TRITIUM FUEL CYCLE Introduction

9th IAEA DEMO and Fusion Plants Workshop

Aomori, Japan

Christian Day,
Kyoto Fusioneering Europe GmbH

June 2025

KYOTO FUSIONEERING

Tritium Fuel Cycle – Technology context

Fuel cycle technology roadmapping

Recent efforts in EU and US

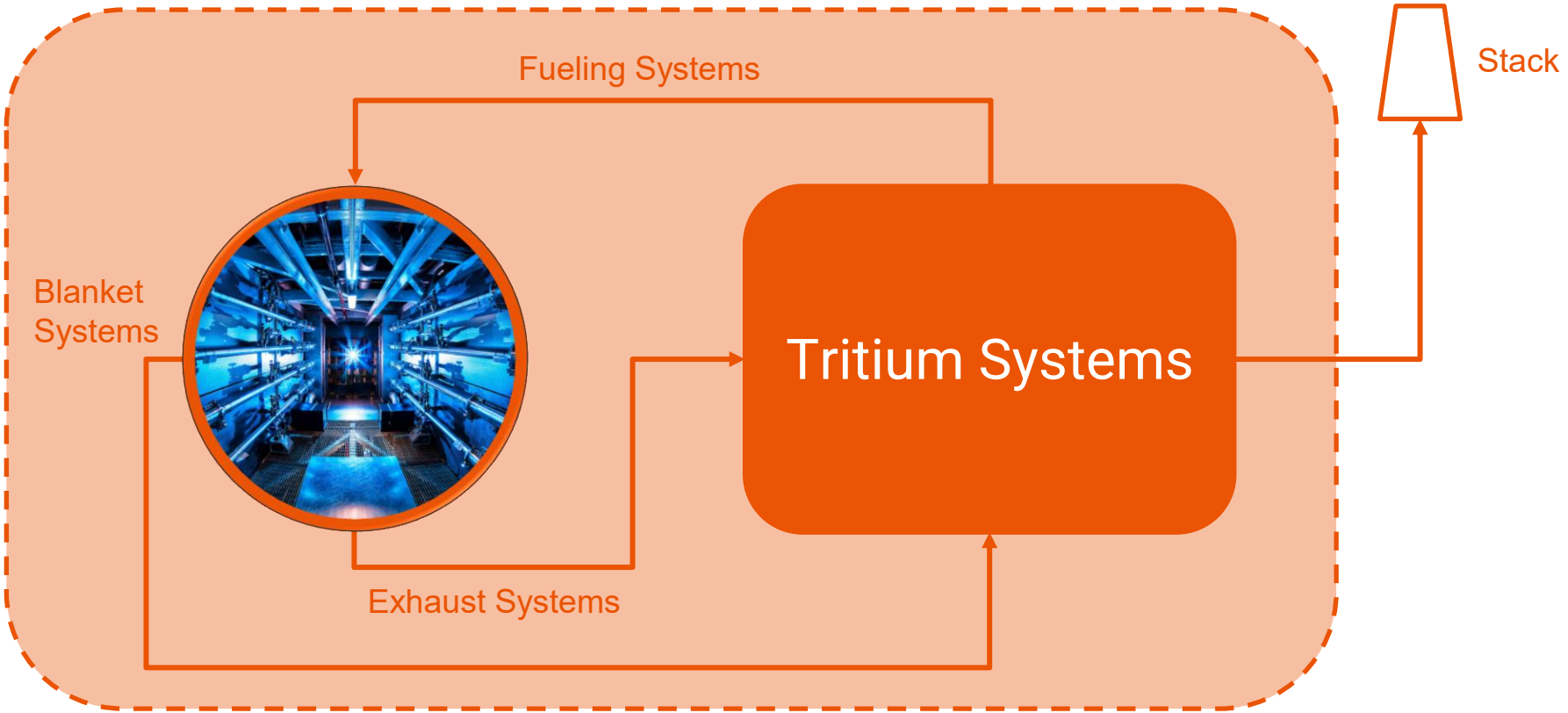
- Community effort organized with in-person workshop being held in March 2025 at F4E.

GO4FUSION | BUILDING A EUROPEAN FUSION ENERGY PARTNERSHIP

- Development of the National FS&T Roadmap via a series of workshops development. This framework rests upon the FESAC Long Range Plan (LRP) science drivers and incorporates information from the Community Planning Process report, formal input obtained gained through charges to FESAC, and numerous previous community-led workshops and reports.
- Recent in-person event held in April 2025 hosted by ORNL.

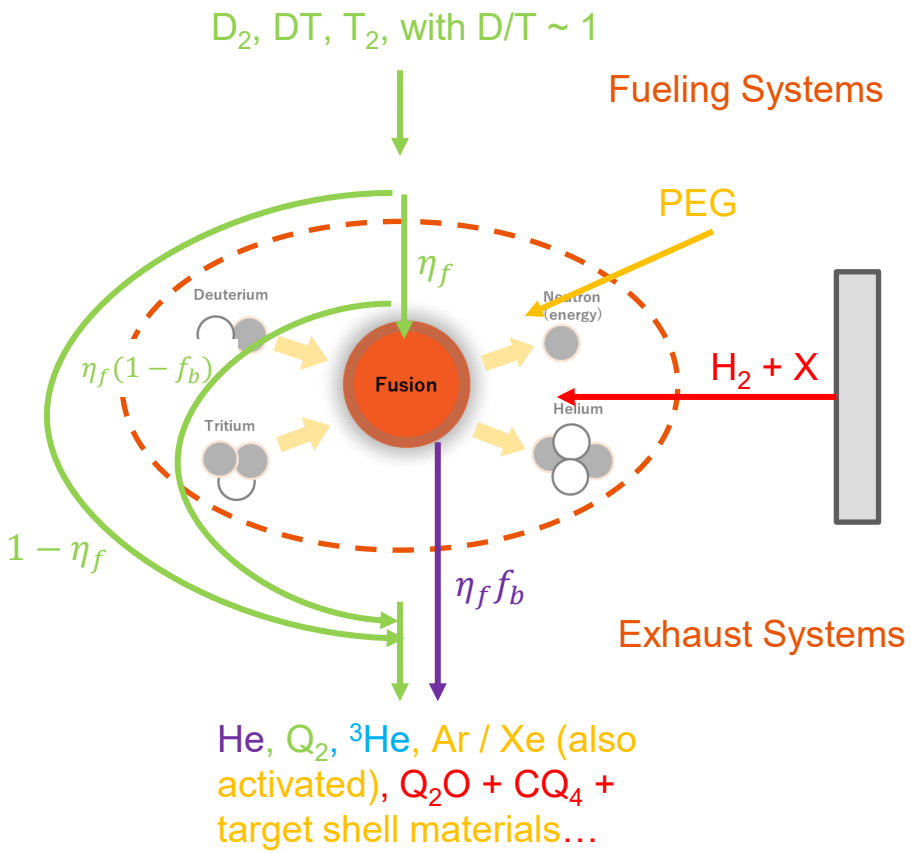
The tritium fuel cycle – at high level concept agnostic

Holistic high-level view



https://en.wikipedia.org/wiki/National_Ignition_Facility#/media/File:Preamplifier_at_the_National_Ignition_Facility.jpg

The fuel cycle as a service provider to the plasma

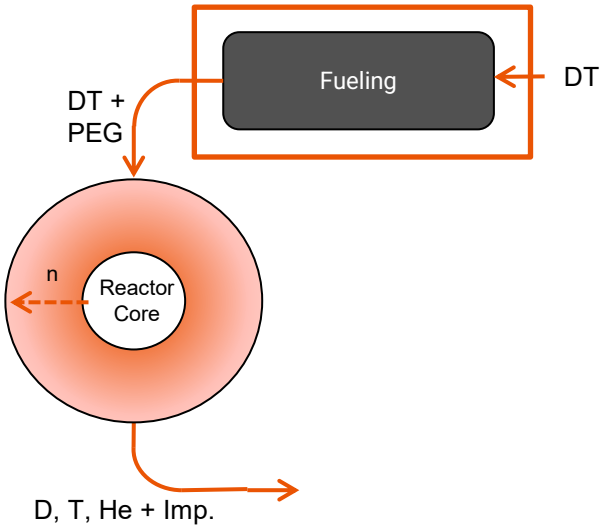


Requirements and loads:

