

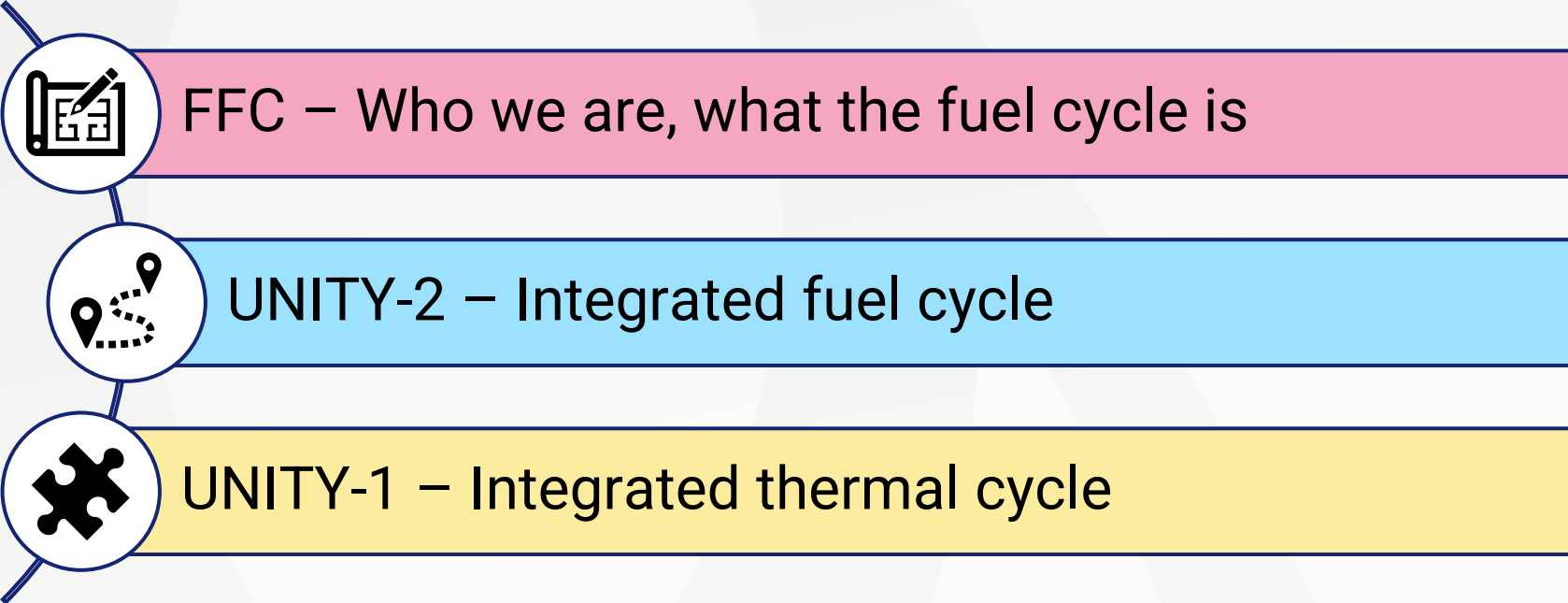


FUSION FUEL CYCLES

Developing and deploying
D and T fusion fuel cycles in
Canada and Japan

**CHRISTIAN DAY,
CHIEF TECHNOLOGY OFFICER**

STRUCTURE OF THE TALK



OUR ORIGINS

A strategic venture combining CNL's tritium & processing capabilities with KF's fusion fuel cycle plant expertise



Canadian Nuclear
Laboratories

200 acres lab complex, 17 nuclear facilities
~4,000 employees, 1,600 technical staff



**FUSION
FUEL CYCLES**



UNITY -1, Facility for Fusion Thermal Cycle
System., Fusion Heating Systems
5 Global locations, 150 staff



Products & Services



Design and engineering consultancy services for fusion fuel cycle systems (manufacturing through trusted supply chain)



Assembly, and commissioning of fuel cycle components and integrated systems.

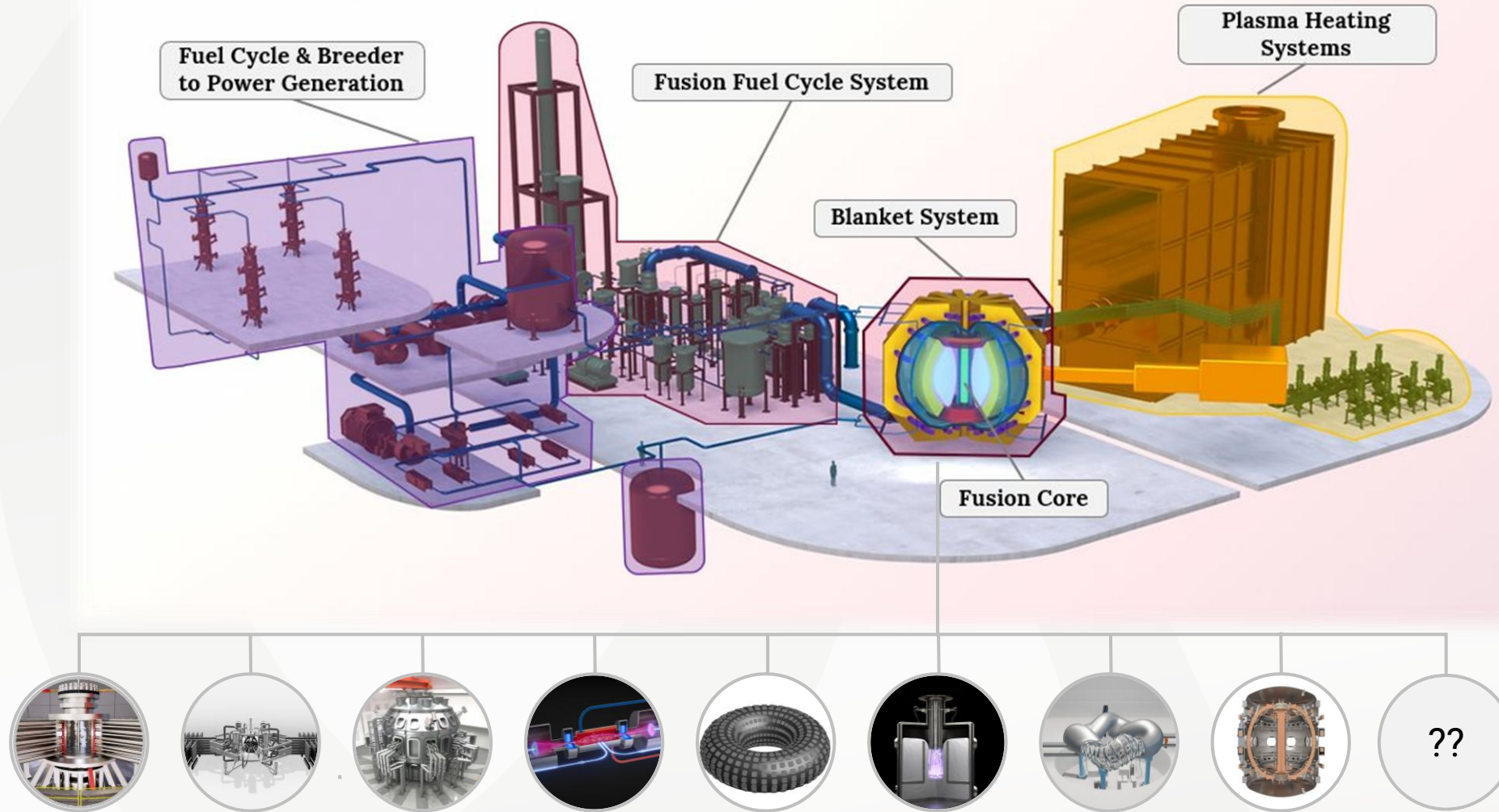


Field services and support for delivered equipment and systems



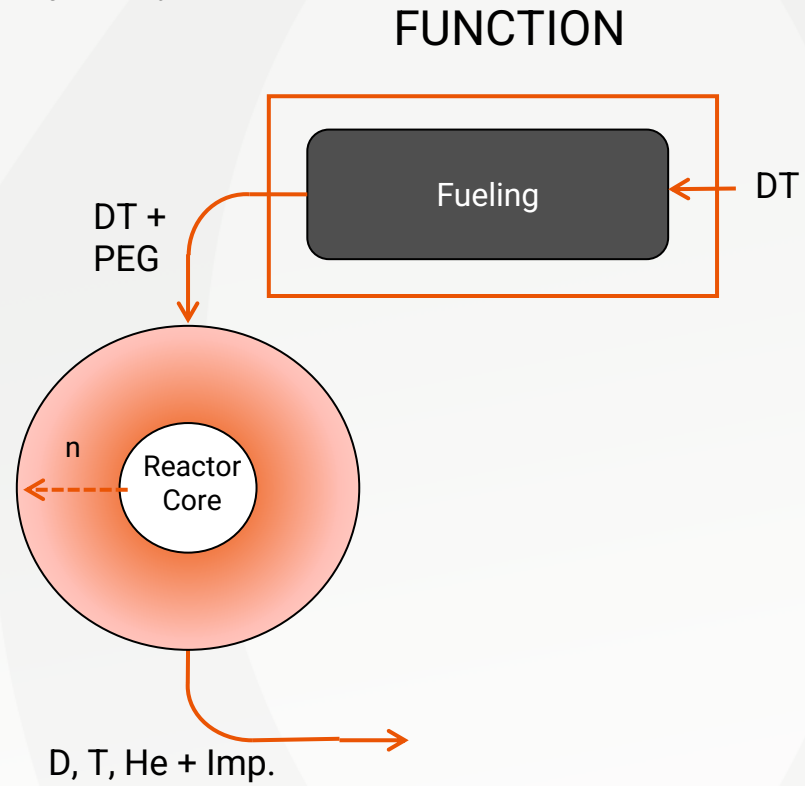
Access to a fully integrated fusion fuel cycle system (UNITY-2)

CRITICAL PATH "BALANCE OF PLANT" NEEDS



THE FUSION FUEL CYCLE SYSTEMS – FUELING

Let's build a fuel cycle...

