# Technology Development Programme

## Technology Mapping
2025 Series

## Fusion Fuel Cycle

FUSION FOR ENERGY

EUROfusion

# Version history

| VERSION | DATE | CHANGES |
|---|---|---|
| 0.0 | 30/01/2025 | First issue: input data for online workshop. Covers:<br>1. Introduction<br>2. The mapping process<br>3. Fuel cycle technology breakdown (draft)<br>Other sections will be completed after the workshop. |
| 1.1 | 05/03/2025 | After the online workshop, incorporating the changes agreed to the technology map |
| 2.0 | 13/06/2025 | After the in-person workshop - Draft final report for comments by participants |
| 2.1 | 04/07/2025 | Final report for publication |

# Contents

# Foreword

We are entering a new era for the fusion sector, marked by a significant acceleration in technology development. Academia, public research organisations and private actors now need to rise to the challenge and coordinate efforts to ensure that the community follows a common technology roadmap that clearly shows how to advance critical technologies for fusion from fundamental research to industrial application.

EUROfusion and F4E, as European fusion technology hubs, can play a significant role at the heart of the fusion ecosystem, identifying research and development opportunities for future fusion power plants, facilitating exchange of knowledge and fostering partnerships across the fusion community.

It is with this ambitious objective in mind that F4E organised with the support of EUROfusion experts the first technology mapping workshop on fuel cycle technologies. As a result of a participative process involving over 150 participants from 64 public and private actors, we are now proud to present this report which will serve as a valuable resource for all interested economic operators seeking national, international, and private funding.

Thanks to the insights gained during the workshop, a blueprint has been developed. It is our intention to apply this model to other relevant technology areas to drive innovation and progress across the fusion sector.

F4E will immediately make funds available to complement the EUROfusion resources already committed to fusion fuel cycle technology development. Our efforts will not be enough. We hereby invite all stakeholders to take action. Let’s accelerate fusion technology development together!

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# Executive summary

Fuel cycle technologies are critical to the success of fusion as an energy source from a technical, safety and economic points of view. The 2025 Fuel Cycle Technology Mapping exercise is a groundbreaking initiative to accelerate their development across Europe. This comprehensive assessment, involving over 150 participants from 64 public and private organisations, provides the first systematic evaluation in Europe of critical technologies required for fusion fuel cycles. It delivers an overview of the current European capabilities in the field and establishes a strategic roadmap for the next phase of fusion fuel cycle technology development in the territory. The output of the exercise is intended to be used by the public and private European fusion fuel cycle community as a reference document to guide current and future investment.

**Technology mapping**
The mapping exercise identified and characterized 48 technologies across 4 primary domains:

- Fuelling and storage,
- Pumping,
- Membrane and packing and
- Tritium management.

Each technology was evaluated for Technology Readiness Level (TRL), applicability to other sectors, criticality, development needs, and European capabilities. This data was presented conveniently in a visual dashboard for each technology for reference and regular update.

**European Competitive Position:**
World-class capabilities were identified in

- cryogenic and process plant technologies,
- mechanical pumping systems,
- and tritium analytical systems.

The European supply chain for fusion fuel cycle technologies also benefits from the ripple effect of strong investments in ITER and other fusion-related projects.

The assessment revealed the following weaknesses that may threaten Europe's competitive position:

- shortage of tritium test facilities (only two operational facilities with meaningful capacity),
- limited diversity in pellet injection system development,
- gaps in membrane technologies and inertial fusion target delivery capabilities,
- supply chain monopolies for critical components, particularly tritium-compatible pumps.

The report points out four key opportunities to strengthen European capability in the delivery of fusion fuel cycle systems:

- accelerating tritium test facility deployment
- leveraging cross-sector synergies (fission, defence, vacuum industries)
- improving coordination across the diverse European ecosystem
- developing a European fusion-specific tritium regulatory frameworks.

**Strategic Roadmap**

The technology development roadmap prioritizes actions across multiple timelines:

*Immediate Actions (2025-2027):*

- Secure enhanced access to existing tritium facilities
- Launch prototype development for pellet injection systems
- Scope prototype and test facility for inertial fusion target delivery
- Initiate membrane and packing technology optimization
- Establish communities to coordinate European action in the fields of process simulation, tritium permeation and tritium accountancy

*Medium-term Objectives (2028-2030):*

- Commission new tritium handling facilities in Romania and France to qualify technologies for tritium compatibility
- Validate advanced tritium processing technologies
- Develop European supply chain alternatives for critical components

*Long-term Vision (2031+):*

- Establish major European tritium test facility (100g+ capacity)
- Complete technology demonstration for key commercial fusion applications
- Achieve supply chain independence for critical fuel cycle components
- Develop a common and graded set of standards and regulations for tritium management

**Investment Implications**

Whilst Europe possesses fundamental technological strengths, strategic investments into fusion fuel cycle technologies totalling hundreds of millions of euros in the next 5 to 10 years will be required to fill gaps and maintain competitive advantage. Europe, by design, has access to a large diversity of funding sources. They include European and national public grants, private funding, and funding from international collaborations. A coordinated approach between those diverse funding sources, fostering a fluid exchange of knowledge and information, will be key to successfully develop fusion fuel cycle technologies in Europe during that timeframe.

# 1 Introduction

## 1.1 Context

In 2024, Fusion for Energy launched a Technology Development Programme (TDP) as part of the implementation actions of its Industrial Policy. This TDP is dedicated to building and reinforcing European Fusion Supply chain capabilities for technologies that are deemed to be critical for the future of commercial fusion. The programme requires the identification of key technologies to direct R&D contracts to European contractors.

Since 2014, EUROfusion has been paving the way for fusion power reactors by funding research based on the "European Roadmap to the Realisation of Fusion Energy" as a joint programme within Euratom Horizon Europe. EUROfusion currently manages a research programme evolved from short-, mid- and long-term roadmaps.

Prioritizing and allocating funding opportunities across both organizations requires a comprehensive review of the involved technologies on each major fusion technical domain. Doing this exercise in a collaborative way will enable stakeholders to identify which technologies are fundamentally needed (technology mapping) and when are they needed (technology road mapping). A roadmap built through consensus of key stakeholders in the field can also serve as a powerful argument when seeking additional funding from national and international public and private investors.

To coordinate these efforts, Fusion for Energy and EUROfusion have launched a technology mapping initiative uniting academia, research laboratories, industry, start-ups and the ITER Organization to develop a comprehensive technology development roadmap for Fuel Cycle domain.

The outcome of this exercise will serve all stakeholders to guide their action in their respective domains, allowing an effective investment of resources. Given the fast evolution of technology, a periodical follow-up of the workshop outcome shall be assured in subsequent technology mapping exercises.

## 1.2 Fuel cycle technology mapping

The scope of the first such mapping exercise is the fusion fuel cycle. Fuel cycle technologies are critical to the viability of fusion as a source of energy. From a technical point of view, pumping and injection technologies ensure the sustainability of the reaction. Tritium processing technologies contribute to the continuous supply of fuel whilst minimizing the total tritium inventory of the facility, which is critical to optimize safety and limit radiological risks. Minimizing inventory is also key to securing the status of fusion as an economically viable source of energy since tritium is an extremely expensive fuel. Inefficient tritium processing or excessive waste generation could also add to future power plants operational costs, limiting their competitiveness in the energy market.

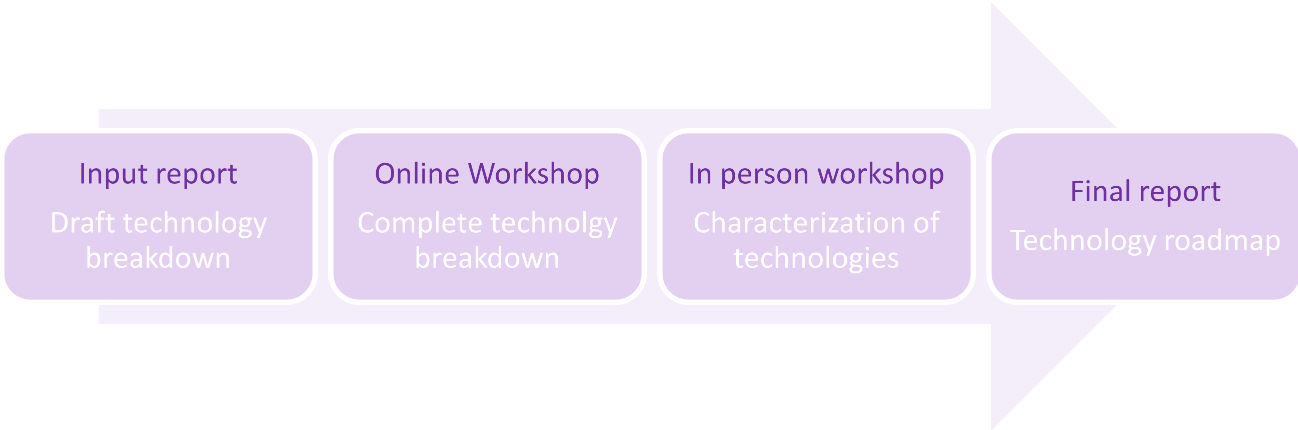
The scope covered for this mapping exercise includes vacuum pumping, fuel purification, storage and injection, isotope separation, water detritiation, air detritiation and tritium management. Tritium breeding technologies such as blanket modules and Lithium enrichment and the related tritium extraction from breeding blanket cooling systems will be the subject of a separate exercise.

The main associated event was a workshop held in February and March 2025 to generate most of the relevant data and provide an opportunity for participants to network and exchange knowledge.

This document provides a complete overview of the exercise, detailing the process and scope through a comprehensive technology breakdown, summarizing the meetings held and providing the resulting proposed technology development roadmap.