- Fueling with educts: D, T with D/T = 1
- [Plasma enhancement gas]
- Exhaust of products: He
- [Target debris]
- Limited fuelling efficiency (η_f) and burn-up fraction (f_b) of fuel
- Decay of tritium ($\tau_{1/2} = 12.3$ a)
- Plasma interaction with and outgassing from structural materials, X = Q_2O, CQ_4, …

The fusion fuel cycle technologies - fueling

Let's build a fuel cycle…

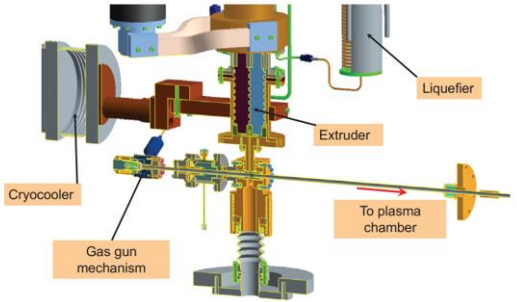


Fueling (1/2)

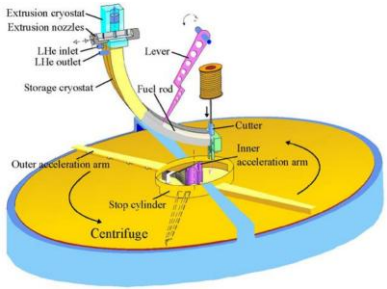
Magnetic Confinement (MCF)

- Comparable for Tokamak and Stellarator
- Main challenge: How to get the fuel nuclei to the plasma core
- Prime method for hot burning magnetically confined plasma:
  - Cryogenic Pellet Injection System

There is no demonstration of tritium-compatible continuous DT pellet injection.



D. Rasmussen, US ITER Fusion Integration, "D-T Pellet Injection for ITER Plasma Fueling", TUG, Oak Ridge, TN, 2018



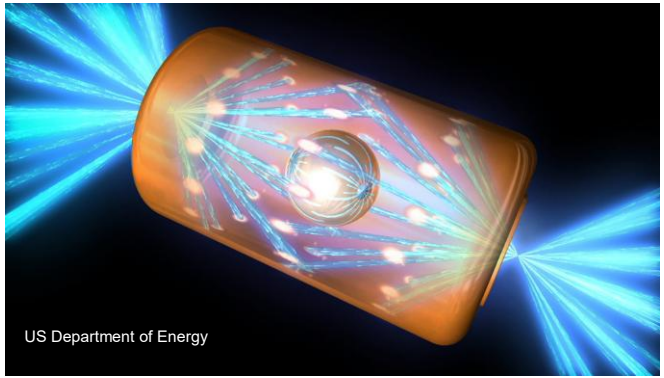
P. Lang et al., EURO*fusion*, "A flexible pellet injection system for the tokamak JT-60SA: The final conceptual design", 2017

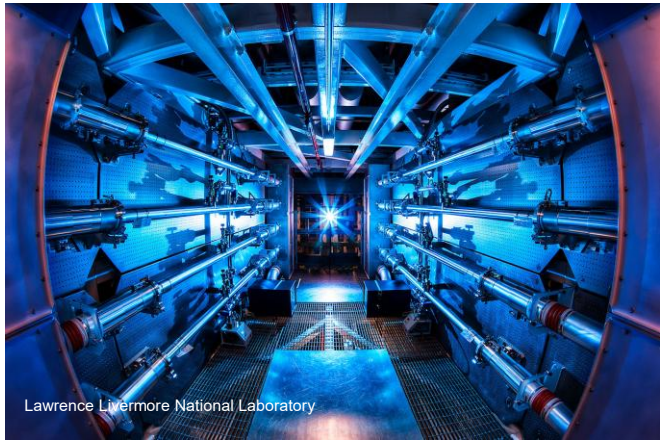
Fueling (2/2)

Inertial Confinement (ICF)

- Comparable for most inertial confinement concepts
- …, but of course the devil lies in the details
- Main challenges:
  - High frequency (order of 10 Hz) for deployment of targets
  - … which equals 1 million targets per day per power plant
  - Target properties (homogeneity, …) to allow absorption of driver beams (direct/indirect drive)
  - Debris/vaporized material from targets (indirect drive, ablator), which the fuel cycle needs to keep at acceptable levels and process it

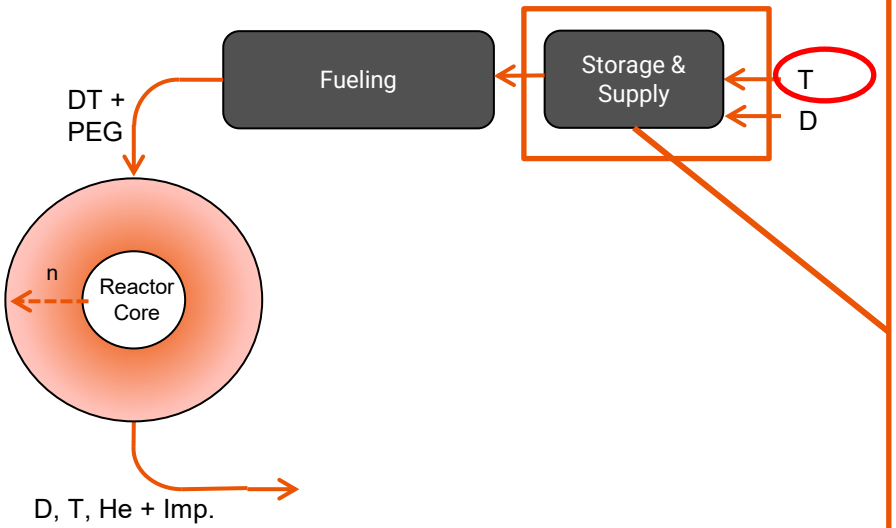
Target production and injection at the rates for an inertial fusion power plant.

