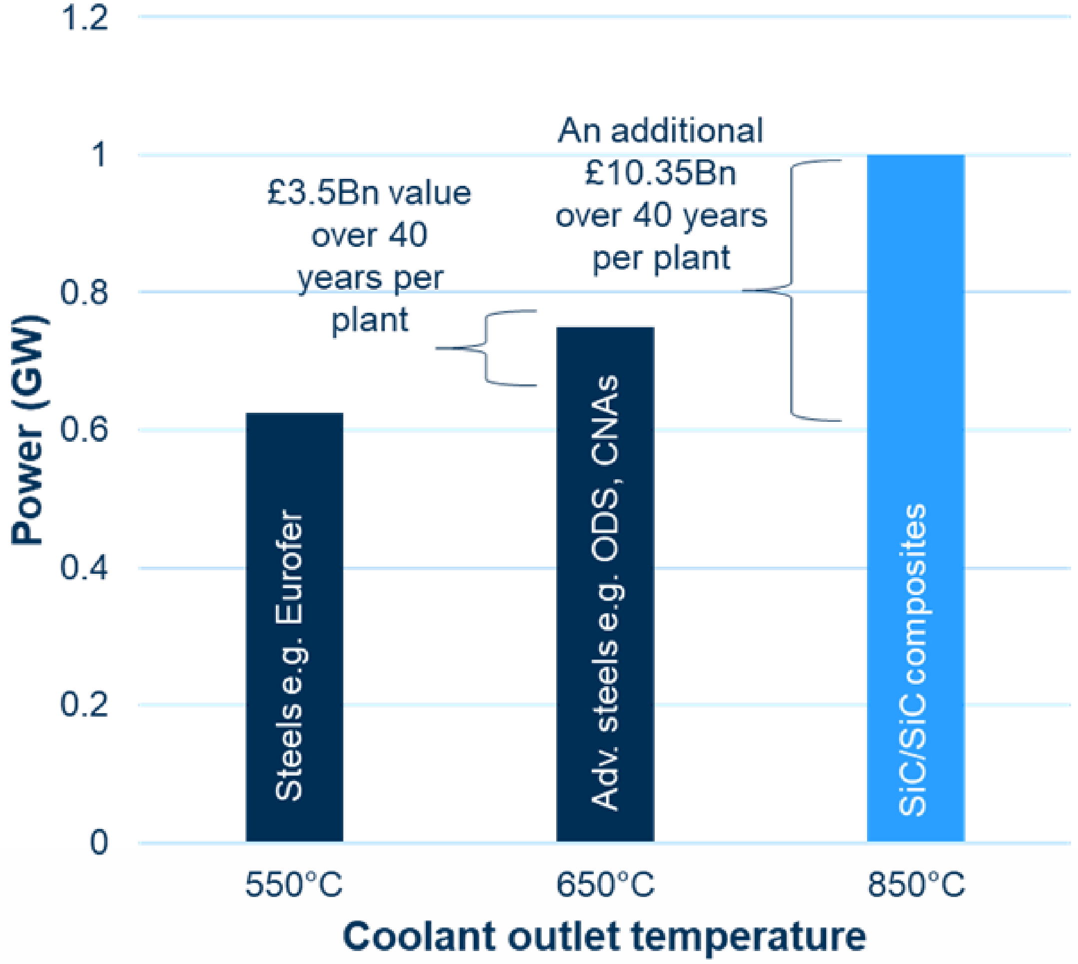
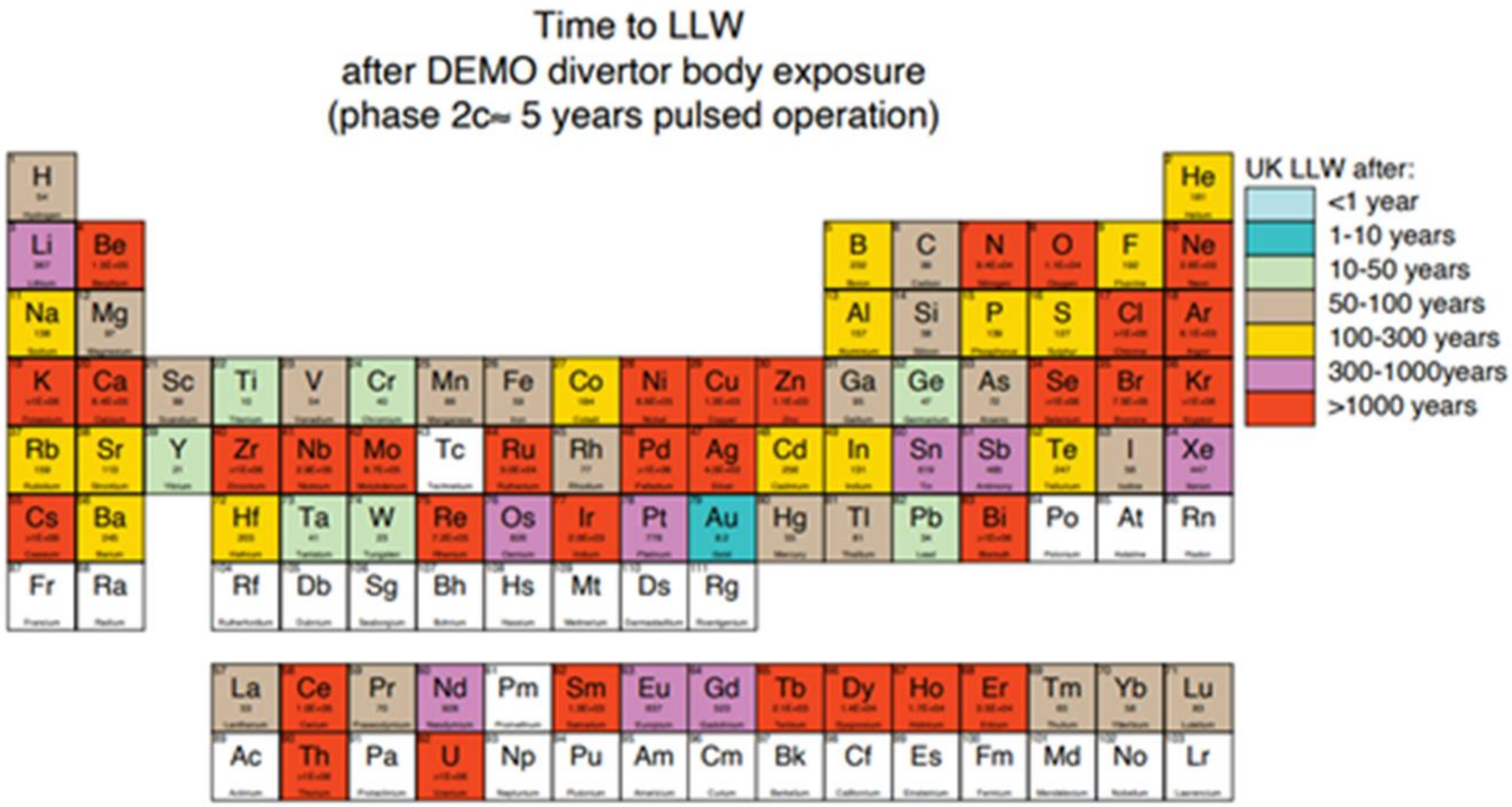