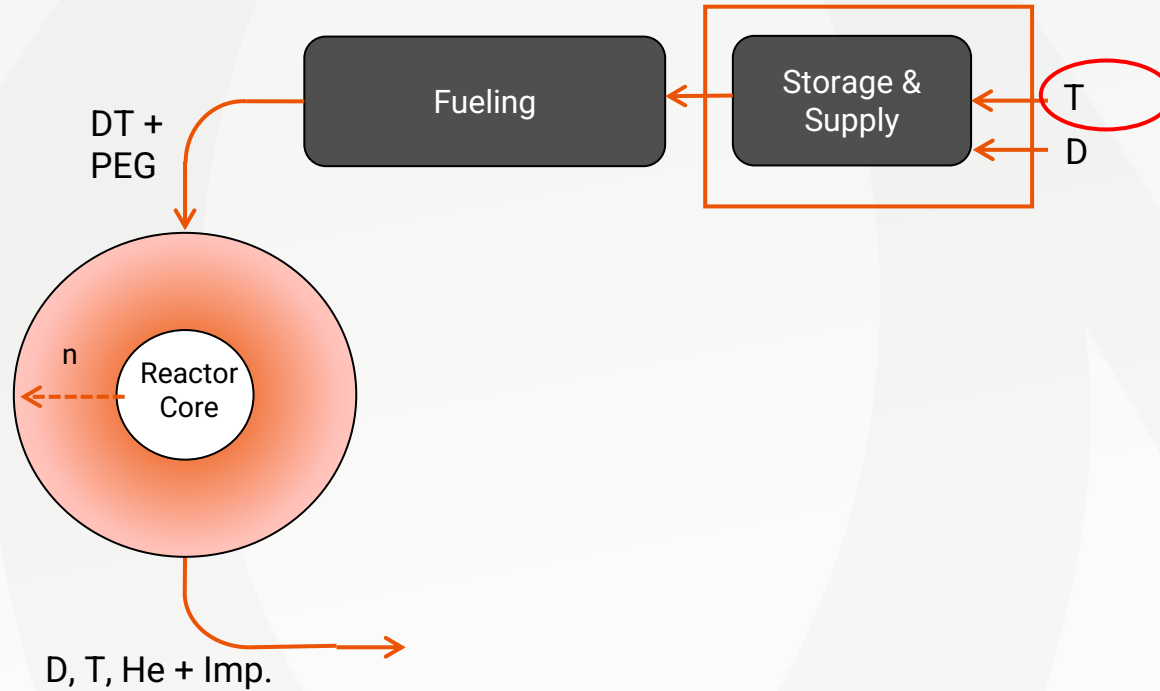


TECHNOLOGY

Target injection (ICF); pellet injection (MCF)

THE FUSION FUEL CYCLE SYSTEMS – STORAGE

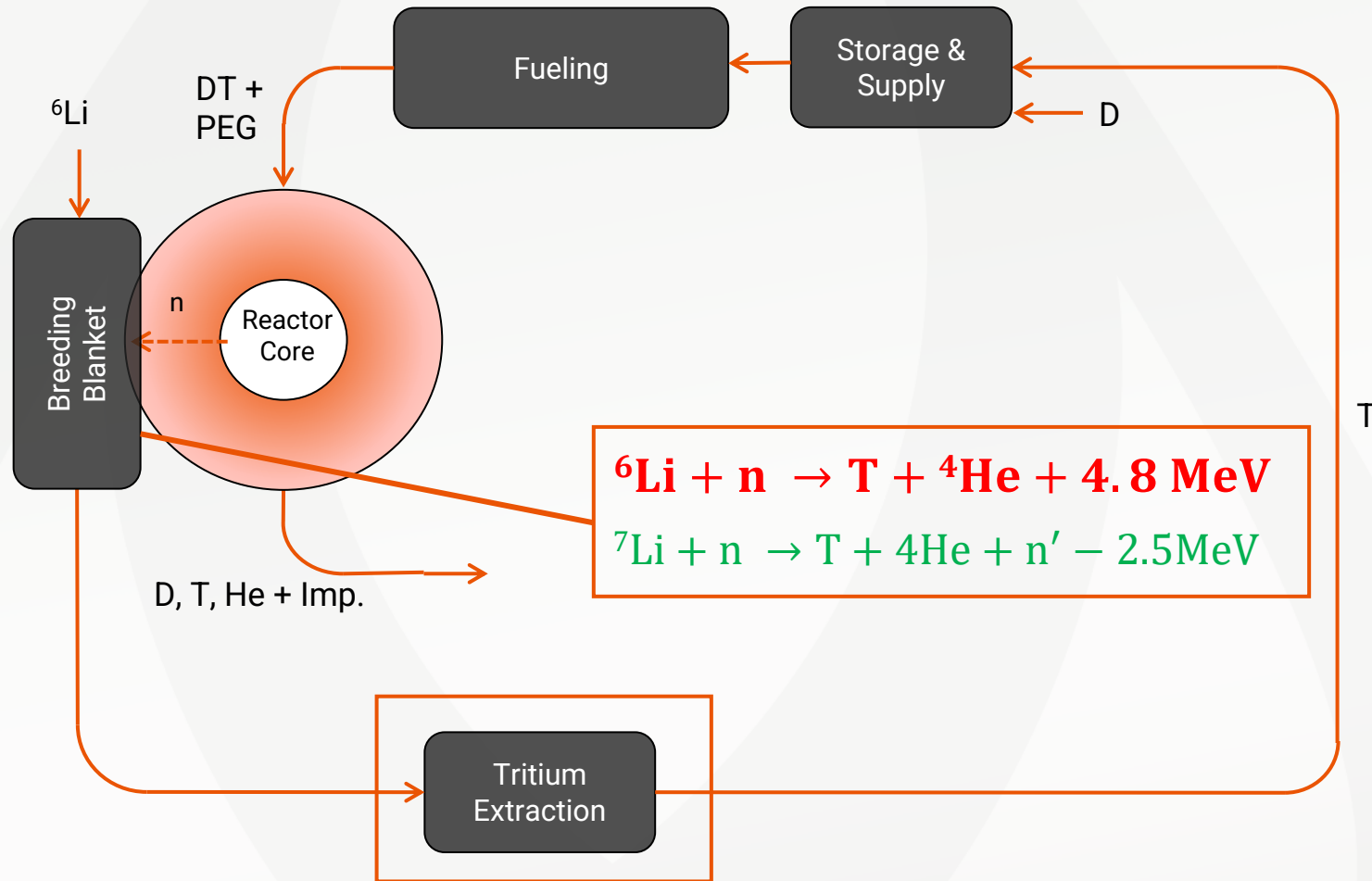
Storage of hydrogen isotopes



Depleted uranium storage beds have unbeatable performance, but dU is a nuclear material.

THE FUSION FUEL CYCLE SYSTEMS – TRITIUM BREEDING BLANKET

The blanket loop is the outer fuel cycle

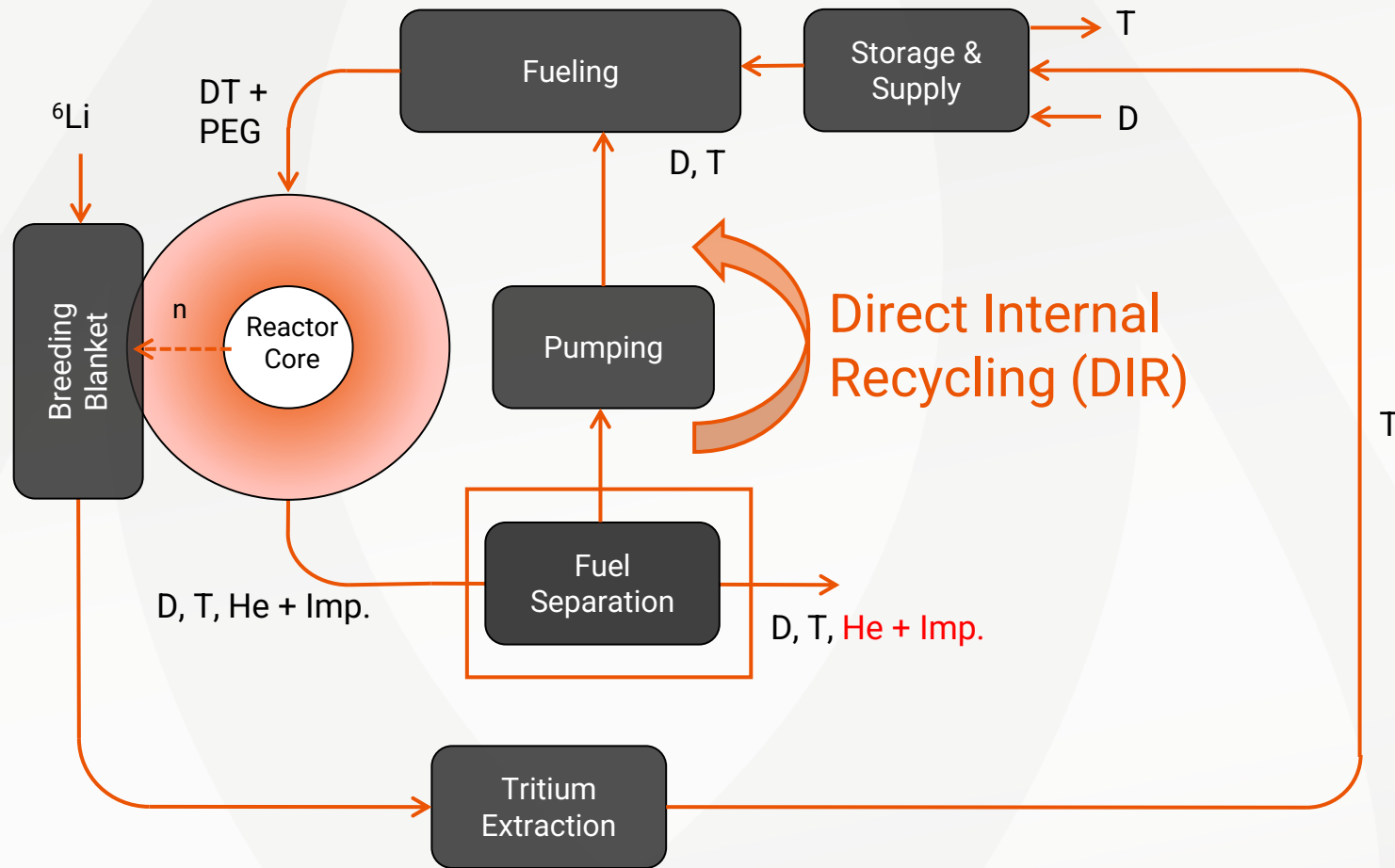


Prime blanket concepts require lithium enriched in Li-6. Access to Li-6 is difficult.

