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This original Publication was created by Jack Acres, Head of Engineering Power & Cooling,

on 27 Feb 2026.

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This work has been funded by STEP, a major technology and infrastructure programme led by UK Industrial Fusion Solutions Ltd (UKIFS), which aims to deliver the UK's prototype fusion powerplant and a path to the commercial viability of fusion.

DEVELOPING A TECHNOLOGY ROADMAP FOR THE STEP (SPHERICAL TOKAMAK FOR ENERGY PRODUCTION) SCO2 CYCLE: SHOCC

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HEAD OF ENGINEERING
POWER & COOLING

UKIFS

04/03/2026

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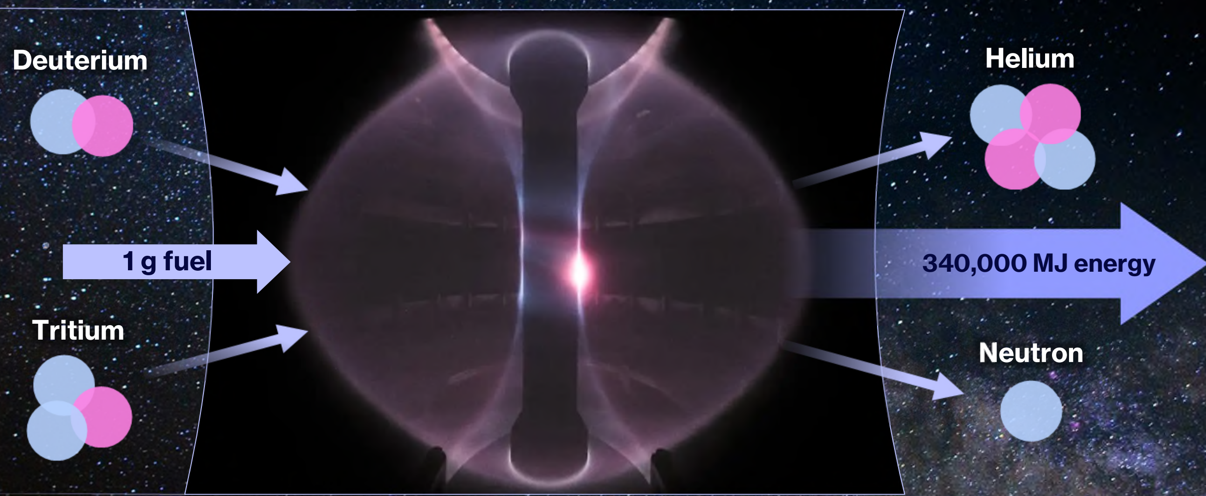
WHAT IS FUSION

Fusion is the process that powers the sun and stars by fusing hydrogen nuclei at the core…



$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow n\,(14.1\ MeV) + {}^{4}_{2}He\,(3.5\ MeV)$$

… unlike its fission counterpart, fusion relies on fusing two lighter atomic particles. The mass deficit of the subatomic particles releases energy (e=mc2)

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BENEFITS OF FUSION

LOW CARBON

Fusion is low carbon, with low land usage

SAFE

The fusion process is readily and safely controllable

RELIABLE

Fusion energy will be baseload and does not depend on seasonal variation, the sun, or the wind