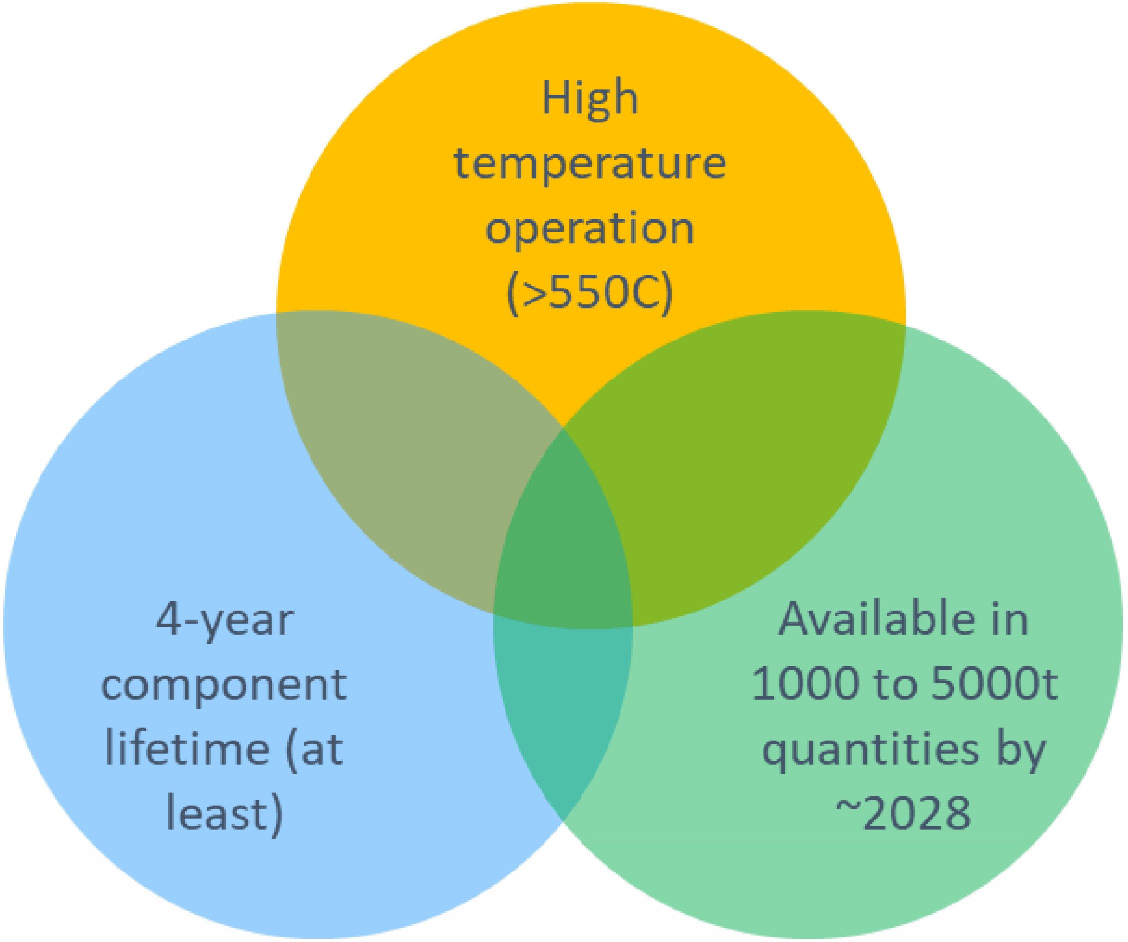
Development of Materials – Breeder Blanket