As there is no lead blanket concept, there is no lead tritium extraction technology. Technologies for liquid breeders are permeation against vacuum, gas liquid contacting and vacuum sieve tray. For solid breeder is Helium purge.

THE FUSION FUEL CYCLE SYSTEMS – DIR

Direct Internal Recycling is the prime way to reduce the overall tritium inventory in a FPP fuel cycle

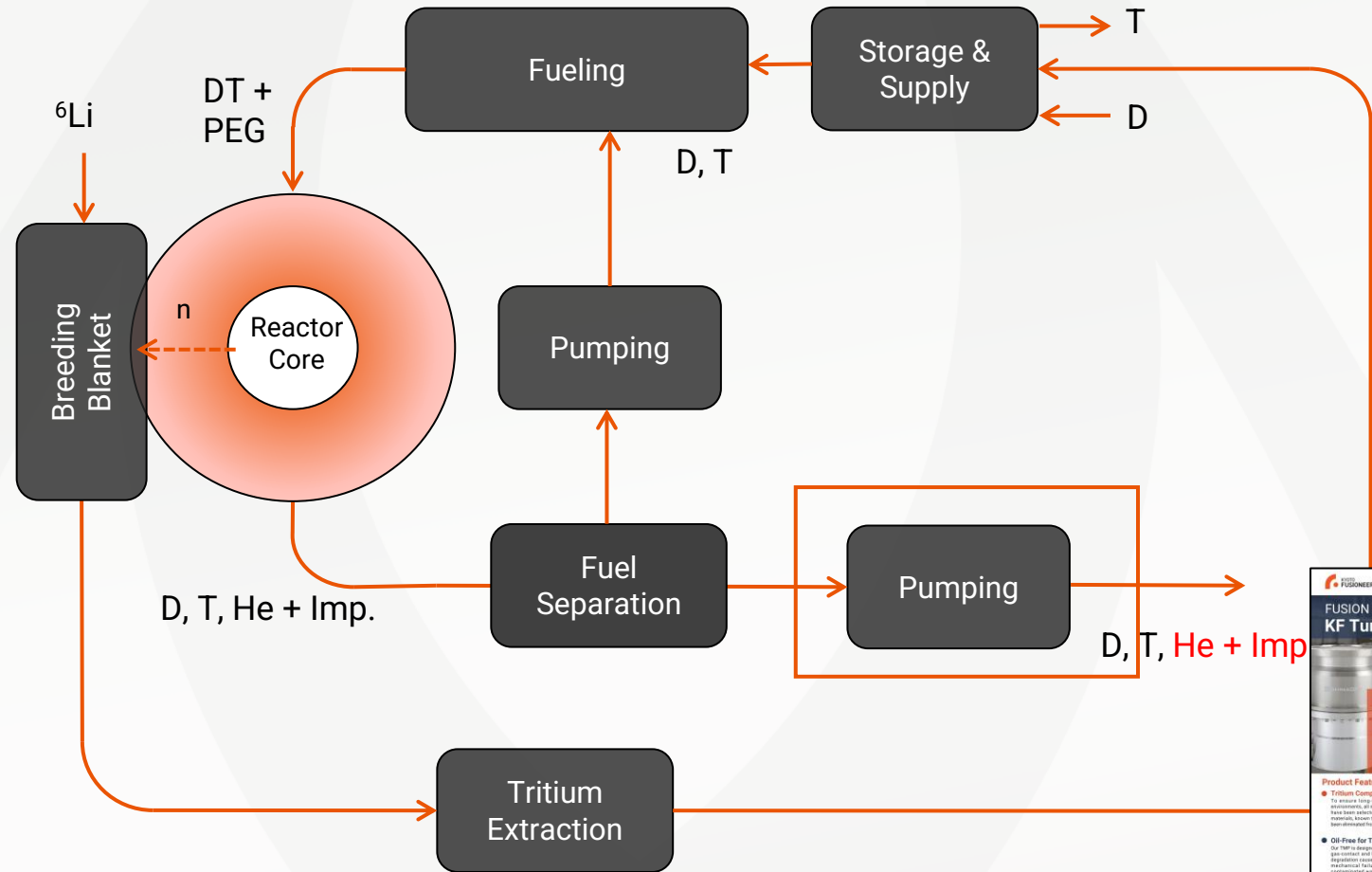


DIR has become reference for high throughput fuel cycles.

Candidate technologies are metal foil pump and proton conductor pump. But have not yet been translated in a complete first-of-a-kind component.

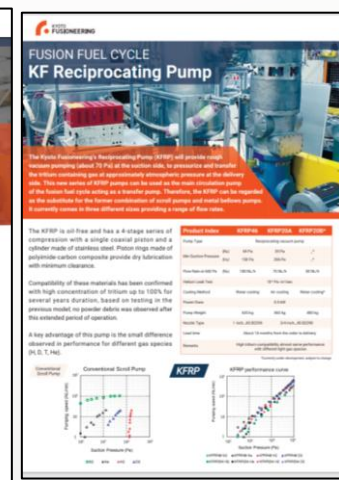
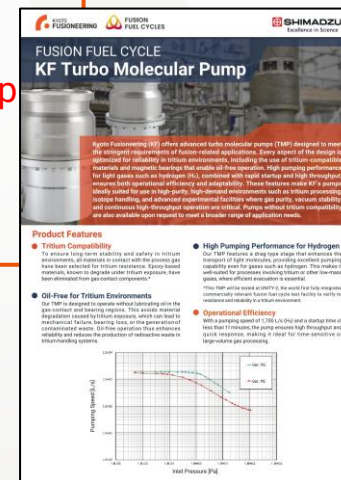
THE FUSION FUEL CYCLE SYSTEMS – VACUUM PUMPING

Compression from high vacuum to overatmospheric requires a serial connection of different technologies



The potential fusion market leads to development of tritium-compatible vacuum pumps, which did not happen before due to lack of commercial interest:

- Tritium-compatible turbopump
- Tritium-compatible dry roughing pump
- Tritium-compatible overatmospheric bellows pump



The diagram illustrates the fuel cycle for a fusion reactor. It begins with a **Reactor Core** (a red circle) surrounded by a **Breeding Blanket** (a grey rectangle). ${}^6\text{Li}$ is input to the blanket, and neutrons (n) are shown moving from the core to the blanket. The blanket outputs **DT + PEG** to the core and **D, T, He + Imp.** to the **Fuel Separation** unit. The **Fuel Separation** unit is connected to two **Pumping** units (grey rectangles). One pump feeds **D, T** into the **Fueling** unit (grey rectangle), which then feeds into the **Storage & Supply** unit (grey rectangle). The **Storage & Supply** unit outputs **T** and **D** to the core. The other pump feeds into the **Exhaust Processing** unit (grey rectangle), which is part of a larger system labeled **Q₂**. The **Exhaust Processing** unit outputs **T** to the **Storage & Supply** unit and **D** to the **Fueling** unit. The **Exhaust Processing** unit also outputs **He + Imp.** to the **Tritium Extraction** unit (grey rectangle), which then feeds back into the **Breeding Blanket**.


**FUSION
FUELS CYCLES**

FUSION FUEL CYCLE Palladium Diffuser

Kryo Fluorinating (KF) offers a palladium (Pd) diffuser capable of high-purity separation of hydrogen, deuterium and tritium from other gases. Our proprietary design maximizes the performance of the Pd membrane while ensuring compatibility with demanding tritium environments. The system is ideally suited for tritium fuel cycle applications and is used in nuclear power reactors for the high-purity hydrogen. Its compact and robust design ensures reliable operation even in space-constrained or safety-critical environments.

Product Features

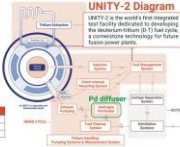
- High Purity Separation**
 Pd membranes selectively permeate H_2 (hydrogen) and its isotopes (deuterium and tritium), while the membrane blocking other gas species such as the (helium), N_2 (nitrogen), and O_2 (oxygen). This enables the stable production of ultra-high-purity gas at the 9N (99.9999999%) level. Such performance makes this technology ideally suited for tritium fuel circulation processes in fusion systems.
- Compatible with Tritium Environments**
 To prevent the diffusion of tritium to the exterior, a vacuum-insulated outer vessel is applied to the system, allowing permeated tritium gas to be efficiently recovered. This configuration contributes to the safety and containment required in fusion applications, supporting fuel cycle operations.

Compact Design

The high separation performance of a single membrane module enables the overall system to be designed in a compact and simple form. It allows for high-purity hydrogen (stable) purification even in limited installation spaces.

Continuous Operation

Pd membrane separation is driven by differential pressure, requiring no moving parts. This enables continuous and stable operation under controlled conditions, offering high operational efficiency for the separation and purification of hydrogen isotopes.



UNITY-2 Diagram

UNITY-2 is the world's first integrated fusion power plant. It is the first fusion power plant to be designed and built in the Americas. It is the first fusion power plant to be designed and built in the Americas. It is the first fusion power plant to be designed and built in the Americas.