# 2 Technology mapping process

The technology mapping process consists of 4 stages.




## 2.1 Input report

In preparation of the exercise, staff from Fusion for Energy and EUROfusion prepared a draft technology breakdown with some input from ITER Organization colleagues, listing technologies of interest and grouping them functionally.
This breakdown, together with a brief description of each selected technology, was included in a draft input report (see section 3) for consultation by participants ahead of the first meeting (an online workshop).

## 2.2 Online workshop

The online workshop was the opportunity for all participants to the technology mapping exercise to come together. It lasted 3 hours with the following agenda:

- Welcome and introductory remarks
- The technology mapping process
- Short introductory presentations about the field of interest (Fuel Cycle in this case)
- Networking opportunity between participants
- Brief overview of technology breakdown
- Joint review of the technology breakdown
- Explanation of the next step (in person workshop)
- Survey feedback and wrap-up

The main output of the online workshop was an exhaustive list of relevant technologies agreed between all participants in the workshop. This breakdown formed the basis of the technology mapping, the main output of the initial workshop exercise. An updated version of the input report with an updated technology breakdown (section 3 of this document) was made available to participants before the in-person workshop.

## 2.3 In person workshop

The in-person workshop aimed at providing a detailed characterization of the technologies part of the breakdown agreed during the online workshop including their prioritization (timeline).
The characterization of technologies took place in four steps applicable to each technology:

- Agreement on current Technology Readiness Level (see Appendix 1 for definitions)
- Definition of the next step (e.g. analysis, prototype, testing, industrialization plan etc) and time permitting of the medium to long term.
- Quantification of the characteristics of the technology (see appendix 2 for the list of characteristics to be evaluated).
- A timeline with a classification of what is needed when, for the technologies considered in the technology mapping. Roadmaps can cover short, medium and long term objectives.

The workshop was highly collaborative, with sessions designed for participants to exchange, build consensus and provide feedback on specific interests and the mapping process itself.
The workshop also provided ample opportunities for participants to share knowledge and form partnerships over a typical duration of one and a half day which includes specific times for formal and informal networking.

## 2.4 Final report

After the in-person workshop, the outcome was compiled the outcome into this final report. The report includes an overview of European capabilities in the field as well as the proposed technology roadmaps detailing and prioritizing possible actions for the period until the next review (typically 2 to 3 years). This report is the result of a collective effort, with many participants providing valuable comments before the final version of the report was published.

# 3 Fuel Cycle technology Breakdown

## 3.1 Fuel Cycle overview

The plasma in a fusion machine needs to be continuously fuelled with deuterium and tritium and is processed in the fuel cycle to be re-used, for technical, safety and economic reasons.

The fuelling of a plasma in a fusion power plant will likely be done with a fixed deuterium and tritium ratio, and the plasma size in a **magnetic confinement fusion plant** requires that the fuel arrives as deep as possible into the core of the plasma. Reaching the core of a highly confined plasma requires the **injection of frozen solid deuterium and tritium pellets at very high speeds** through guiding tubes with complex shape.

In the case of **inertial confinement fusion,** the targets need to be created in a high repetition rate and need to be precisely transferred to the focal point of the lasers.

For control purposes, additional plasma enhancing and heat load controlling gases are injected, and a vacuum system is required to **pump the hydrogen isotopes with the additional gases** as well as the reaction products, which include Helium.

Since only a small fraction of the fuel injected will be burnt (maximum a few percent in the case of magnetic confinement machine), technologies which could **quickly separate hydrogen isotopes from other gases for direct fuel recycling** without further treatment would be of particular interest as it would reduce and optimize the tritium plant size and tritium inventories.

The vacuum system transfers the gas mixture to the tritium plant for **separation of the hydrogen isotopes from the other gases as well as separation and purification of the hydrogen isotopes** for the purpose of rebalancing the injected D-T ratio.

This is a long process which mobilizes a large tritium inventory, thus requiring a large tritium start-up inventory which is costly and extremely limited in supply. **Accelerating fuel treatment is of interest to reduce the overall start-up inventory** necessary to operate a fusion power plant. Similarly, keeping the tritium in the fuel cycle to reduce losses requires measures to **limit tritium permeation in the plant.**

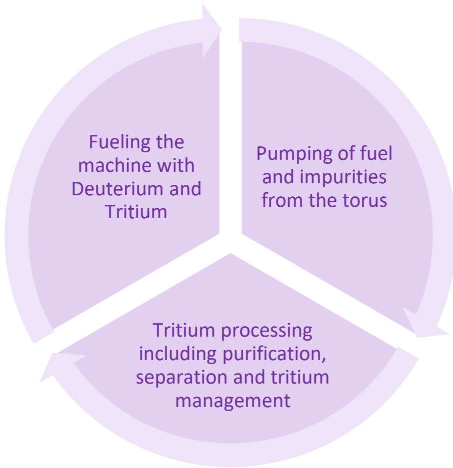
Additional duties of a fusion tritium plant will be to **store fuel**, process tritium from the breeding blankets, **air** and **water detritiation systems** as well as **tritium measurement and accountancy**.

A large variety of technologies is used in the three fields of Fuelling, Pumping and Tritium processing. For most of them, the process know-how and manufacturing experience is currently still within research institutions throughout Europe.

## 3.2 Technical breakdown of technologies

As seen above, the plant systems of a fusion fuel cycle can be split into three main fields:

- Fuelling and Storage,
- Pumping technologies,
- Tritium processing technologies.




The **fuelling technologies** cover pellet/target production and injection and hydrogen storage technologies.

The **pumping technologies** cover mainly the primary and rough pumping systems for torus and vacuum vessel pumping. The primary vacuum pumping system contains specially designed vacuum pumps, able to work under the harsh environmental conditions at their installed location. The rough pumping system contains mechanical or cryogenic pumps for the intermediate pressure range and for viscous pressure range. Additionally, gas transport pumps are working at or above atmospheric pressure used in the tritium plant. Some of those technologies may have the secondary function of separating hydrogen isotopes from other gases for the purpose of direct recycling as explained in the previous section.

The **tritium processing technologies** cover a wide range of technologies because of the different functions required for gas separation, hydrogen isotope purification and general tritium management. The detritiation of gases, liquids or molten salts also need to be addressed by tritium processing technologies.
This wide area of technologies is split into two sub-sections:

- **Membranes and Packing technologies**
- **Tritium management**

## 3.3 Map of individual technologies

The purpose of this section is to provide a brief overview of the technologies used in the fusion fuel cycle and to explain their functions in simple terms, allowing non-expert readers to gain a basic understanding of their applications. Detailed information about each technology including development needs and list of actors is included in the dashboards (see section 5.1).

### Overview

**Fuelling and storage**

- Pellet Source
- Centrifugal acceleration for solid injection
- Gas-gun acceleration mechanism for solid injection
- Diagnostic System for pellet injection
- Inertial Fusion Target Delivery
- Modelling and Software Developments
- Metal Hydride Beds

**Membranes and Packing**

- Column packings
- Packed Beds
- Pd-Ag Membranes
- Cryogenic distillation
- Temperature/Pressure Swing Adsorption (TSA/PSA/TCAP)
- Equilibrators
- Combined Electrolysis and Catalytic Exchange (CECE)
- Liquid Phase Catalytic Exchange (LPCE)
- Electrolyser
- Water distillation
- Vapor Phase Catalytic Exchange (VPCE)
- Wet Scrubbers
- Catalytic Reactors for Hydrogen Oxidation
- Membrane Absorption
- Quantum Sieving

**Pumping**

- Cryogenic Adsorption pumps
- Temperature Staged cryogenic condensation and adsorption pumps
- Continuous Cryogenic Diffusion Pump / Snail Pump
- Cryogenic Viscous Compressor (CVC)
- Cryogenic Temperature Sensor
- Non-Evaporable Getter (NEG) pumps
- Metal foil pump
- Proton conductor pump
- Liquid metal diffusion pump
- Liquid Ring pumps
- Oil diffusion pumps with tritium compatible oils
- Metal bellows pumps
- Scroll pumps
- Roots pumps
- Piston pumps
- Screw pumps
- Turbo Molecular Pumps and Cryogenic TMPs

**Tritium Management**

- Tritium permeation barriers
- Instruments to measure hydrogen isotope concentrations
- Non-destructive Tritium detection in solids
- Wearable tritium detector
- Room tritium detector
- Real time tritium detector for water
- Tritium sealing of dismountable Flanges
- Tritium accountancy
- Process Simulation Model Validation

### 3.3.1 Fuelling and Storage Technologies

Experimental tests with protium and deuterium do not allow to scale to the properties of tritium pellets. The pellet injectors need to be tested with tritium and tritium containing mixtures to investigate effects like decay heat and helium-3 production with the effect on the pellet stability. It is unanimously recommended to carry out experiments with tritium pellets however this is not currently possible. An integrated test facility would need to be licensed for significant amounts of tritium, and this is not available in Europe. The main near-term possibility for such tritium testing is currently at the Canadian Nuclear Laboratories (CNL) and will be operated by Fusion Fuel Cycles Inc.

## Magnetic confinement injection

## Pellet Source

### Extruder

The technology involves creating continuously dense hydrogen rods (deuterium and tritium, with the potential option to mix plasma enhancement gases), typically using cryogenic methods. Hydrogen gas is cooled and frozen to form a solid hydrogen rod, which is then cut into pellets. This technology is the key technology for the plasma core fuelling of ITER and fusion power plants.

### Pellet Cutter

While the extruder is producing a continuous rod of hydrogen ice it needs a cutter to produce the final pellet.

### Pellet puncher

Once the pellets are produced, they need to be dislodged from the pellet source to be accelerated. A pellet puncher is sometimes used to move the pellet from the pellet source into the acceleration system.