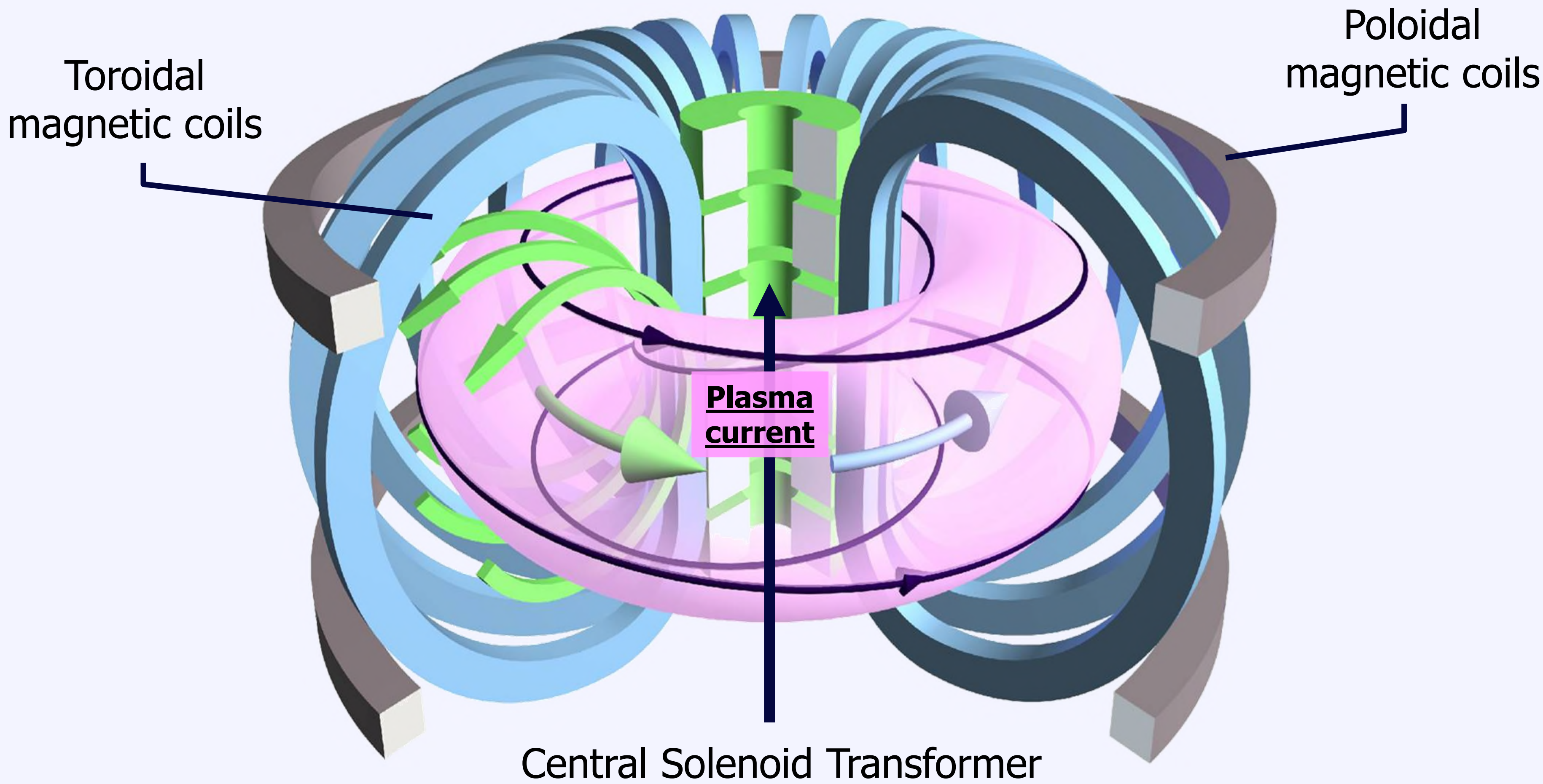
SUSTAINABLE

Fusion fuel is potentially abundant in our seas and the Earth's crust

ENERGY EFFICIENT

Fusion provides the most power-dense process available on Earth

HOW TO DO FUSION: THE TOKAMAK



S T E P

N O N O T T H A T S T E P …

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WHAT IS STEP?

SPHERICAL TOKAMAK FOR ENERGY PRODUCTION

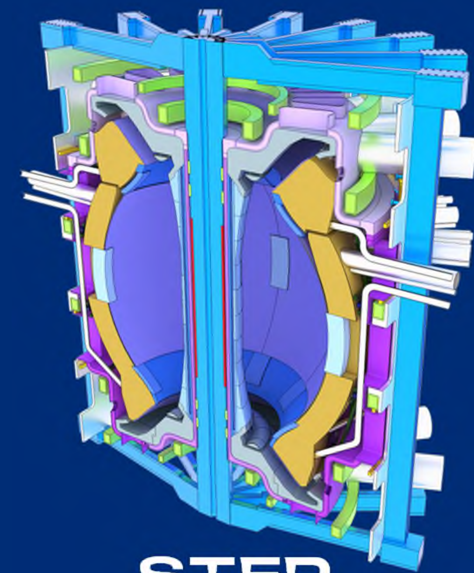
A pioneering, prototype fusion powerplant that will demonstrate:

- Net energy
  100 MWE
- Fuel self-sufficiency
  TRITIUM BREEDING RATIO > 1
- Maintainability of fusion powerplants –
  MAINTAINABLE & AVAILABLE
- A route to the commercial viability of fusion
  £££

STEP has progressed through five Concept Maturity Level reviews and three independent Fusion Technical Advisory Group reviews.

STEP will be delivered in 3 phases:
Phase 1 – develop concept design and select a site
Phase 2 – detailed engineering design and permissions and consents as well as pre-construction works by early 2030s
Phase 3 – manufacturing and construction – targeting operations around 2040.

SPHERICAL TOKAMAK BASIS



STEP

- Cored apple shape
- Novel exhaust options – Super-X Divertor
- Fewer, smaller magnets
- Smaller buildings
- Lower costs due to compact nature

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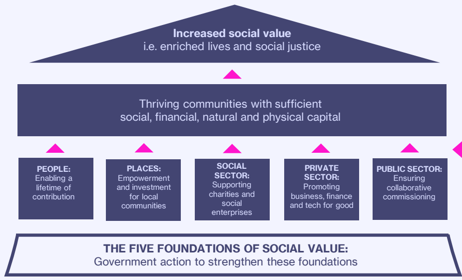
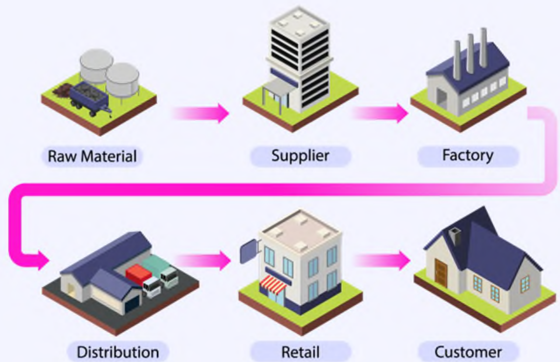
MORE THAN JUST A PLANT



