UK Atomic Energy Authority

Increasing the heat: Developing next-generation high-temperature steels to deliver commercial fusion energy

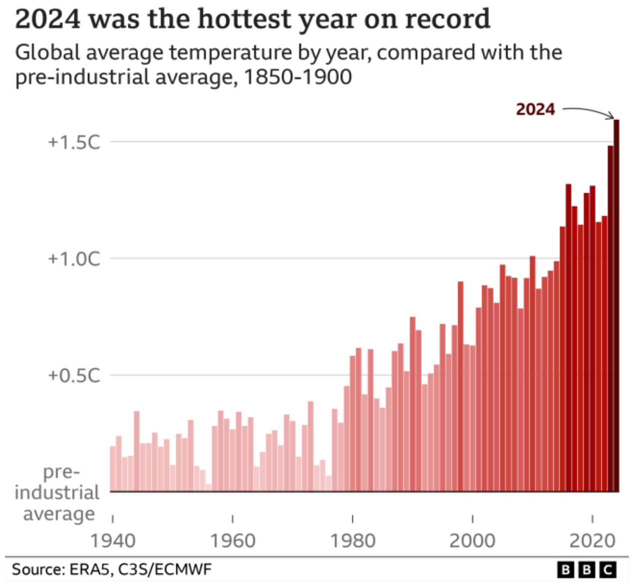
Dr. David Bowden – Materials Science and Engineering Group Leader, UKAEA

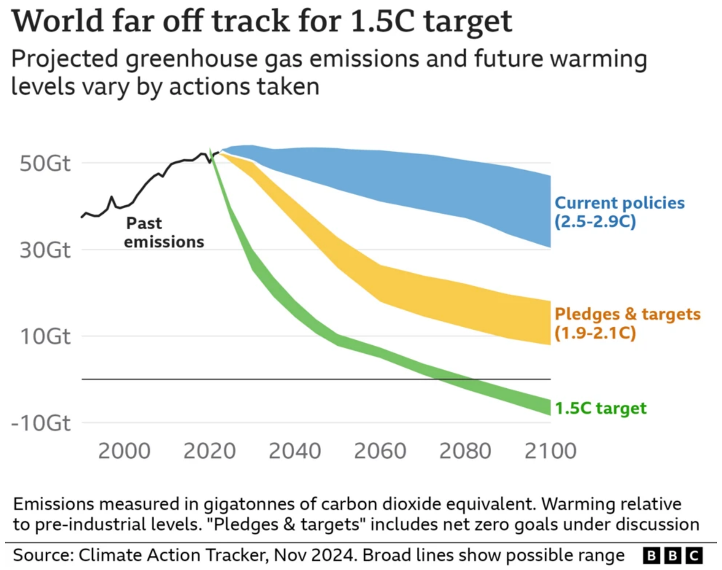
The climate emergency

https://www.scientificamerican.com/article/what-caused-the-la-wildfires-how-investigators-will-find-out/

https://www.worldweatherattribution.org/climate-change-increased-the-likelihood-of-wildfire-disaster-in-highly-exposed-los-angeles-area/

- Climate change increased likelihood of weather conditions leading to wildfires by 35%.
- Coupled with more extreme seasonal drought – wet cycles; hydroclimate whiplash.





https://www.bbc.co.uk/news/science-environment-24021772

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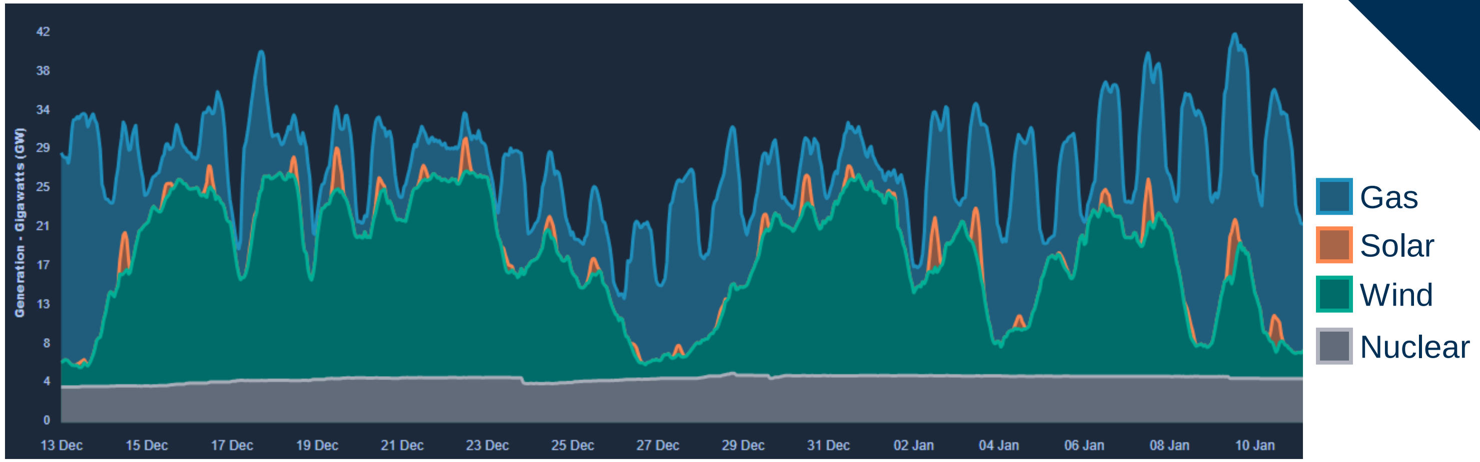
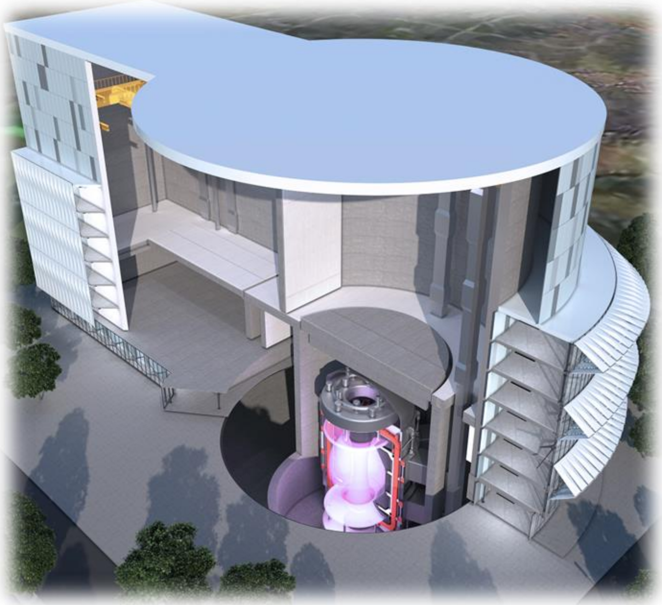
Fusion as part of the solution



Source: https://www.energydashboard.co.uk/historical

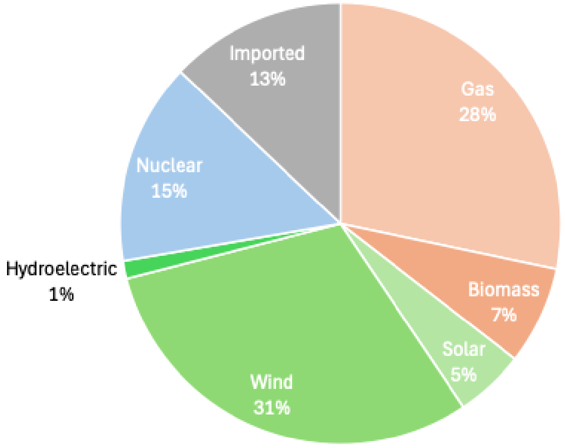


Global energy demand expected to increase by 50% by 2050 [1], with double the demand forecast within the UK [2].

Coincidentally – UK net zero target set for 2050 [3].

Reliable baseload supply needed to replace dependence on fossil fuels – government ambition to deliver 24GW of nuclear power by 2050 [4].

Fission: SMR, HTGR, development of Hinkley Point and Sizewell C.



Source: https://grid.iamkate.com

[1] https://www.eia.gov/outlooks/ieo/consumption/sub-topic-03.php
[2] https://assets.publishing.service.gov.uk/media/5fdc61e2d3bf7f3a3bdc8cbf/201216_BEIS_EWP_Command_Paper_Accessible.pdf
[3] https://assets.publishing.service.gov.uk/media/6194dfa4d3bf7f0555071b1b/net-zero-strategy-beis.pdf
[4] https://www.gov.uk/government/publications/great-british-nuclear-overview/great-british-nuclear-overview

Outline

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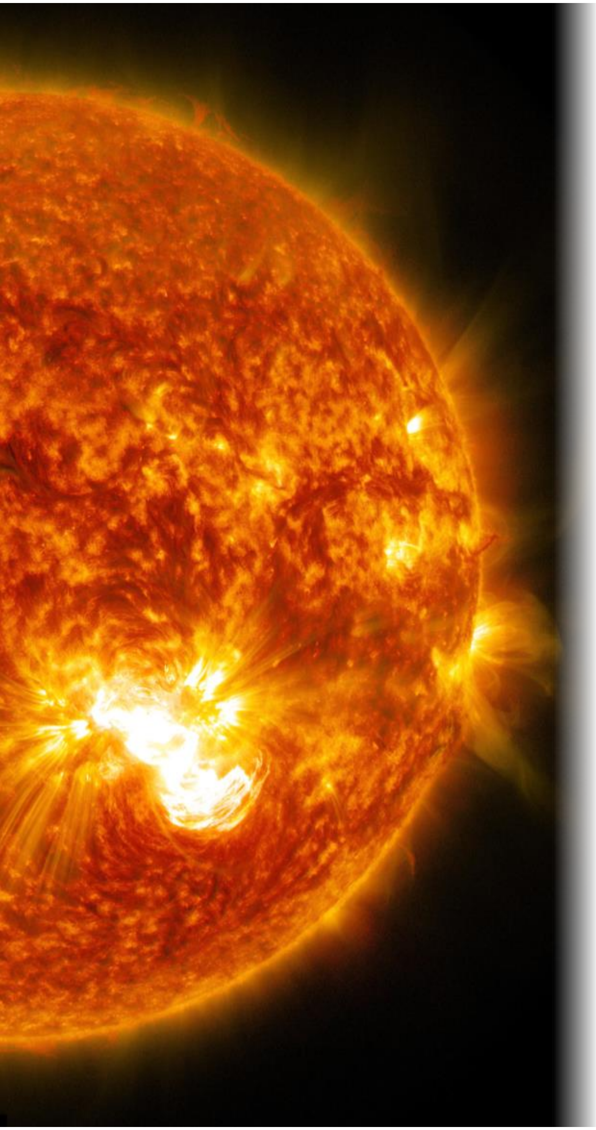
- The need for alternative energy sources.
- What is fusion and what role can it play?
- The fusion landscape and UKAEA.
- Why are steels important and what do they offer us?
- Critical technical challenges.
- How the UK can lead – a ‘call to arms’

What is nuclear fusion?