## Pellet Accelerators

### Gas-gun acceleration mechanism for solid injection fuelling

To reach the plasma core in larger fusion machines the speed of pellets needs to be very high. The gas gun technology uses pressurized gas that accelerates the pellet into the vacuum/plasma chamber. By this technology the acceleration gas is also entering the plasma chamber and adds as an additional gas load to the fuel cycle.

### Centrifugal acceleration for solid injection fuelling

This technology for tritium containing pellets injection avoids an additional gas load to the plasma chamber. It is using rotational force of a centrifuge to propel the solid pellet into the plasma chamber.

### Diagnostic systems for pellet injection

Fusion power plants will require a well-understood and characterized pellet diagnostics system that can be used to judge the quality of the pellets and their successful injection into the plasma. Such a system must cope with the high speed of the pellets, tritium compatibility, and other requirements.

## Target delivery for Inertial Confinement Fusion

### Target Filling

The process refers to the filling of a tiny spherical fuel capsule with a precise mixture of deuterium and tritium. The capsule can be made of polymer, diamond-like carbon or beryllium. The filling itself is done by deuterium and tritium gas introduced under high pressure or by cryogenic filling. In case of cryogenic filling the DT mixture must form a homogeneous solid with a precise geometry within the capsule.

### Target Storage

The filled target needs to be stored safely and thermally isolated until it is injected into the fusion chamber. Technology concepts that are efficiently maintaining the target properties and keeping them until the injection of the target are required. As for magnetic confinement fusion, diagnostic controls will need to be developed to determine the quality of the filled target.

### Target injection

The target needs to be injected into the fusion chamber. Various injection systems (gas-gun, centrifugal, magnetic, gravitational etc) could be considered.

### Target tracking

The filled targets need to arrive or be positioned in the laser focal area or a hohlraum. Controls and diagnostic tools for the injection of the target into the fusion chamber are required.

### Energy dissipation gas

To protect the first wall in the inertial fusion chamber from the pulsed energy load the chamber could be filled with an energy dissipation gas (e.g. Argon). The fuel cycle for inertial confinement fusion would then require separation of unburned deuterium and tritium and the product gas helium from the energy dissipation gas that would be the dominant gas species.

## Metal hydride beds

Mostly depleted Uranium is used to absorb hydrogen isotopes and store them in the solid materials. The hydrogen release is controlled by heating the materials to several hundred degrees Celsius. There are strong arguments to avoid the use of Uranium for a future fusion power plant and development of non-nuclear material for storage bed should be envisaged. ZrCo alloy is the currently best researched material candidate.

## Modelling and Software Developments

This technology relates specifically to the Fuelling and Storage area for which a huge variety of models must be developed: pellet creation, pellet doping, acceleration and injection, tube optimization up to the plasma/pellet interaction.

# 3.3.2 Pumping Technologies

## Cryogenic vacuum pumps

### Cryogenic Adsorption pumps (primary pumping)

The cryogenic adsorption pumping technology has been fully developed and manufactured for several different tokamaks and fusion research facilities as the main pumping system, including for the Torus-Cryostat and Neutral Beam Cryopumps at ITER. It is a very efficient pumping technology with the disadvantage of being a batch pumping technology which mobilises inventory and requires regular regeneration.

### Continuous Cryogenic Diffusion Pump / Snail Pump (primary pumping)

The concept of this cryogenic pump was developed in the US about 30 years ago. The plasma exhaust gas is condensed on a cold metal surface and a rotating scraper continuously removes the ice layer while the cryopump is in operation. With this concept one gets a cryogenic pumping technology in continuous operation without the regeneration needs of a classical cryogenic accumulation pump.

### Temperature Staged cryogenic condensation and adsorption pumps (primary pumping)

The system uses different pumping technologies to achieve a separation of the plasma exhaust gases. Such a staged cryogenic pumping system could be used for a first separation of the tokamak exhaust at divertor level. The achievable separation efficiency is not reported in detail and the final system requires large sized separation valves between the adsorption and condensation stages (~Ø1m).

### Cryogenic Viscous Compressor (CVC) (rough pumping)

The technology operates as secondary pump to a cryogenic pumping system. It can achieve high compression rates due to a regeneration in a small volume. It has the capability to separate helium from all other exhaust gases, but it does not separate the hydrogen isotopes from other “impurity” gases. A preliminary design has been designed, manufactured and tested by the ITER Organization with ITER-US.

### Cryogenic Temperature Sensor

There is no adequate cryogenic temperature sensor on the European market that covers a temperature range between 4 K and 500 K. It needs to be radiation hard against neutron flux from the tokamak (for example $10^5$Gy for ITER). Its structure and materials need to be compliant with magnetic fields, tritium and vacuum conditions. The compliant sensors that were used for the ITER cryo-adsorption pumps are not any more available on the market.

## Non-Evaporable Getter (NEG) pumps

NEG pumps operate by chemically absorbing gas molecules onto a reactive metal surface. Once activated by heat, the getter material (usually zirconium-based) binds gases like oxygen, nitrogen, and hydrogen, creating a vacuum. NEG pumps work passively, require no moving parts, and are ideal for ultra-high vacuum (UHV) applications. They are applied as supporting/selective pumps in some ITER applications. NEG pumps cannot pump noble gases.

## Hydrogen specific high-vacuum pumps

### Metal foil pump (primary pumping)

This pump technology applies hydrogen specific super-permeation (i.e. pressure independent permeation driven by energetic hydrogen) through thin metal foils. Hence, gas separation is done immediately during pumping. If this technology is used as primary pump, it requires a second pump for the non-hydrogenic gases downstream the metal foil pump.

### Proton conductor pump (primary pumping)

The PCP utilizes the capability of ceramic materials under an electrochemical potential at high temperatures to let selectively pass hydrogen particles. This technology combines the hydrogen isotope separation function with a hydrogen recovery function from hydrogen containing molecules in the exhaust gas, such as water or methane.

## Non-dry pumps

### Liquid Metal Diffusion Pumps

In this pump, the operating fluid is a liquid metal (mercury or lithium for example), tritium compatible and easy to evaporate. To protect the upstream systems from mercury contamination due to vapor back-streaming, a trap system (baffle) needs to be integrated.

### Liquid ring pumps

A liquid ring pump is a rotating positive displacement pump that uses a rotating impeller and a liquid ring to compress gas and create vacuum. The liquid forms a seal, trapping and compressing gas. For tritium compatibility the liquid proposed for the fusion fuel cycle is mercury.

### Oil diffusion pumps with tritium compatible oils

In these pumps, oil is used as operating fluid. The oil could contaminate the process gas and usually is not tritium compatible as oils tend to show a quick chemical degradation in the presence of tritium. There have been investigations launched in the US to identify tritium compatible oils.

## Mechanical displacement pumps (primary-, roughing- or gas transfer pumps)

### Scroll pumps

A vacuum pump that uses two interleaved spiral-shaped scrolls to compress and move gas. One scroll remains stationary while the other orbits, gradually reducing the volume of trapped gas between the two scrolls and forcing it toward the centre, where it is expelled. Scroll pumps are oil-free and can be made all metal sealed, making them tritium compatible. They are used for ITER and are available on the market for different pump efficiencies (single supplier in Europe).

### Screw pumps

A positive displacement pump that uses two or more intermeshing screws to move fluid along the pump's axis. As the screws rotate, fluid is trapped in cavities and transported smoothly without pulsation. Screw pumps are currently not available as tritium compatible technology, but they are an interesting pump type for several applications in the vacuum system of a fusion power plant. They are used by ITER for the non-tritiated cryostat cryopumping system.

### Root pumps

A vacuum pump that uses two counter-rotating shaped rotors to move gas. The rotors trap and compress gas, expelling it at higher pressure. It operates oil-free, providing high pumping speed. An all-stainless-steel pump has been developed and prototyped by ITER and is available on the European market.

### Metal bellow pumps

A metal bellows pump is a hermetically sealed, positive displacement pump that uses flexible metal bellows to transfer the gases. It eliminates dynamic seals, preventing leaks and contamination, making it ideal for high-purity and hazardous applications as needed in the fusion fuel cycle.

### Piston pumps

Piston pumps are applied for applications with high pressure fluid/gas movements. Due to the reciprocating piston tritium compatible solutions are not easily available on the market. For pellet injector applications, a tritium compatible piston pump from a Japanese supplier is used for ITER.

### Turbo Molecular Pump (TMP)

#### Normal turbo molecular pumps

A Turbo Molecular Pump creates a high vacuum by using rapidly spinning rotor blades to impart momentum to gas molecules, directing them toward the exhaust. It operates on molecular flow principles, making it effective for high vacuum applications. With no oil contamination it is an interesting pumping technique for the fuel cycle. Magnetic field and tritium compatibility need to be carefully addressed.

#### Cryogenic turbo molecular pumps

The pump is based on a Turbo-Molecular-Drag Pump (TMDP) operating at cryogenic temperature (25 to 80K): since gas density varies inversely with temperature, the pump delivers proportionally higher mass flow rate at low temperature than at room temperature for a given size. The principle was tested with prototypes and gas temperatures between 25 K and 80 K. It is proposed as a possible solution for continuous primary pumping of the exhaust gases from the plasma.

### Compressors (process gas transfer)

The following pump technologies can also be applied as compressors, i.e. for gas compression to a pressure higher then ambient pressure:

- **Piston pumps**
- **Liquid Ring pumps**
- **Metal bellows pumps**

Currently the used technology for tritium compression are metal bellows pumps. The only known supplier is in the US. ITER is working on the development of higher throughput pumps with this American supplier. No European supplier for tritium compatible metal bellows pumps is known.

