UKAEA Vanadium Strategy

Davidson Sabu[1], Asma Ramzi[1], Paul Goodwin[1], Allan Harte[1]

Manufacturing Technology and Equipment Qualification, Fusion Technology Division

[1]UKAEA, 2A Lanchester Way, Advanced Manufacturing Park, Rotherham, S60 5FX

UK Atomic Energy Authority

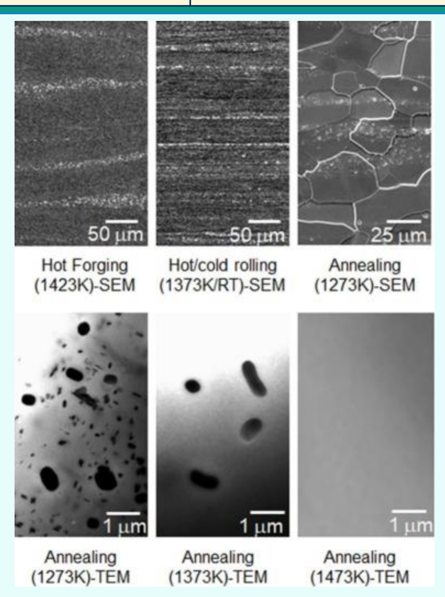
Vanadium alloys, combined with liquid metal breeder blankets, have long been considered a promising option for tritium breeding in fusion reactors. These vanadium-based alloys exhibit excellent high-temperature creep resistance, high thermal strength and strong resistance to swelling under irradiation. Their low activation characteristics make them attractive structural materials; an **alternative candidate** to conventional reduced-activation ferritic/martensitic steels. The high thermal conductivity and favourable nuclear properties of V-4Cr-4Ti alloys also reduce the need for neutron multipliers or lithium-6 enrichment in liquid lithium breeder blanket systems.

UKAEA is developing strategy & International positioning in the vanadium-alloy landscape (R&D, supply chain, industrialisation).