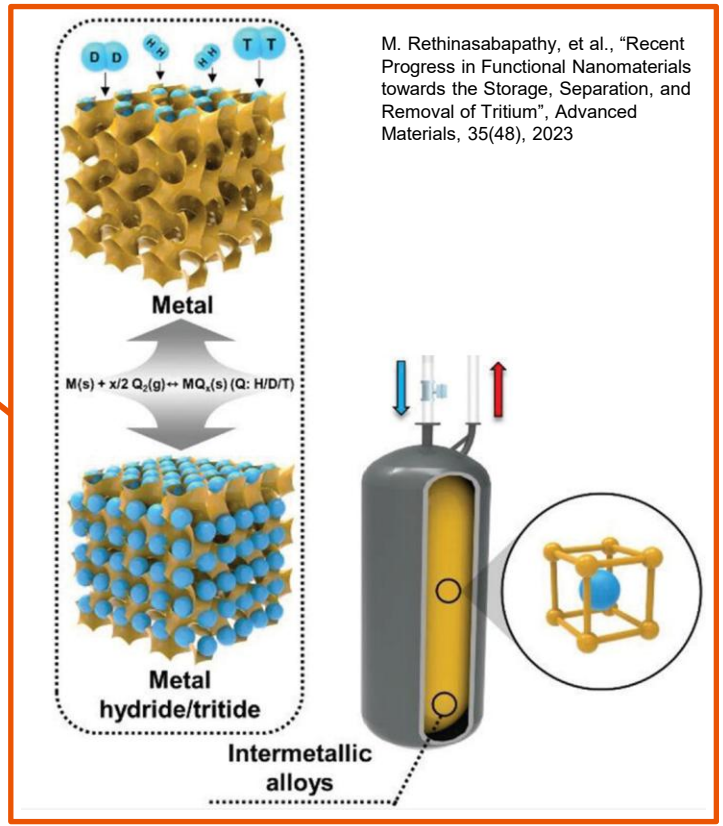




The fusion fuel cycle technologies - storage

Storage of hydrogen isotopes



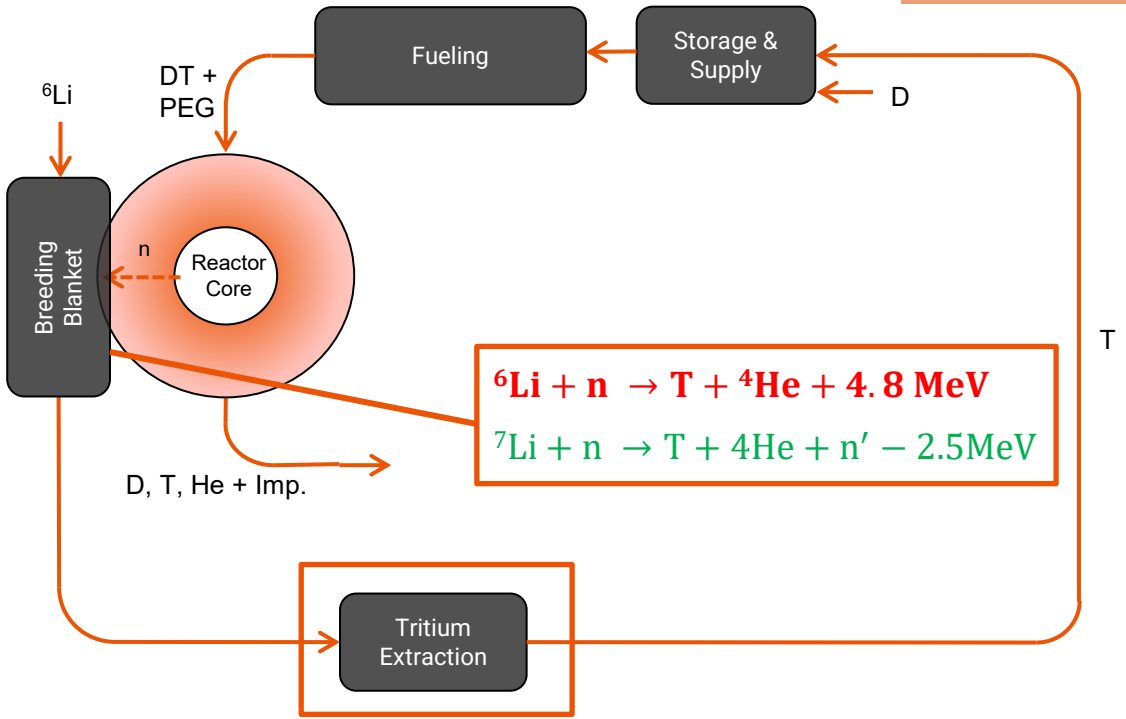


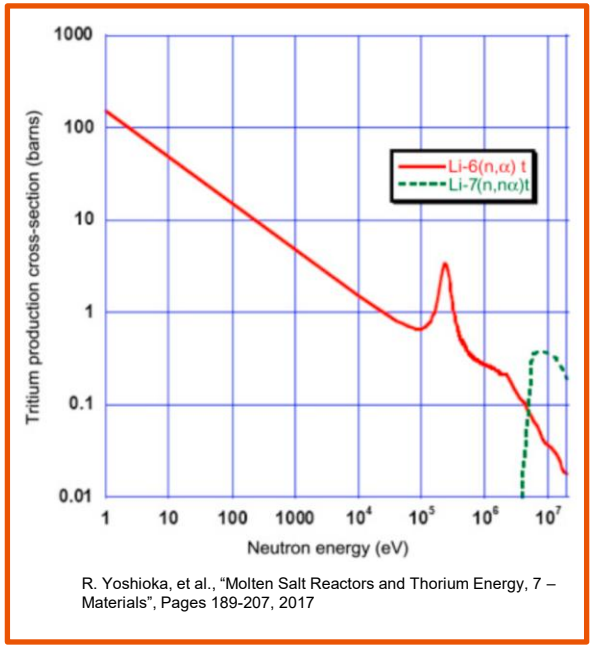
Depleted uranium storage beds have unbeatable performance, but dU is a nuclear material.

The fusion fuel cycle technologies – 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.





R. Yoshioka, et al., "Molten Salt Reactors and Thorium Energy, 7 – Materials", Pages 189-207, 2017

Tritium extraction from breeder

Tritium extraction systems recover bred tritium from lithium-containing materials in the breeding blanket

- Extraction efficiency: Extraction techniques that cannot handle large volumes and low concentrations, or with low efficiency of extraction, reduce the available bred tritium inventory, impacting self-sufficiency.
- Challenging environment: Ensuring the extraction technique or process is compatible with the harsh environment in the blanket, typically high temperature, corrosive, and with the presence of activated products (including Activated Corrosion Products; ACPs).
- Minimising retention: Tritium remaining in breeder systems (including both breeder and structural materials) reduces the amount of usable tritium in the fuel cycle.

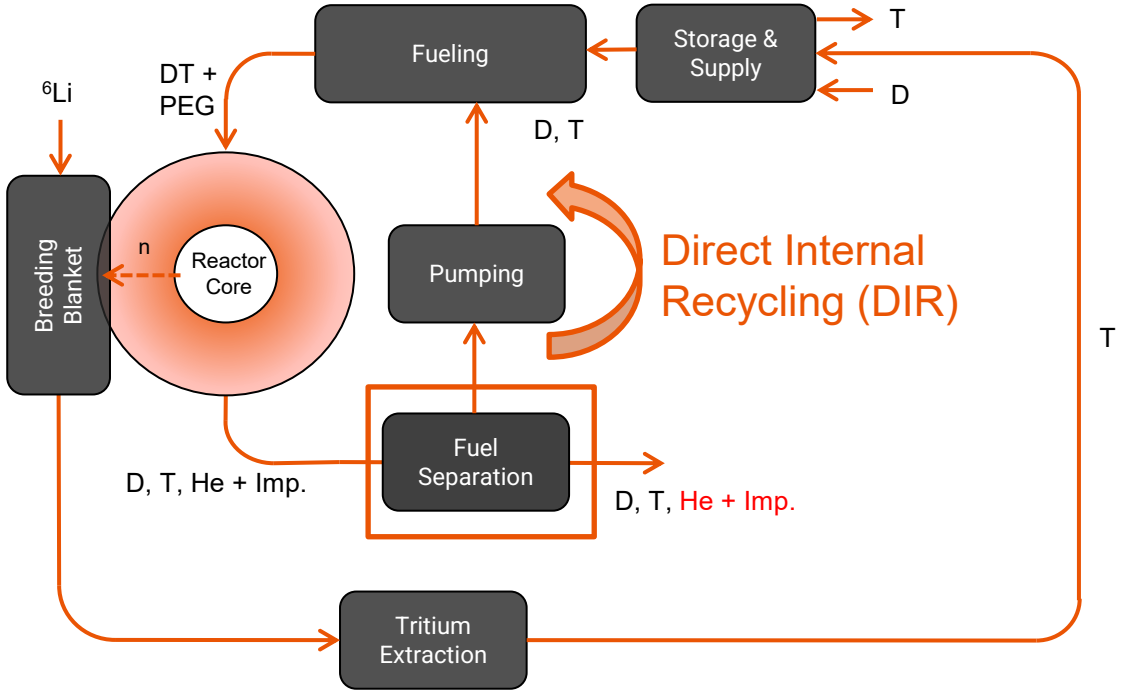
As there is no lead blanket concept, there is no lead tritium extraction technology. Technologies for liquid breeders are permeation against vacuum, gas liquid contacting and vacuum sieve tray. For solid breeder is Helium purge.

FIRST VST OPERATION WITH LIQUID LITHIUM-LEAD

Vacuum sieve tray commissioned in April 2025

The fusion fuel cycle technologies - DIR

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

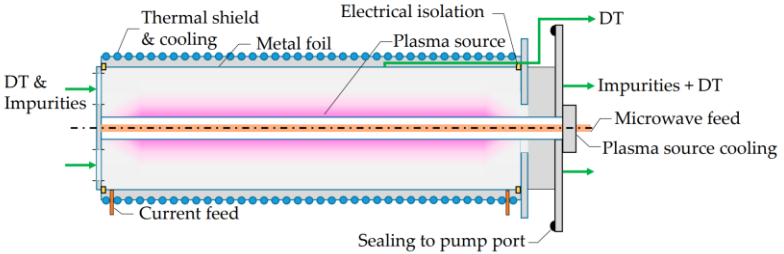


- DIR has become reference for high throughput fuel cycles.