Pd diffuser

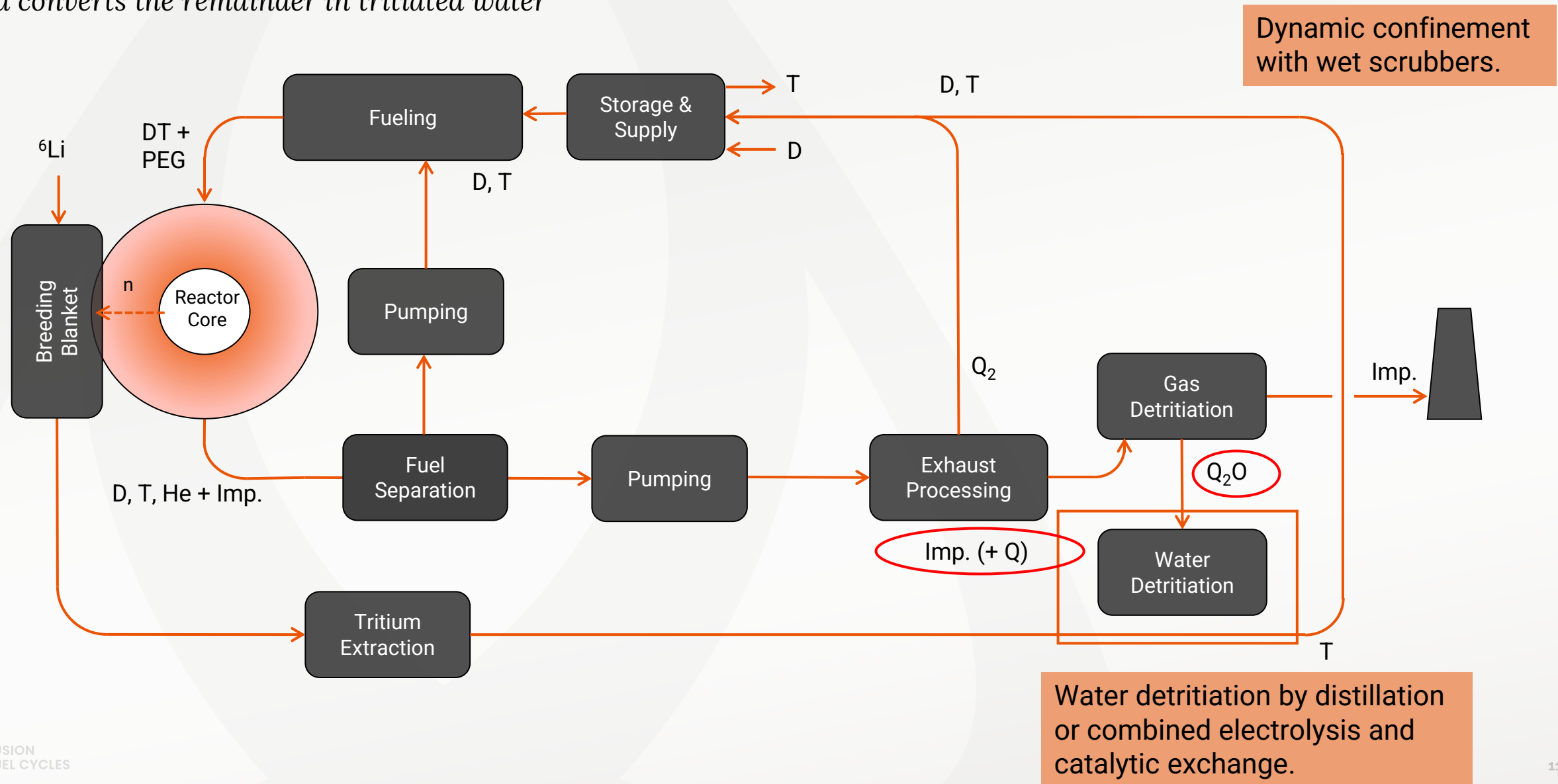
Item	Value
Flow rate (L/min)	100
Flow rate (m³/hr)	0.0028
Flow rate (m³/day)	0.067
Flow rate (m³/yr)	24.3
Flow rate (m³/decade)	243
Flow rate (m³/century)	2430
Flow rate (m³/millennium)	24300
Flow rate (m³/billion years)	243000
Flow rate (m³/trillion years)	2430000
Flow rate (m³/quadrillion years)	24300000
Flow rate (m³/quintillion years)	243000000
Flow rate (m³/sextillion years)	2430000000
Flow rate (m³/septillion years)	24300000000
Flow rate (m³/octillion years)	243000000000
Flow rate (m³/nonillion years)	2430000000000
Flow rate (m³/deci-trillion years)	24300000000000
Flow rate (m³/centi-trillion years)	243000000000000
Flow rate (m³/milli-trillion years)	2430000000000000
Flow rate (m³/micro-trillion years)	24300000000000000
Flow rate (m³/nano-trillion years)	243000000000000000
Flow rate (m³/pico-trillion years)	2430000000000000000
Flow rate (m³/femto-trillion years)	24300000000000000000
Flow rate (m³/atto-trillion years)	243000000000000000000
Flow rate (m³/zepto-trillion years)	2430000000000000000000
Flow rate (m³/yocto-trillion years)	24300000000000000000000

Specification Details

Item	Value
Pd diffuser (kg)	100
Pd diffuser (m³)	0.0028
Pd diffuser (m³/day)	0.067
Pd diffuser (m³/yr)	24.3
Pd diffuser (m³/decade)	243
Pd diffuser (m³/century)	2430
Pd diffuser (m³/millennium)	24300
Pd diffuser (m³/billion years)	243000
Pd diffuser (m³/trillion years)	2430000
Pd diffuser (m³/quadrillion years)	24300000
Pd diffuser (m³/quintillion years)	243000000
Pd diffuser (m³/sextillion years)	2430000000
Pd diffuser (m³/septillion years)	24300000000
Pd diffuser (m³/octillion years)	243000000000
Pd diffuser (m³/nonillion years)	2430000000000
Pd diffuser (m³/deci-trillion years)	24300000000000
Pd diffuser (m³/centi-trillion years)	243000000000000
Pd diffuser (m³/milli-trillion years)	2430000000000000
Pd diffuser (m³/micro-trillion years)	24300000000000000
Pd diffuser (m³/nano-trillion years)	243000000000000000
Pd diffuser (m³/pico-trillion years)	2430000000000000000
Pd diffuser (m³/femto-trillion years)	24300000000000000000
Pd diffuser (m³/atto-trillion years)	243000000000000000000
Pd diffuser (m³/zepto-trillion years)	2430000000000000000000
Pd diffuser (m³/yocto-trillion years)	24300000000000000000000

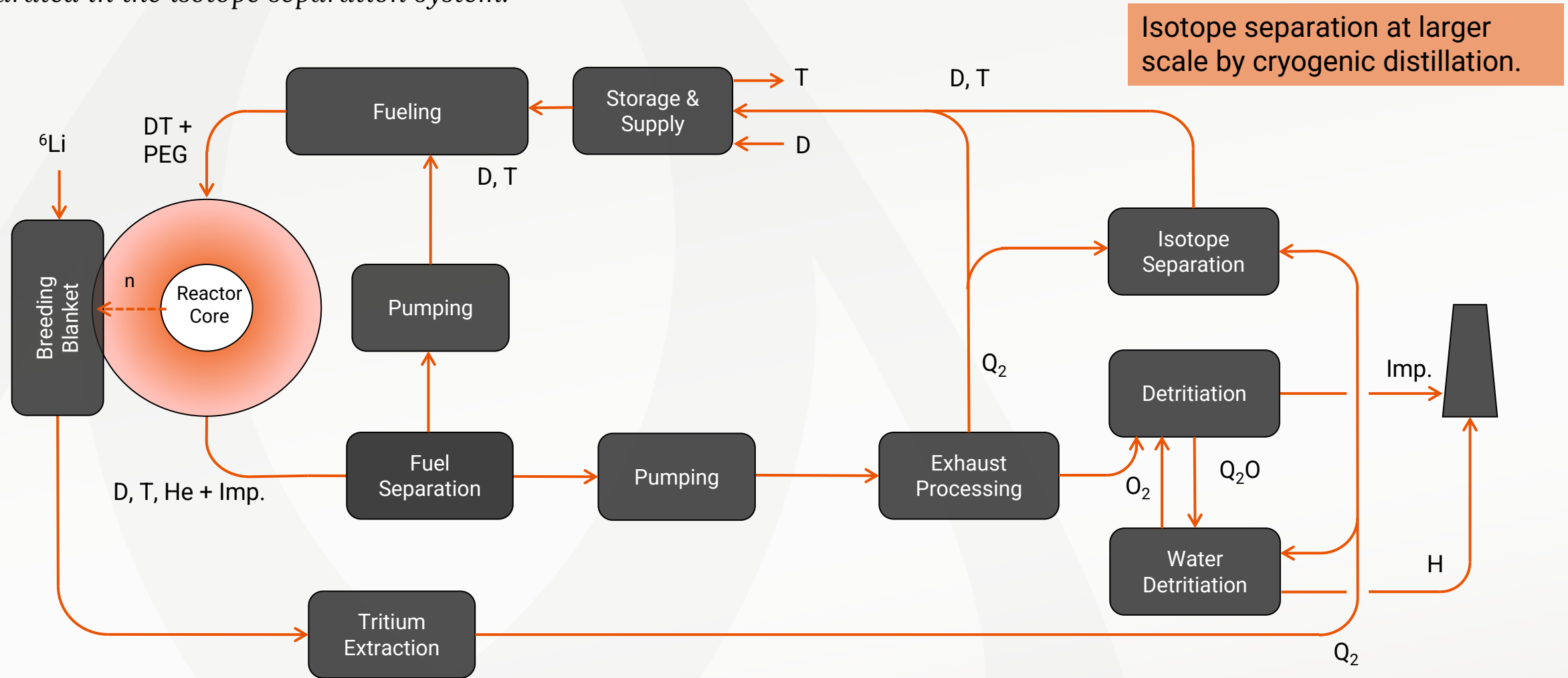
THE FUSION FUEL CYCLE SYSTEMS – GAS AND WATER DETRITIATION

The detritiation system reduces the tritium content in the gas stream to levels allowed for release and converts the remainder in tritiated water



THE FUSION FUEL CYCLE SYSTEMS – ISOTOPE SEPARATION

The water detritiation system extracts hydrogen good to go to stack and returns tritiated Q_2 that is then separated in the isotope separation system.