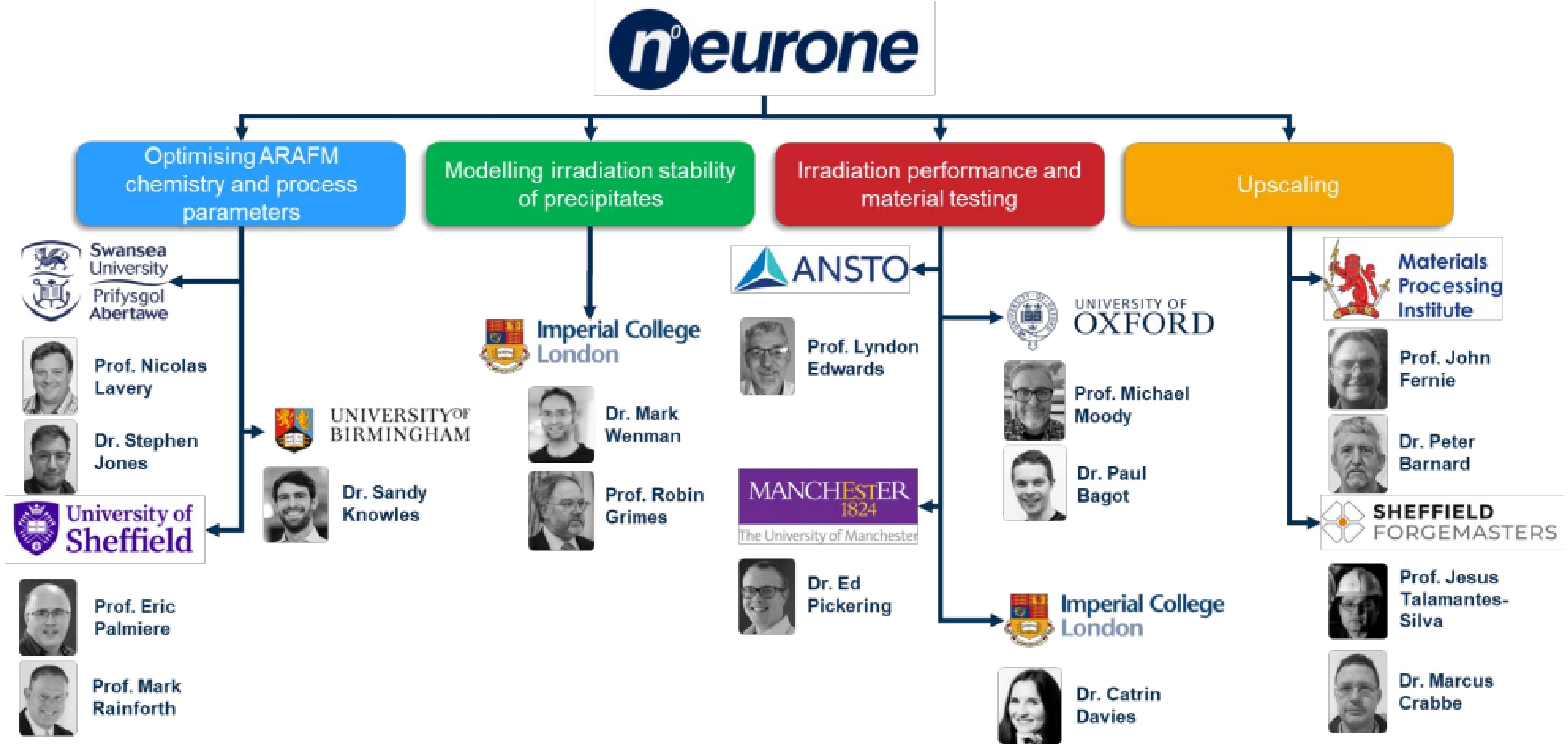
Development of Materials – Breeder Blanket