## 3.3.3 Membranes and Packing Technologies

### Column packings

Packed columns are mainly used for the processing of tritiated water. Catalytic Exchange columns (LPCE, VPCE, CECE – see the outline below) or water distillation columns are using packing material to increase the reaction surface and to introduce a catalyst in the process. The process efficiency depends on the packing characteristics and the different application ask for different optimization parameters. The performance data of packings is mainly received from the industrial suppliers and does often not reflect the operation conditions within a fusion fuel cycle.

### Packed Beds

Packed beds are used for hydrogen removal from a gas stream with low hydrogen concentration (e.g. primary gas coolant, carrier gas and glove boxes ventilation). Their efficiency is driven by their accumulation and extraction capabilities. They are used in batch operations and the regeneration and control requirements define their final design and the choice of technologies for cooling and heating. Zeolite Molecular Sieve beds, CuO beds, catalytic beds, and getter beds are different options.

### Pd-Ag Membranes

Membranes are used for the removal of impurities in a dominated hydrogen stream. Membranes efficiency is directly linked to the material properties, the geometry and the associated pumping unit while lifetime is associated to the integrity of the entire membrane module (including welding/joints). Their applications include the tokamak exhaust and the tritium recovery from liquid breeders.

Technologies are mainly based on Pd-Ag membranes with different Palladium alloys and different membrane thicknesses.

Other materials, such as the transition metals from group V (vanadium, niobium and tantalum) are also proposed for membranes and supported membranes. Proton-conducting membranes are additional candidates for the technology.

## Cryogenic Distillation

### Isotopes separation

Cryogenic distillation uses the temperature differences in the boiling points of the six hydrogen isotopes to separate them. The boiling points are at very low temperatures (20 K to 25 K) and have only small differences in between each of them, requiring systems of several cryogenic distillation columns to achieve purification levels of part per billion (ppb). This method is demanding but efficiently separates hydrogen isotopes to very high purification level.

### Use of cryogenic distillation to separate D and T from plasma exhaust

In case a fusion power plant does not need a separated fueling of Deuterium and Tritium, and could be fuelled with a D/T mixture, the separation of the D/T stream from the plasma exhaust gas stream could possibly be realized by cryogenic distillation.

## Temperature/Pressure Swing Adsorption (TSA/TCAP)

Other names for this hydrogen isotope separation technology are Membrane Coupled -TSA (MC-TSA) or Thermal Cycling Adsorption Process (TCAP). The technology is used to separate gases based on their adsorption characteristics at different temperatures or pressures. Adsorbents capture gases like hydrogen isotopes at a defined temperature, then release them at a higher temperature. The adsorption/desorption efficiencies depend on the hydrogen isotopes. The process is faster than cryogenic distillation and can be important for the inner fuel cycle (fast cycle) of a future fusion power plant.

## Equilibrators

Equilibrators are used for balancing hydrogen isotope gas streams within the Isotope Separation System of the fusion tritium plan and therefore improve the separation efficiency of the cryogenic distillation columns. The equilibrators typically contain catalysts based on aluminium oxide pebbles coated with palladium.

## Detritiation of water

### Combined Electrolysis and Catalytic Exchange (CECE)

Combined Electrolysis and Catalytic Exchange (CECE) is a combination of the LPCE technology with an electrolyzer. It could be used for Water Detritiation with higher efficiency than the classical water distillation.

### Liquid Phase Catalytic Exchange (LPCE)

Liquid Phase Catalytic Exchange (LPCE) is a process that removes tritiated hydrogen from liquid streams, typically water. The method involves passing the liquid over a palladium catalyst, facilitating the exchange of tritiated hydrogen with non-radioactive hydrogen. Process efficiency, linked to water distribution and catalyst integration into the columns (using hydrophilic and hydrophobic internals) is a key point to reduce system dimensions.

### Electrolyser

The electrolysis cell splits water into hydrogen and oxygen using electricity. The technology helps to manage and decontaminate tritiated water and is commonly used in nuclear and fusion research. The electrolyser is required for the CECE technology.

### Water distillation

Water detritiation by distillation is a technology that separates tritiated water from regular water. It utilizes the slight differences in boiling points between normal water and tritiated water, where repeated distillation reduces the tritium concentration, resulting in lower levels of radioactive contamination. Due to the small separation coefficient, huge distillation columns are required (in the case of ITER, the distillation column has 50 m overall height with a diameter over 1m).

## Detritiation of air/gas

Air detritiation technologies are designed to remove tritiated gases from air. Different methods can be adopted: the wet scrubbing, the catalytic oxidation of molecular hydrogen followed by removal of tritiated water vapor either by adsorption or by isotopic exchange with liquid water, and gettering. Technologies mainly include wet scrubber columns, CuO beds, catalytic beds, zeolite beds and getters.
Technology choice may depend on the amount and composition of the gas to be detritiated. Key applications are the detritiation of ventilation air, glove boxes enclosures, etc.

### Vapor Phase Catalytic Exchange (VPCE)

Vapor Phase Catalytic Exchange (VPCE) is a process used to remove tritiated hydrogen from air or gas streams. It involves passing the gas over a catalyst, typically palladium, where tritiated hydrogen exchanges with non-radioactive hydrogen. Process efficiency is a key point and driven by an optimized packing in the distillation column.

### Wet Scrubber

Wet scrubbers are effective for air detritiation, ensuring environmental safety and compliance with regulatory standards. The wet scrubber removes tritiated vapor in air by bringing it into contact with clean water. The contaminated tritiated vapor is passed through the liquid, where impurities are absorbed or dissolved.

### Catalytic Reactors for Hydrogen Oxidation

Catalytic reactors for hydrogen oxidation are used to safely convert hydrogen gas, including tritium, into water by reacting it with oxygen over a catalyst, typically platinum or palladium. This process is crucial in fusion fuel cycle systems for removing hydrogen isotopes from gas streams. It is combined with the wet scrubber technology to enhance the efficiency.

### Membrane Absorption

Membrane absorption techniques can be used for air detritiation in continuous operation mode. Systems with full material compliance for the use in tritium plants are required.

## Quantum Sieving

Quantum sieving exploits quantum mechanical effects to separate hydrogen isotopes based on their mass and quantum mechanical properties. It typically uses nanoporous materials where delocalization depends on the mass of the isotope, allowing lighter isotopes to pass more easily. Key factors are pore size, material properties, and operating temperature.

# 3.3.4 Tritium management

## Tritium Permeation Barriers

Hydrogen permeates through stainless steel or other materials. This effect is used for the separation of hydrogen isotopes from other gases, but in the case of cooling loops or process loops for tritium breeding, the permeation of tritium is a problem requiring additional complex detritiation systems. Permeation must, in those cases be minimized.

### Coating technologies for permeation barriers

For a future power plants, the use of surface coatings as tritium permeation barriers are of importance. A variety of coating technologies is available in industry and their applicability for coating materials usable as tritium permeations barriers is of high interest. Practical solutions for fusion relevant applications, covering quite different geometries and environmental conditions need to be studied. Diamond-like carbon coating or aluminium-based coatings are the most promising coating solutions currently identified.

### Material characterization Technologies/Industrial Standard for permeation

Reliable and standardized characterization methods for hydrogen isotope permeation are required to produce a reliable database. Impact of material properties (e.g. neutron radiation effects), manufacturing processes, effects of temperature, thermal gradients, material interface effects and mechanical stress need to be addressed. Test conditions need to be standardized to get comparable test results throughout a community working on the topic. Finally, an industrial standard for the determination of permeation data would complete the program.

#### Material database for permeation

A database that sets the permeation properties for the hydrogen isotopes through bulk materials of interest for a fusion power plant is fundamental.

### Instruments to measure hydrogen isotope concentrations

Several technologies can be used to measure the concentration of hydrogen isotopes in a gas mixture. Mass Spectroscopy, Gas Chromatography and Raman Spectroscopy are some of the applied technologies in tritium handling facilities.

### Non-destructive tritium detection in solids

Non-destructive tritium detection in solids involves techniques that identify and quantify tritium embedded in solid materials without altering or damaging the sample. This is essential for assessing tritium retention in structural components, safety analysis, and material recycling in fusion reactors. Methods include beta-induced X-ray spectrometry, ion beam analysis, calorimetry and advanced imaging technologies.

### Wearable tritium detectors

To date, tritium air concentration is monitored in real time by ionization chambers positioned in the working area. The doses to which workers are exposed are evaluated ex-post through urine or breath analysis. A personal real time monitoring approach would allow early detection in case of tritium release incidents.

### Room tritium detectors

The detectors operate with the detection of the beta-particle emitted by the decay of tritium. Real-time tritium detectors for the use in air or volumes with inert gases are needed in several areas of the fusion fuel cycle. Instruments for tritiated systems suffer from the phenomenon of the tritium memory effect. One time the instrument was exposed to tritium it “remembers” this exposure to the tritium radiation, and this degrades the function of the instruments. Development of real time tritium detectors that are compliant with magnetic fields would also be of interest for magnetic confinement fusion applications.

### Real time tritium detectors for water

Tritium detection in liquids for cooling water loops or tritium breeding loops is another application of real-time detectors. A detector for water with sufficient efficiency will need to be developed. Definition of requirements and compliance with Directives need to be made. The technical solutions need to address background mitigation and memory effects.

### Tritium sealing of dismountable flanges

Tritium sealing of dismountable flanges focuses on developing reliable sealing solutions to prevent tritium leakage at flange joints in fusion systems. These seals must maintain integrity under high temperatures, radiation, and pressure while allowing periodic disassembly for maintenance. Advanced materials and sealing technologies, such as metal gaskets and surface coatings, are explored to ensure long-term tritium containment and compliance with safety and environmental regulations.