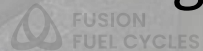




UNITY-2 TEAM

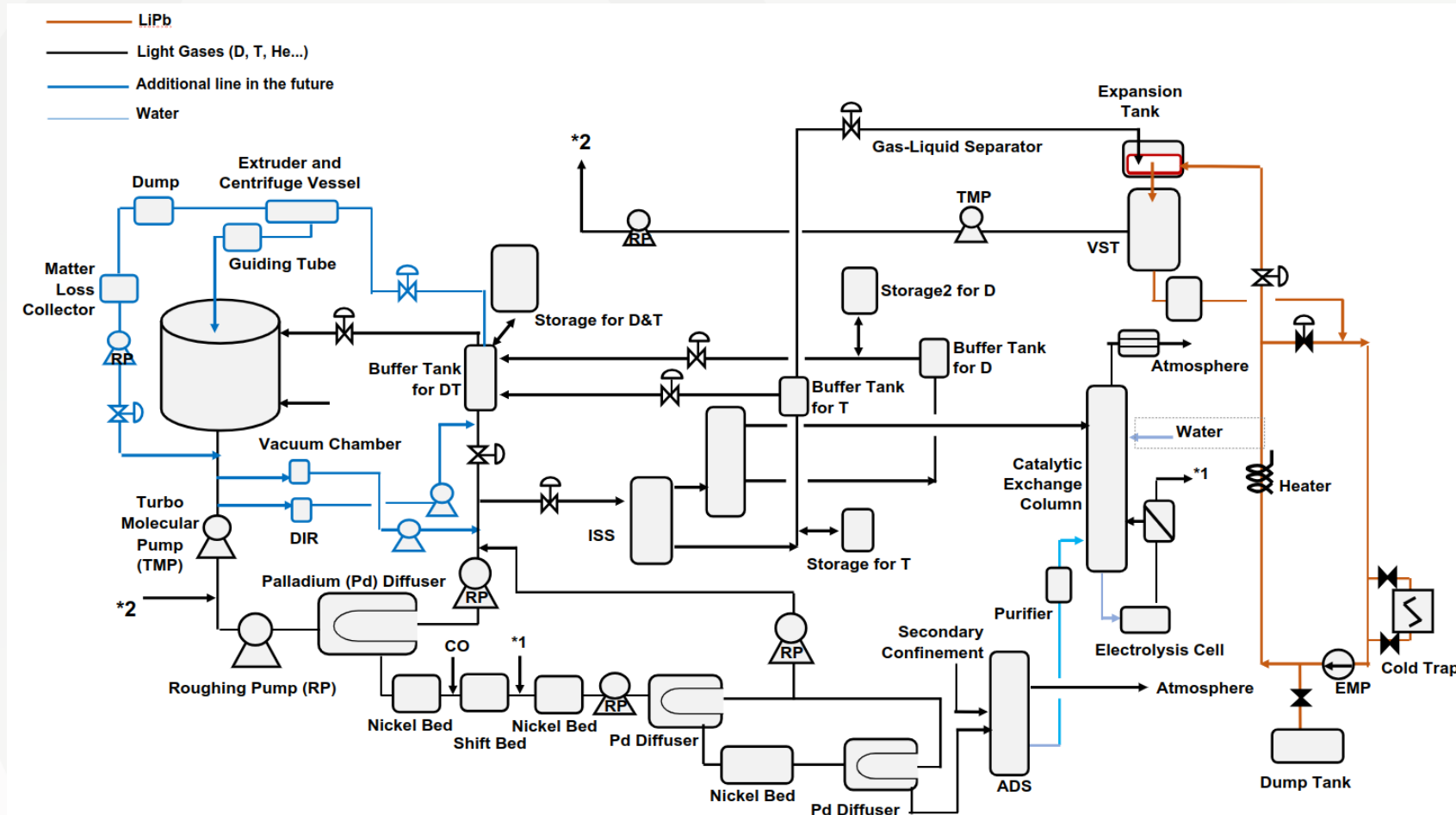
A global team with more than
40 mission-driven members

'Seeing is believing'



CONCEPT DESIGN OF UNITY-2

UNITY-2 will be the global first integrated continuously operated deuterium-tritium fusion fuel cycle development platform.