SOCIAL VALUE

Skills, jobs, investment, regional infrastructure



INDUSTRIAL STRATEGY

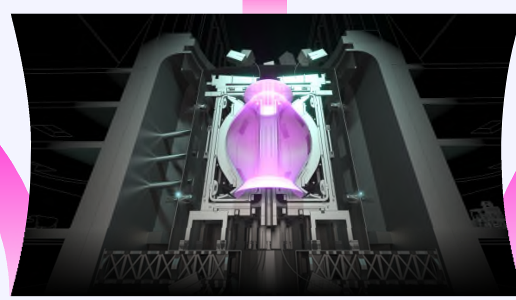
Supply Chain

£

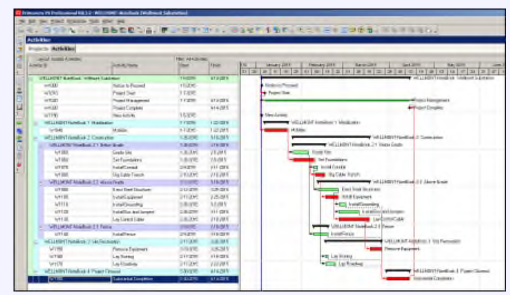
UK ECONOMIC VALUE

Exports, contracts, spin-offs

GLOBAL FUSION FACILITY



POWER PLANT DEMONSTRATION

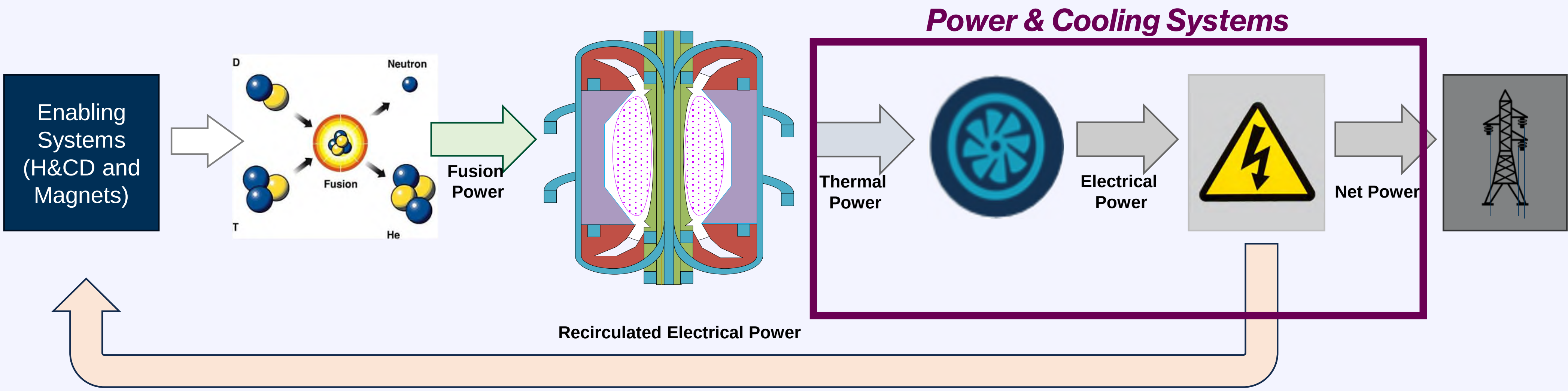


INFORMATION BASELINE

STEP

STEP
POWER &
COOLING

WHAT IS POWER & COOLING



Power & Cooling Key functions

***Cooling the tokamak*:** cooling the tokamak while extracting useful thermal energy.

***Generating power*:** conversion of thermal energy to electrical energy (power generation).

***Managing energy*:** management of the site-wide distribution, storage and energy export.

STEP

PROBLEM STATEMENT

The F1 dilemma

I need the dynamic performance of a F1 car with the efficiency of Prius, but I don’t even know how to drive yet.

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MAGNETICALLY CONFINED FUSION
A UNIQUE POWER SOURCE

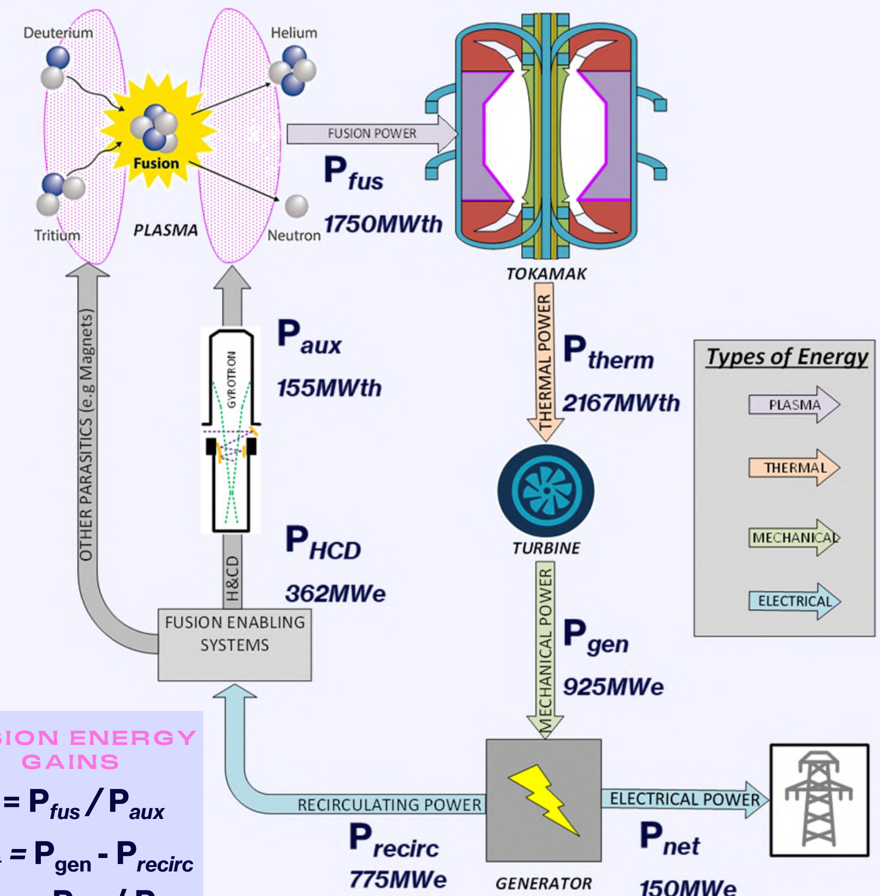
4 KEY CHALLENGES UNIQUE TO FUSION POWER GENERATION:

Challenge 1: Need for efficiency

Challenge 2: Need for heat integration

Challenge 3: Need for flexibility

Challenge 4: Need for viability



FUSION ENERGY GAINS

$Q = P_{fus} / P_{aux}$

$P_{net} = P_{gen} - P_{recirc}$

$Q_{eng} = P_{net} / P_{fus}$

GT2024-126730 Fusion Energy and Future Fusion Power Plants, ASME Turbo Expo 2024
Jack Acres, Chris Clements; https://doi.org/10.1115/GT2024-126730

Staying positive: producing net power, Royal Society Phil. Trans. A
Acres J., et al. DOI: 10.1098/rsta.2023.0404