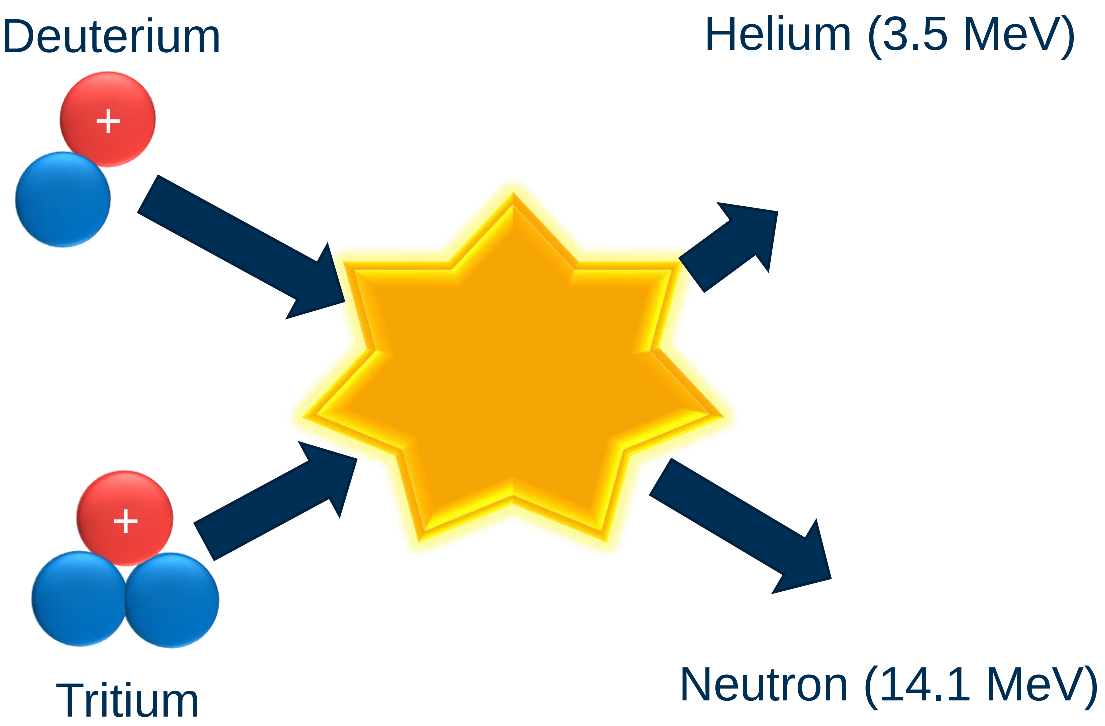


In the sun:

- Core temperature of 15,000,000°C.
- Fuse hydrogen isotopes to form He. Stellar fusion continues all the way up to iron!
- Uses gravity to enable fusion.

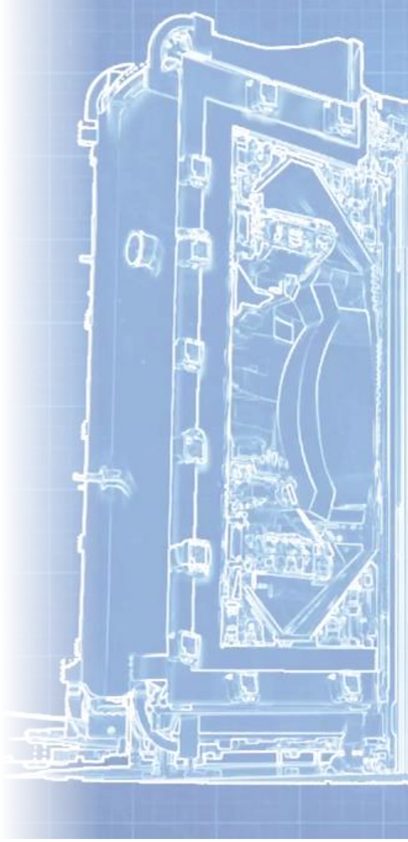
In a fusion power plant:

- Plasma at 150,000,000°C.
- Fuse hydrogen isotopes; deuterium and tritium.
- Generate 17.6MeV energy per fusion reaction.
- Use a combination of high temperature and magnetic confinement to enable fusion (other methods possible).



Coal-fired plant (1GW)
= 2.7 MT coal p/a

Fusion plant =
250 kg DT p/a



International fusion landscape

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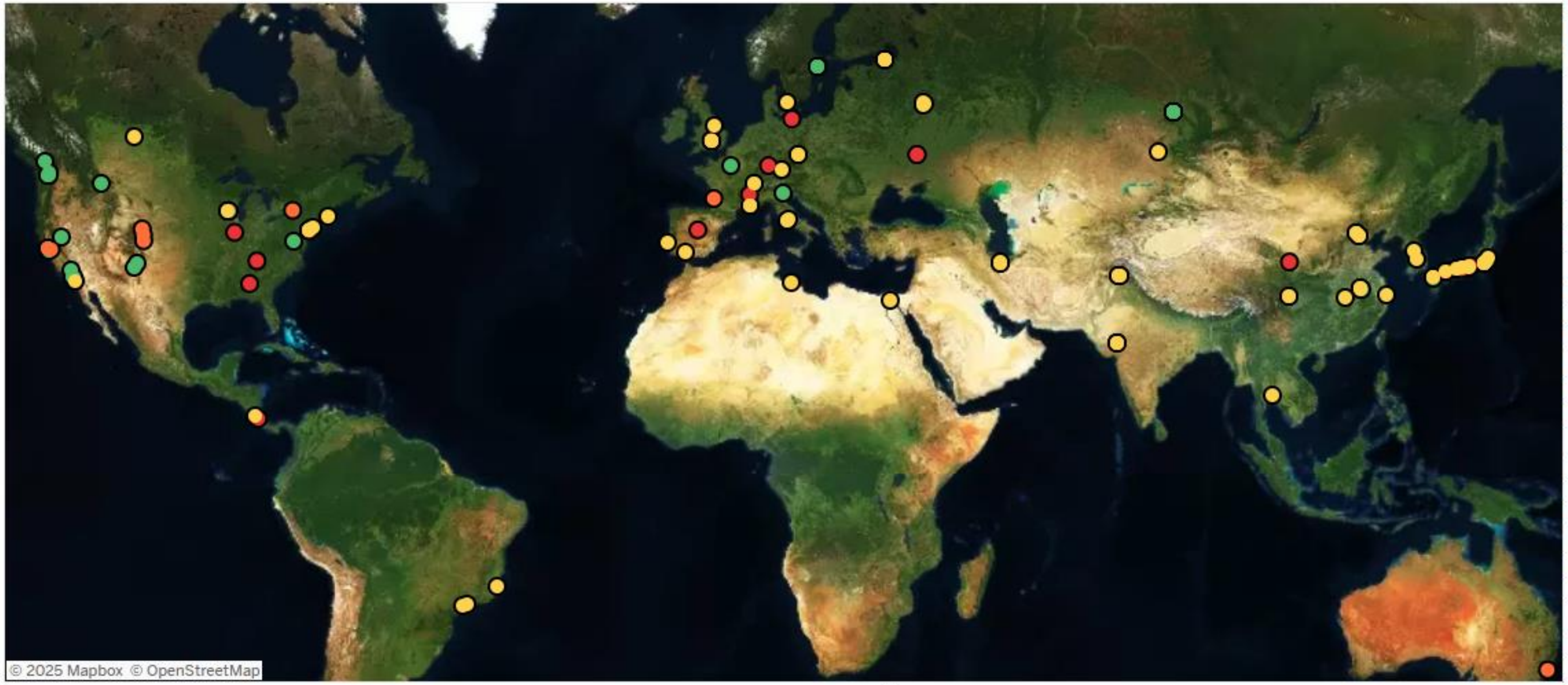
Total	Tokamaks	Stellarators/Heliotro..	Laser/Inertial	Altern. Concepts	Exp	Plant
163	80	23	14	46	142	21

Tokamaks
Stellarators/Heliotrons
Laser/Inertial
Altern. Concepts



Operating	Under construction	Planned	Public	Private
101	14	48	112	51

Country	
United States	45
Japan	26
China	14
Russia	14
United Kingdo..	8
France	5
Germany	5
Italy	4
Pakistan	4
Sweden	4
Brazil	3
Canada	3
India	3
Iran	3
Republic of K..	3
Costa Rica	2
Czech Republic	2
Spain	2
Switzerland	2
Ukraine	2
Australia	1
Denmark	1
Egypt	1
European Uni..	1
Israel	1
Kazakhstan	1
Libya	1
Portugal	1
Thailand	1

Source: https://nucleus.iaea.org/sites/fusionportal/Pages/FusDIS.aspx

Total funding*:

- £5.8bn to date
- £750m in 2024
- £343m public
- Subsequently an extra £1bn announced in late 24/25!

Compare this to Hinkley Point C predicted to cost ~£45bn!

*from Fusion Industry Association report 2024

What does UKAEA do?

UK Atomic Energy Authority

- We lead the delivery of sustainable fusion power and maximise scientific and economic benefits
- We deliver high-impact research, partnering with companies and the international research community
- We own UK Industrial Fusion Solutions on behalf of UK government

RESEARCH
building the knowledge base of fusion

- Generate and curate knowledge from our technical centres of excellence
- Solve challenges across the full lifecycle of fusion
- Integration of technologies for fusion
- Operate world-leading facilities
- Analyse what is needed for the widespread use of fusion

DELIVER
fusion powerplants

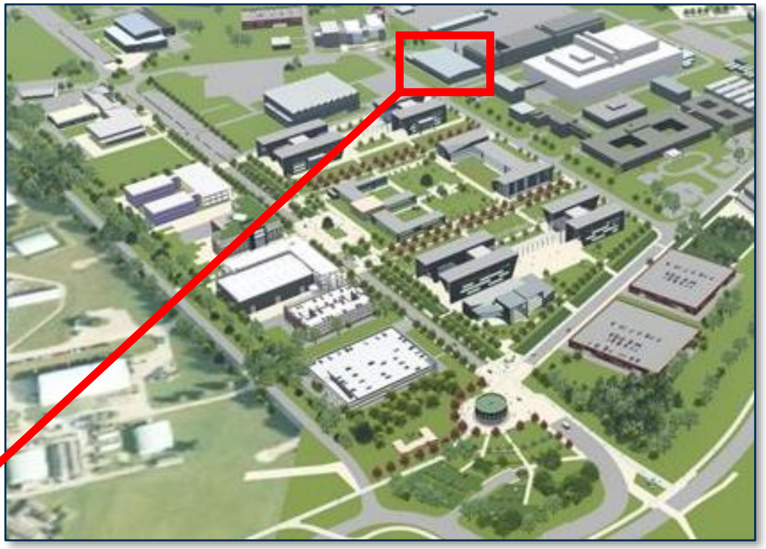
- Use our skills, facilities and expertise to help partners deliver fusion powerplants
- Work with major industrial partners in a national programme to deliver the STEP prototype fusion powerplant

ENABLE
the fusion community

- Grow a fusion cluster
- Support a fusion industry
- Develop skilled people #fusiongeneration
- Support the regulation of fusion
- Seek out growth opportunities for fusion technology
- Communicate the opportunities

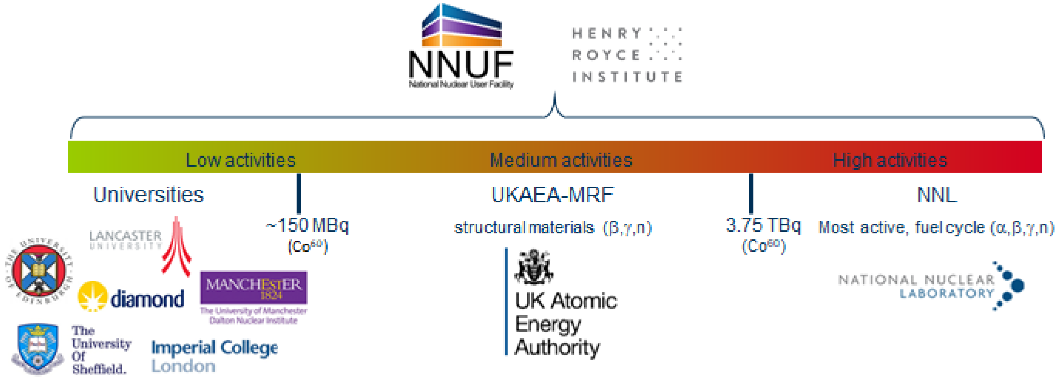
UKAEA and materials R&D

- Collaborate closely with ***fusion technology drivers, sector suppliers,*** *and* ***academia,*** to assess the performance of materials in nuclear and fusion environments.
- Division of ~80 people, including scientists, engineers, operators, technicians and graduates.
- Hosting secondees, summer students and apprentices.
- 40+ PhDs and masters projects.
- £50m nuclear materials development and testing facility.