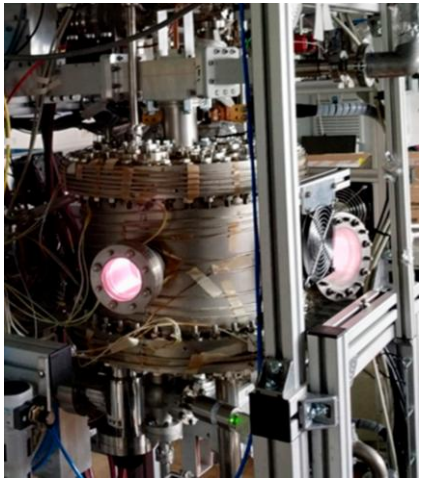
Direct Internal Recycling

A closer look into Direct Internal Recycling = fuel separation at low pressures

- DIR requires ultra-pure separation of hydrogen because we want to minimize the processing time (i.e. residence time)
- Currently, two main technologies are under development for low density fuel separation:
  - **Metal Foil Pump (MFP)**
    - Superpermeation of energetic hydrogen atoms/ions through metal foil
  - **Proton Conductor Pump (PCP)**
    - Electrochemical separation of Q protons through a solid-oxide proton conductor



Y. Kathage, et al., "Experimental Progress in the Development of a Metal Foil Pump for DEMO", MDPI Plasma, 6(4), 2023.

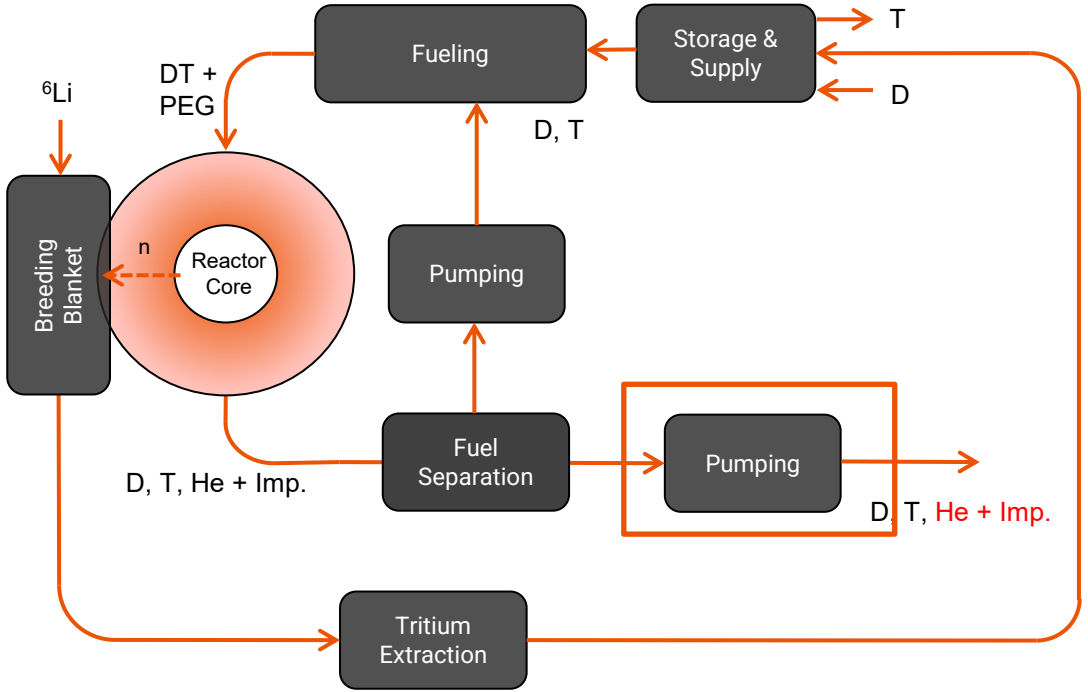


"Advancing Fusino Technology – Kyoto Fusioneering's Approach to Accelerating Commerical Viability", Kyoto Fusioneering Whitepaper, 2024, available at https://kyotofusioneering.com/en/whitepaper

Both technologies have not yet been translated in a complete first-of-a-kind component.

The fusion fuel cycle technologies – vacuum pumping

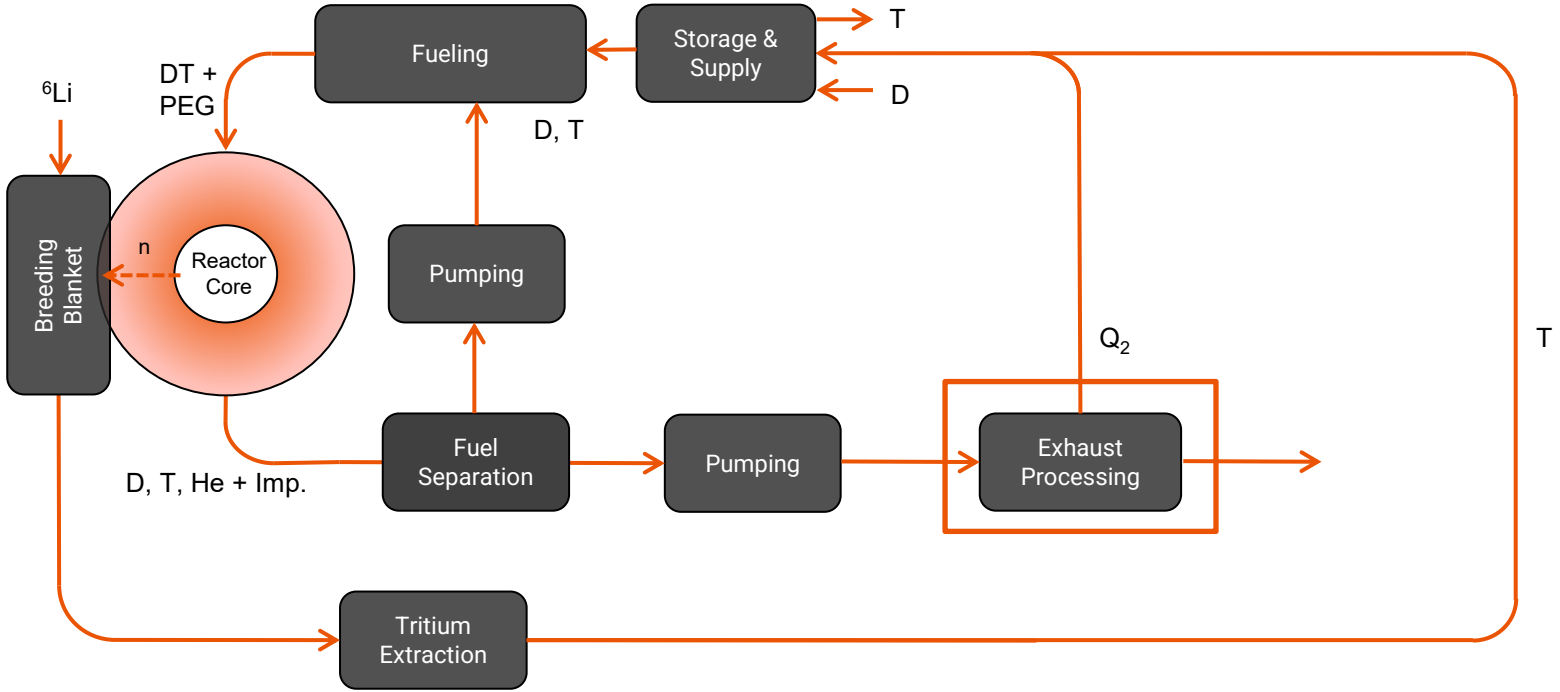
Compression from high vacuum to overatmospheric requires a serial connection of different technologies



- 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 cryopump
- Tritium-compatible all-metal scroll pump
- Tritium-compatible dry roughing pump
- Tritium-compatible overatmospheric bellows pump

The fusion fuel cycle technologies – exhaust processing

The main function of the exhaust processing is the extraction of hydrogenic species

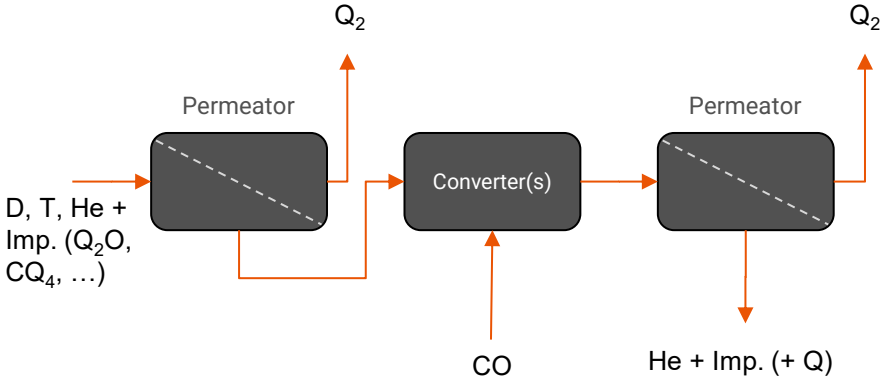


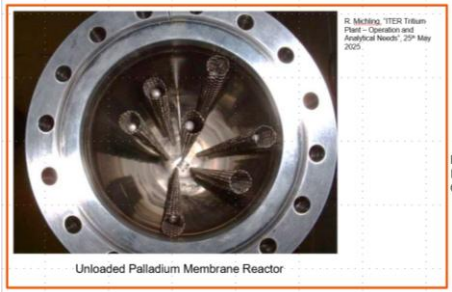
Exhaust processing and clean-up

A closer look into exhaust processing = fuel separation at overatmospheric pressure