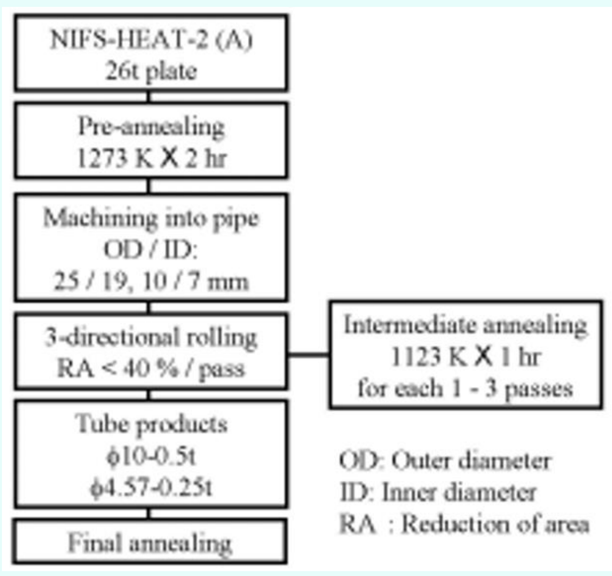
Vanadium alloy manufacturing

Examples of V–4Cr–4Ti manufacturing

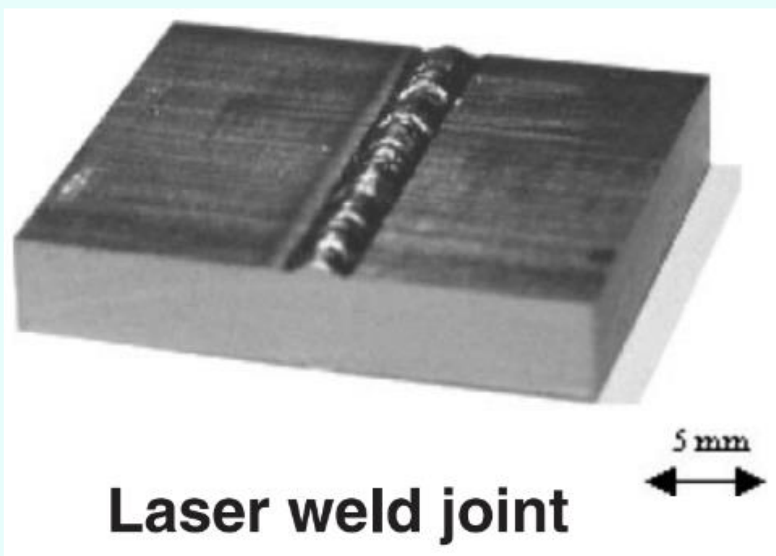
Study / Reference	Starting Material	Melting / Refining Route	Scale	Forming & Processing Steps	Annealing / Heat Treatment
1200 kg Industrial Heat (Johnson & Smith)	Vanadium from aluminothermic reduction + high-purity Cr/Ti	EBM purification → Double Vacuum-Arc Melting (VAM)	1200 kg	Extrusion → warm/cold rolling → tubing/Plate/sheet/Rod	Repeated vacuum anneals at 1000–1050 °C between steps
NIFS-HEAT-1 (Muroga et al.)	Vanadium purified after aluminothermic reduction (with enhanced impurity control)	EBM of V, Cr, Ti → Vacuum Arc Remelting (VAR) to form alloy	30 kg (200 kg planned)	No downstream forming	Heat cycles during calcination, EBM & VAR; no formal post-forming annealing
SWIP-30 (Fu et al.)	Vanadium from aluminothermic reduction	Double Electron-Beam Melting (EBM) in high vacuum	30 kg	Hot forging → hot rolling (~85% deformation) → cold rolling to final thickness	Vacuum annealing at 1273–1293 K + additional controlled cycles (SA, SAA, SACWA) for strengthening



Evolution of microstructure with temperature: Precipitate formation during the fabrication process of NIFS-HEAT [1]



Tube forming process flow for high purity, low activation V-4Cr-4Ti alloy [2]

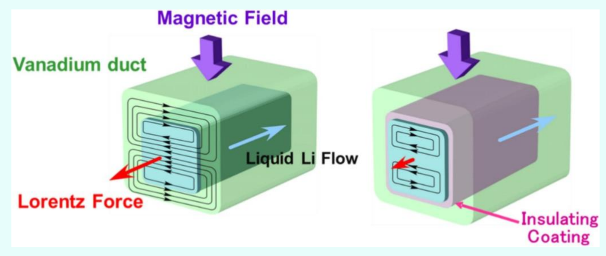


Joining of V-4Cr-4Ti by Gas Tungsten Arc and laser welding methods were demonstrated. Optimisation of the Post Weld Heat Treatment was made by optimising precipitation in weld metals [3]

Environmental testing

Liquid metals

- Necessity to specify a **standard composition** with impurity limits
- **Purity** of commercial Li today is lower than that in 80s/90s
- Taking into account **MHD pressure drop** and consideration of coatings → Liquid metals conduct electricity and higher pumping power is needed to move the liquid metal.
- Potential coatings may also be for: **Tritium permeation barrier**, and **corrosion resistance**.
- Improved **predictive modelling** of **mass transfer** (dissolution and deposition of elemental and product species) under non-isothermal and dissimilar-material concentration gradients is needed.
- **Li removes O from V** (preventing embrittlement), but C, N in Li diffuse into V-alloys



Schematic illustration of MHD (Magnetohydrodynamic) pressure drop (left) and the role of insulator coating (right) when electrically conductive coolants [1]

Irradiation

- **Low swelling** under **neutron irradiation**
- Effect of interstitials and optimisation of Ti-rich precipitates for **resistance to irradiation hardening**
- Radiation accelerated corrosion and cracking needs to be studied.
- Neutron irradiation and transmutation-produced He effects and their impact on similar and dissimilar **joints** need to be studied.
- At high temperature, effects of oxygen from irradiation environment are essential, especially at higher dose levels [4].
- **Synergistic testing requirements.**