MATERIALS RESEARCH FACILITY

- 4400m^2 for processing and analysis of neutron (and proton) irradiated materials.
- Open to universities and industry for bespoke and standardised test techniques.



The fusion power plant

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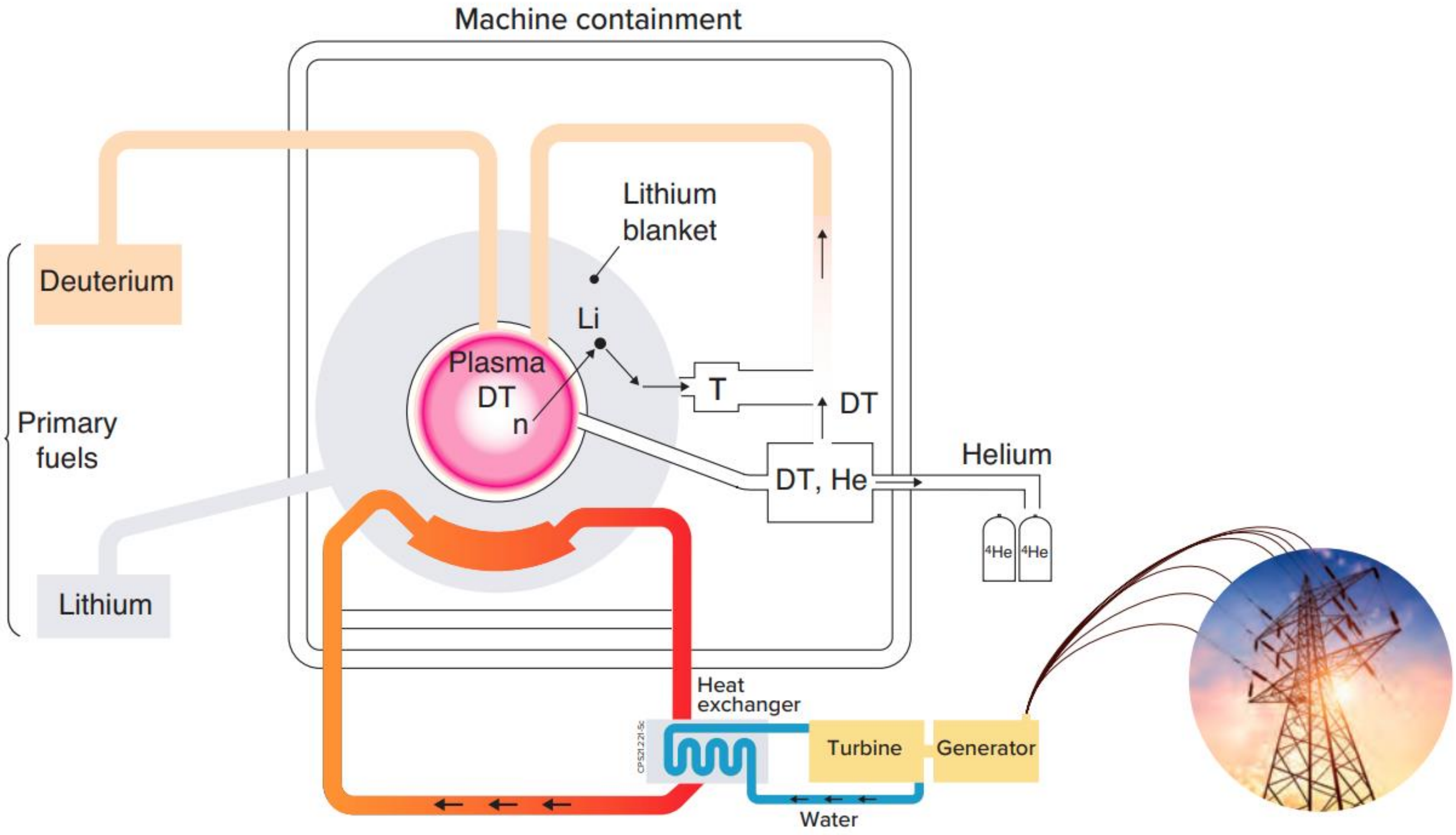
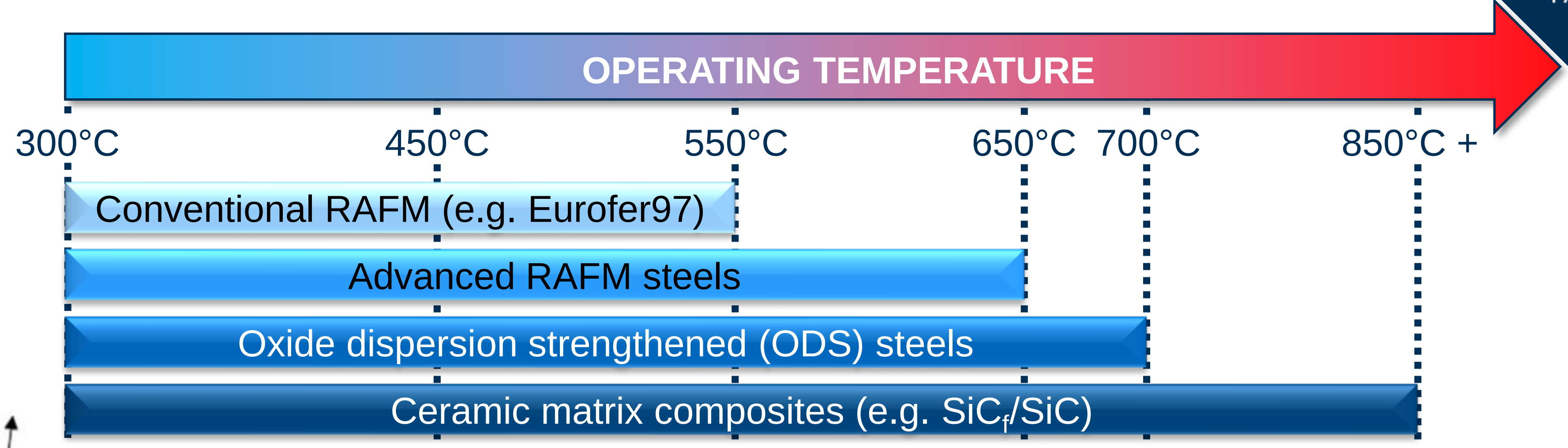
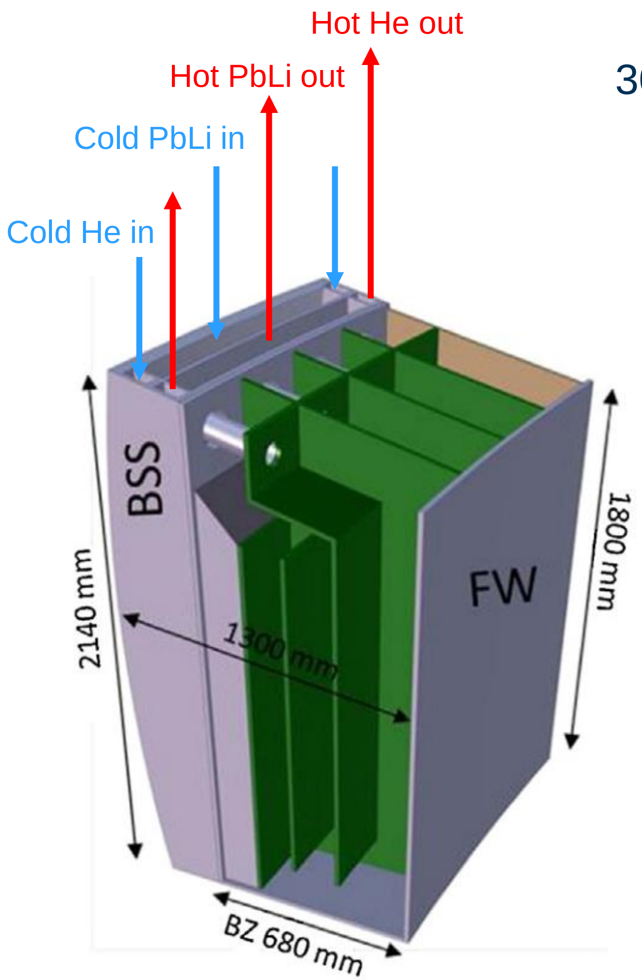


Economic case for higher temperatures





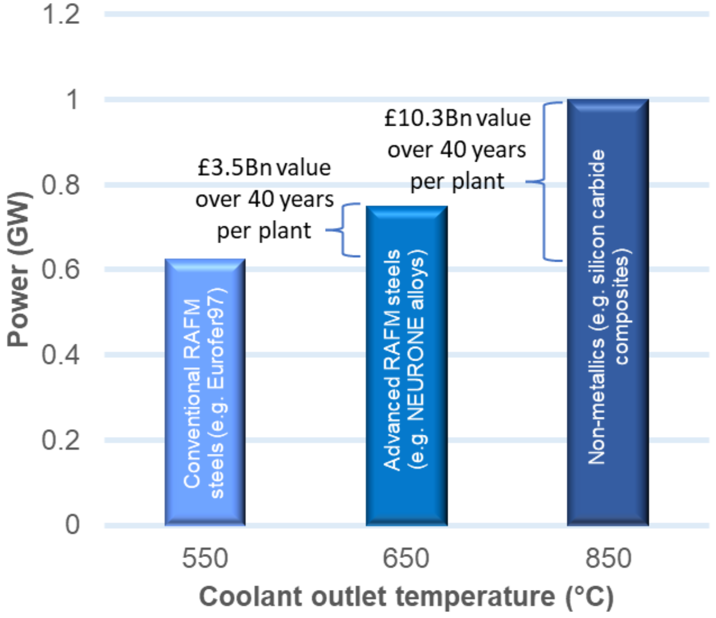
L. V. Boccaccini, et. al, Objectives and status of EUROfusion DEMO blanket studies, Fusion Eng. Des. 109–111 (2016) 1199–1206. https://doi.org/10.1016/j.fusengdes.2015.12.054.