- Main functions of the exhaust processing system:
  1. Separation of Q_2 by selective membrane permeation
  2. Chemical conversion of Q-containing species to Q_2
     - Hydrocarbon cracking: $CQ_4 \leftrightarrow C + 2Q_2$
     - Steam Reforming: $CTH_3 + H_2O \leftrightarrow 2H_2 + HT + CO$
     - Water Gas Shift: $Q_2O + CO \leftrightarrow Q_2 + CO_2$
     - Isotope exchange: $XQ_y + H_2 \leftrightarrow XH_y + Q_2$ (e.g. $Q_2O \rightarrow H_2O$, $CQ_4 \rightarrow CH_4$)

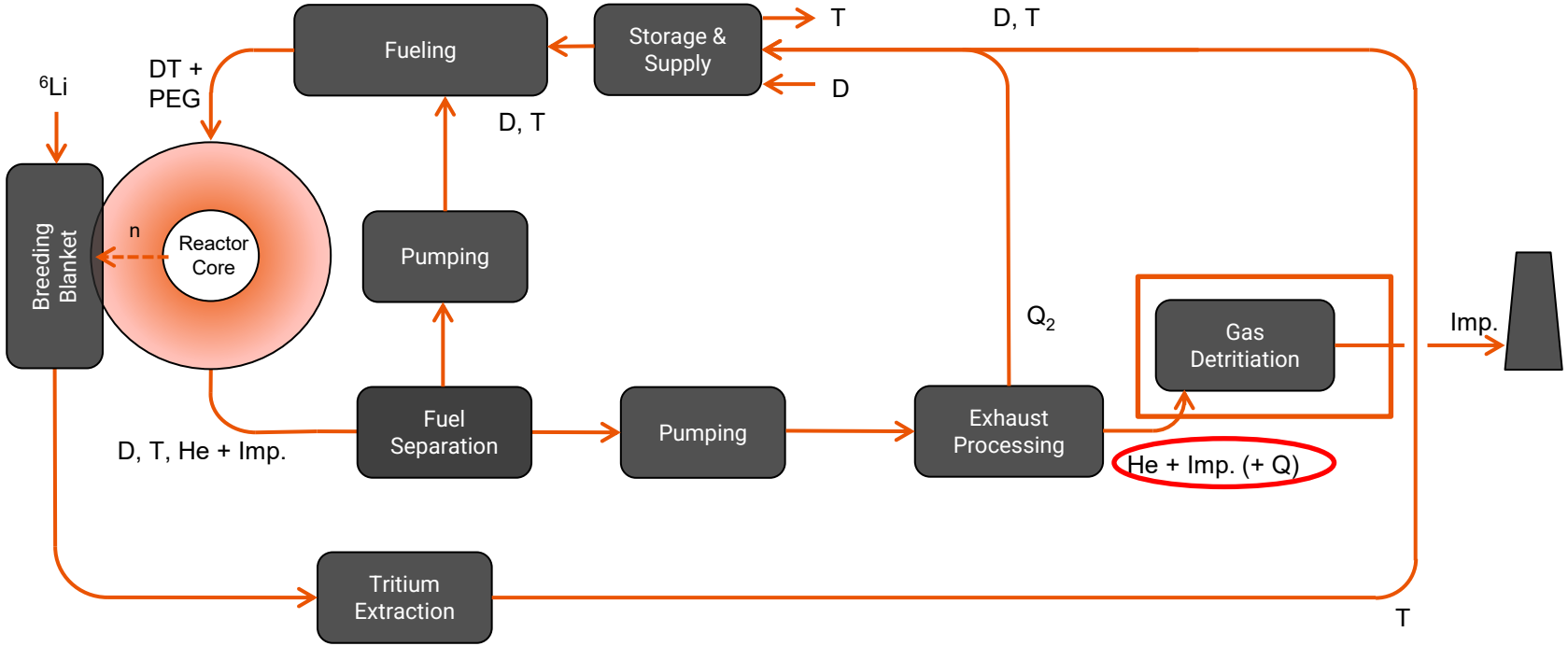
Permeators get industrialized. Supply chain being built.





The fusion fuel cycle technologies – gas detritiation

The detritiation system reduces the tritium content in the gas stream to levels allowed for release



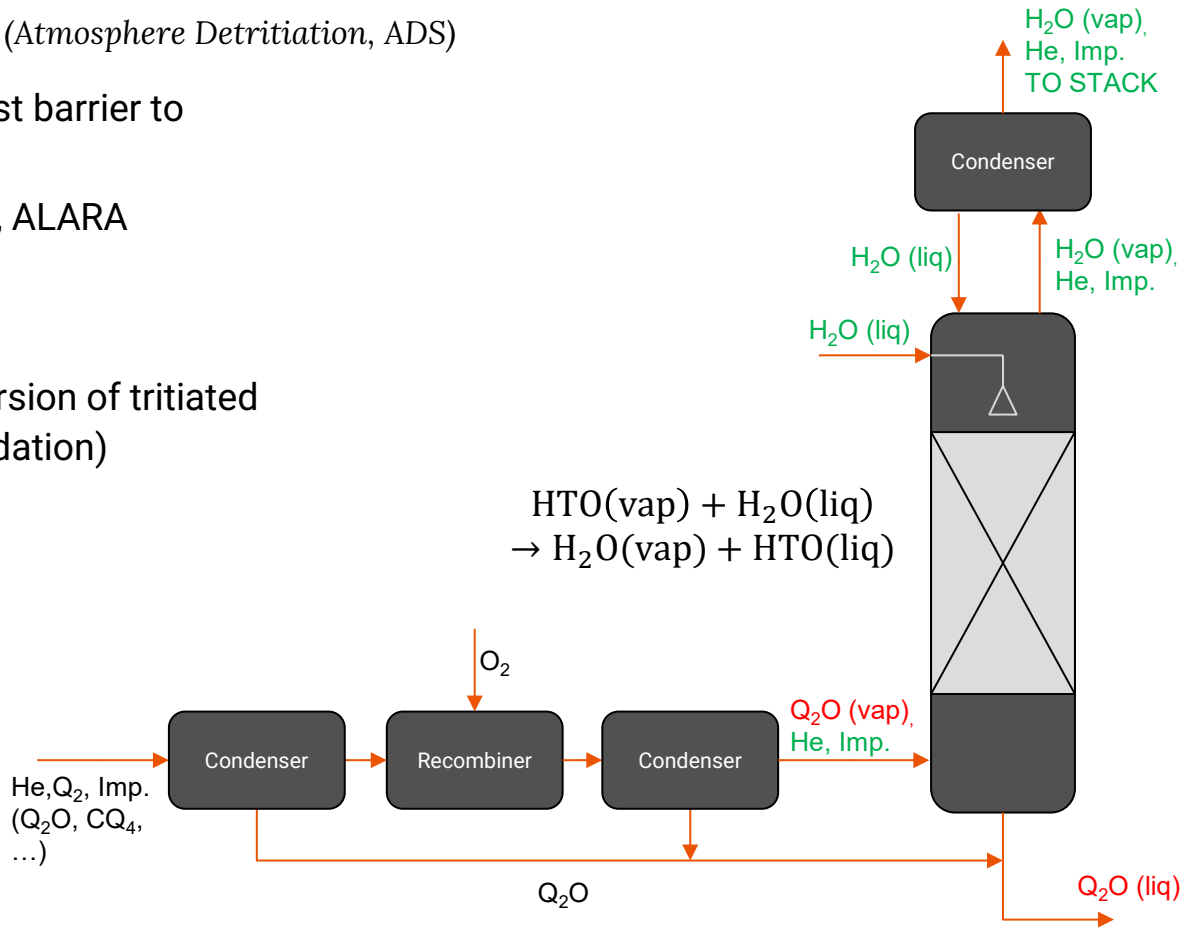
Gas/Atmosphere detritiation

A closer look into the (Gas) Detritiation System (Atmosphere Detritiation, ADS)