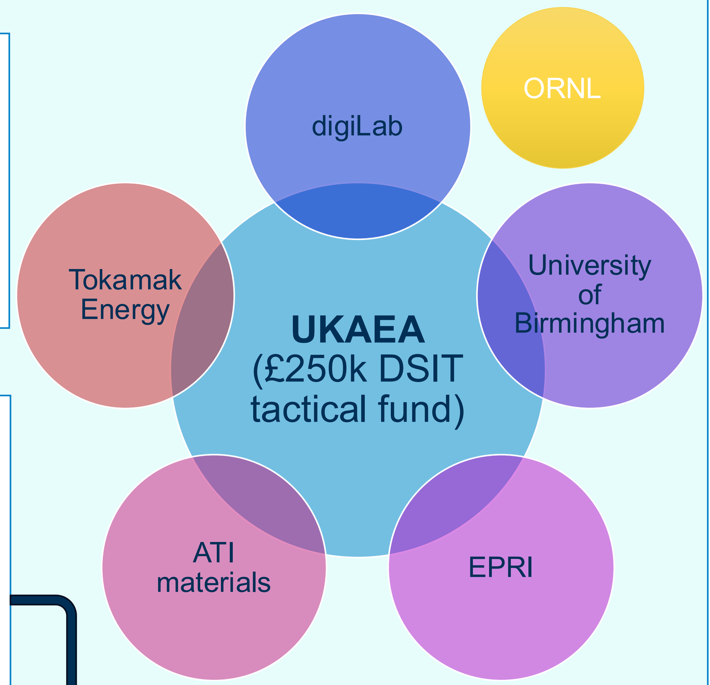
Novel Qualification Strategy

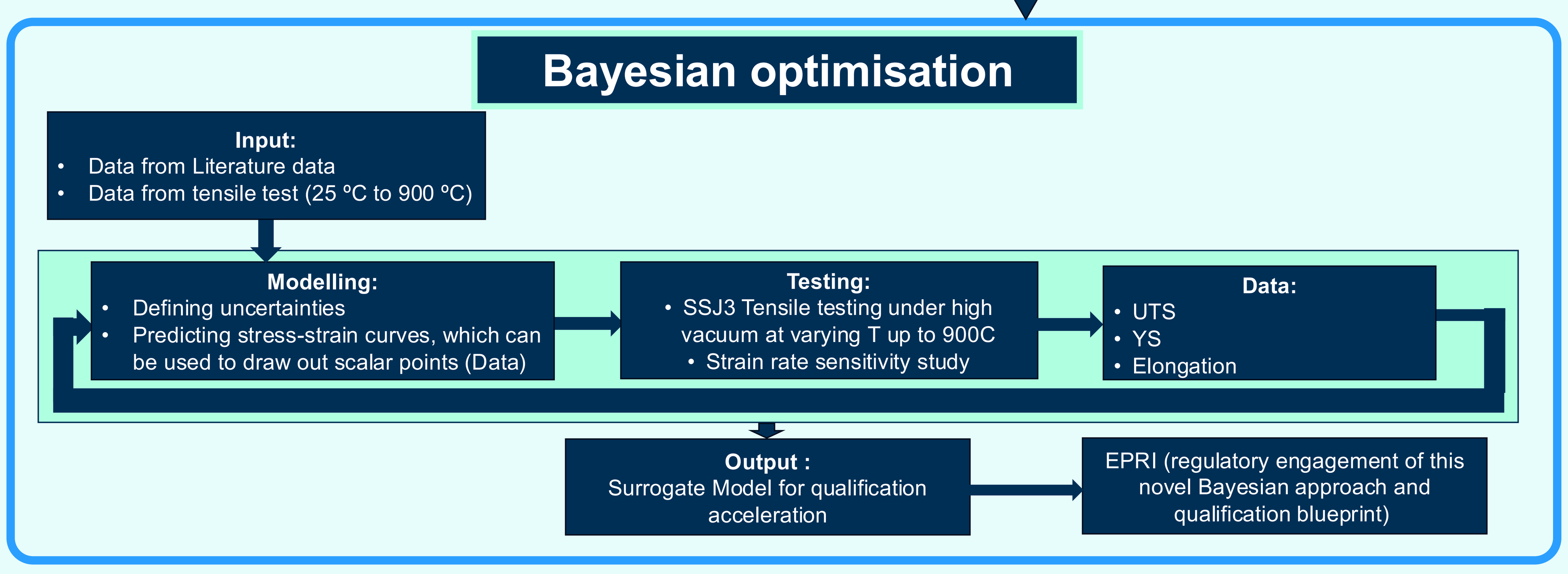
Main Goal (DSIT tactical project)