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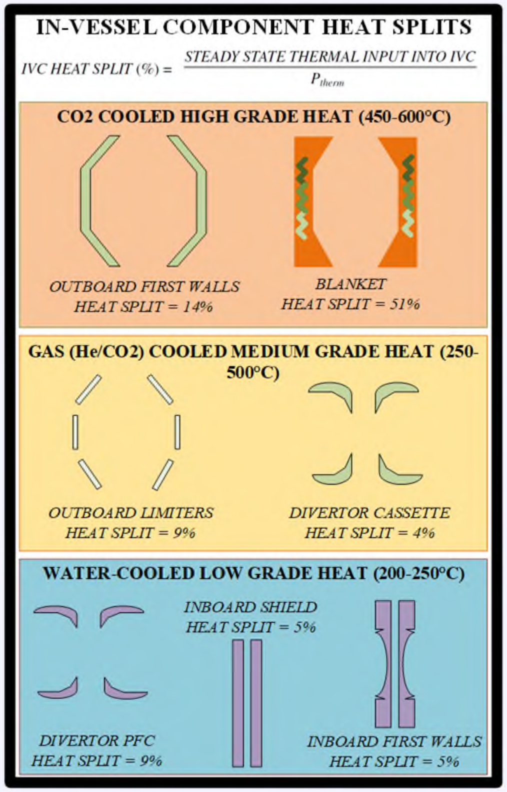

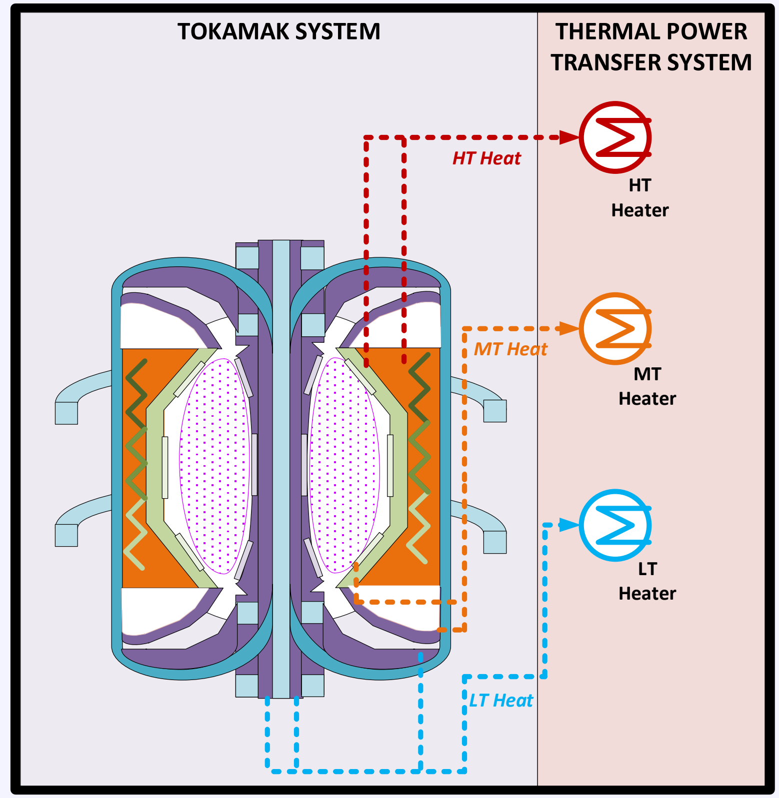

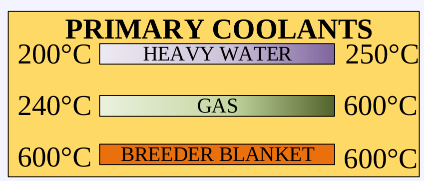

Staying positive: producing net power, Royal Society Phil. Trans. A
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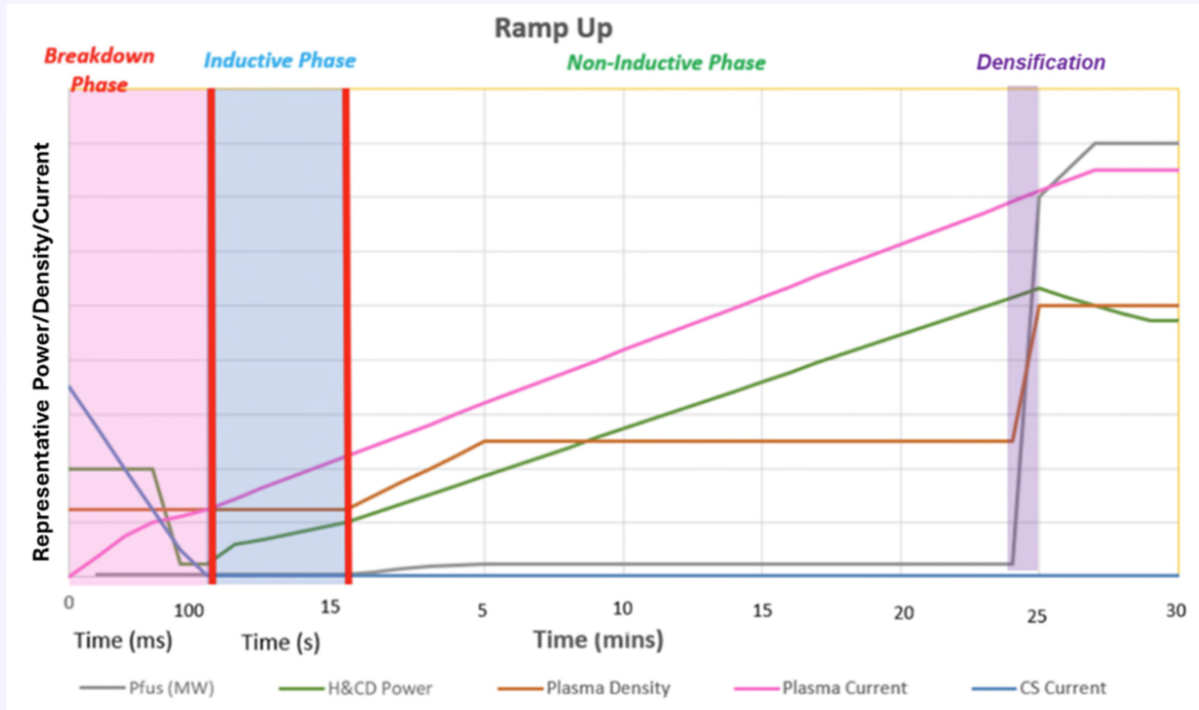
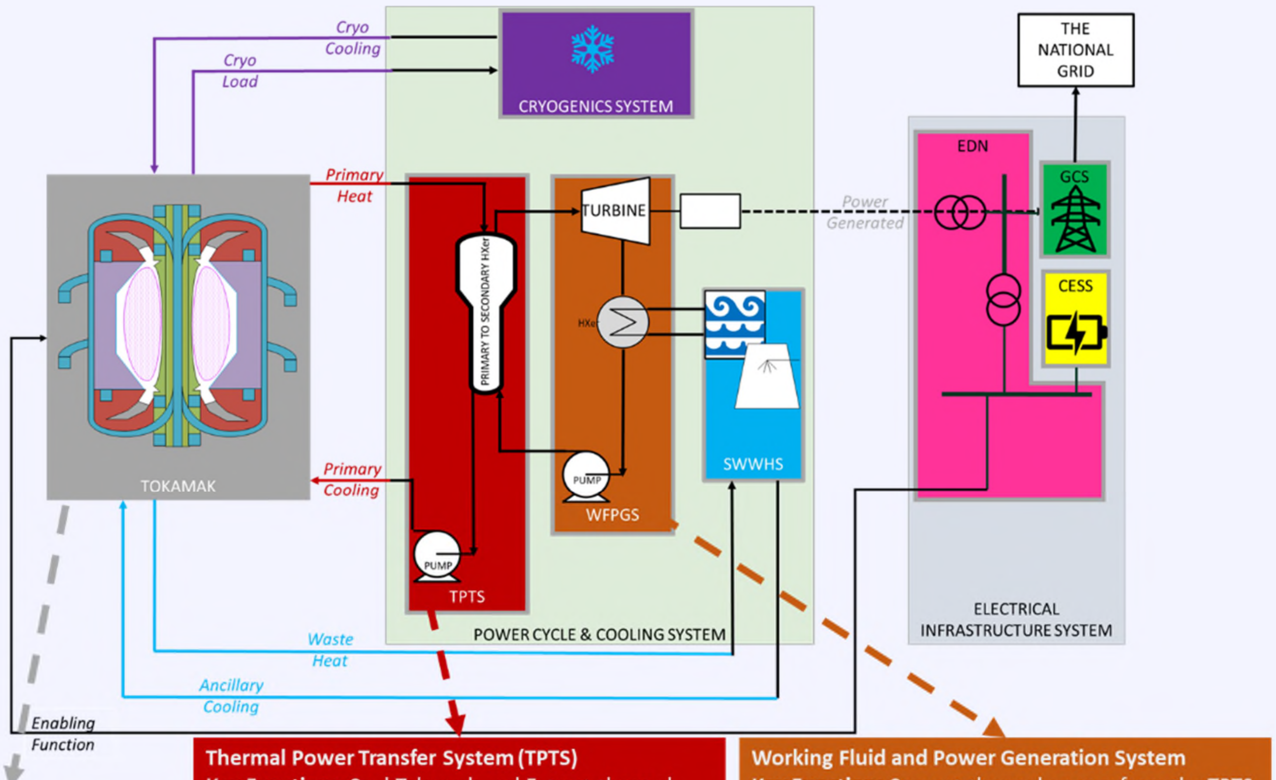