- The gas detritiation system is the last barrier to environment
- Remove tritium down to trace levels, ALARA
- Process steps:
  1. Condensation of Q_2O
  2. Gas phase recombiner: Conversion of tritiated species to Q_2O (controlled oxidation)
     - $2Q_2 + O_2 \rightarrow 2Q_2O$
     - $CQ_4 + 2O_2 \rightarrow CO_2 + 2Q_2O$
  3. Wet Scrubbing

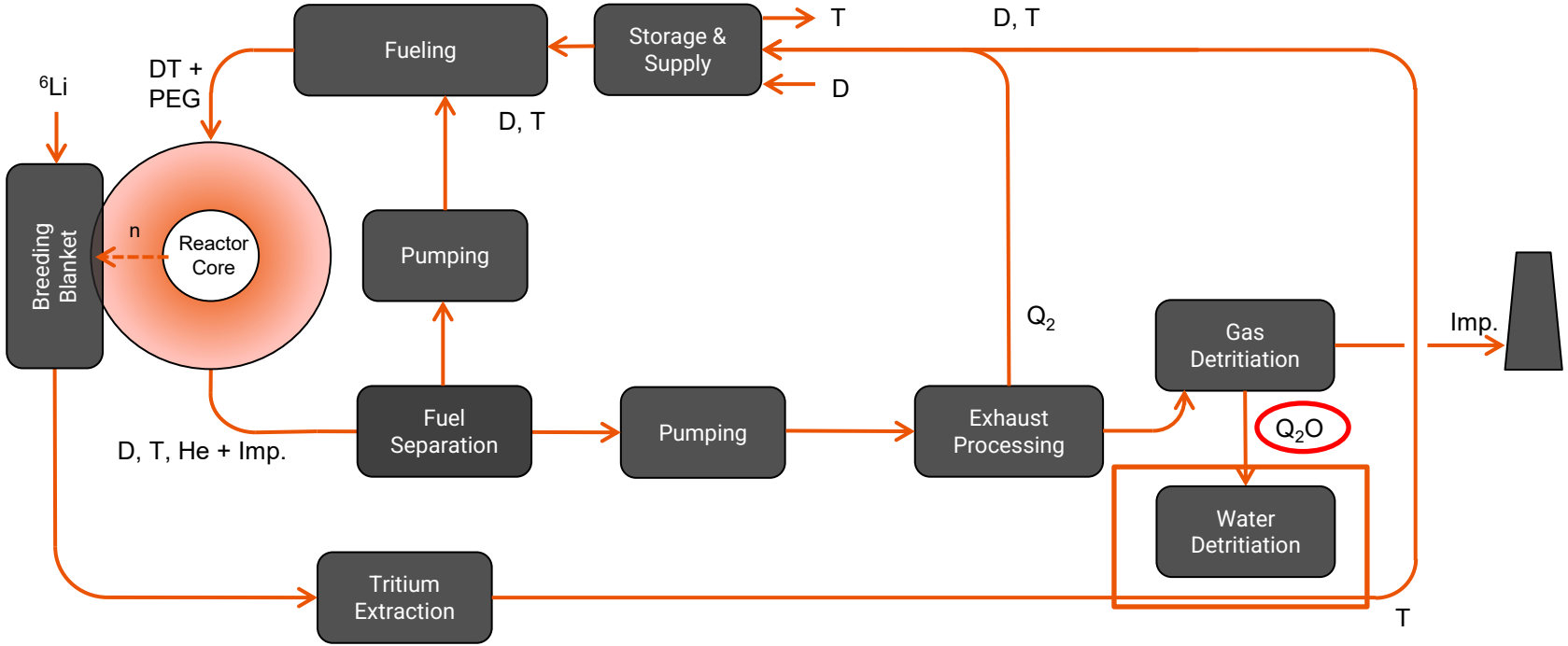
Dynamic confinement.

$$HTO(vap) + H_2O(liq) \rightarrow H_2O(vap) + HTO(liq)$$



The fusion fuel cycle technologies – water detritiation

The water detritiation system extracts hydrogen good to go to stack and returns tritiated Q2