### Tritium accountancy

The fuel cycle of fusion power plants will have many sub-systems and tritium processing components. Tritium will be partly retained in these components and a sophisticated inventory control throughout the fuel cycle needs to be developed. Accurate tritium accountancy requires reliable and precise measurements for which developments must be defined.

### Process Simulation Model Validation

The validation of process simulation tools requires benchmarking against experimental data. Where needed specific tests need to be launched to complete the validation of simulation codes. Cross-checks in between different simulation tools to ensure they provide consistent results is also important.

The process simulations require a validated database for all hydrogen isotopes or relevant gases in the fuel cycle that covers all state phases - gaseous, liquid and solid - for the required temperature range. This is a fundamental basis for the comparison of analysis by different entities.

# 4 Summary of the workshop

In total, 151 people registered for participation to the 2025 Fuel Cycle Technology Mapping workshop. The online workshop registered a peak of 119 participants whilst 86 people attended the in-person workshop. 64 public and private entities were represented. Fusion for Energy and EUROfusion wish to thank all participants for their inputs during and after the workshop.


*Logos of participating entities (excluding EUROfusion and Fusion for Energy)*

*Geographical repartition of the participants to the in-person workshop*

Details of the meetings can be found on the event web page[1]. The agenda and outputs including presentations, documents and recordings are also available there.

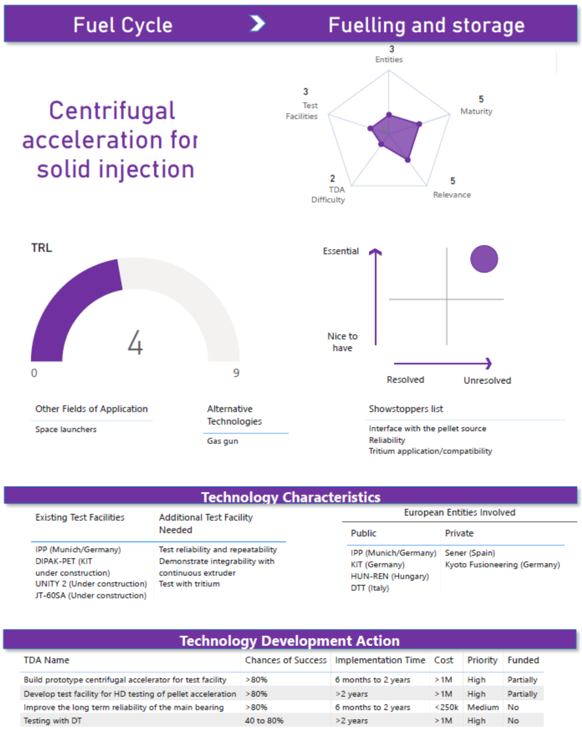
# 5 Outcome: technology road-mapping

## 5.1 Technology dashboards

During the in-person workshop and in the process of preparing this report, a lot of valuable data was collected into a database. For each technology, the following data is now available:

- TRL
- Criticality
- Other fields of application
- Alternative technologies
- Potential showstoppers
- Existing and needed test facilities
- European entities involved
- Technology development actions

This data has been arranged into a dashboard for each of the technologies:




*Typical technology dashboard*

*Note that the spider diagram (scores out of 9) has been arranged in such a way that the more the colored area, the more development is needed.*

[1] https://app.swapcard.com/event/fuel-cycle-technology-development-roadmap

All technology dashboards are available in Appendix 3: Technology dashboards. The dashboards are a view of the database at the time of publishing this document. The database will be updated regularly, and Appendix 3 may be re-published as necessary. We encourage the community to communicate updates to their Fusion for Energy or EUROfusion contact. In the future, we may publish this data for interactive consultation on the EUROfusion and Fusion for Energy websites.

## 5.2 Overview of the fusion fuel cycle landscape in the EU

### 5.2.1 SWOT analysis

| **Strengths**: | **Weaknesses** |
|---|---|
| • Cryogenic pumping<br>• Mechanical pumping<br>• Packings and process plants based on column exchange<br>• Tritium analytical technologies<br>• Ripple effect of ongoing projects | • Tritium test facilities<br>• Pellet injection systems<br>• Membranes<br>• Inertial fusion target delivery<br>• Monopolies |
| **Opportunities**<br>• Accelerate the deployment of tritium test facilities<br>• Better leveraging EU strengths in other sectors<br>• Improved coordination and exchange of knowledge to exploit diversity of actors and funding sources<br>• Develop common, flexible, graded and goal-oriented tritium handling regulation | **Threats**<br>• Tritium handling regulations<br>• Centralised and well-funded strategies in other regions |

**Strengths**:
The EU ecosystem covering academia, research institutions and private actors is particularly strong and able to compete at world level in the fields of **cryogenic and mechanical pumping** as well as **packings, columns, tritium process plants and tritium analytical systems**.

- Research is particularly active in those fields and is exploring opportunities such as metal foil pumps, quantum sieving, LPCE, CECE etc.
- The EU is home to many suppliers of mechanical vacuum pumps, some of whom have developed world leading solutions for fusion fuel cycles such as roots pumps (Pfeiffer) and scroll pumps (EUMECA).
- The EU has supplied cryogenic pumping systems for ITER, along with related test facilities such as those at IPP-Munich and the MITICA neutral beam test site. This strong foundation in vacuum technology is now being advanced through the development of DEMO vacuum pumping systems at KIT.
- Actors in Canada, the US and Korea have traditionally been supplying the world's demand in tritium processing plants for civil applications. With the promise of a significant part of the ITER tritium processing plant being supplied in the EU, multiple companies previously involved in cryogenics or petrochemical processing plants are now demonstrating interest and building up skills in that area.
- With the expertise at KIT, SMOLSYS and IS Instruments Ltd, Europe is a world class player in tritium analytical technologies.

The EU can count on a **strong ripple effect from public and private funding of fusion fuel cycle projects:**

- ITER remains the engine generating significant pull for fuel cycle research and development in Europe. A significant part of the 1bEur necessary to develop the ITER tritium plant facility is being spent with European parties involved on ISS, WDS, tritium detection and pellet injection systems.
- The EU is a major contributor to JT-60SA. In the frame of a collaboration with QST (Naka), multiple pellet injection systems will be procured by Fusion for Energy in the EU.
- The Divertor Test Tokamak project located in Italy will also require fuel cycle components (notably pellet injection systems) so will the Volumetric Neutron Source and DEMO machines being considered by EUROfusion.
- Multiple fuel cycle specific projects have been funded in Germany such as the DIPAK test facility and the Inertial Fusion Energy Targetry HUB.
- In Romania, the Cernavodă-1 CANDU power plant is being refurbished with the inclusion of a tritium removal process plant costing over 200MEUR and including technologies relevant for fusion fuel cycles.
- EU laboratories and companies can also derive significant benefit from Fusion Fuel Cycle specific test facilities being planned or built outside the EU:
    - ENI-UKAEA H3AT facility (UK), with EU parties being involved through ENI and the third-party contribution of UKAEA in EUROfusion.
    - UNITY-2 (Canada) which will be developed and operated in part by the EU branch of Kyoto Fusioneering through a joint venture with Canadian Nuclear Laboratories.
- Several start-ups headquartered or with a branch in the EU are involved in projects with some focus on fusion fuel cycle activities. They include Focused Energy, Gauss Fusion, GenF and Kyoto Fusioneering.

## Weaknesses

The main weakness affecting the acceleration of fusion fuel cycle technology development in the EU is **the lack of existing tritium test facilities**. Only two such facilities are currently operating with an active licence for civil experimentation with tritium:

- Tritium Laboratory Karlsruhe (up to 40g)
- Curium test facility (up to 2g)

Fusion is not the only sector where tritium experimentation is necessary and this lack of availability forces EU actors to seek testing services outside the EU (mainly in the UK, US and Canada).

**The EU ecosystem for pellet injection is not very diverse**. Most technology development activities are running from HUN-REN Centre for Energy Research (Budapest) and CEA (Grenoble) with IPP (Garching), CIEMAT (Madrid) and CEA (Cadarache) also involved to a lesser extent. In terms of supply chain, the only active actors are SENER (Spain) who supplied recently a centrifugal accelerator for JT-60SA and Kyoto Fusioneering, developing a centrifugal accelerator then a complete pellet injection system under the German Fusion 2040 programme. For pellet sources, the only commercial supplier in the world is currently based in Russia (PELIN, St Petersburg).

Some of the tritium process technologies have not benefited from the ripple effect from ITER since they are procured from parties outside Europe. **There are limited fusion R&D development activities ongoing in the field of membranes** and metal hydride beds for fuel storage. Whilst the TRL of metal hydride beds is quite high and thanks to other applications (hydrogen economy, fission) this technology will most probably continue to be developed, membrane technologies for specific fusion applications would benefit from additional funding in the near term. This effect is less felt for the pumping technical area since the US DA, responsible for part of the system, is procuring key equipment (primarily mechanical pumps) from European suppliers.

Similarly, **technology development activities for inertial fusion injection in the EU has been quasi-inexistent** in the last 20 years. Leadership in that field has been handed over to the US and Japan and an effort is required to catch up. This has now restarted thanks to local efforts in Germany, the Czech Republic and France and funding needs to be rapidly increased in that area.

Finally, since the Fusion market is very immature, **there are monopolies in the supply chain** for critical components (even with high TRL) which may threaten its long-term sustainability. For fuel cycle technologies, this is particularly true for:

- tritium compatible roots, scroll and metal bellows pumps (supplier based in the US for the later)
- centrifugal accelerator for pellet injection.