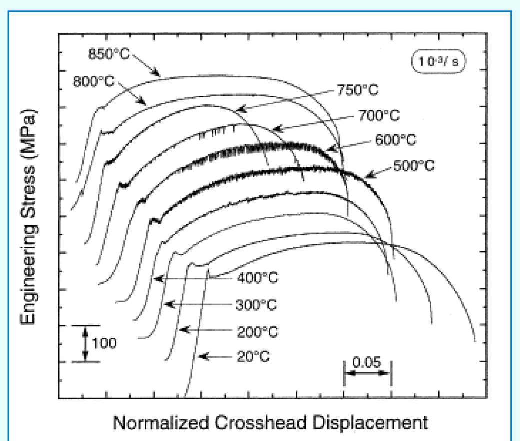
Develop and validate a novel **digital qualification approach** for **V-4Cr-4Ti** structural material, while engaging **regulators** to ensure **acceptance and compliance**

Successful Outcomes

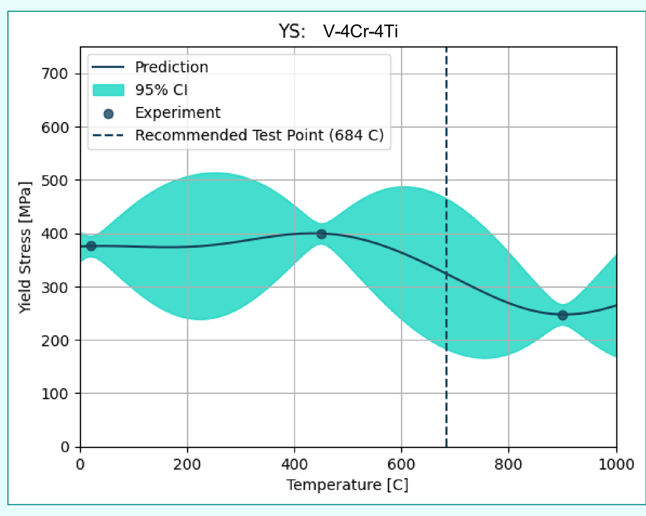
- Novel Digital Qualification method trialled and validated
- Qualification Pipeline for materials required in fusion, specifically Tokamak Energy (inc. Inspection & Testing Plan)
- White Paper on Industrialisation of V-4Cr-4Ti