- Blankets will experience a temperature gradient between coolant inlet and outlet regions.
- Promoting a wider separation between the two increases the thermal efficiency of the plant.

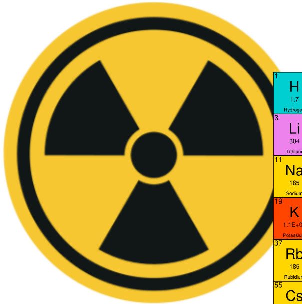
$$\eta_{th} \leq 1 - \frac{T_C}{T_H}$$

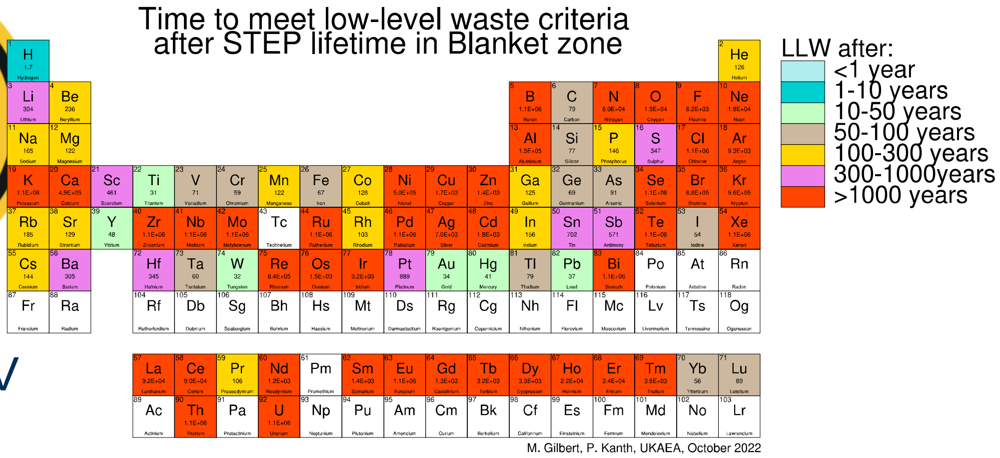
- Capturing more thermal energy in coolant increases T_H, leads to additional power output.
- This necessitates materials capable of operating at increased temperatures.

Net power generated for different coolant outlet temperatures (3.5GWth fusion plant concept)

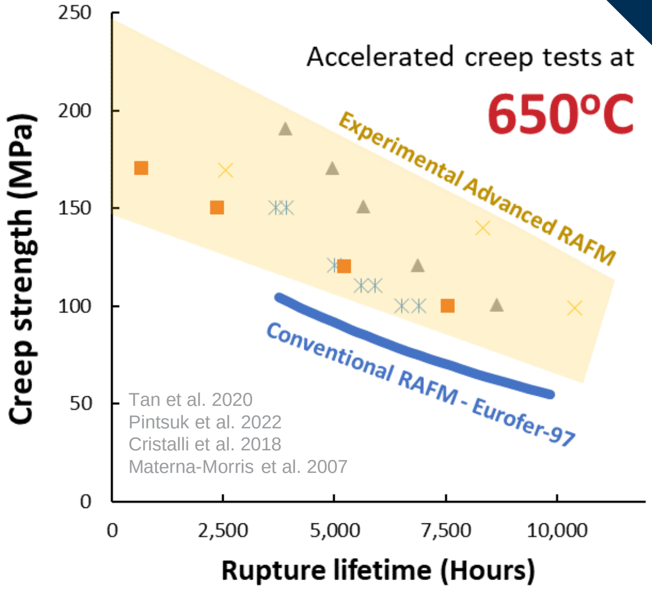


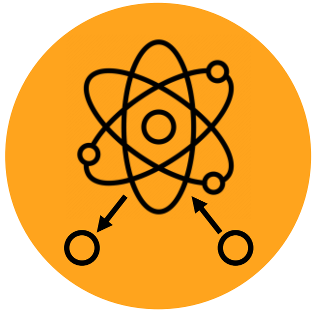
Fusion steel challenges

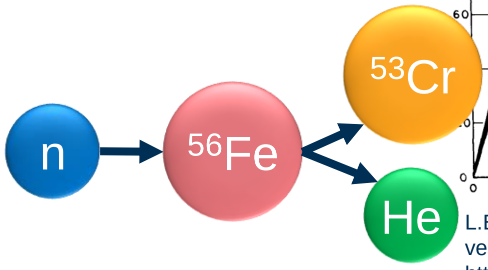


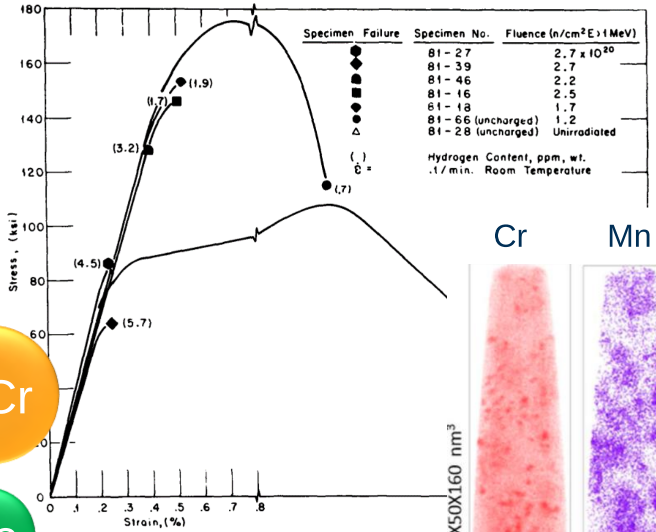


n 14 MeV

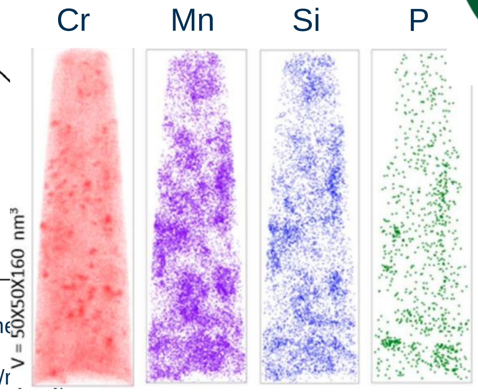








L.E. Steele, Neutron irradiation embrittleme... vessel steels, in: 1969. https://doi.org/https://inis.iaea.org/records/r...



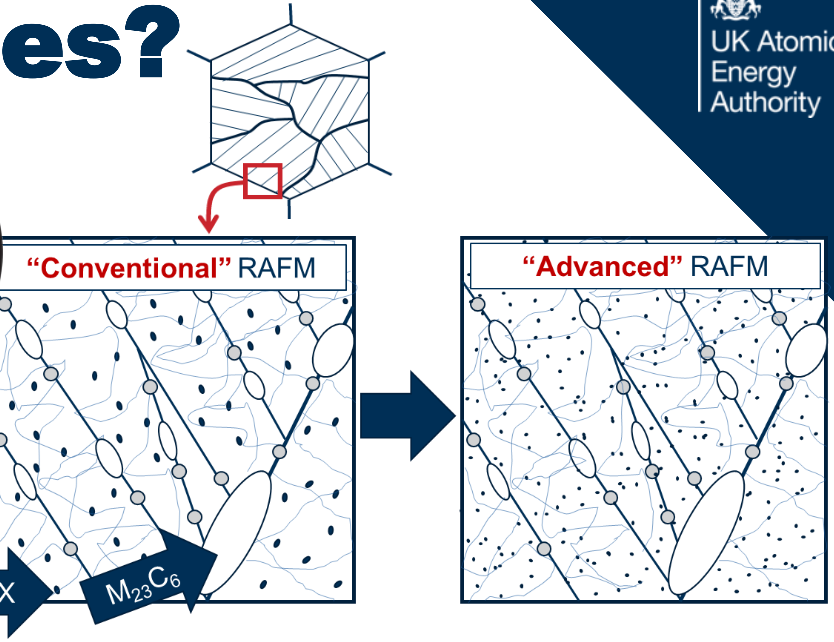
https://doi.org/10.1016/j.jnucmat.2020.152228

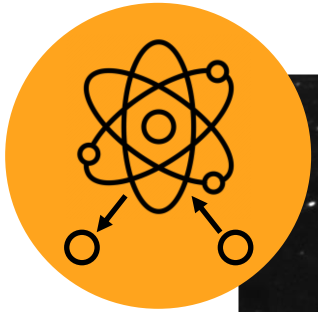
How to address these challenges?