2023



Initiation

2024

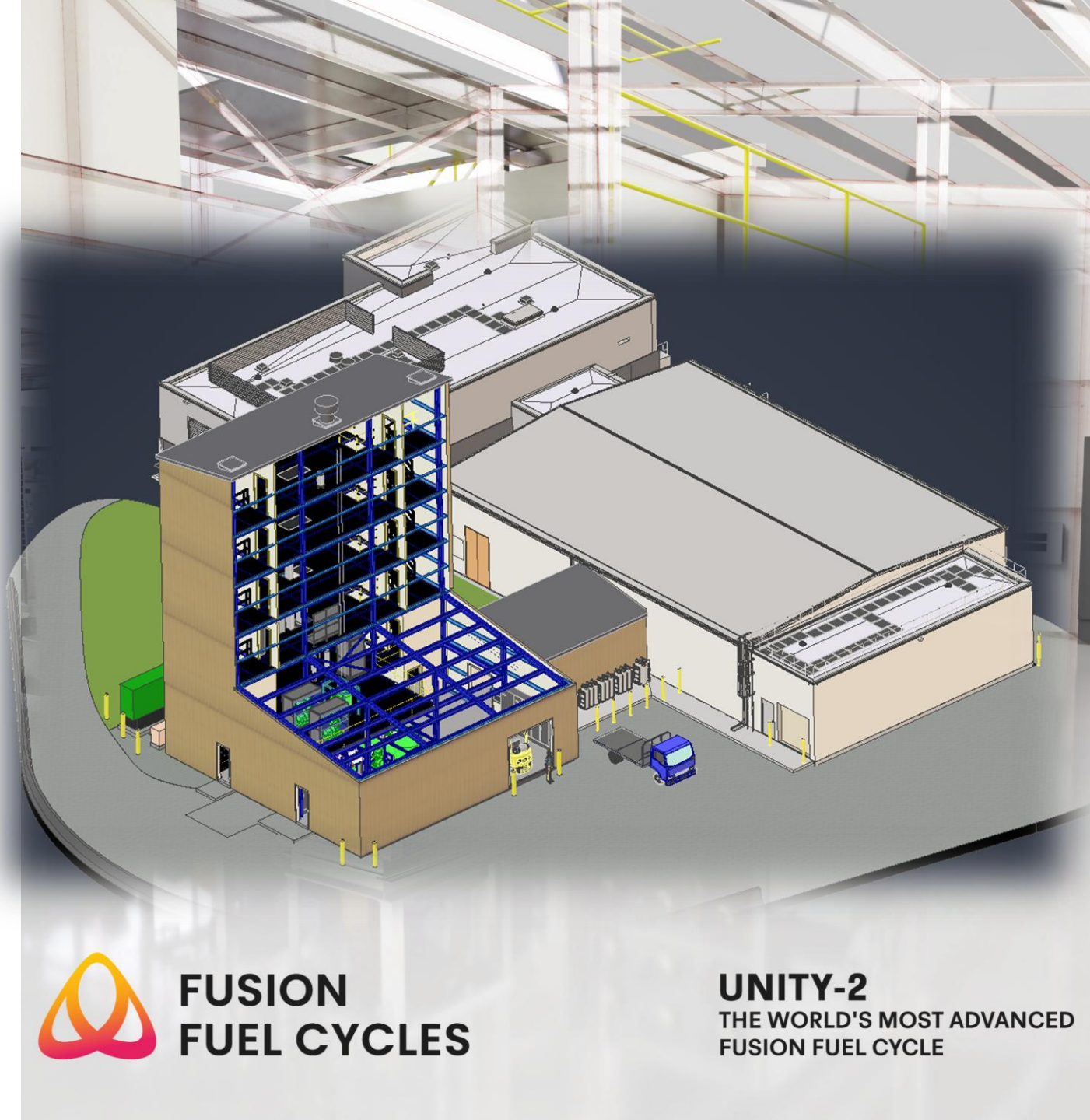
Procurement:
Long lead items

2026

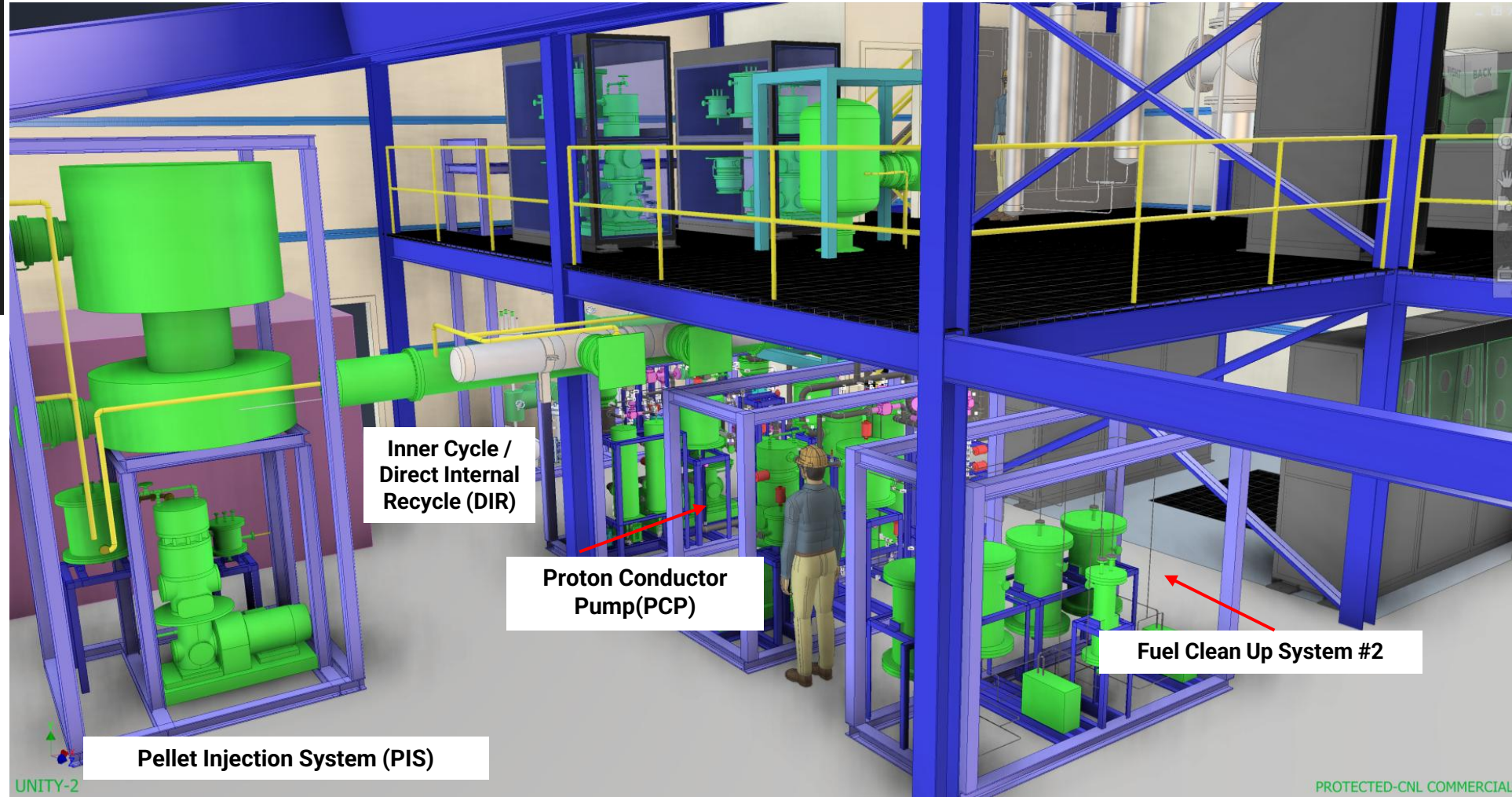
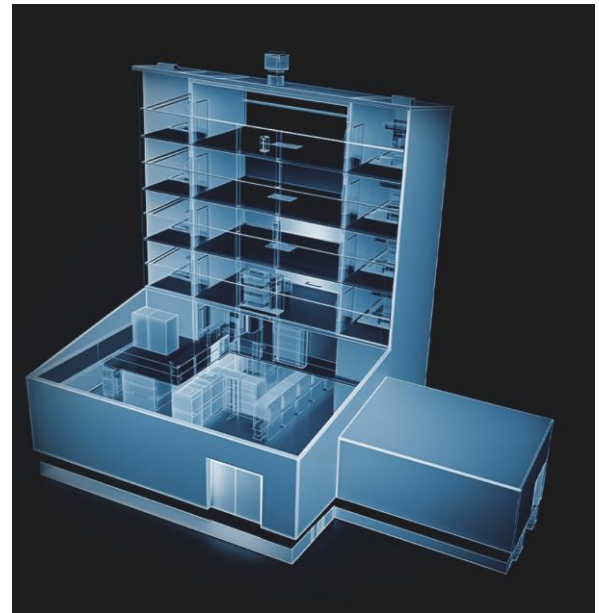
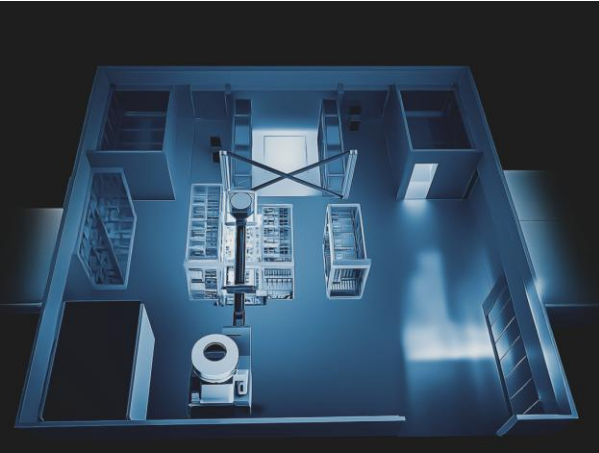
Installation:
Integration of systems. Planned
commissioning start

UNITY-2 SITE

UNITY-2 will be housed in CNLS's existing Tritium facility in Chalk River, Ontario

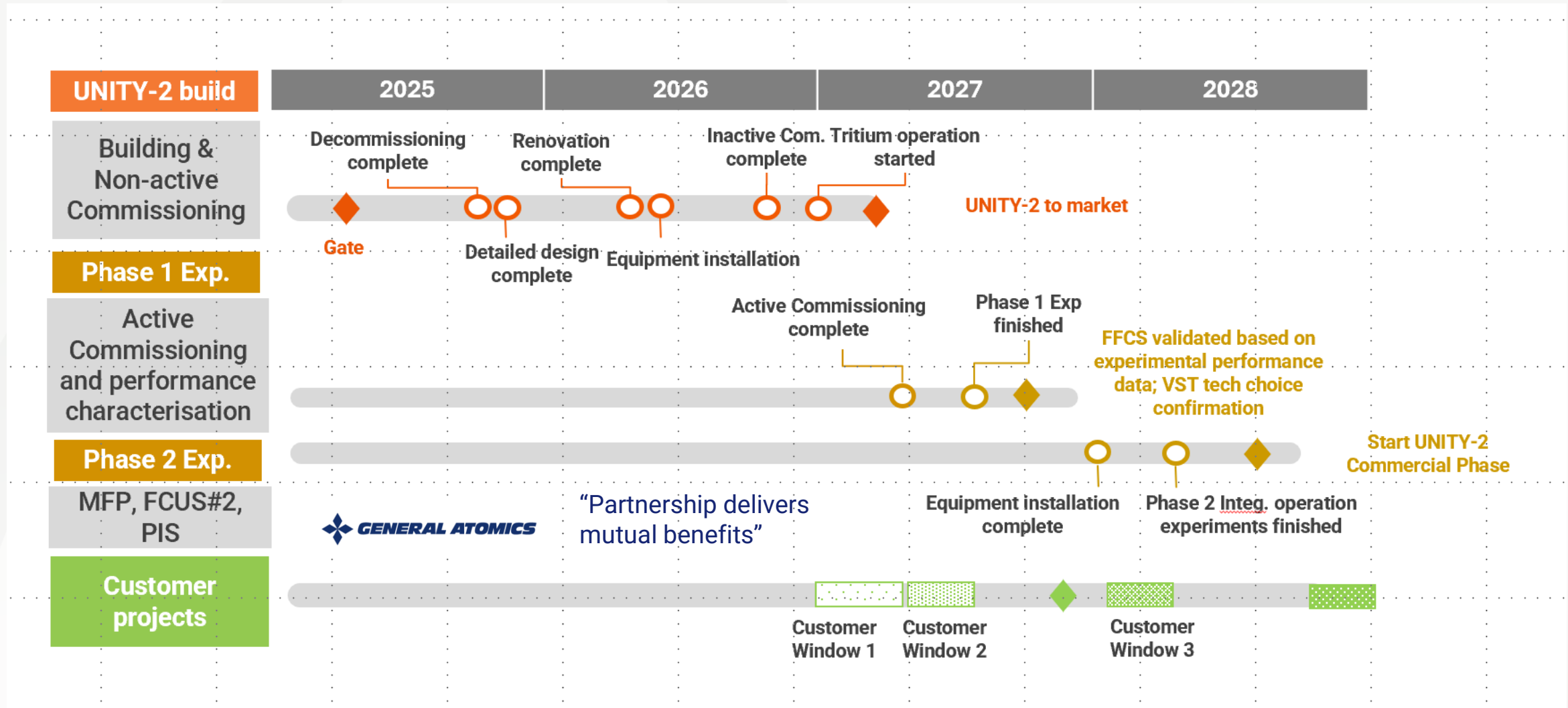


UNITY-2 RENDER, CURRENTLY IN DETAILED DESIGN STAGE



UNITY-2 OPERATION

Timelines and opportunities for customer projects



FUEL CYCLE TECHNOLOGY MATURATION

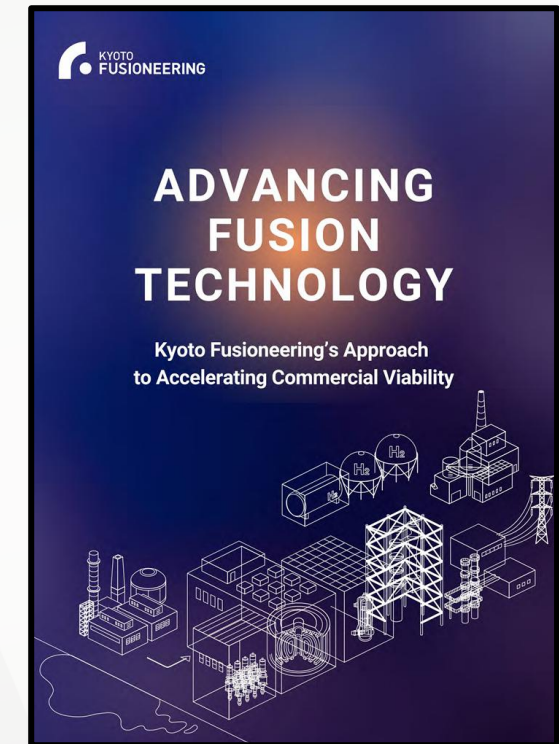
Significant advances to Technical readiness levels

■ Current TRL

■ Improvement through UNITY-2

Function	Technology	TRL								
		1	2	3	4	5	6	7	8	9
Primary pumping	TMP	■	■	■	■	■				
	KFRP	■	■	■	■	■	■	■		
Fueling	PIS	■	■	■	■	■	■	■		
DIR	Membrane	■	■	■	■	■	■	■		
	PCP	■	■	■	■	■	■	■		
	MFP	■	■	■	■	■	■	■		
ISS	CD	■	■	■	■	■	■	■		
WDS	CECE	■	■	■	■	■	■	■		
ADS	WSC	■	■	■	■	■	■	■		
Storage	dU	■	■	■	■	■	■	■		
	ZrCo	■	■	■	■	■	■	■		