STEP Targets – Breeder Blanket



Neurone

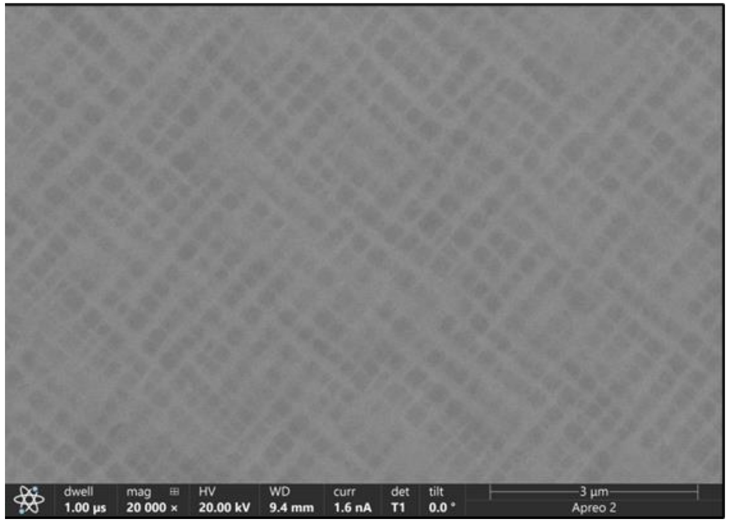


(Above) The 2023 NEURONE consortium and partner institute leads.

Mechanical Property Requirements – Breeder Blanket

To meet the challenge of the fusion reactor a huge effort is on going to develop/evolve new materials to meet the challenge, including evolution of EUROFER and F82H-mod plus new RAFM steels including BRAFM, ODS (Oxide Dispersion Strengthened) steels, CNA (Castable Nanostructured Alloy), High Enthalpy Alloys.

Example of novel microstructures for enhanced creep strength. Similar to the γ/γ' structure used in aerospace for single crystal turbine blades.