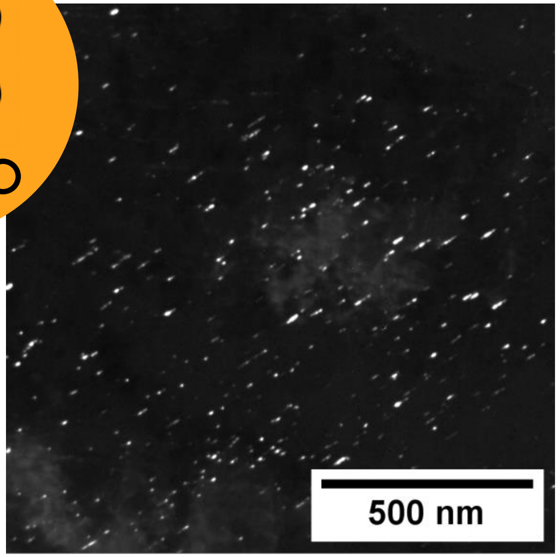
28 Ni	41 Nb	42 Mo

Reduced-activation ferritic-martensitic (RAFM) steel

74 W	73 Ta	23 V







Void swelling

0.3 to 0.6 Tm

FCC = 1% dpa^{-1}
BCC = 0.2% dpa^{-1}

Clustering

25 Mn	14 Si

Supply chain
High quality

Circularity
Ring-fenced

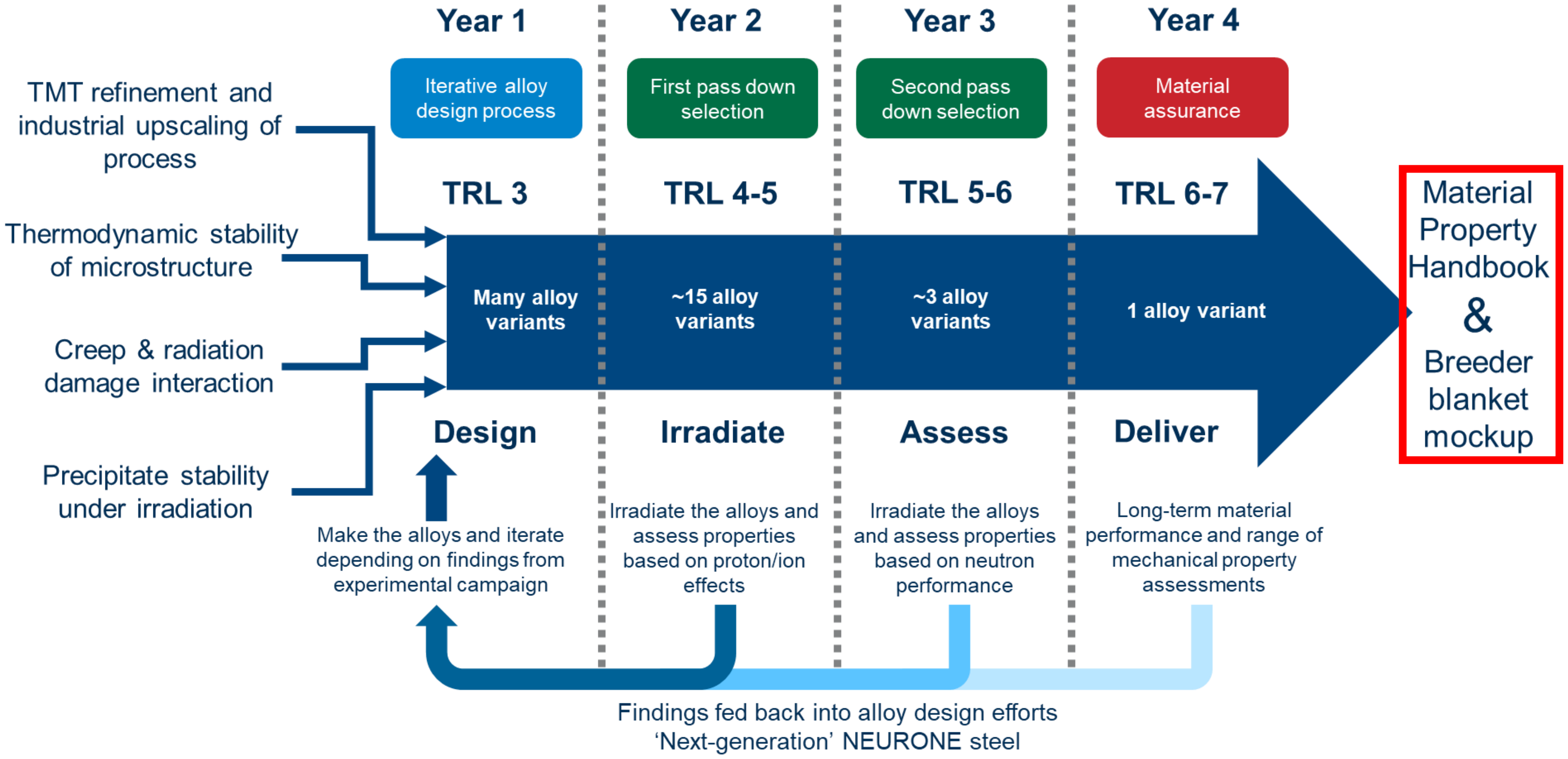
Introducing NEURONE

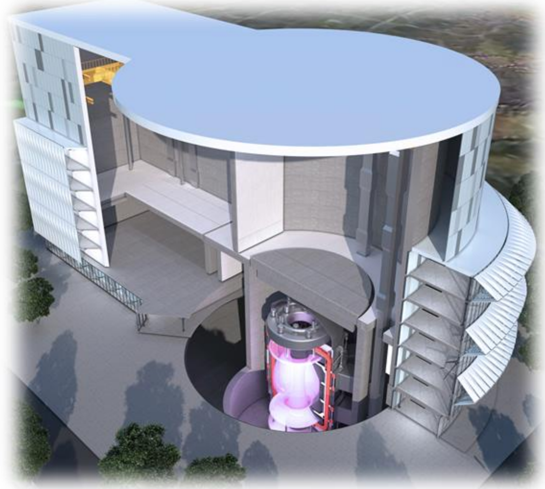
NEUtron iRradiatiOn of advaNced stEels

£12.5m until 2028

~70 collaborators across 11 organisations.

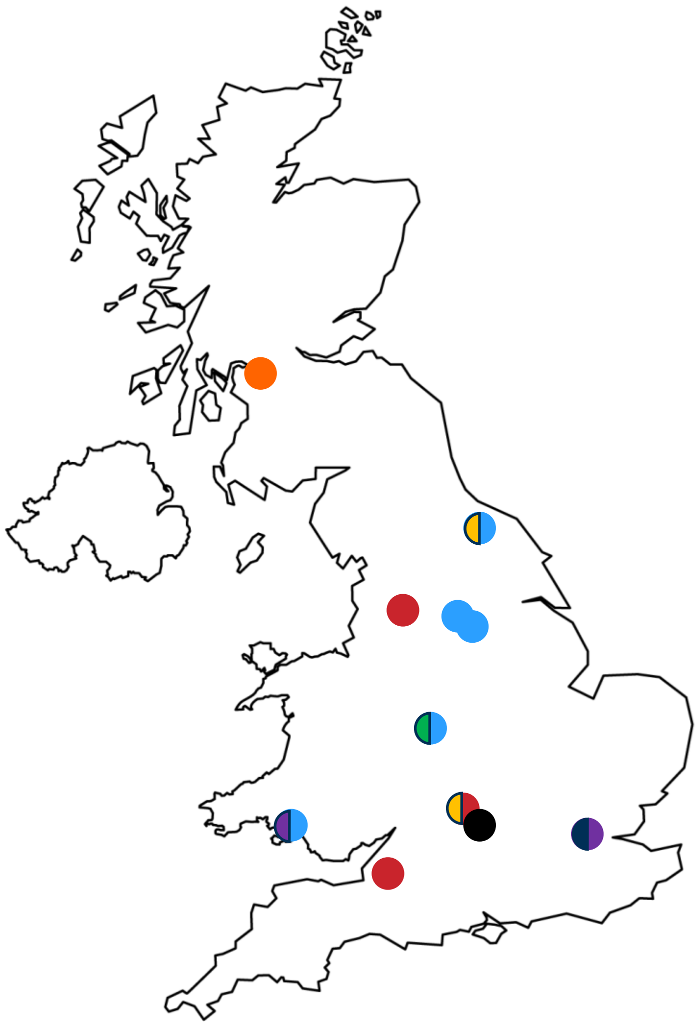
Develop and deliver an industrially scalable fusion-grade advanced steel capable of operating up to 650°C in a fusion breeder-blanket environment.





NEURONE – WPs partners and goals

UK Atomic Energy Authority



A national programme

neurone

WP1: Alloy development and upscaling – Dr. David Bowden
- Swansea University / Prifysgol Abertawe
  - Prof. Nicolas Lavery
  - Dr. Stephen Jones
- University of Sheffield
  - Prof. Eric Palmiere
  - Prof. Mark Rainforth

WP2: Irradiation – Dr. Slava Kuksenko
- Materials Processing Institute
  - Dr. Richard Birley
  - Dr. Abdollah Bahador
- University of Birmingham
  - Prof. Sandy Knowles
- Sheffield Forgemasters
  - Prof. Jesus Talamantes-Silva
  - Dr. Marcus Crabbe

WP3: Microscopy and characterisation – Dr. Jack Haley
- ANSTO
  - Prof. Lyndon Edwards
  - Prof. Michael Moody
- University of Birmingham
  - Prof. Enrique Jimenez-Melero

WP4: Micromechanical testing – Dr. James Gibson
- Manchester 1824 – The University of Manchester
  - Dr. Ed Pickering
- University of Oxford
  - Dr. Paul Bagot
- University of Bristol
  - Dr. Tomas Martin

WP5: Bulk mechanical testing – Dr. Jim Johnson
- University of Oxford
  - Prof. Dave Armstrong
- Materials Processing Institute

WP6: Manufacture and joining – Dr. Paul Goodwin
- Imperial College London
  - Dr. Catrin Davies
- Swansea University / Prifysgol Abertawe
  - Prof. Mark Whittaker
  - Prof. Rob Lancaster

WP7: Modelling – Dr. Chris Hardie
- University of Strathclyde Glasgow
  - Prof. Brad Wynne
- Imperial College London
  - Dr. Mark Wenman
  - Prof. Robin Grimes

Plus:
- 6 PDRA's
- 10 PhDs
- 1 secondment
- Hosted five summer students at UKAEA, with capacity to host 15 more in future years

Independent advisors
- **Dr. Peter Morris** – Ex-Tata / 9Cr steel development
- **Prof. Ted Darby** – Ex-RR / Fission / C&S / qualification
- **Matthew Green** – Liberty / 9Cr steel development
- **Dr. Peter Barnard** – Ex-MPI/ Steel development

Advanced RAFM alloy development

UK Atomic Energy Authority

Alloy chemistry & *Thermomechanical treatments*

	Eurofer97 Spec. [1]			NEURONE Spec.
Cr	9%	Corrosion resistance and minimise DBTT shift	No change	8-9%
W	1.1%	Reduce Laves phase, solution strengthening	Increase for higher strength	1.5 - 2%
Mn	0.4%	Austenite stabiliser	Reduce to minimise irradiation clustering	0.05 – 0.25
V	0.2%	Precipitate former (compensate for Ta reductions)	Increase for more MX	0.2 - 0.3%
Ta	0.12%	Precipitate former, grain refinement	Reduce to lower austenisation temperature	0.05 – 0.1%
C	0.11%	Precipitate former	Decrease for less $M_{23}C_6$	0.07 – 0.1%
N	0.03%	Precipitate former	Increase for higher strength	0.03 - 0.1%
Si	0.05%	Ferrite stabiliser, flowability	Reduce to minimise irrad. clustering	0.05%
Ti	0.02%	Precipitate former	Increase for more MX	0 - 0.07%
B	0%	Precipitate refinement	Increase for enhanced creep life	0 - 0.03%

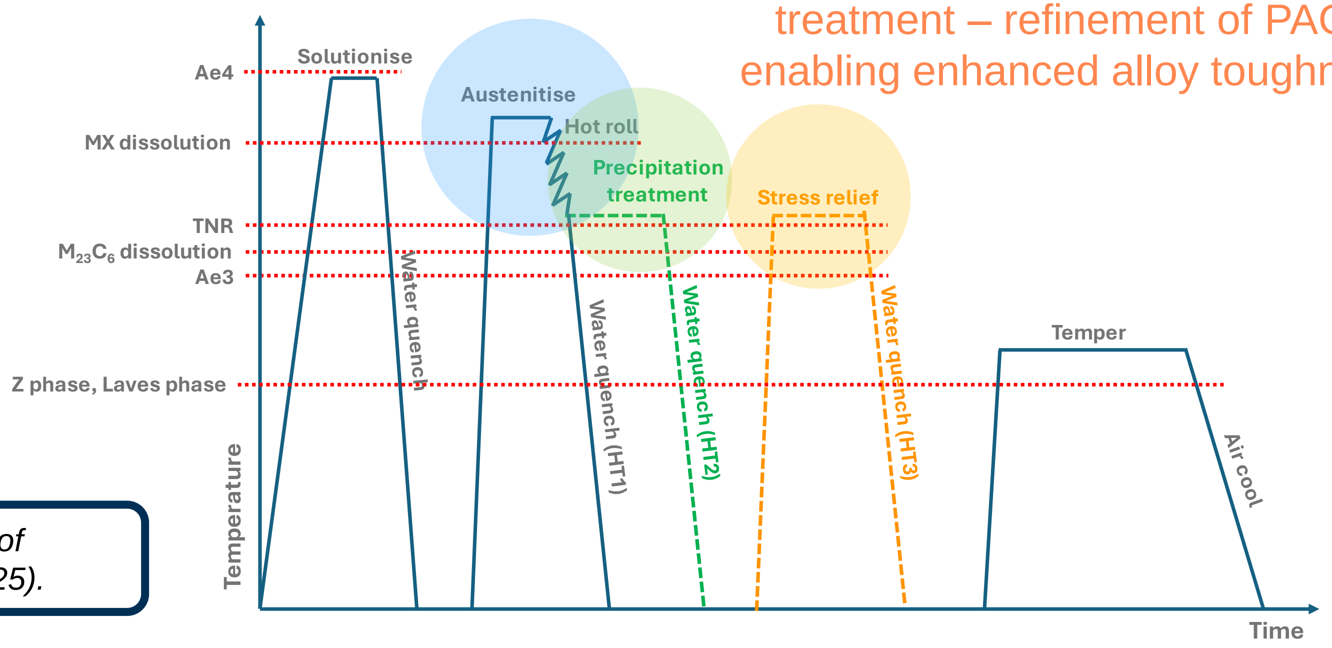
[1] E. Gaganidze et al., Development of EUROFER97 database and material property handbook, Fusion Eng. Des. 135 (2018) 9–14. https://doi.org/10.1016/j.fusengdes.2018.06.027.