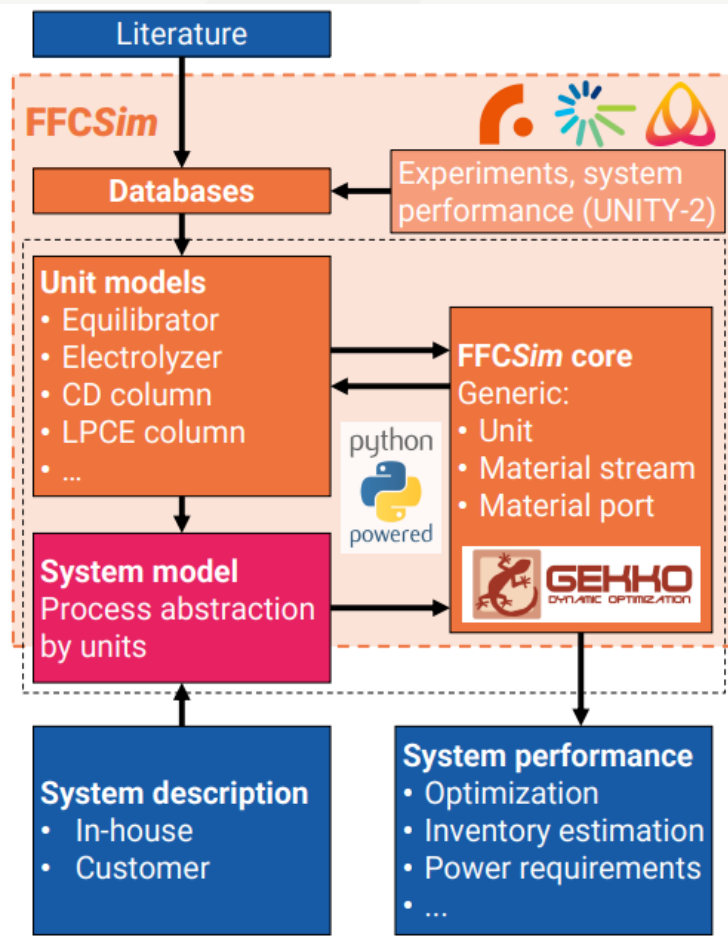
Requires separate testing under a magnetic field (planned)



HOLISTIC FUEL CYCLE MODELING

UNITY-2 will be used to build modelling and simulation-based predictive design and scaling capabilities.

Architecture of FFCSim



Features

- Fully fletched process simulator for fusion fuel cycles
 - Steady-state and dynamic simulation
 - Flow-sheet based architecture (currently text only)
 - Equation based modelling (APMonitor / GEKKO)
 - Modern, object-oriented languages (Python)
- An inventory measurement and accountancy tool for tritium tracking, once informed by achievable uncertainties with various tritium diagnostics.

Possible Use cases

Simulation of systems or components	Simulation of integrated fuel cycles
- Mainly steady state simulation - Parameter scans - Design / sizing and optimization	- Mainly transient simulations - Multi-system optimization - Validation of integral performance - Scenario simulation

UNITY-2 PURPOSE AND ACHIEVEMENTS

UNITY-2 shall provide verification and validation for tritium fuel cycle technologies in five different aspects, which are:

- **Technology performance** / It allows to characterise the operation of individual fuel cycle technologies with tritium.
- **Technology integration** / It allows to characterise the integrated operation of different fuel cycle technologies coupled together under tritium operation, this is for the first time ever.
- **Safety and operability demonstration** / It allows to verify the safe operation of low inventory continuously operated multi-loop fuel cycle architectures.
- **Regulatory acceptability** / It allows to demonstrate the necessary regulatory accountability of the fusion fuel cycle.
- **Scale-up transfer** / It allows to validate design codes and with using them allows to derive validated customer specific architectures up to power plant scale.

With these capabilities UNITY-2 is a one way effort to develop all DT fuel cycles for private and public fusion endeavours.

LITHIUM-LEAD LOOP TECHNOLOGY

Vacuum Sieve tray technology scaled from UNITY-1 loop in Kyoto.

Kyoto Fusioneering is operating the UNITY-1 facility (with 500°C blanket test section)

- UNITY-2 loop will be $\sim 1/5^{\text{th}}$ of the UNITY-1 loop, with 50 L inventory and 10 L/min flow rate

UNITY-1 will provide baseline design information to de-risk the UNITY-2 loop

UNITY-2 will then validate:

- that performance can be met with tritium.



UNITY-1: Blanket and Heat Utilization

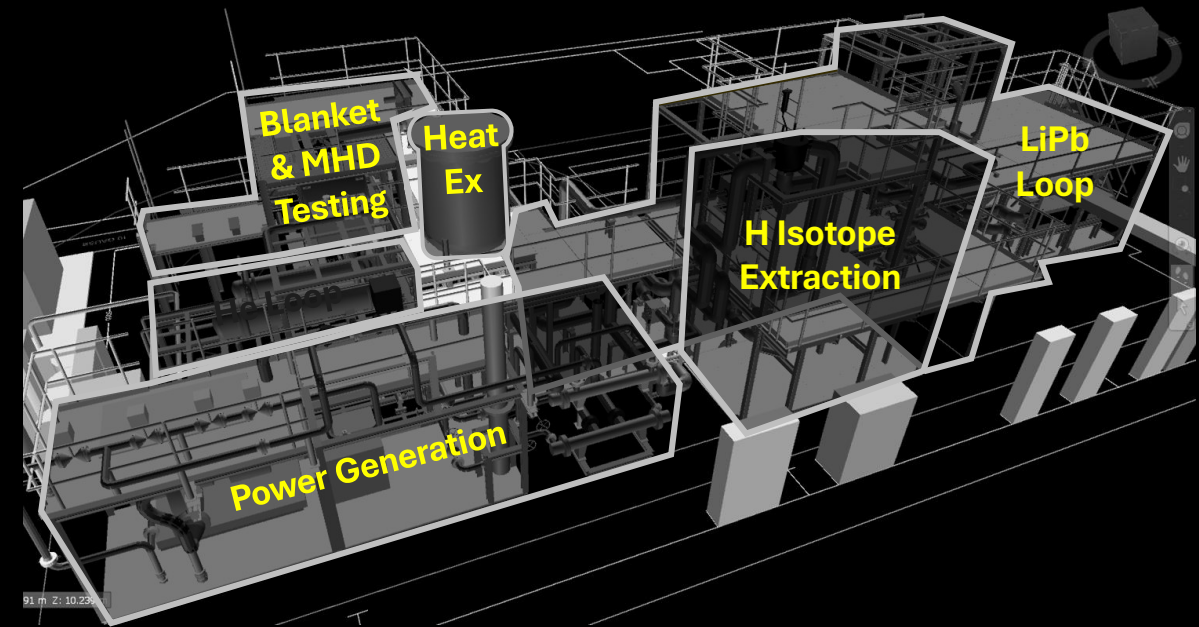


Primer:

UNITY-1 is a Thermal Cycle and Blanket development platform located in Kyoto, Japan (no neutrons, no tritium).

First integrated demonstration to **elevate System Readiness Level** with

- Blanket testing with 4T magnetic field
- 300 L of LiPb up to 1000°C
- Open Brayton cycle power generation
- Novel materials testing (e.g., SiC_f/SiC, Mo)
- Hydrogen isotope extraction
- Liquid-Li and FLiBe testing at lower TRL
- **Model and design tool validation**



Commercialization Pathways:

Hardware Supply

Engineering Services

Facility Use

LiPb LOOP

Operation completed successfully

Operation temperature : 300-500°C,

LiPb flow rate : 75 L/min

Cold trap operation : 280°C – 5 L/min

Heating operation 400->500°C

Emergency shutdown operation safely



MHD TEST SECTION

- Superconducting Coil Piping Installation Completed
- 10 L/min LiPb Flow Operation
- Loop Heating up to 500°C
- MHD Test Campaign ongoing



BLANKET TEST SECTION

- 4T magnetic field for piping
- Bore size : f300mm
- >1T magnetic field for blanket
- 2 coils distance : 810mm
- LiPb temperature : 300-1000°C