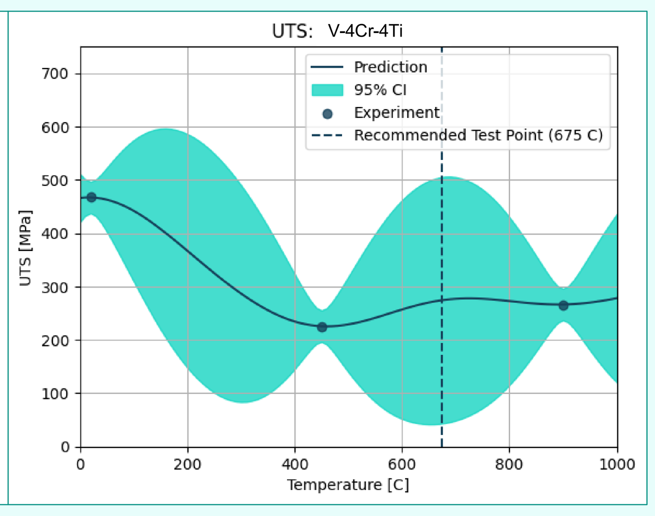




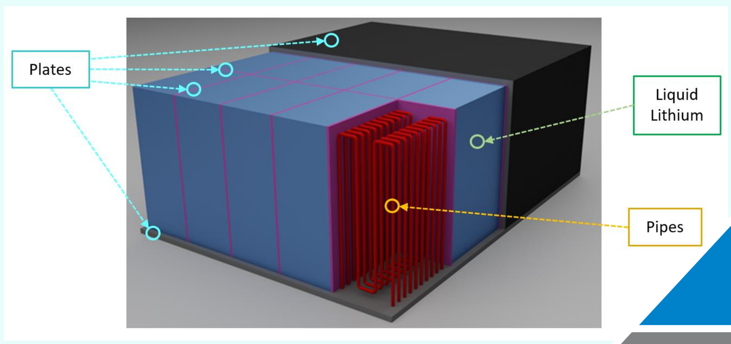
Tensile curves for annealed V-4Cr-4Ti at a strain-rate of 10^{-3} s^{-1} illustrating Dynamic Strain Ageing regime [5]