Courtesy Sandy Knowles, University of Birmingham

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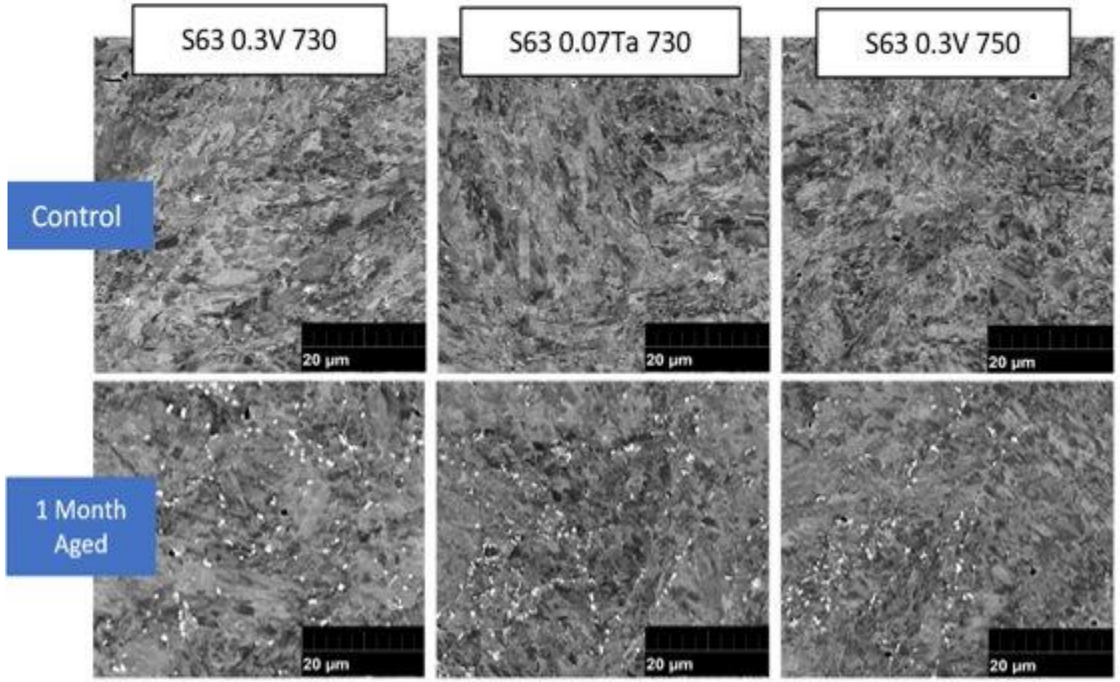
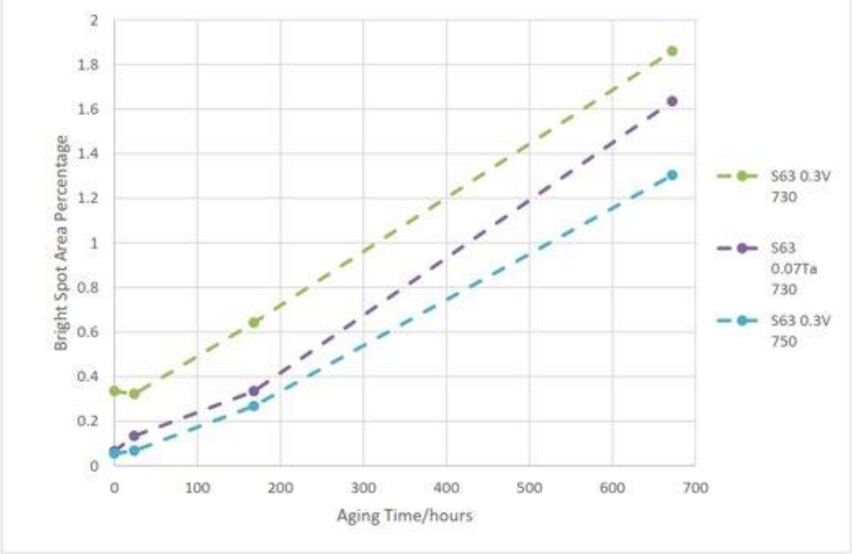
Neurone

BSE-SEM Images



Growth of Z phase precipitates

(VN → Cr(V,Nb)N)