INHERENTLY PULSED
INHERENTLY PROTOTYPIC

TECHNOLOGY SELECTION



Tokamak key design choice:
- Outboard= gas cooled (CO_2 cooled Blanket & OFW)
- Inboard = water cooled
- Divertor= hybrid cooled (water & gas cooled)

Thermal Power Transfer System (TPTS)
Key Function: Cool Tokamak and Extract thermal energy from tokamak
Key Technologies:
- sCO_2 loop for the Blanket & OFW
- PCHE
- Gas Circulators

Working Fluid and Power Generation System
Key Function: Convert thermal energy from the TPTS to Electrical Power,
Key Technologies:
- sCO2 power cycle
- Aux heat integration
- Thermal Buffer

WHY SCO2?

WHY USE SCO2 POWER CYCLE? TO ADDRSS OUR 4 CHALLENGES!

Challenge 1: Need for efficiency

sCO_2 solution: at proposed temperature sCO_2 cycle is competitive in efficiencies, and allows for high temperature benefits to be maximised in future higher temperature machines (unlocked by material advances)

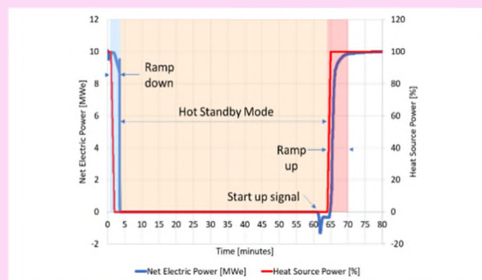
Dhinesh Thanganadar, Jack Acres "Thermodynamic performance evaluation of power cycle technologies for spherical Tokamak Energy Production" Fusion Engineering and Design Volume 222, January 2026, 115451

Challenge 2: Need for heat integration

sCO_2 solution: RCBC perfectly poised to integrate excessive low and medium grade heat

Challenge 3: Need for flexibility

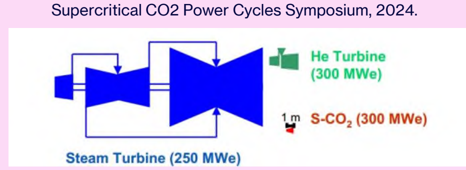
sCO_2 solution: Highly responsive



M. McDowell and J. Acres, "Evaluation on the rapidity of sCO2 cycle power up and down events using the STEP dynamic simulation model," The 8th International Supercritical CO2 Power Cycles Symposium, 2024.

Challenge 4: Need for viability

sCO_2 solution: Compact and competitive

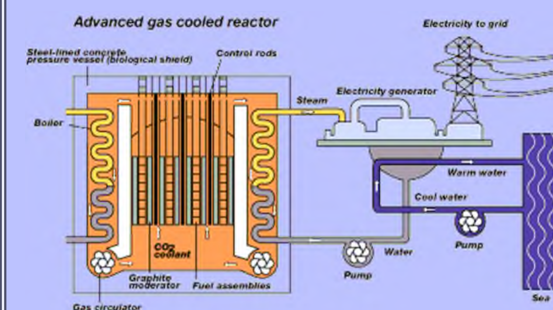


Dostal, Vaclav, Michael J. Driscoll, Pavel Hejzlar. "A supercritical carbon dioxide cycle for next generation nuclear reactors." PhD diss., Massachusetts Institute of Technology, Department of Nuclear Engineering; 2004.