Keep an eye out for: D. Bowden, et al., Engineering the next-generation of industrially scalable fusion-grade steels, J. Nucl. Eng. In preparation (2025).

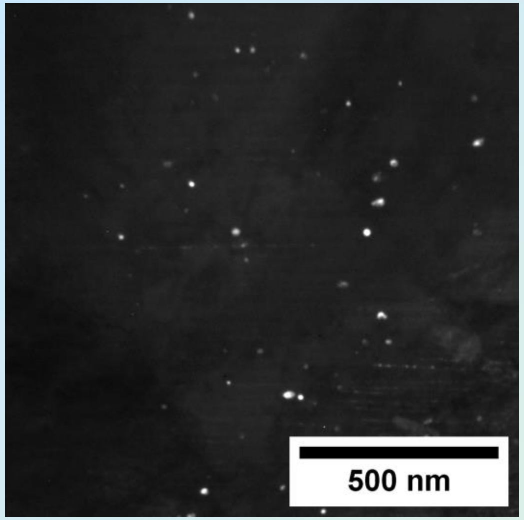
Significant dislocation density – drives up precipitate formation

Extended duration to evolve MX precipitates enabling high temperature strength and irradiation tolerance

Optional step for a cyclic heat treatment – refinement of PAGs enabling enhanced alloy toughness

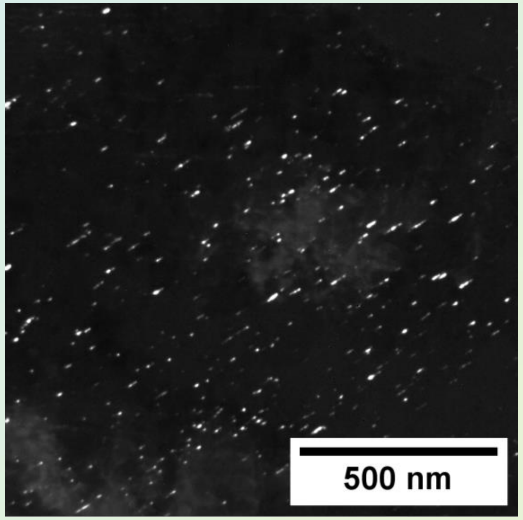


Alloy microstructures

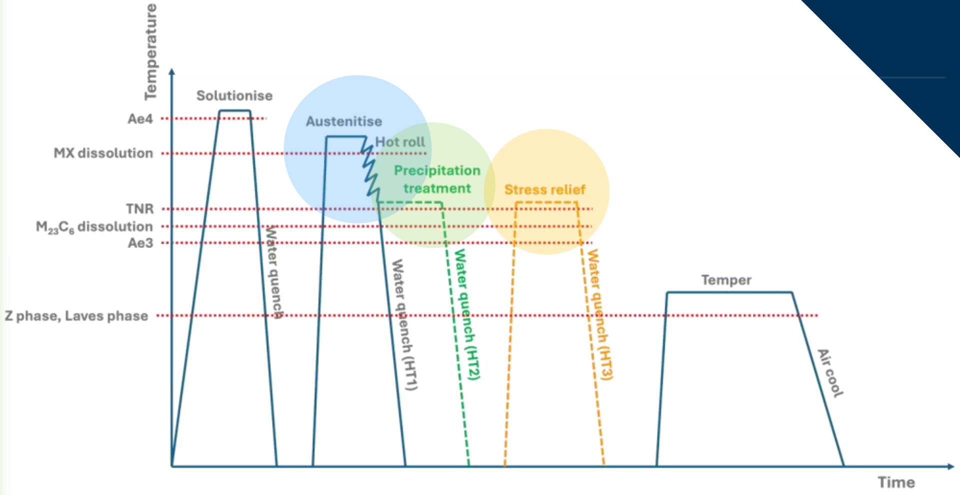


"Conventional" RAFM
(Eurofer97)

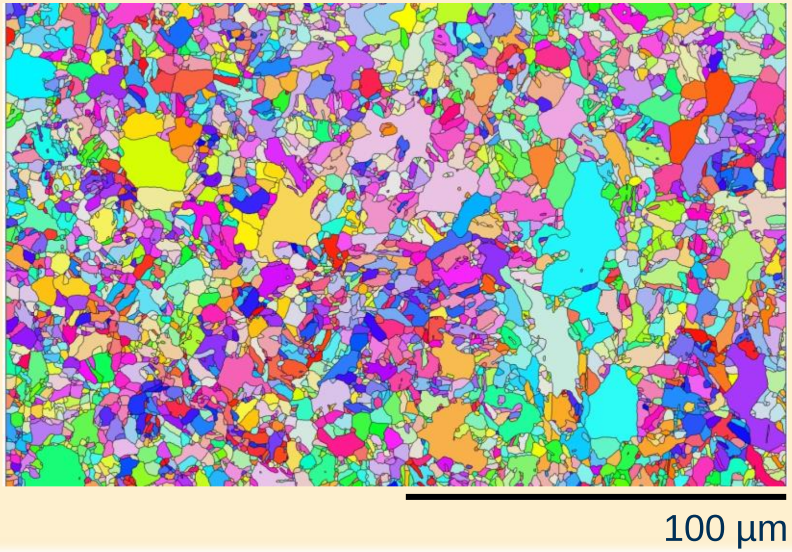
10× increase in MX precipitate density



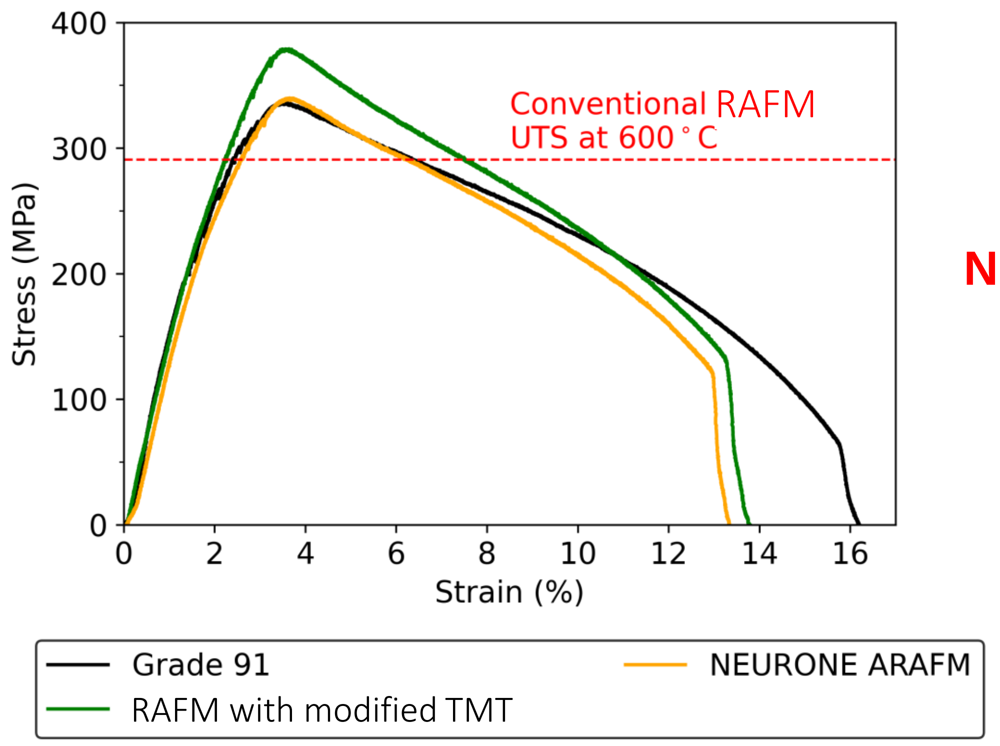
"Advanced-" or "A-"RAFM
(NEURONE steel)