Example of the potential use of novel strengthening phases

Courtesy Eric Palmiere, University of Sheffield

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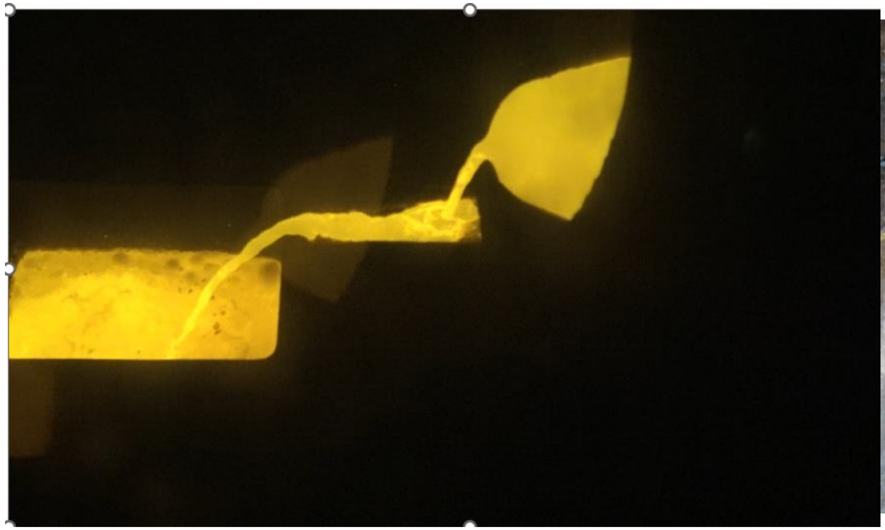
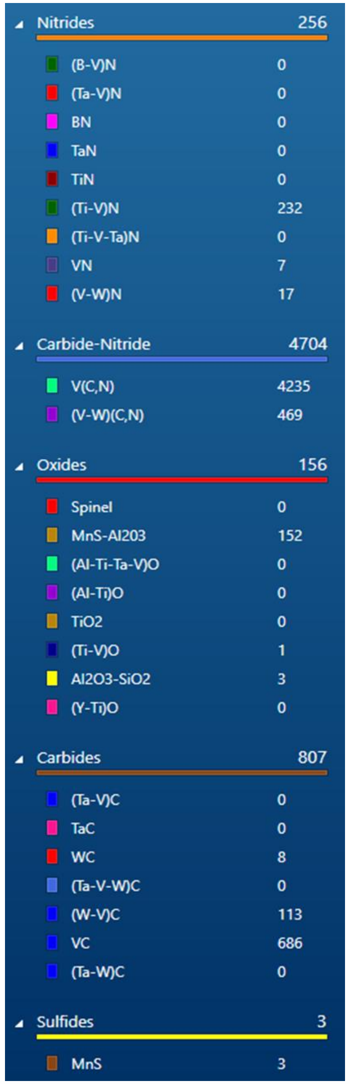
Neurone



SEM Automated Feature Analysis – Axial 5nm

Nitrides, µm	<0.006	<0.007	<0.008	<0.009	<0.01	<0.015	<0.02	<0.05	<0.1	<0.7	Total
(B-V)N	0	0	0	0	0	0	0	0	0	0	0
(Ta-V)N	0	0	0	0	0	0	0	0	0	0	0
BN	0	0	0	0	0	0	0	0	0	0	0
TaN	0	0	0	0	0	0	0	0	0	0	0
TiN	0	0	0	0	0	0	0	0	0	0	0
(Ti-V)N	84	65	18	23	12	18	10	1	1	0	232
(Ti-V-Ta)N	0	0	0	0	0	0	0	0	0	0	0
VN	5	2	0	0	0	0	0	0	0	0	7
(V-W)N	8	3	2	1	1	2	0	0	0	0	17
Carbide-Nitride, µm	<0.006	<0.007	<0.008	<0.009	<0.01	<0.015	<0.02	<0.05	<0.1	<0.7	Total
V(C,N)	1669	1295	294	338	181	344	74	30	3	7	4235
(V-W)(C,N)	201	142	32	25	22	33	5	5	3	1	469
Oxides, µm	<0.006	<0.007	<0.008	<0.009	<0.01	<0.015	<0.02	<0.05	<0.1	<0.7	Total
MnS-Al203	53	43	13	18	7	14	1	1	0	2	152
(Al-Ti-Ta-V)O	0	0	0	0	0	0	0	0	0	0	0
(Al-Ti)O	0	0	0	0	0	0	0	0	0	0	0
TiO2	0	0	0	0	0	0	0	0	0	0	0
(Ti-V)O	1	0	0	0	0	0	0	0	0	0	1
Al2O3-SiO2	2	0	0	1	0	0	0	0	0	0	3
(Y-Ti)O	0	0	0	0	0	0	0	0	0	0	0
Carbides, µm	<0.006	<0.007	<0.008	<0.009	<0.01	<0.015	<0.02	<0.05	<0.1	<0.7	Total
(Ta-V)C	0	0	0	0	0	0	0	0	0	0	0
(Ta-W)C	0	0	0	0	0	0	0	0	0	0	0
TaC	0	0	0	0	0	0	0	0	0	0	0
WC	2	4	1	0	0	0	0	1	0	0	8
(Ta-V-W)C	0	0	0	0	0	0	0	0	0	0	0
(W-V)C	52	29	10	5	3	13	1	0	0	0	113
VC	323	204	31	50	27	41	6	4	0	0	686
(Ta-W)C	0	0	0	0	0	0	0	0	0	0	0
Sulfides	<0.006	<0.007	<0.008	<0.009	<0.01	<0.015	<0.02	<0.05	<0.1	<0.7	Total
MnS	1	0	0	1	0	1	0	0	0	0	3