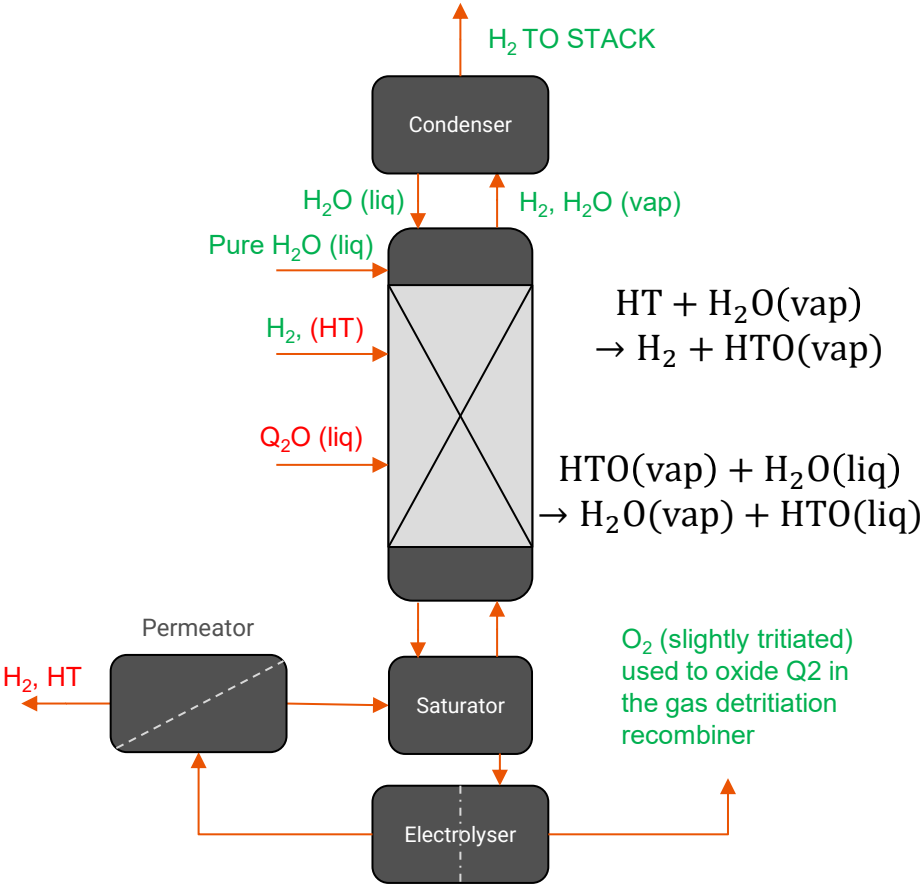


Water detritiation with CECE

A closer look into the Water Detritiation System

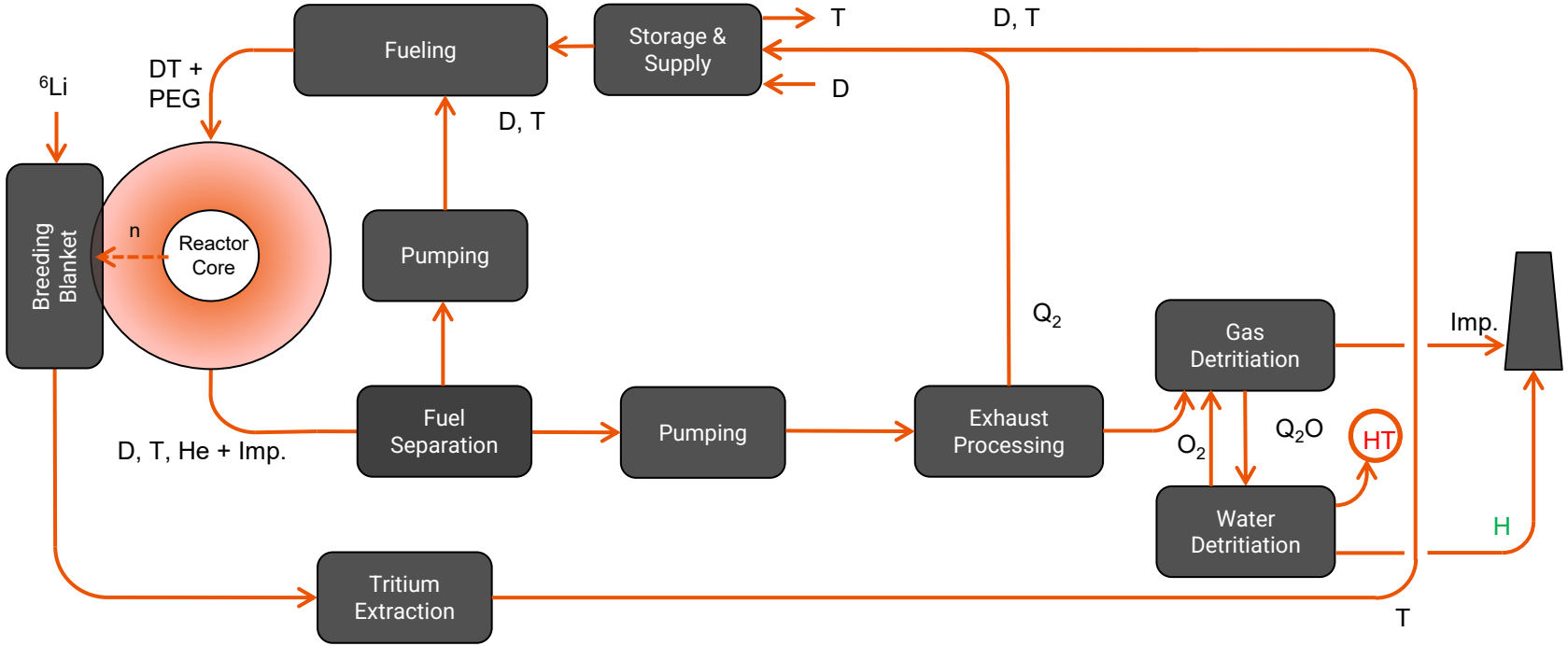
- The Water Detritiation System's (WDS) main function is to remove DT from tritiated water.
- Water detritiation can be done by distillation, and/or by Combined Electrolysis Liquid Phase Catalytic Exchange (CECE) Process.
- CECE steps are shown here.

Activity limits for electrolysers.



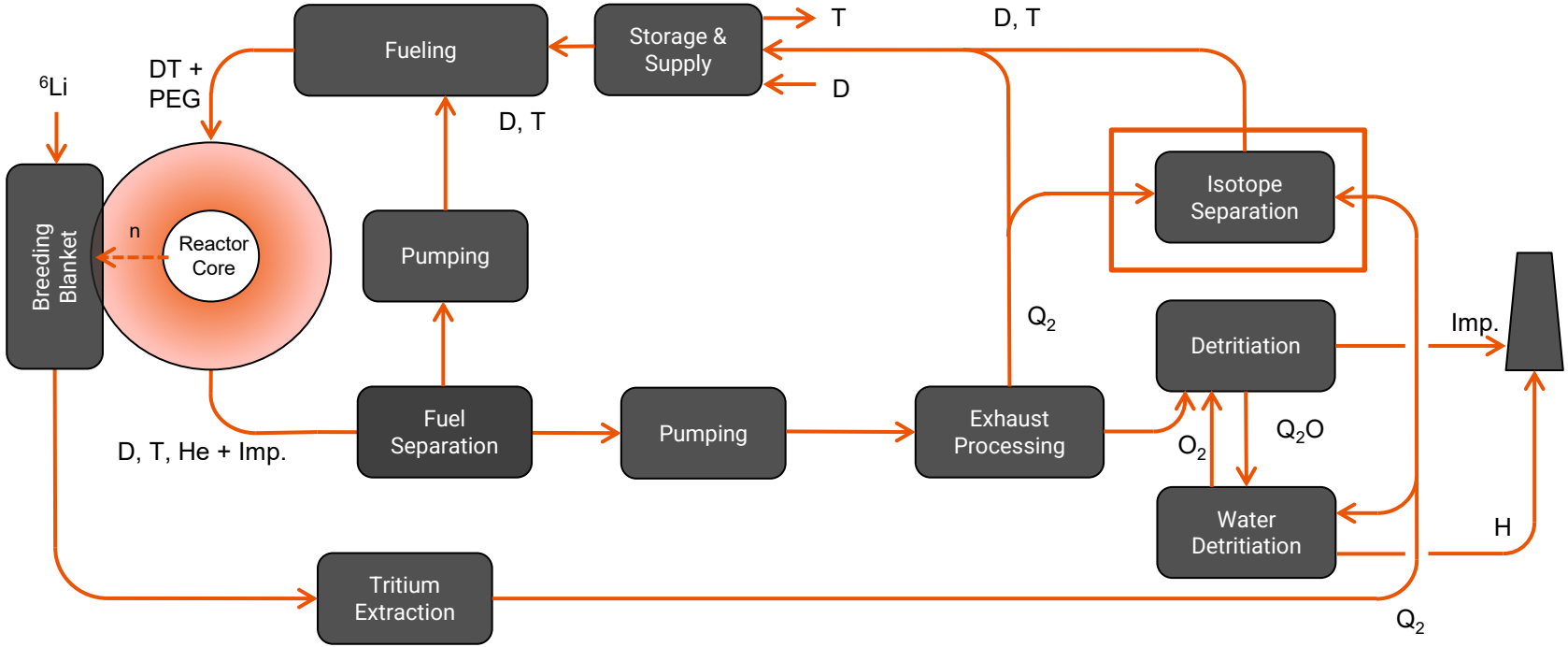
The fusion fuel cycle technologies – water detritiation (2)

The water detritiation system extracts hydrogen good to go to stack and returns tritiated Q2



The fusion fuel cycle technologies – isotope separation

The Isotope Separation System (ISS) has the main function to separate Q2 into H, D, T enriched streams