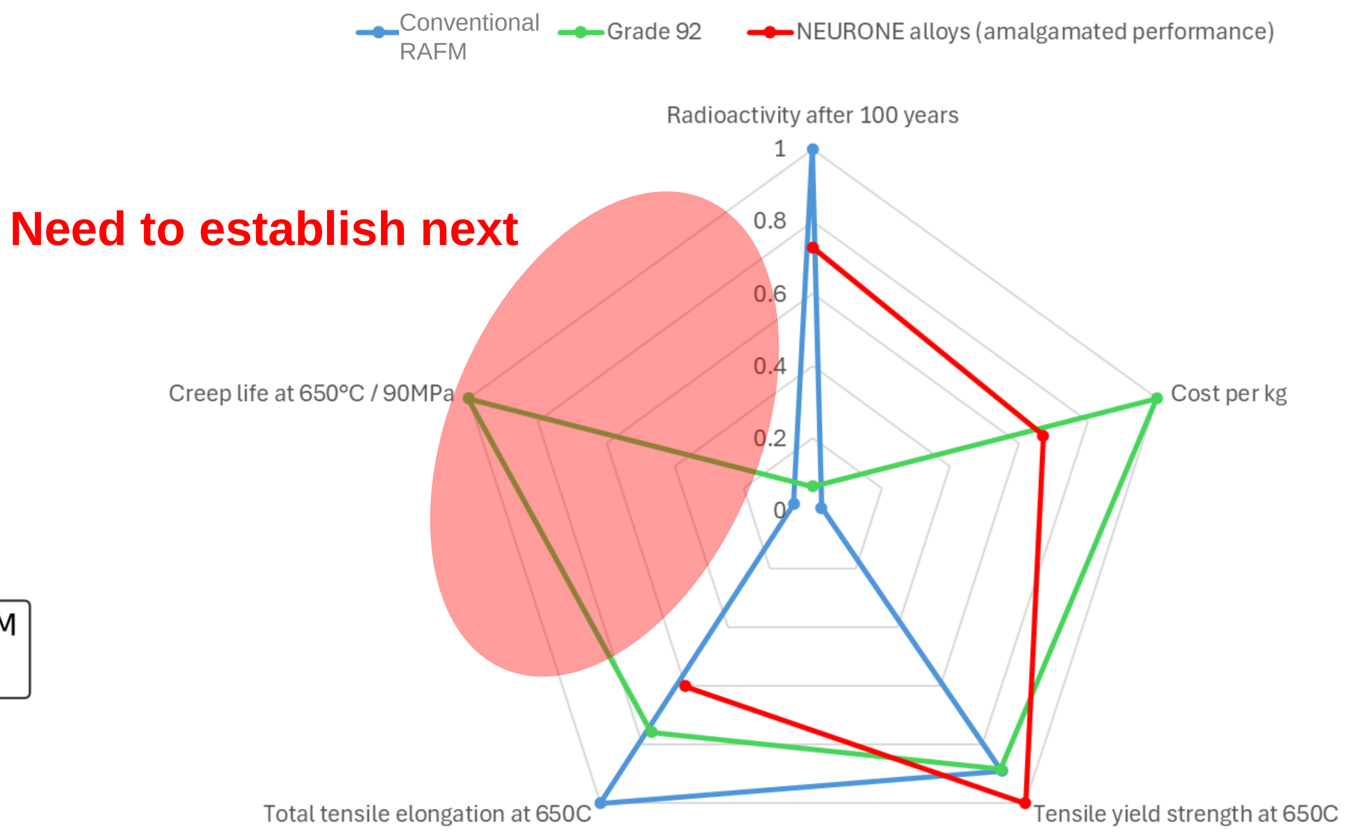
58% refinement in grain size



Alloy performance

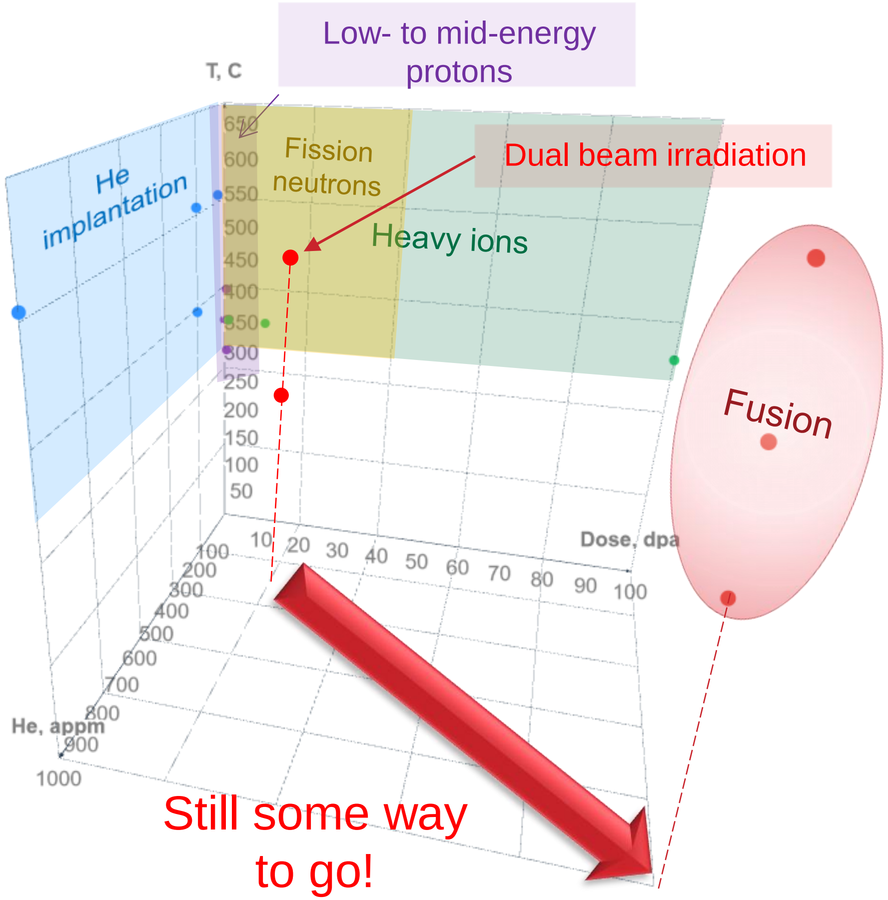


30% improvement in high temperature strength using conventional RAFM (Eurofer) alloy chemistry with modified TMT.

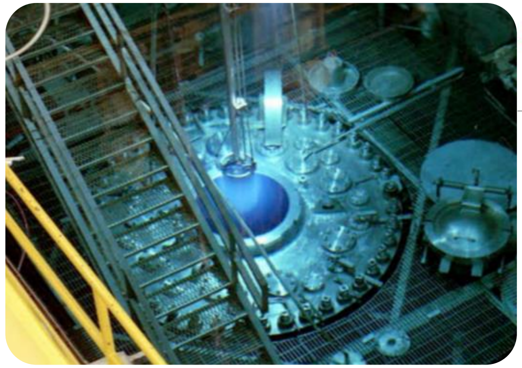


Higher values = better performance or value

Irradiation performance



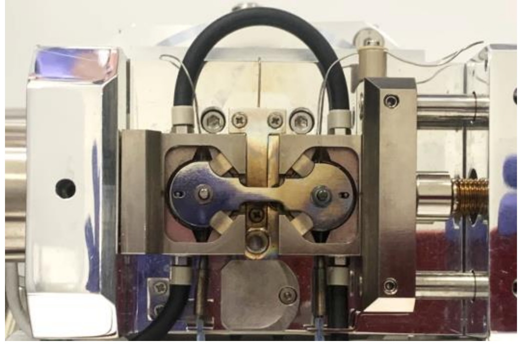
Fission neutrons – Material Test Reactors



Oak Ridge National Laboratory

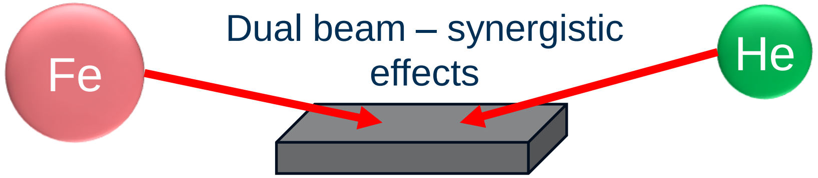
ANSTO

Ion and proton beams – accelerator driven sources



Manchester 1824
The University of Manchester
Dalton Nuclear Institute

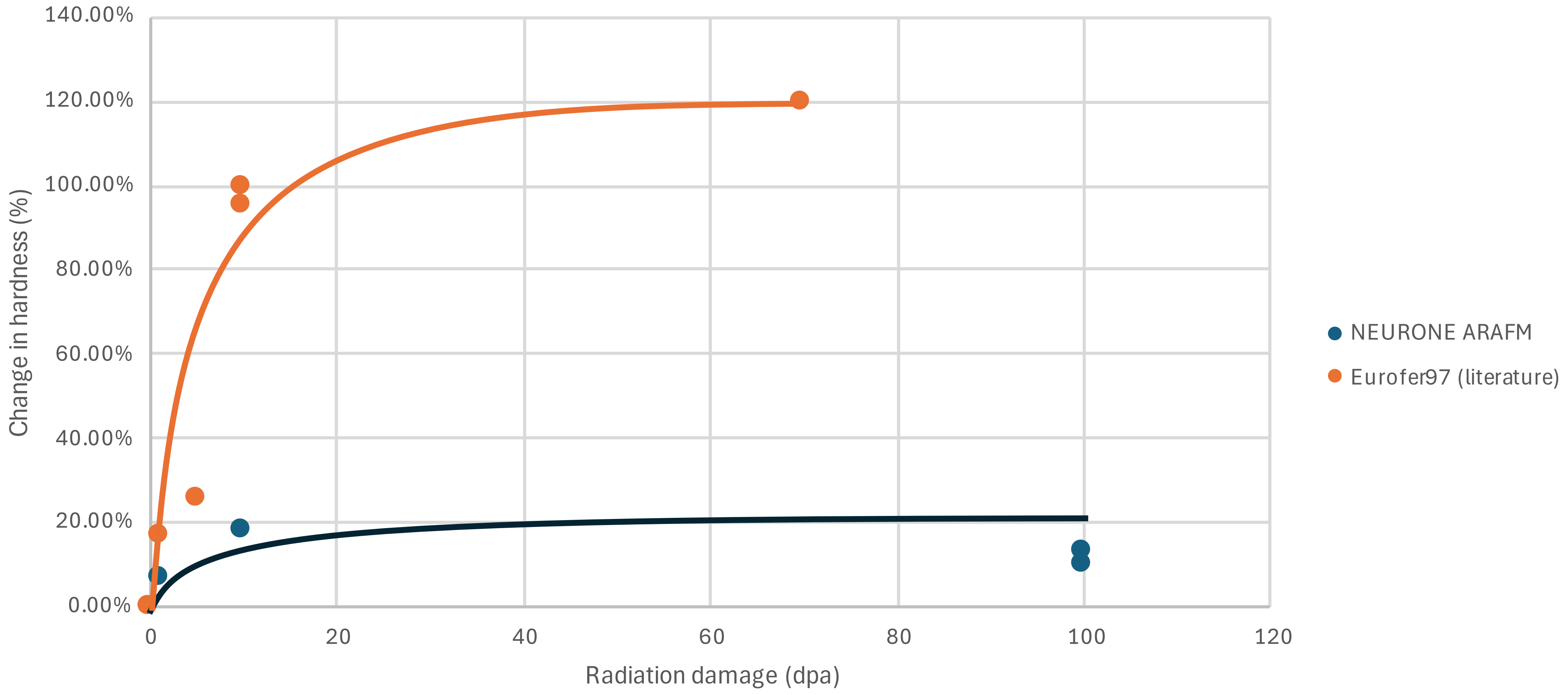
University of Birmingham



Irradiation performance

2MeV self ion (Fe^{2+}) irradiation at 350°C.

Nanoindentation data (irradiated region only 1μm thick!).