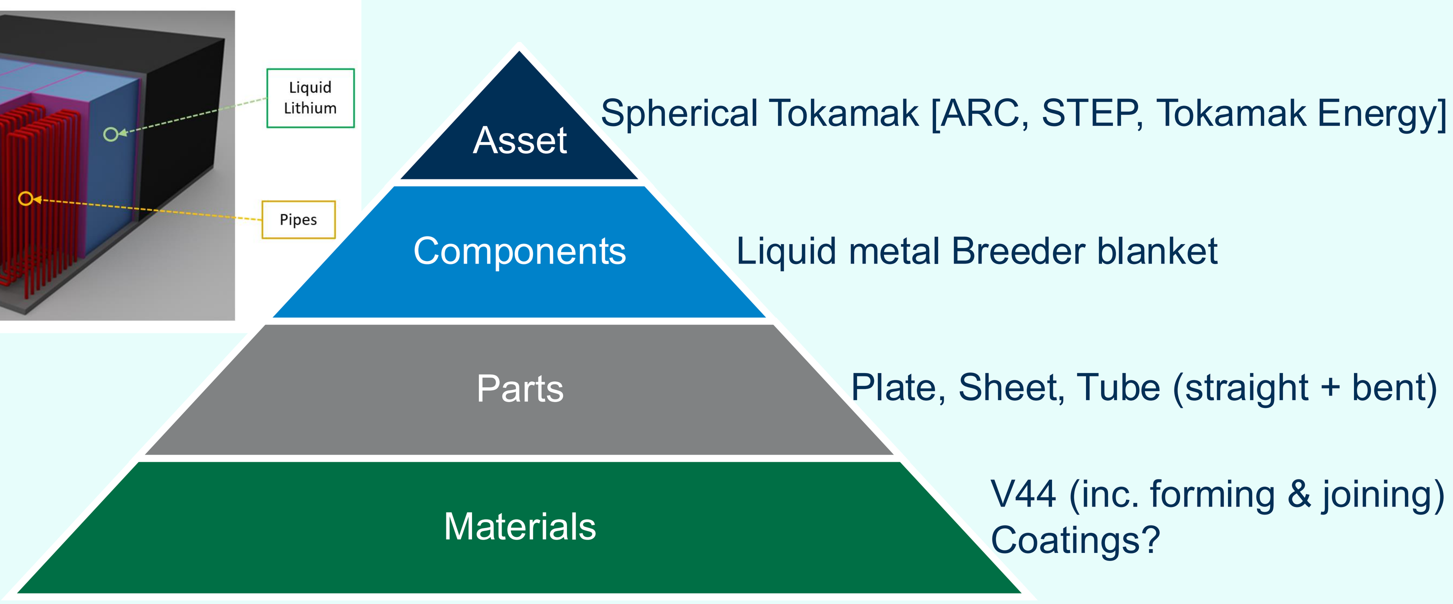


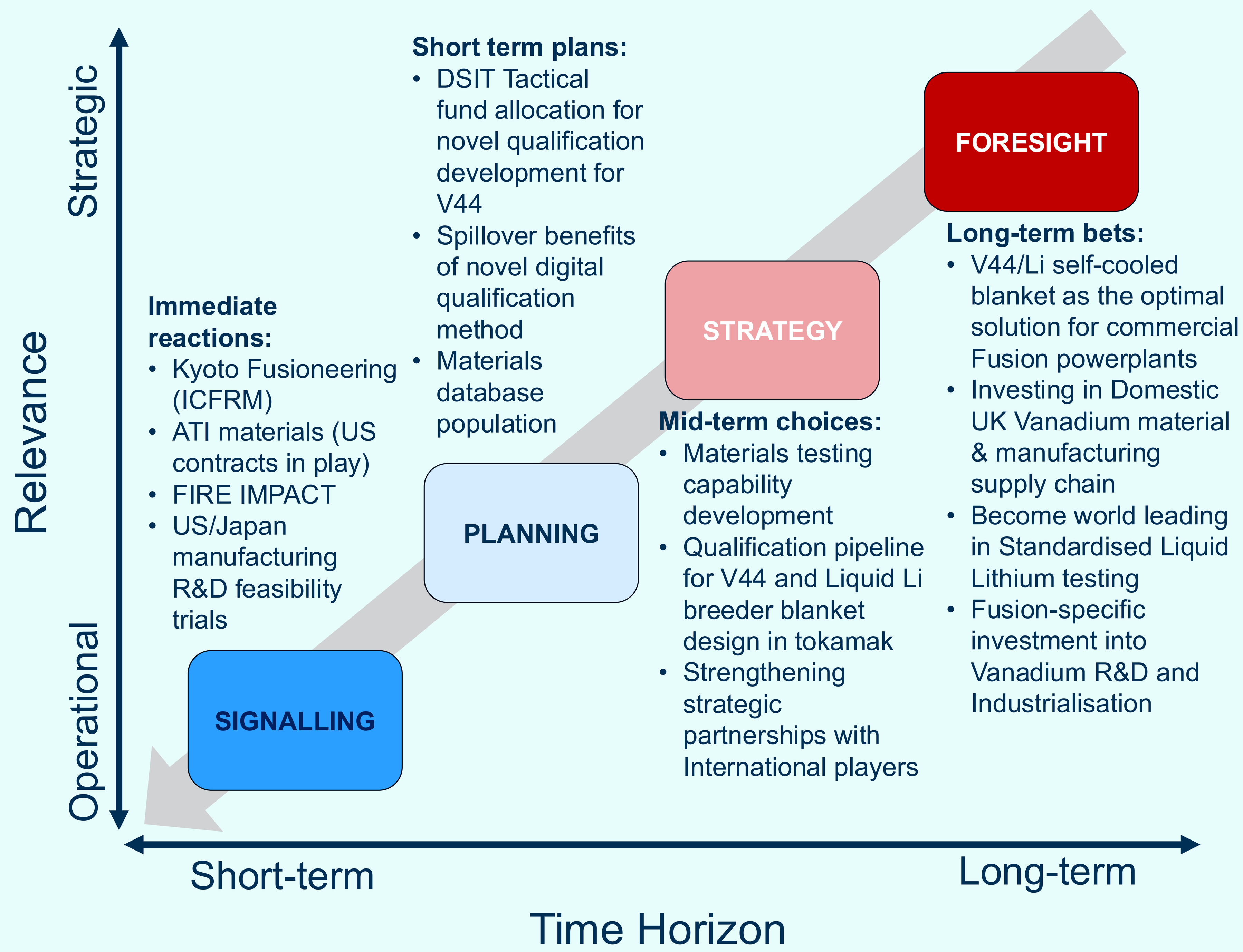
Bayesian Optimisation progress for Yield Stress



Bayesian Optimisation progress for Ultimate Tensile Stress







For more Information or questions, please contact:
Davidson.sabu@ukaea.uk

The UK Atomic Energy Authority's mission is to lead the delivery of sustainable fusion energy and maximise scientific and economic benefit

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[3] T. Muroga, "Vanadium Alloys for Fusion Blanket Applications."

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