WHY SCO2 IN THE PRIMARY LOOP

Blanket and OFW coolants must:

- Enable tritium breeding
- Manage high heat flux loads in the OFW
- Be compatible with selected in-vessel component materials



Gas coolants can meet these requirements. CO2 is preferred over Helium as it is:

1. Readily available in bulk quantities
2. More affordable/sustainable
3. CO_2 will leak less
4. CO_2 is also generally easier to circulate.

STEP

A SHOCC TO THE SYSTEM

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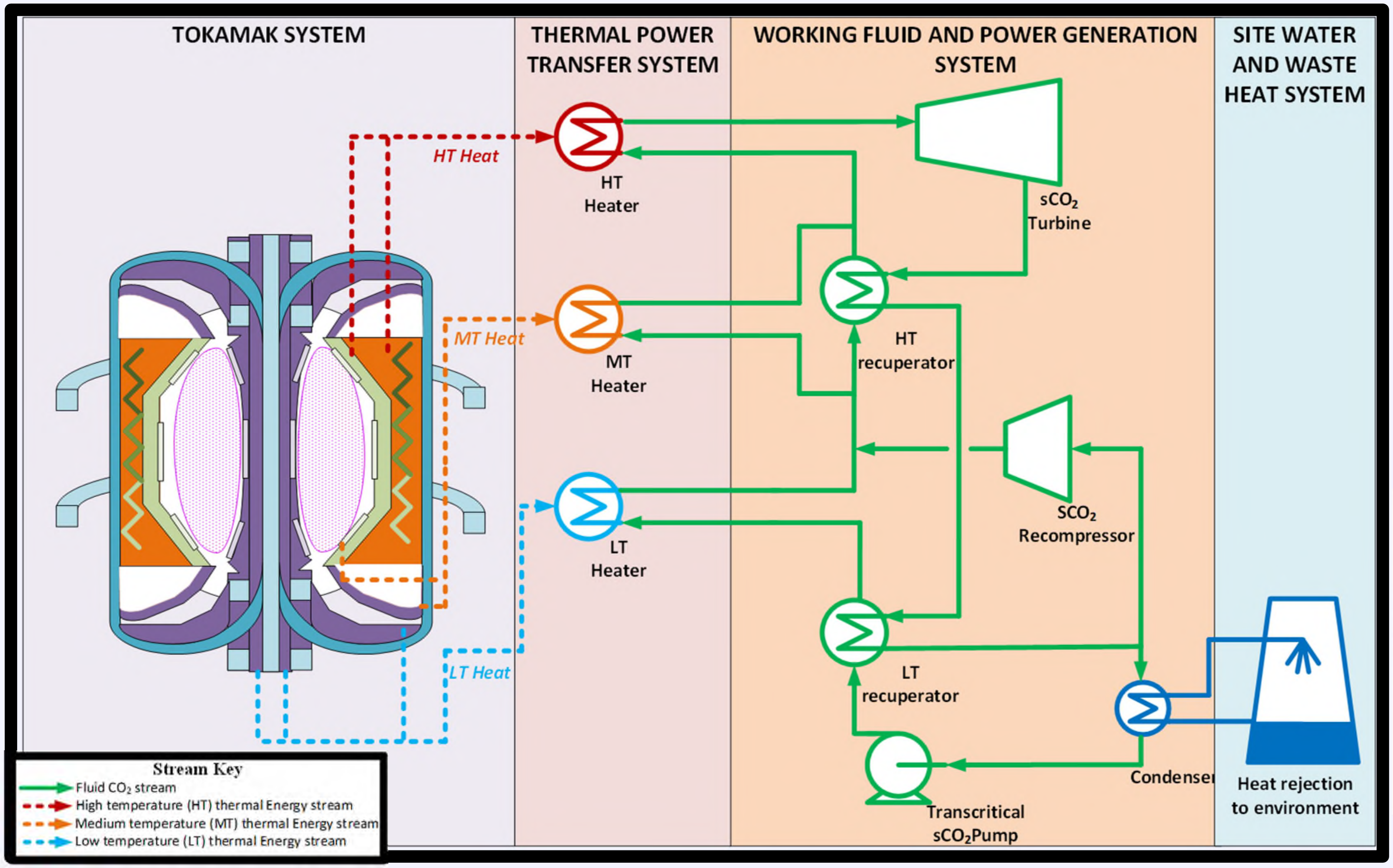
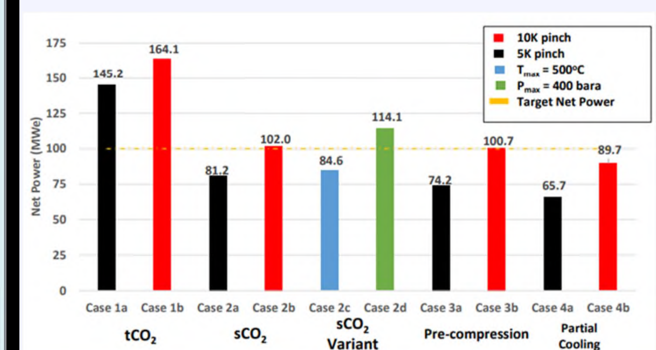
SHOCC: THE TCO2 SOLUTION

SHOCC = STEP HYBRID OPERATIONS CO2 CYCLE



A TRANSCRITICAL VARIANT OF THE RCBC WHICH ENABLES RAPID TRANSIENT OPERATIONS UTILISING VARYING HEAT SOURCES (FUSION AND A FUSION INDEPENDENT HEAT SOURCE).

A TRANSCRITICAL CYCLE IS PREFERRED DUE TO THE INCREASED EFFICIENCIES:



Dhinesh Thanganadar, Jacob Connors, Jack Acres "Multi-Objective Technoeconomic Optimisation of Closed Loop CO2 Power Cycle for Spherical Tokamak Fusion Reactor" ASME TURBO EXPO 2025, GT2025-152393

SCO2 TECHNOLOGY SHORTFALLS

SURELY PLASMA IS THE HARD PART?