## Threats

The EU ability to quickly develop fusion fuel cycle technologies requires suitable tritium handling regulations. Like in other territories such as Japan, EU local **tritium handling regulations are mostly inherited from the fission sector**. Other players like the UK and US have already implemented fusion specific regulations, less stringent than those applying to fission. This enables them to significantly accelerate the licensing process which provides them a significant competitive advantage to develop tritium-related activities, crucial to fusion fuel cycle development. China has also issued an ISO standard on fusion technologies that Europe should carefully review and amend to prevent potential disadvantages in the future European market. Finally, the recently published ISO16646 “Fusion installations – criteria for the design and operation of confinement and ventilation systems of tritium fusion facilities and fusion fuel handling facilities” lacks a graded approach and promotes restrictive safety provisions, currently under revision in the ITER project. Its direct implementation without considering the actual radiological risks at stake could impact the development of tritium facilities for fusion.

Compared to the EU, other territories also tend to have **more centralised and coordinated funding mechanisms**. Whilst a more decentralized approached brings some advantages, it could become a threat to the EU dominant position in some of the fuel cycle technologies should those players decide to direct a large part of their centralized effort to fuel cycle activities.

## Opportunities

The first opportunity is to **accelerate the deployment of tritium test facilities**. Three specific actions could be taken:

1. Secure access to existing test facilities

Within the EU, only two test facilities able to handle significant amounts of tritium (>1g) are currently available for testing of fusion fuel cycle components.
The main one is the Tritium Laboratory Karlsruhe operated by KIT. Its focus in recent years has been somewhat driven away from fusion and towards astrophysics. This is being rebalanced. For example, a cryogenic Isotope Separation System prototype developed by ITER will soon be tested there. This trend needs to continue to ensure that this critical asset for fusion development in Europe is developed and improved. Similarly, using the Curium test facility should be investigated by interested parties.
EU laboratories and companies could also gain privileged access to facilities which are existing or under construction outside the EU. This could be achieved through the signature of collaboration agreements with operators (UKAEA for the AGHS facility, UKAEA and ENI for H3AT and Fusion Fuel Cycle Inc for UNITY-2 in Canada).

2. Ensure adequate resourcing of planned projects

There are currently three projects for new tritium handling facilities for fusion applications in Europe. One is proposed by CEA on its Cadarache site, the other two are located in Romania. In Cernavodă, a new Tritium Removal Facility is under construction and it will be operated by Nuclearelectrica SA. In Valcea, a tritium laboratory with a maximum inventory of 0.5g is also being built. These three projects should be supported with adequate resources.

3. Evaluate the possibility to exploit sites with existing tritium handling licences

It is important to identify and exploit opportunities to convert or extend sites with existing tritium handling licences which may currently be dormant or under used by other sectors.

4. Plan a large scale pan-European facility

Next to the support and exploitation of existing facilities it is highly recommended that the EU considers the establishment of a major tritium test facility in Europe that can operate an inventory not less than 100g of tritium.

Another opportunity is to **better leverage EU strengths in other sectors** to the advantage of fusion activities. Such opportunities exist in:

- fission, mainly for test facilities (see above), tritium permeation and detection applications
- vacuum: this strong supply base (see strengths) could be mobilised quickly in case the demand increased for specific components which cannot yet be sourced in the EU (e.g. Turbo Molecular Pumps, Metal Bellows Pumps) or to limit the monopolies in for roots and scroll pumps.
- defence: Europe has developed significant expertise in inertial fusion with the construction of Laser Megajoule, and this could be exploited for energy production applications. One such example is the creation by Thales of GenF, more initiatives could follow.

EU fusion activities could also benefit from **improved coordination and exchange of knowledge** to exploit the rich diversity of actors and funding sources on its territory. This is necessary to ensure that competitive initiatives are launched only when necessary (typically for more strategic technologies or when chances of success are slim) to maximise the impact of public funding in Europe. EUROfusion and Fusion for Energy should take a leading role in this matter. The workshop and publication of this report is a first step. For the Fuel Cycle area, it is suggested to launch several communities in the areas of process simulation, tritium permeation and tritium accountancy to accelerate technology development through networking and exchange of knowledge.

Finally, to accelerate the development of tritium test facilities and tritium compatible systems, **the EU could develop a common, flexible, graded and goal-oriented regulatory framework for tritium handling and management,** addressing the stakes in fusion facilities associated to tritium in a more adequate manner than the current regulations, mainly targeted at fission power plants. Establishing industrial standards for fusion technologies within Europe would support the development of necessary manufacturing methods and help prevent reliance on international standards set outside Europe.

### 5.2.2 Main test facilities

As seen above, access to test facilities is critical to develop Fuel Cycle technologies. The tables below list the main relevant facilities (including operating fusion reactors) established in the EU, in EUROfusion third parties outside the EU (UK and Switzerland) or in partnership with EU entities.

#### Facilities established in the EU

| Name | Operator | Status | Tritium licence | Relevant Fuel Cycle applications |
|---|---|---|---|---|
| Asdex Upgrade (AUG) | IPP (Munich) | Operating machine | N | Pellet injection |
| DIPAK and DIPAK-PET | KIT (Karlsruhe) | Under construction (start-up 2030) | N | Pellet injection<br>Pumping |
| W7X | IPP (Greifswald) | Operating machine | N | Pellet injection |
| WEST | CEA (Cadarache) | Operating machine | N | Pellet injection |
| Divertor Test Tokamak | ENEA (Frascati) | Under construction (Start-up 2032) | N | Pumping<br>Pellet Injection |
| Cryogenic Pellet Laboratory | HUN-REN CER (Budapest) | Operational | N | Pellet injection |
| Cryogenic Pellet Laboratory | CEA (Grenoble) | Operational | N | Pellet injection |
| Tritium Laboratory Karlsruhe | KIT (Karlsruhe) | Operational | Y (40g) | Tritium processing<br>Storage<br>Tritium detection |
| Pilot plant for Tritium and Deuterium Separation | ICSI (Valcea) | Operation | N | Tritium processing<br>Storage |
| Tritium Laboratory Facility | ICSI (Valcea) | Under construction (start-up TBC) | Y (0.5 g) | Tritium processing<br>Storage<br>Tritium detection |
| Tritium Removal Facility | Nuclearelectrica SA (Cernavodă) | Under construction (start-up 2028) | Y (TBC) | Tritium processing<br>Storage |
| Tritium test facility | Curium (Lyon) | Operating | Y (2g) | |
| Cryopump test facility | ITER (Cadarache) | Operating | N | Cryopumping |
| Spider | RFX (Padova) | Upgrade with Getter Pumps ongoing | N | Commercial cryopumps and Non-Evaporable Getter pumps |
| Multifunctional test facility | ENEA (Frascati) | Planned (Start-up 2028) | N | Tritium processing |
| Tritium processing test facility | CEA (Cadarache) | Planned (start-up 2031) | Y (TBC) | Storage<br>Tritium processing |

## Facilities established in EUROfusion third-parties outside the EU or in partnership with EU entities

| Name | Operator | Status | Tritium licence | Relevant applications |
|---|---|---|---|---|
| UNITY-2 | Kyoto Fusioneering (Canada- as part of Fusion Fuel Cycles Inc) | Under construction (start-up 2027) | Y (100 g) | Pellet injection<br>Pumping<br>Tritium processing<br>Storage |
| JT-60SA | Fusion for Energy (Japan – with QST) | Under upgrade (start-up 2027) | N | Pellet injection<br>Cryopumps |
| AGHS | UKAEA (Culham) | Operational | Y (100 g) | Pumping<br>Tritium processing<br>Storage<br>Permeation<br>Accountancy |
| H3AT | UKAEA-ENI (Culham) | Under construction (start-up 2028) | Y (100 g) | Storage<br>Pumping<br>Tritium processing |

### 5.2.3 Gaps in the ecosystem

This section describes the areas where new actors (R&D or Suppliers) would need to be mobilized to successfully develop the associated technology. This covers all actors based in the EU, UK and Switzerland.

| Research and development | | |
|---|---|---|
| Handful of actors | One actor | No identified actor |
| • Diagnostic systems for pellet injection<br>• Inertial fusion target delivery<br>• Equilibrators<br>• Cryogenic Adsorption Pumps<br>• Turbo Molecular Pumps<br>• Cryogenic Viscous Compressor<br>• Metal foil pumps<br>• Instruments to measure hydrogen isotopes concentration<br>• Tritium permeation barriers<br>• Electrolyzer<br>• Metal Hydride Beds | • Packed beds<br>• Liquid Ring Pumps<br>• Liquid Metal Diffusion Pumps<br>• Roots pumps<br>• Cryogenic temperature sensor | • Wet scrubbers<br>• Proton conductor pumps<br>• Snail pump<br>• Diffusion pumps with Tritium compatible oils<br>• Piston pumps*<br>• Metal bellows pumps*<br>• Screw pumps*<br>• Scroll pumps*<br>• Temperature staged cryogenic condensation and adsorption pumps |

*For mechanical displacement pumps, industrial suppliers with expertise in core pump functions are needed to develop compatible systems for application in the fusion fuel cycle. These development and qualification efforts must address tritium compatibility, magnetic field tolerance, and seismic and fire load testing to ensure compliance with confinement requirements.

| Supply chain | | |
|---|---|---|
| Handful of actors | Monopoly | No active supplier |
| • Centrifugal acceleration for solid Injection<br>• Quantum sieving<br>• TSA/TCAP<br>• Instruments to measure hydrogen isotopes concentration<br>• Tritium sealing of dismountable flanges | • Equilibrators<br>• Membranes<br>• VPCE<br>• Liquid Metal Diffusion Pumps<br>• NEG pumps<br>• Roots pumps<br>• Scroll pumps<br>• Real time tritium detection in water<br>• Cryogenic temperature sensor<br>• Metal foil pumps<br>• Wet scrubbers | • Diagnostic systems for pellet injection<br>• Gas gun acceleration for solid injection<br>• Inertial fusion target delivery<br>• Pellet source<br>• CECE<br>• Snail pump<br>• Cryogenic Viscous Compressor<br>• Metal Bellows Pumps<br>• Diffusion pumps with Tritium compatible oils<br>• Piston pumps<br>• Proton conductor pumps<br>• Screw pumps<br>• Non-destructive Tritium detection in solids<br>• Tritium accountancy software<br>• Real time tritium detection in water |