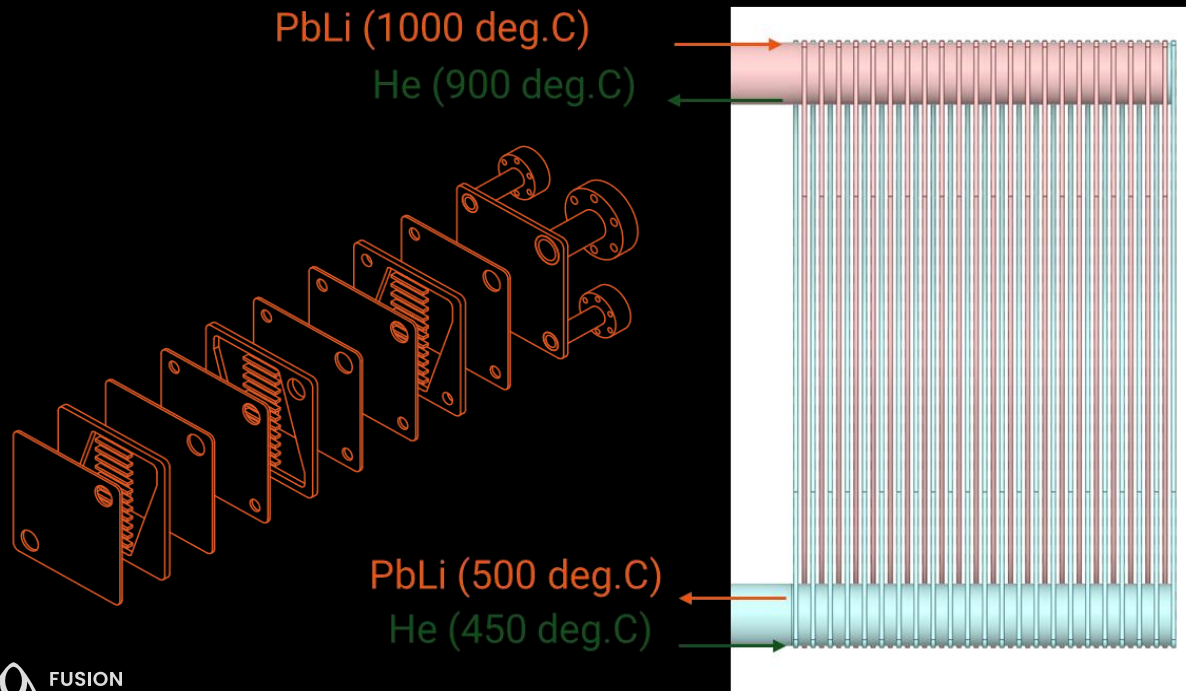


LiPb-He HEAT EXCHANGER

Heat duty: 140 kW

- LiPb 1000°C -> 500°C
- He 450°C -> 900°C

Size: W250 x H500 x L350mm



1000°C TEST SECTION

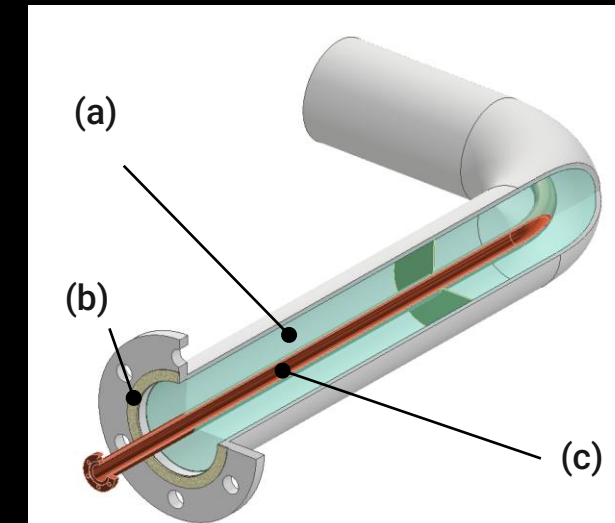
Heating system

IH heater applied in the system

Double piping system

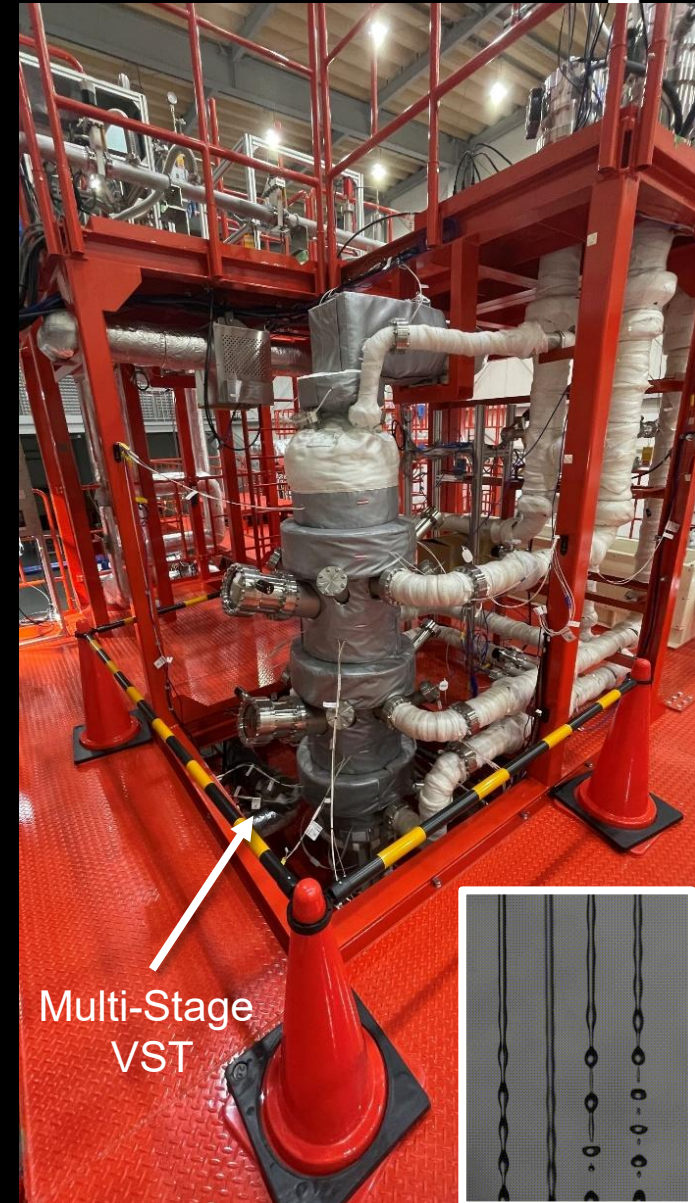
Vacuum thermal insulation system applied

- (a) Insulation with super low thermal conductivity
- (b) Anti-tritium permeation joint
- (c) Flexible support to reduce thermal stress



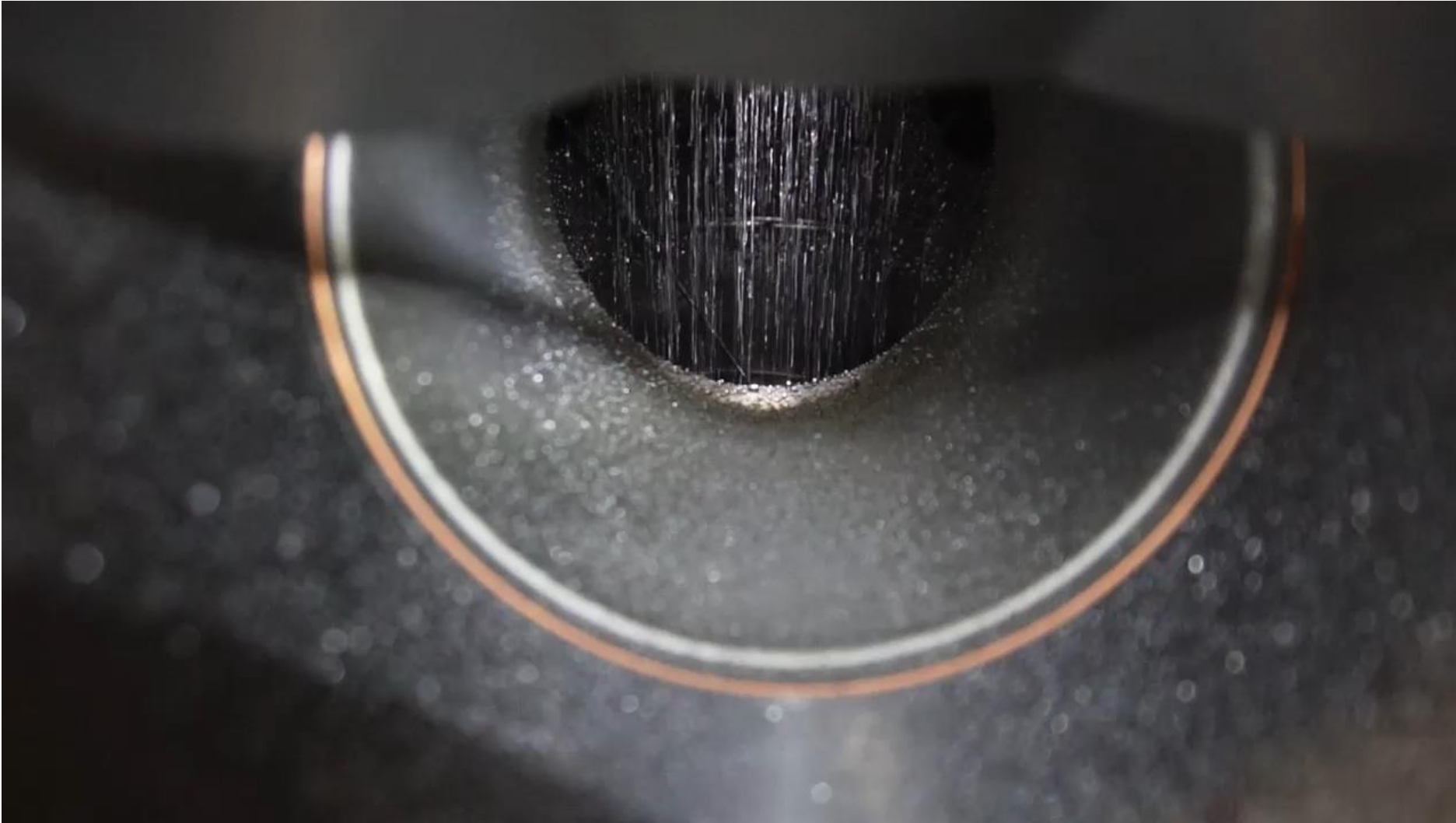
HYDROGEN EXTRACTION

- 7 L/min LiPb Flow Operation
- Vacuum Achieved: 10^{-5} Pa
- Loop Heating up to 500°C
- **Vacuum Sieve Tray** characterization test campaigns ongoing



FIRST VST OPERATION WITH LIQUID LITHIUM-LEAD

Vacuum sieve tray commissioned in April 2025



SUMMARY

- **FUSION FUEL CYCLES Inc.** is developing and deploying fusion fuel cycles in Canada and Japan.
- The focus is given to the integrated character of these facilities.
- It is addressing the remaining challenges of fuel and thermal cycle to enable the scale-up towards efficient fusion pilot and power plant designs.
- **FUSION FUEL CYCLES Inc.** is your entrance gate to access this know-how.



TRUSTED PARTNER IN YOUR FUEL CYCLE JOURNEY





TRUSTED PARTNER IN YOUR FUEL CYCLE JOURNEY

For further details, please reach out to info@ffc.inc