Nano Scale LAM ME/ML/1020-A, Axial sample.

Distribution of Precipitate Sizes X50K Magnification

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Mechanical Property Requirements – Accelerated testing

Target life is 60 years of operation. How long do we test for?

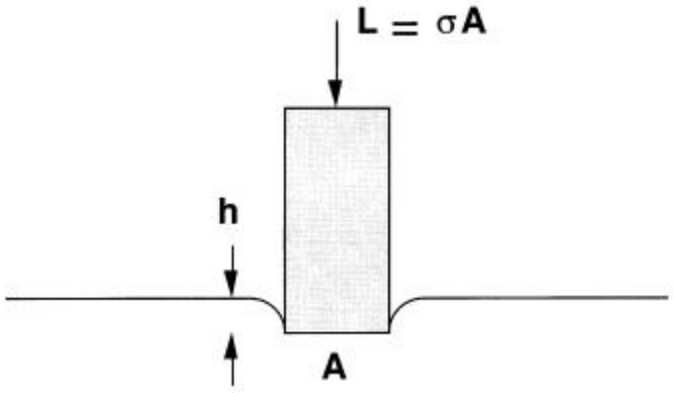
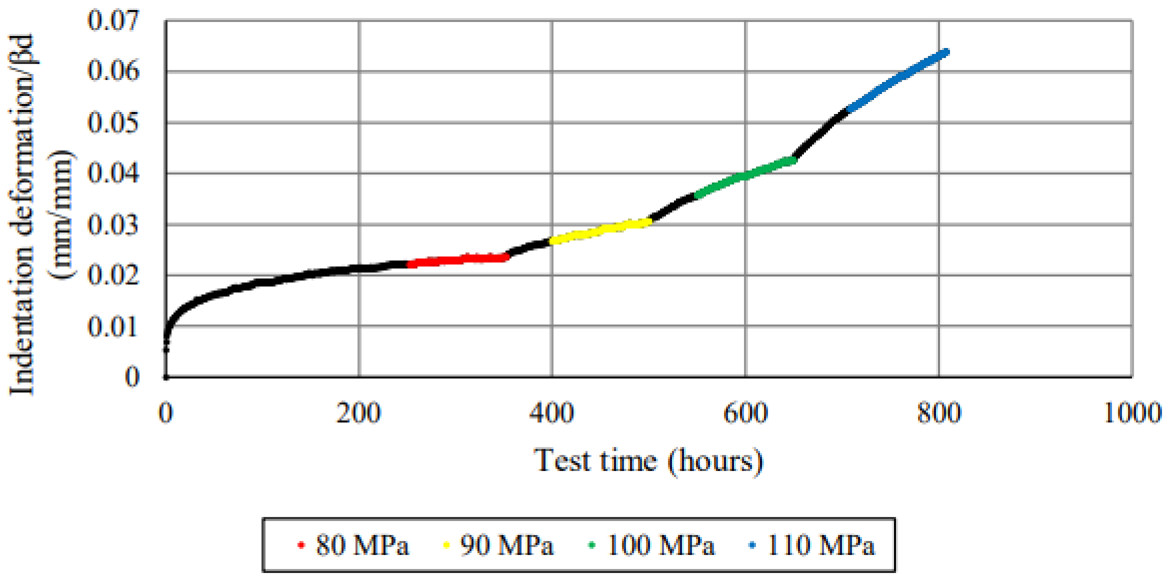


Fig. 1. Impression testing.