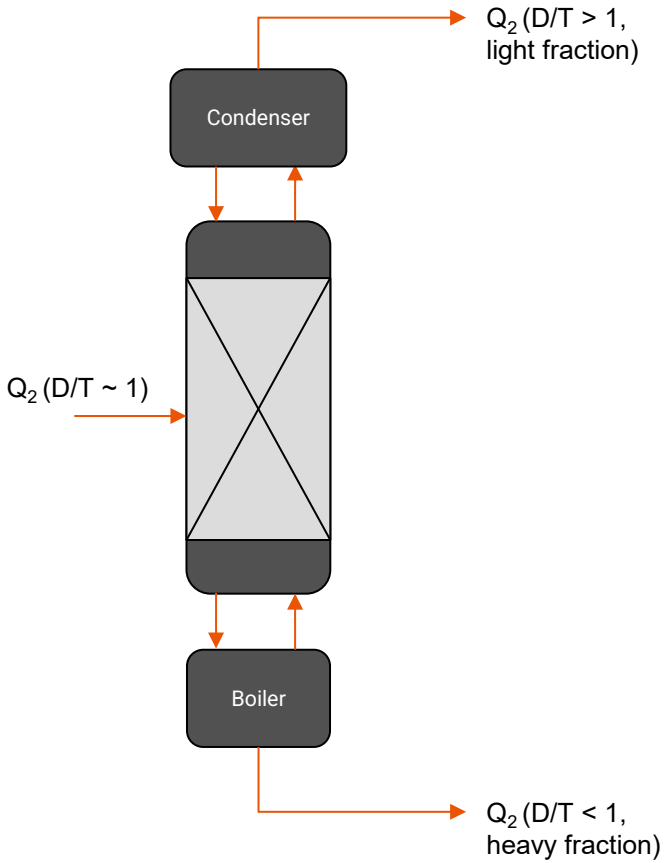


Isotope separation by cryogenic distillation

A closer look into the Isotope Separation System

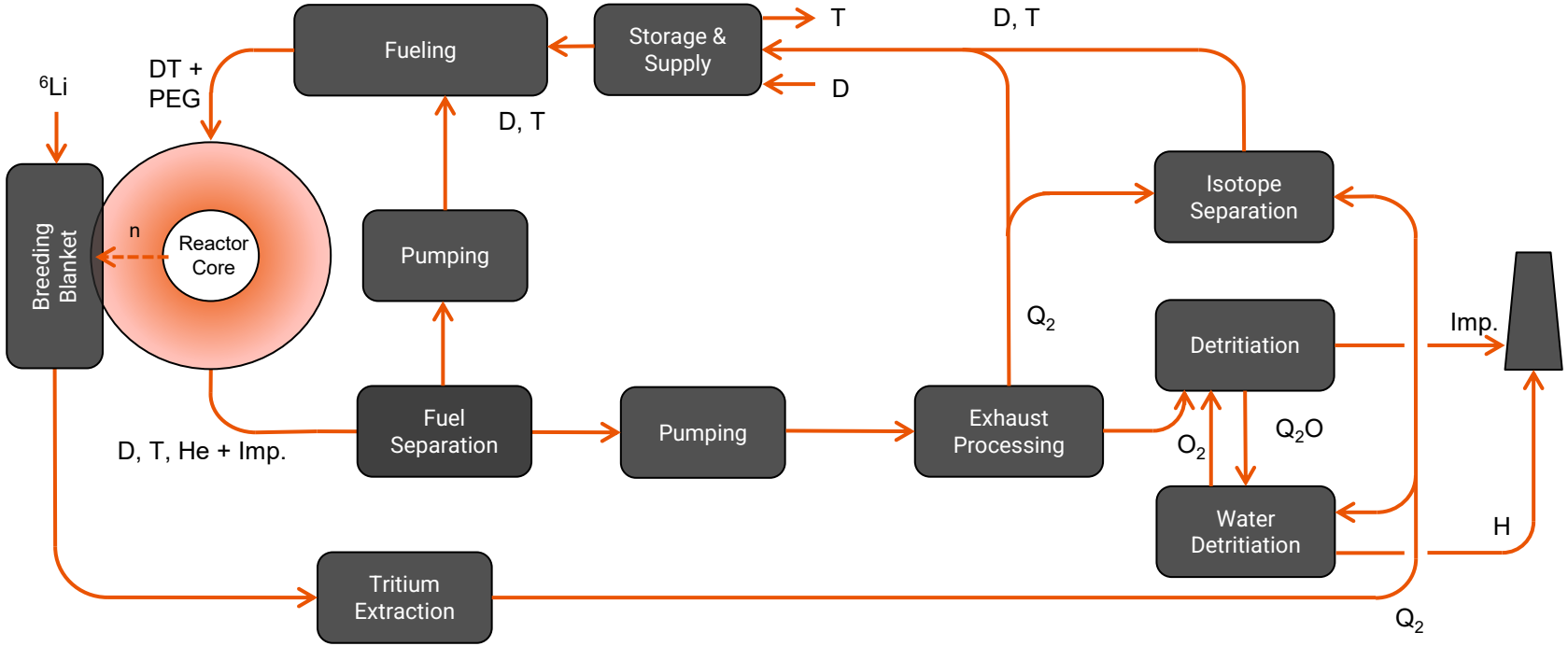
- There are different technologies. Most prominent is
- Temperature Swing Absorption (TCAP)
- Cryogenic distillation, as shown here:
  - One column contains a larger (~100) number of consecutive equilibrium stages
  - Usually, several columns in series depending on
    - Feeds (composition, flow rate)
    - Required purity of product streams (e.g. D/T ratio)

ISS is one of the largest contributors to fuel cycle inventory.



The fusion fuel cycle complete

We built a fuel cycle



Holistic fuel cycle modelling

It is necessary to build validated (calibrated) models and predictive design and scaling capabilities.

- Subsystem understanding: Generate well defined and complete datasets under parametric variation of the decisive parameters – interpolation aspect. To feed physics-based subsystem models that promise to allow for scale-up.
- Subsystems at different scales: Demonstrate experimentally that your code is predicting correctly the subsystem at different scale – extrapolation aspect.
- Process model: Develop a holistic fuel cycle model.
- Integration of the subsystems: Measure integration effects [sum(subsystems) ≠ integrated system] to be used for calibrating the process model.

All this is doable…but needs the data from an integrated test facility

Tritium Fuel Cycle – Operational context

Availability

Ensuring high plant availability while maintaining tritium system safety is a key factor in the economic and operational viability of an FPP. In particular, low availability threatens tritium self-sufficiency.

- Integration with plant systems: The continuous operation of the overall plant is dependent on the efficiency and operating status of the tritium systems. Inefficiencies or failures can reduce plant availability.
- (Remote) Maintenance cycles: Periodic and predictive maintenance, including for detritiation and recovery, must be integrated into plant availability planning.
- Minimizing downtime: Tritium breeding and processing systems must be designed for minimal interruptions, as containment issues can lead to costly repairs, a safety hazard, and extended downtime.

Achievable availability is very very challenging.
Do we need a redundant fuel cycle, or two (hot and cold stand-by)?

Tritium supply

Roll-out of fusion must be accomplished within the existing tritium economy.

- Fusion power plants will breed their own tritium... but:
  - Fusion power plants need to be supplied with their initial tritium inventory to start operation
  - Available civil stockpiles for tritium are limited
  - ~ 5% of available tritium decays per year
  - Tritium sequestration
- Several stepping stones can act as tritium sinks
  - ITER, VNS, FAST, STEP, BEST,…
- Notable tritium production:
  - CANDU fission reactors (CA, KO, RO) ~ 2 kg / year
  - TPBAR programme (US) up to 2 kg / year
-

ToDo	Options
Lower Operational Inventories	**Improved fuel cycle technologies** (Isotope Separation, Vacuum Pumping)
Raise Initial Availability	**Integrated Test Facilities** (DIPAK, CHIMERA, UNITY, H3AT…)
Increase Plant Lifetime	**Advanced Blankets & Materials** (SiC, Liquid First Walls, ODS steels)
Reduce Tritium Sequestration	
Mitigate Impact of Exploding Global Tritium Stockpiles	**Continuous Accountancy Tuneable TBR** (Lithium Isotopic Tailoring)

Initially, there is a risk of having too less tritium, then we run into the risk of having too much.

Tritium safety

Tritium is radioactive. Tritium is dual-use (Export-control).

- Worker safety: Minimizing exposure to tritium for personnel in fusion plants requires monitoring and protective measures. Ensuring all areas where tritium is handled have appropriate containment and ventilation systems filter and recapture tritium before air is vented (ADS).
- Emergency response: A well-developed emergency response plan in the case of a tritium leak is needed to ensure quick containment and to mitigate risk to both personnel and the public.
- Containment: Tritium is highly permeable and diffuses through most materials, in particular at elevated temperatures (blanket area). Permeation barriers and containment structures that prevent tritium escaping into the environment or within the plant are needed.
- Dual-use: Tritium's use in weapons complicates its use in fusion. While not subject to nuclear safeguards, tritium still requires tight security protocols to prevent diversion.
- Export controls: Establishing controls for the movement of tritium across borders will be critical for balancing security and the tritium needs of a global fusion economy.

All this is doable…but needs demonstration in an integrated test facility

Tritium accountancy

Tritium accountancy refers to the accurate measurement, tracking, and reporting of tritium quantities within an FPP. Ensuring precise accountancy is key for regulatory compliance (non-proliferation).

- Accurate measurement: Accurate, as close to real-time measurement of tritium stocks and flows within the plant is key for both performance (overall inventory management) and safety. A range of tritium sensors (ideally overlapping in range) are needed for measurements inline, online and offline.
- Balancing systems: Managing tritium within the closed fuel cycle requires tight control to ensure that breeding, usage, and recycling processes work as a system. Imbalances (losses or build-up in certain systems) are a safety hazard and impact plant performance.
- Reporting: Maintaining accurate monitoring, including via a validated dynamic model of the fuel cycle, requires advanced data management and calibration of the system of sensors, important also for ensuring compliance with safety standards set by a regulator.
- Dynamic fuel cycle operation: The proven concept of static batch PVT-a measurements to demonstrate the inventory cannot be followed. This requires the development of new approaches, in agreement with the regulatory body.

Accountancy can turn out to be a showstopper.
The development of a valid approach needs to be done at an integrated test facility.

Structure of this session: Tries to cover most aspects

- **Matthias Dremel**: Fuel cycle technology roadmapping and Actions to close them
- **Rachel Lawless**: Accountancy, inventory and integrated fuel cycle test facility UKAEA-Eni H3AT
- **Sam Suppiah**: Tritium supply and integrated fuel cycle test facility UNITY-2
- **Shutaro Takeda**: View from privates, integrated facility FAST

Looking forward to the session discussion