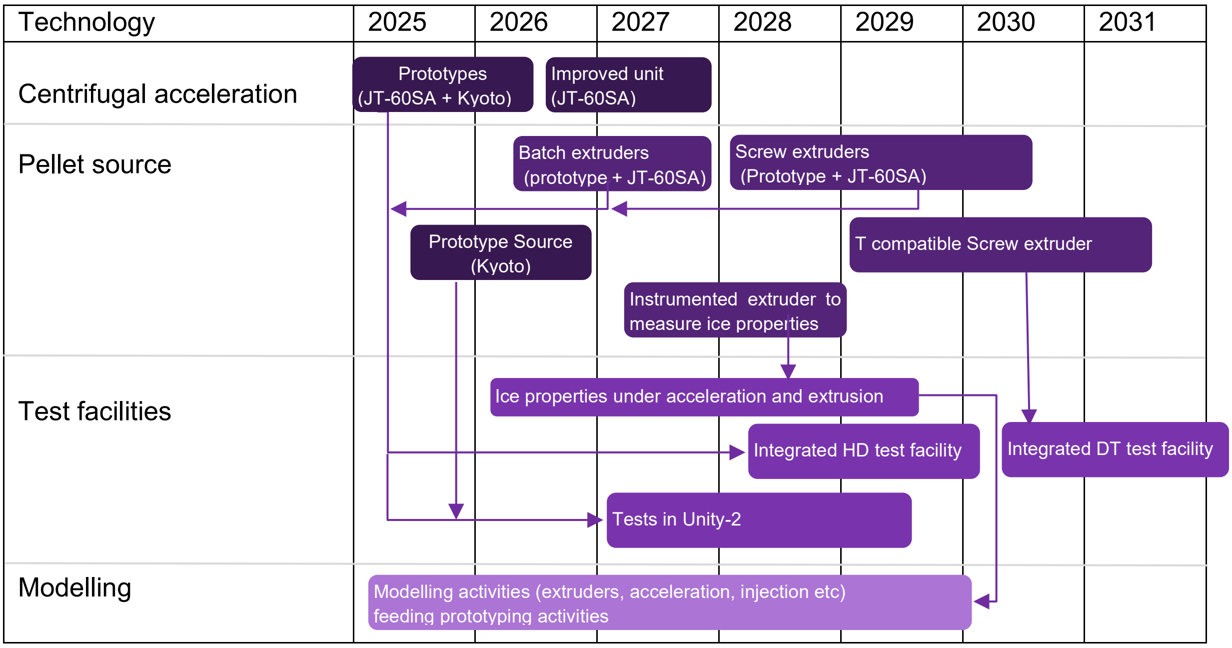
# 5.3 Roadmaps

This section presents some of the Technology Development Actions (TDAs) in the form of roadmaps for relevant technologies. The timings are indicative and may evolve significantly depending on funding available from various sources and associated priorities.

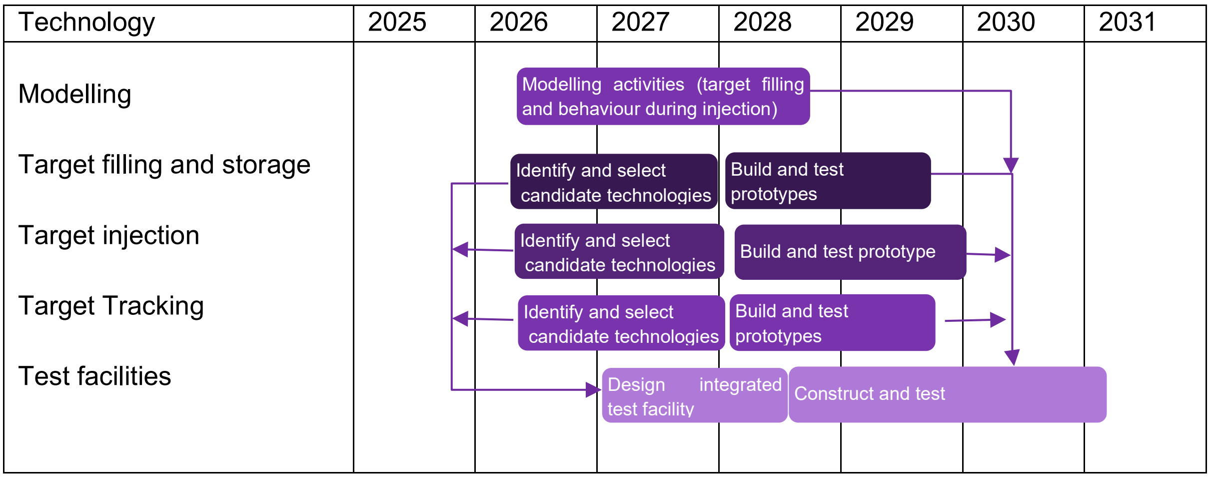
TDAs which are not fundamentally linked to other activities and can be executed independently are not included on roadmaps. This is true, for example, for the pumping area.