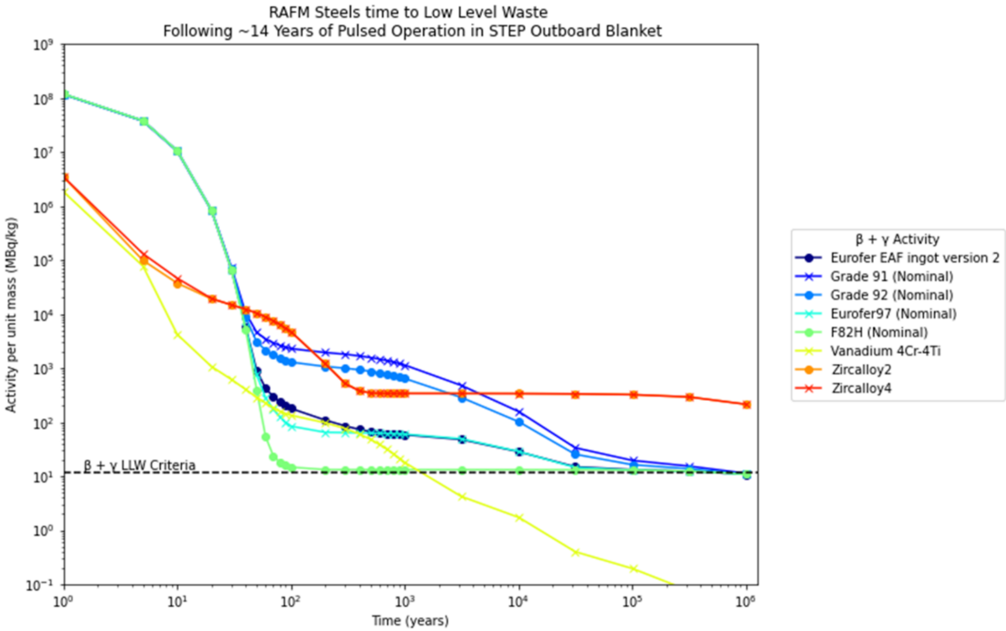
First UK ‘RAFM’ multi-tonne ingot

Materials Processing Institute

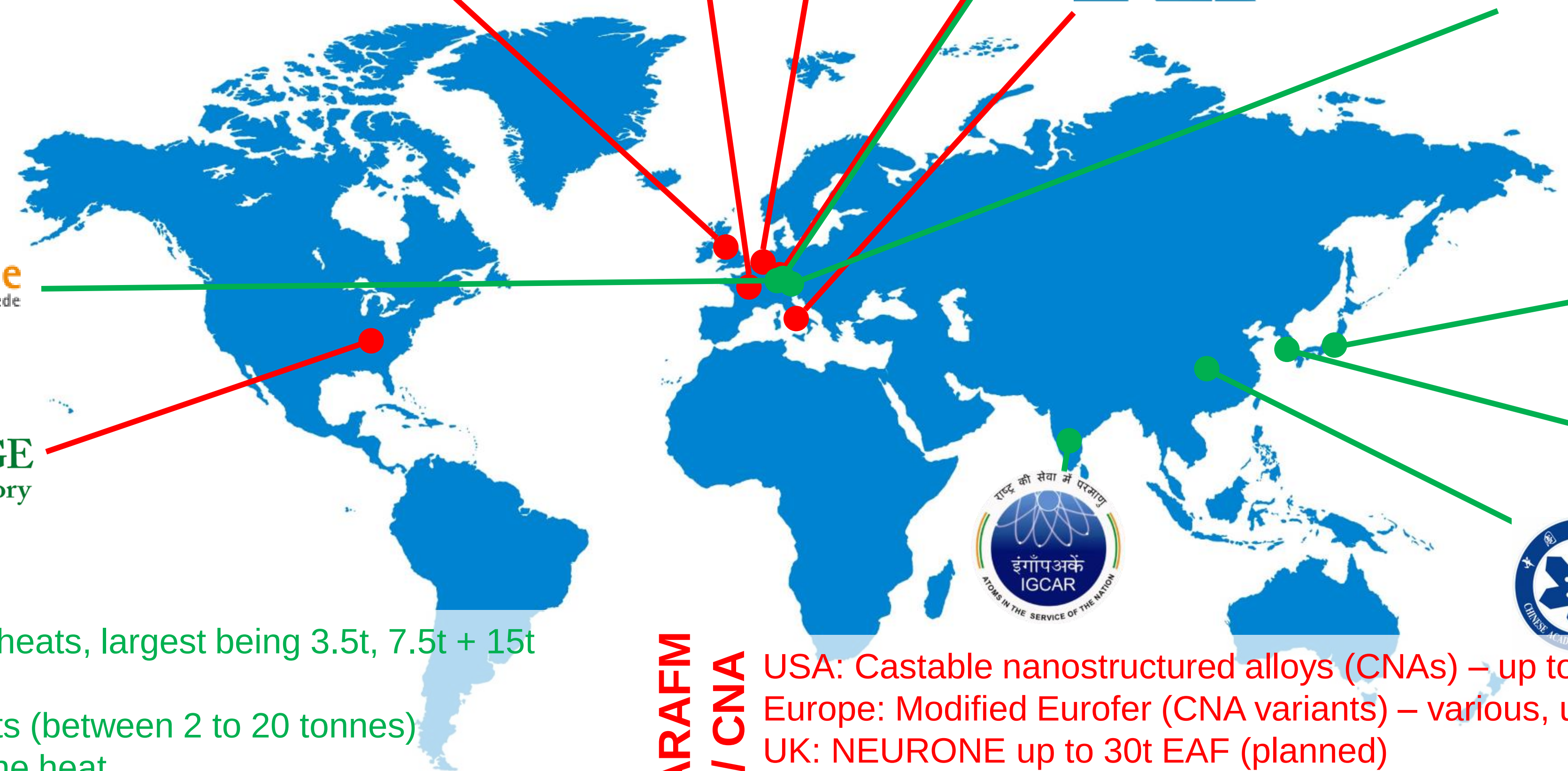
UK Atomic Energy Authority

- Produced by the Materials Processing Institute in June 2024.
- Using Eurofer97 specification chemistry, cast using an electric arc furnace (EAF), replicating industrial-scale conditions.
- Continuous casting used to produce an ingot sized at 0.3 x 0.14 x 13 metres, weighing approximately 5.5 tonnes.
- The EAF production route will next be explored to produce new Advanced RAFM grades, developed in the NEURONE programme, targeting operation at 650°C.
- Residual activity comparable to Eurofer97 after plant shutdown (neither satisfy UK LLW criterion!).

	Cr	Ni	W	Ta	V	Mn	Mo	Si	C	N	P	S	O
Eurofer97 EAF MPI ingot	10.115	0.020	1.004	0.092	0.223	0.457	<0.0005	0.147	0.11	0.023	0.009	0.004	0.007
Eurofer97 nominal targets	8.5 – 9.5	<0.01	1 – 1.2	0.1 – 0.14	0.15 – 0.25	0.2 – 0.6	0.005 max.	0.05 max.	0.09 – 0.12	0.015 – 0.045	0.005 max.	0.005 max.	



The big picture



RAFM

EU: Eurofer97; >10 heats, largest being 3.5t, 7.5t + 15t KIT/OCAS
Japan: F82H; 9 heats (between 2 to 20 tonnes)
Korea: ARAA; 5 tonne heat
China: CLAM; 3 x 6.4 tonne heats, 5t (CLF-1)
India: IN-RAFM; 2.5 tonne heats
UK: EAF-RAFM; 5.5 tonne heat

ARAFM / CNA

USA: Castable nanostructured alloys (CNAs) – up to 5t
Europe: Modified Eurofer (CNA variants) – various, up to 100kg VIM per heat
UK: NEURONE up to 30t EAF (planned)

ODS

Not produced at tonnage-scale.
Efforts across US (ORNL), EU (KIT, CEA, Plansee, Zoz), Japan (JAEA)
Current 'fusion-grade' suppliers are Zoz (Germany) and MBN nanomaterialia (Italy)

Fusion steel economics

UK Atomic Energy Authority

neurone

Advanced RAFM grades

International fusion steel programmes (RAFM and CNAs / advanced variants)

Oxide dispersion strengthened (ODS) steels

Electric Arc Furnace

VIM & VAR/ESR

Atomisation, ball mill and consolidate

Cost

~£10’s/kg

~£100’s/kg

~£1000’s/kg

Scale

100’s tonnes

~10’s tonnes

~100’s kgs

A national opportunity

$6.9 trillion global fusion market forecast [1].

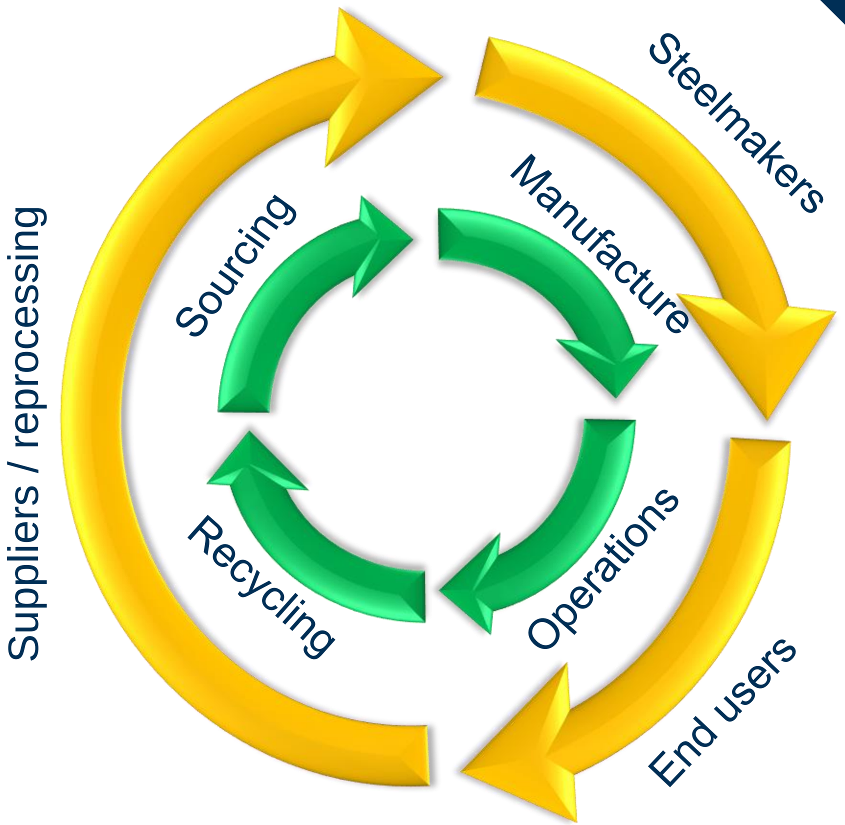
Not just fusion! Fission (GenIV), oil and gas and other markets which may require specialist steels. Opportunities beyond to provide:

Low-volume, high value steels for sovereignty and economic growth within the UK.

The UK's modern industrial strategy [2] & steel strategy:

- 8 priority sectors, including; advanced manufacturing and clean energy industries.

Need to build on the progress within programmes like SUSTAIN [3] and i-SPACE [4] to build a resilient, strategic supply of high-grade scrap.
~9Mt scrap generated in the UK per year.
~8Mt exported [5]



[1] https://assets.publishing.service.gov.uk/media/65301b78d06662000d1b7d0f/towards-fusion-energy-strategy-2023-update.pdf
[2] https://www.gov.uk/government/consultations/invest-2035-the-uks-modern-industrial-strategy/invest-2035-the-uks-modern-industrial-strategy#our-approach--a-modern-industrial-strategy
[3] https://www.sustainsteel.ac.uk
[4] https://www.swansea.ac.uk/science-and-engineering/research/climate-action/research/social-political-change-circular-economy/i-space/#i-space-achievements-february-2023=is-expanded&meet-the-team=is-expanded
[5] Transforming Steelmaking at Port Talbot" given by Richie Hart (Process Technology Manager for Tata Steel UK) on 28th Jan 2025

Bringing it all together

UK Atomic Energy Authority

- The need for a reliable baseload to tackle climate change and meet our growing energy needs.
- Fusion processes and key materials challenges.
- How steel can fulfil an important role within commercial fusion.
- Introduced the UK NEURONE programme exploiting the flexibility of steel to deliver a high-temperature candidate with the properties we require.
- Explored the international landscape and how the UK is in a position to lead the way in developing an integral specialist steel market.

UKAEA will host a 'Future Fusion Steel Suppliers' event later this year:

- Outline the challenges we face around fusion-grade steel.
- Introduce key players in the field and develop a network of specialists.
- Galvanise support to develop a fusion / speciality steel supply chain.
- Bring the national steel industry together.

Thank you for listening

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