Turbomachinery

Turbines, turbines (at relevant conditions) are demonstrated up to 16 MW gross shaft power, at the STEP DEMO facility. Further scale up to the multiple 100s MWe is therefore possible. Further demonstration desired at relevant scale and condition.

sCO_2 compressors at STEP conditions are well demonstrated technologies for lower temperatures. Further demonstration desired at relevant scale and condition (incl. primary loop).

tCO2 pumps at the scale and conditions of STEP will require more significant development.

The sCO2 turbine used at the STEP-DEMO pilot plant. https://eepower.com/news/is-supercritical-carbon-dioxide-the-future-of-power-generation/#

4 Power cycle trains are planned (250 MWe each), to support design & operations but also to reduce TRL burden

	Technology Gap	Effort to address
Turbines	MEDIUM	HIGH
Compressors	MEDIUM	MEDIUM
Pumps	MEDIUM	MEDIUM
HEx	LOW	MEDIUM
Dynamic ops	HIGH	HIGH
sCO2 handling	MEDIUM	MEDIUM

Prioritise dynamic ops proof of concept?

Alfa Laval PCHE https://www.alfalaval.com/globalassets/images/products/heat-transfer/plate-heat-exchangers/pche/pche_explosion.png

Heat Exchangers

Heat exchangers, are relatively mature at scale. A modular approach will be taken. A single module is unlikely to exceed the current state of the art capacity. Further demonstration desired to understand dynamic impacts.

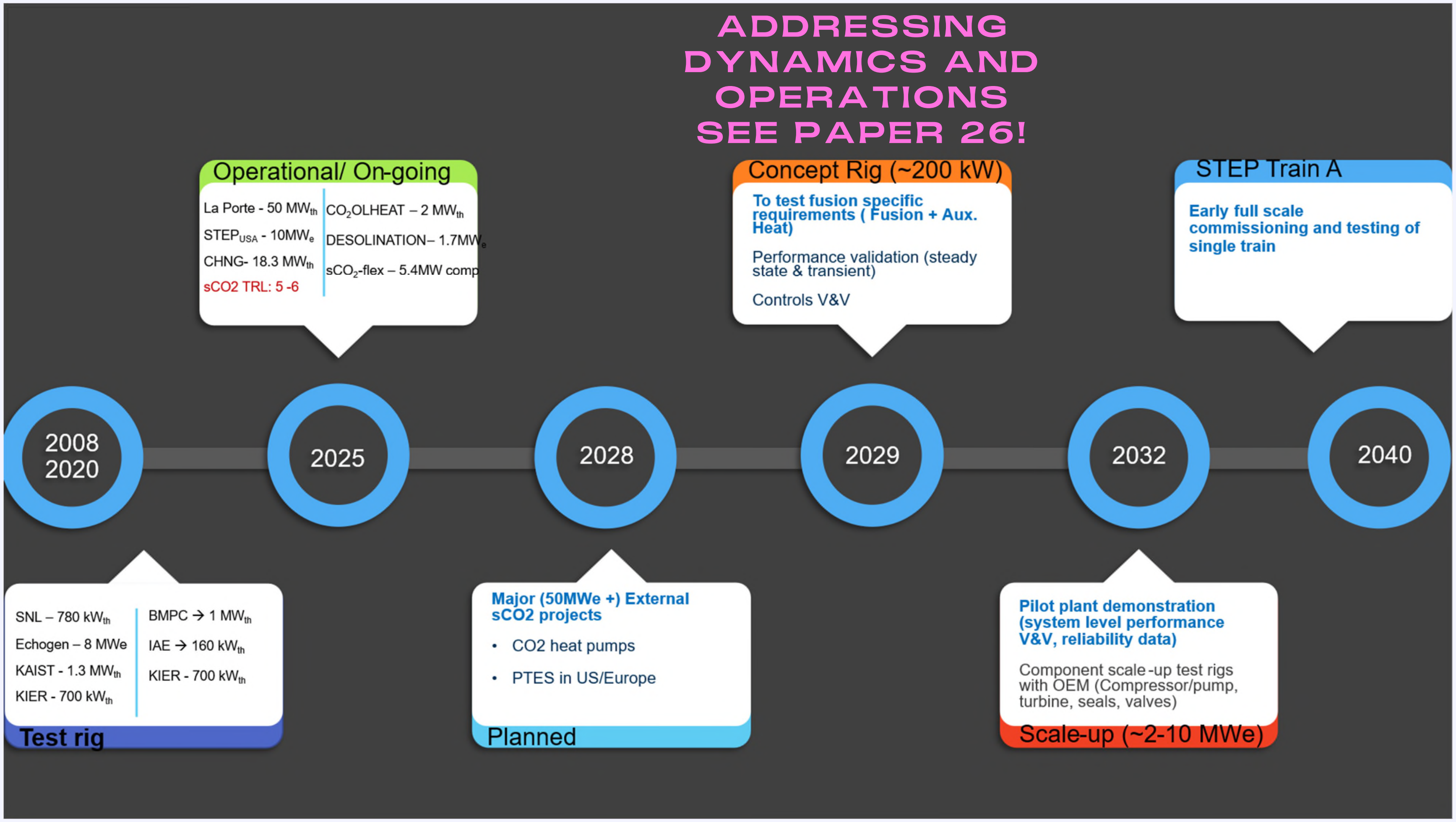
Dynamic ops & sCO2 handling

Dynamic ops: how the overall system may be operated in **highly dynamic scenarios** including ancillary technologies. Of particular interest will be testing how the SHOC cycle design responds to operating mode changes.

sCO2 handling

General sCO2 handling must also be developed, this considers aspects such as safety, materials, and operations. Many learnings can be derived from previous experiment.