Impression creep and other localized tests, J. Li, Materials Science and Engineering A322 (2002) 23–42



Commercialisation of impression creep testing, T. Gallacher et. al., 5th International Small Sample Test Techniques Conference, Swansea University, 2018

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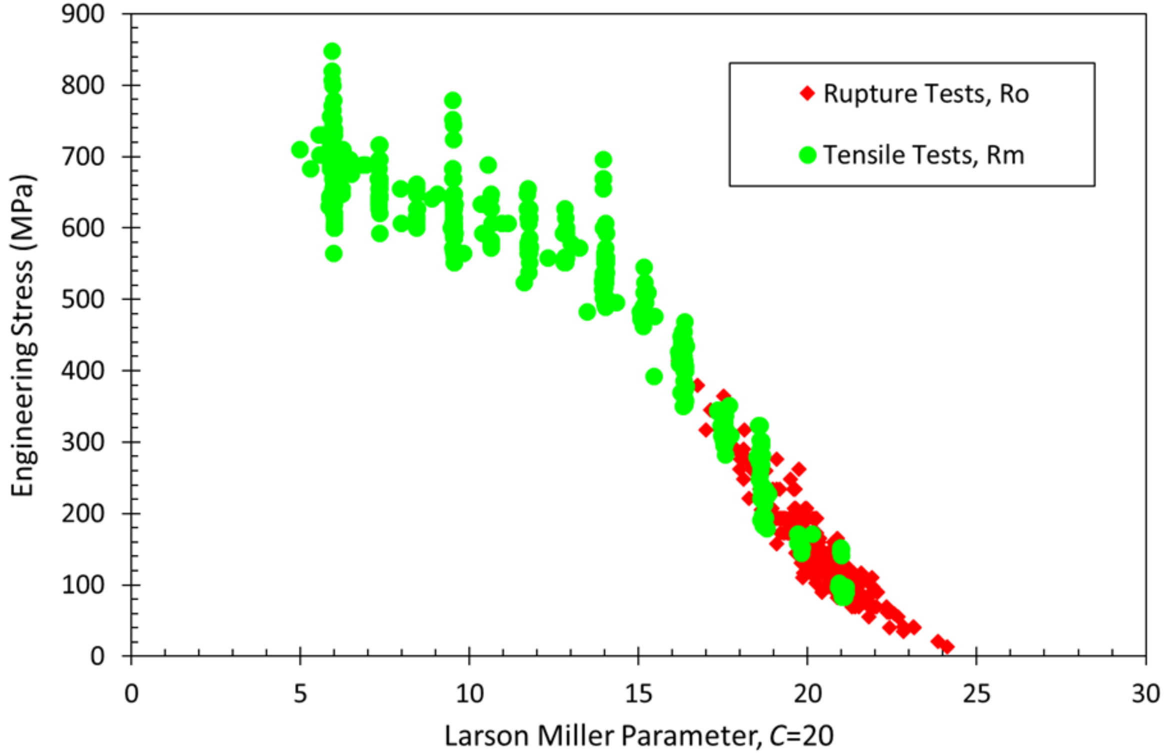
ECCC – Can Rupture Data be Predicted from Tensile Data?



$$Ln(R_m) = Ln(a.E).\left[1 + exp\left\{\frac{-1.\left(\frac{T}{1000}(Log_{10}(time) + C) - x_0\right)}{b}\right\}\right]^{-1}$$

$$E = 215400 - 42.8\,(T - 273) - 0.06185\,(T - 273)^2$$

Parameter	A	b	x_0	C
Value	0.00319835	-2.40006	22.2841	18.7041

Can Long Term Time to Rupture Data be Predicted Using Only Tensile Test Data?, M. W. Spindler, ECCC2021, 5th Int Creep & Fracture Conf., Oct 2021, Virtual.

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Summary

1) Enough money is flooding into the Energy space especially Fusion for a Fusion Powered Plant becoming a reality within the next few decades.

2) The technical challenges and time scales are incompatible with commercialisation of Fusion power by 2040.

3) Collaboration, detailed science, accelerated testing and extrapolation are essential for the success of Fusion power.

4) If you’re interested in power generation material science Fusion is the place to be.

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Thank you for your attention and will try and answer any question.

Pete Barnard

peter.barnard@mpiuk.com
Materials Processing Institute, Middlesbrough, UK

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