A ROADMAP TO SUCCESS



PROPOSED SCALE UP & DEMONSTRATION

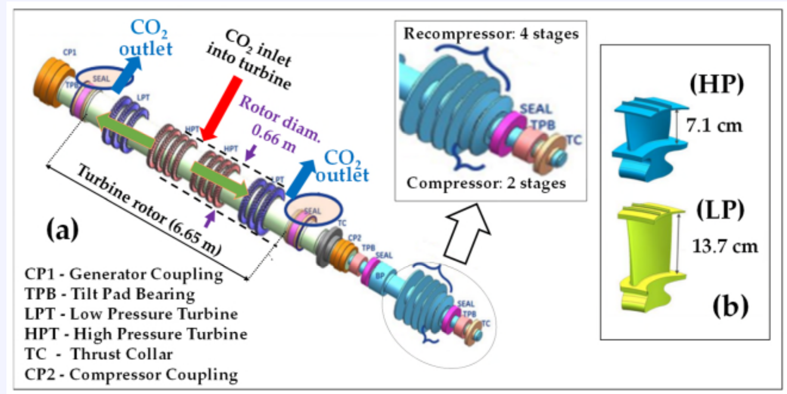
THE PROOF OF CONCEPT WILL NOT BE SUFFICIENTLY LARGE TO DEMONSTRATE KEY COMPONENTS – FURTHER SCALE UP REQUIRED

<u>SHOCC Scale Up programme</u>

After proof of concept (2030+), a new "Scale Up Programme" is proposed. Primarily this will accomplish the full scale up of the turbomachinery at the relevant scale (2-10 MWe) with design relevant architecture.

<u>Primary Circulator Demo programme.</u>

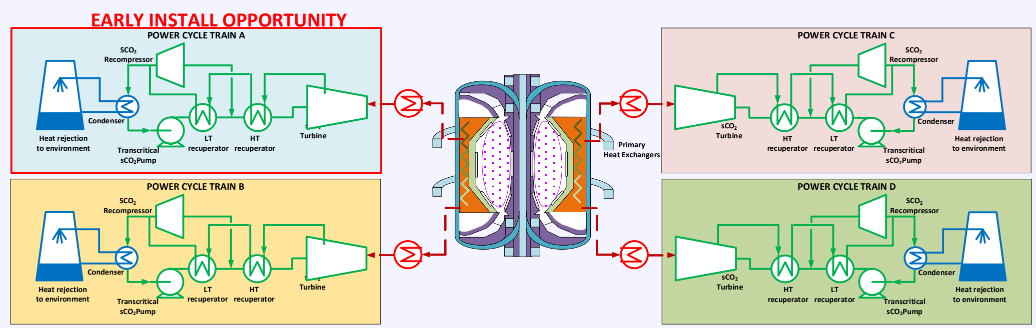
A dedicated development and scale up rig is planned for the later phases of the STEP design phase. The aim is to align this programme at the same time as the SHOCC scale up programme



Study of Turbine-Compressor-Recompressor rotor for a 450 MWe class prototype (DOE's SunShot program)
Michel Moliere et al. "Supercritical CO_2 Power Technology: Strengths but Challenges" Energies 2024, 17(5), 1129

<u>Early install of one of the trains</u>

Debatably, testing of components and cycle, at a further intermediate scale, beyond the Scale Up programme. would be needed. However, this demonstration facility would be significant with little value beyond testing. The current strategy considers the early install of one of the four trains by the late 30s instead.



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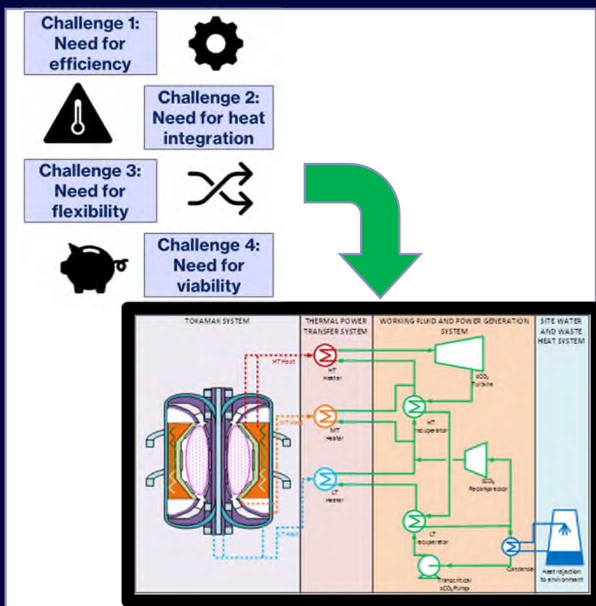
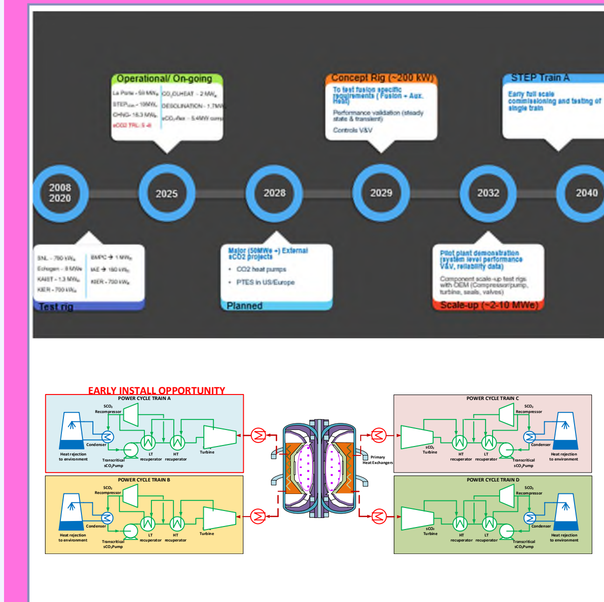
SUMMARY



Four key challenges drives the need for the novel SHOCC cycle, bespoke to fusion

	Technology Gap	Effort to address
Turbines	MEDIUM	HIGH
Compressors	MEDIUM	MEDIUM
Pumps	MEDIUM	MEDIUM
HEx	LOW	MEDIUM
Dynamic ops	HIGH	HIGH
sCO2 handling	MEDIUM	MEDIUM

The Technology gap Is not to be underestimated



BUT we have a PLAN!

STEP

THANK YOU FOR LISTENING!

ANY QUESTIONS?