## 5.3.1 Fuelling

### Pellet injection for magnetic confinement fusion

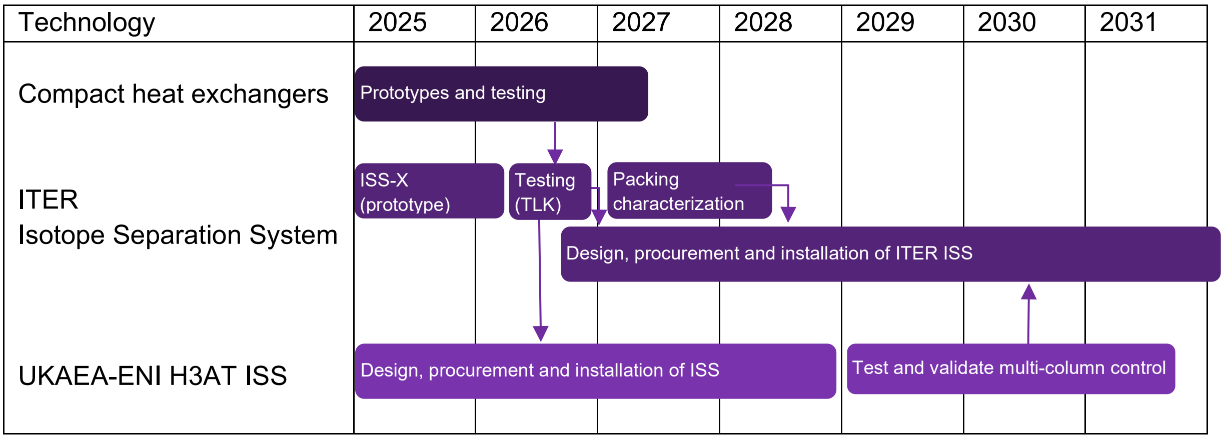



### Inertial Fusion Target Delivery

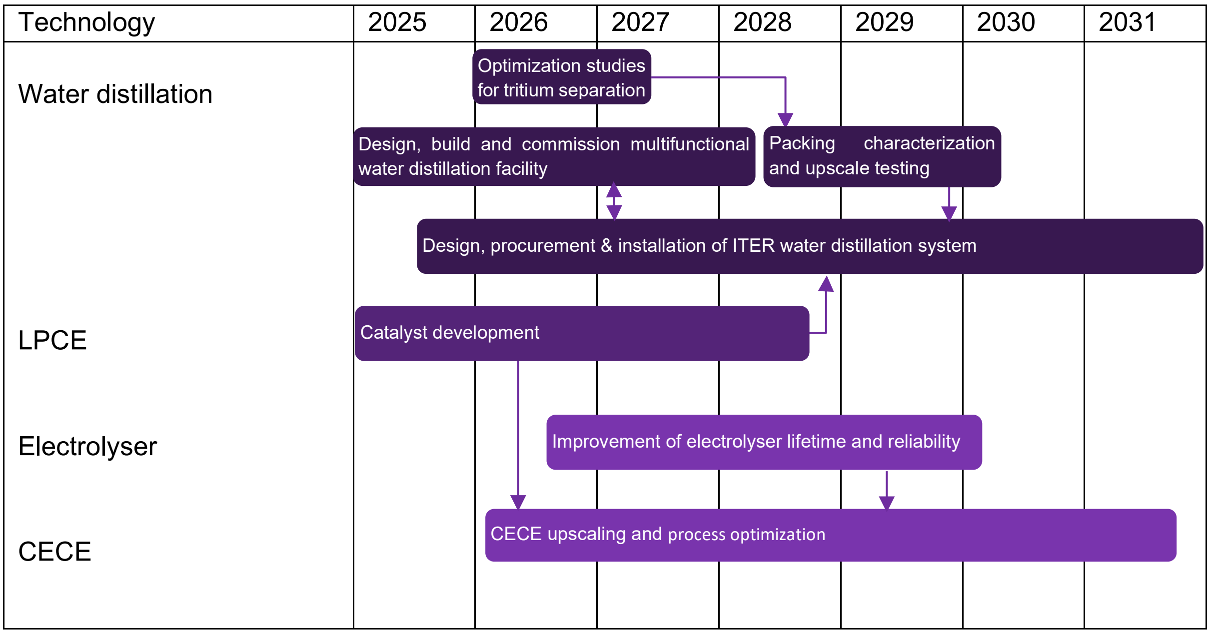


## 5.3.2 Membranes and packing

### Cryogenic distillation

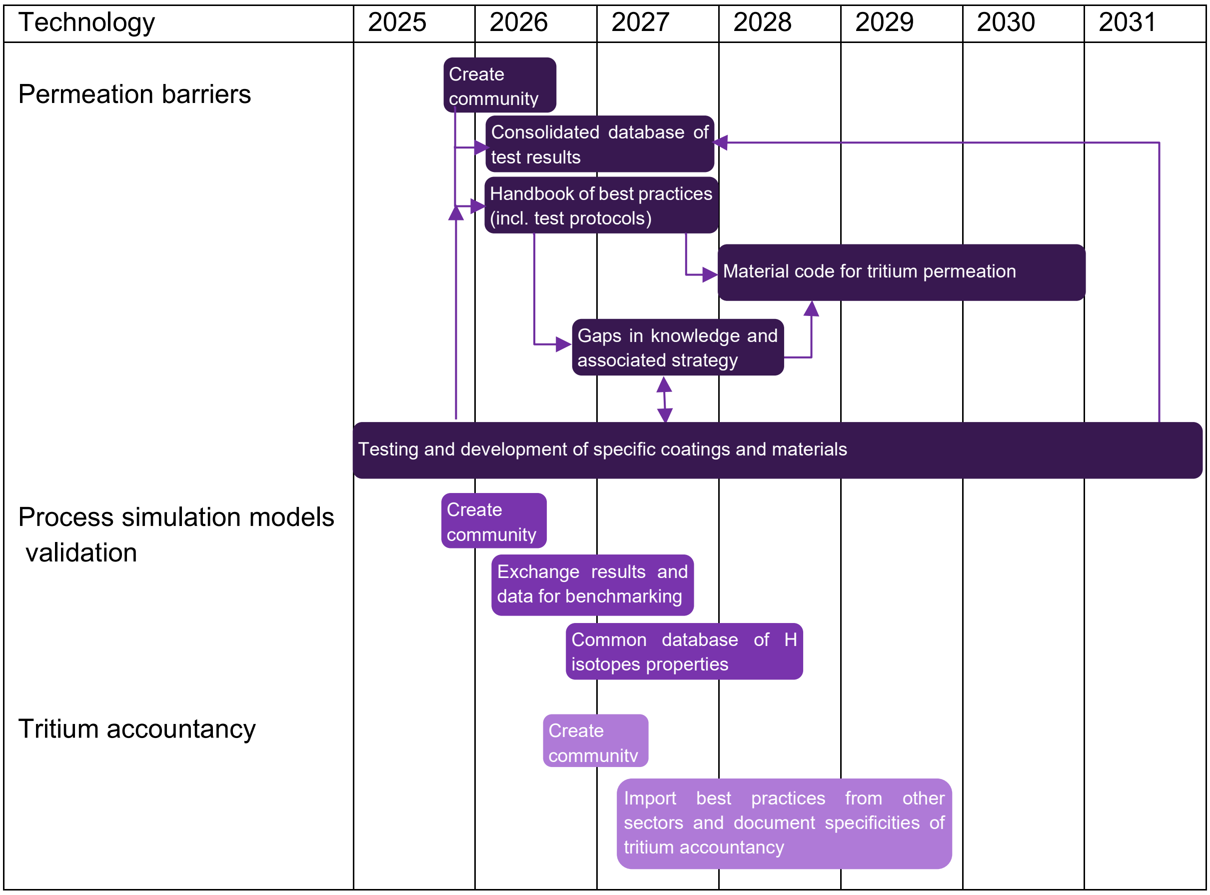



### Water detritiation




A clear roadmap for the development of membranes capability in Europe (specifically for fusion application) must also be developed. This area suffers from a lack of funding and a low number of actors in the field to exploit the existing knowhow in European entities.

### 5.3.3 Tritium management



# 6 Conclusion

The first European Fuel Cycle Technology Mapping exercise represents **a significant first step towards the acceleration of the development of fuel cycle technologies in Europe**. It brought together academia, research institutions, startups and industry to provide an evaluation of current capabilities in Europe and a clear path forward to develop the required fuel cycle technologies in support of fusion as a viable energy source.

## Workshop outcome

The work carried out highlighted **world-class capabilities in several key areas** particularly cryogenic and mechanical pumping, tritium processing and tritium analytics. It also **reveals urgent needs that demand immediate coordinated action.**

The most pressing challenge is the **shortage of tritium test facilities**. With only two operational facilities capable of handling meaningful tritium quantities (40g and 2g respectively), Europe faces a bottleneck that could impact its ability to develop fuel cycle technologies fast enough. Supporting the construction of planned facilities in France and Romania and establishing a major European tritium test facility with licence to handle over 100g of Tritium capacity emerges as a strategic priority, requiring immediate resource allocation.

The roadmaps also established clear development priorities across the fuel cycle spectrum. For fuelling systems, Europe must urgently **diversify its pellet injection capabilities** beyond the current limited ecosystem centred on a few research institutions. The development of tritium-compatible pellet sources and acceleration systems requires sustained investment and international collaboration, for example with facilities like UNITY-2 in Canada.

Europe must also build on its experience with inertial confinement fusion and support the burgeoning efforts to develop the associated fuel cycle requirements for **inertial confinement target delivery**. In tritium processing, while Europe maintains strong capabilities in established technologies, other areas like **membrane separation** require focused development efforts. In some critical, yet to mature fields, such as **process simulation, tritium permeation, and tritium accountancy, the establishment of technology-specific communities represents an important first step** towards the development of a coordinated approach.

Europe's current tritium handling regulations, inherited from fission applications, create competitive disadvantages compared to regions with fusion-specific frameworks. To accelerate fusion fuel cycle technology development and facilitate the emergence of fusion as a viable energy source, **Europe must quickly develop flexible, graded, and goal-oriented tritium handling regulations tailored to fusion**.

**The ripple effects from major projects** like ITER, JT-60SA, and the Divertor Test Tokamak **create significant opportunities for European fuel cycle supply chain development**. Several monopolies for critical components like tritium-compatible pumps represent strategic vulnerabilities that could undermine the independence of Europe in its fusion energy programme. **Funding must be allocated in the medium term to strategically reinforce the European supply chain capabilities**.

## Path Forward

This mapping exercise represents more than a technical assessment, it provides a clear framework for coordinated action. Success will require **a coordinated investment strategy across multiple funding sources**, public and private, national, European and international.

It constitutes a **call to action** for the European fuel cycle community and the fusion energy leadership in general. Funding and resources must now be allocated to the identified technology development actions in a coordinated manner. The proposal to regularly update the technology dashboards, identifying actions that have been funded and gaps that have been filled goes into that direction. **A European fusion fuel cycle community has been established. With adequate resources, it will deliver world class capabilities for Europe.**

# Appendix 1: Technology Readiness Levels

For this workshop, a TRL scale from 1 to 9 will be used, in line with the IAEA definitions[2].
It considers the different criteria for different streams as illustrated in the table below extracted from the document in reference. By default, the "System" stream will be used. For more details, please refer to the TECDOC 2047 itself[1].

| TRL | Systems | Materials | Software | Manufacturing | Instrumentation |
|---|---|---|---|---|---|
| 1 | Basic principles | Evidence from literature | Mathematical formulation | Process concept proposed | Understand the physics |
| 2 | Technology concept | Agreed property targets, cost & timescales | Algorithm implementation documented | Validity of concept described | Concept designed |
| 3 | Proof of concept | Materials' capability based on lab scale samples. | Prototype architectural design of important functions is documented | Experimental proof of concept completed | Lab test to prove the concept works. |
| 4 | Validation in a laboratory environment | Design curves produced. | ALPHA version with most functionalities implemented with User Manual and Design File available | Process validated in lab | Lab demonstration of highest risk components |
| 5 | Partial system validation in a relevant environment | Methods for material processing and component manufacture | BETA version with complete software functionalities, documentation, test reports and application examples available | Basic capability demonstrated using production equipment | Requiring specialist support |
| 6 | Prototype demo in a relevant environment | Validated via component and/or sub-element testing. | Product release ready for operational use | Process optimised for capability and rate using production equipment | Applied to realistic location/environment with low level of specialist support. |
| 7 | Prototype demo in an operational environment | Evaluated in development rig tests | Early adopter version qualified for a particular purpose | Economic run lengths on production parts | Successful demonstration in test. |
| 8 | Test and demonstration | Full operational test | General product ready to be applied in a real application | Significant run lengths | Demonstrated productionised system |
| 9 | Successful mission operation | Production ready material | Live product with full documentation and track record available | Demonstrated over an extended period | Service proven |

[2] IAEA TECDOC 2047 Considerations of TRL for Fusion Technology Components available from: https://www-pub.iaea.org/MTCD/Publications/PDF/TE-2047web.pdf

# Appendix 2: Technology assessment

| 1. Added-Value Towards Nuclear Fusion | | |
|---|---|---|
| *Criterion* | *Scale* | *Explanation* |
| **Need for and potential benefit** | Major / Medium / Minor | *Does this technology address a critical and unresolved challenge in nuclear fusion?* |
| **Availability of alternative solutions** | Yes/No (EU)<br>Yes/No (Outside EU) | *Are there competing solutions in Europe or globally?* |
| **Differentiation / Competitive Advantage** | Yes / No | *Does this technology offer a unique advantage over existing solutions?* |
| **2. Maturity & Feasibility** | | |
| *Criterion* | *Scale* | *Explanation* |
| **Technology Readiness Level (TRL)** | 1 to 9 | *Standard TRL scale (see Appendix).* |
| **Expected time to TRL 9 (full maturity)** | <5 years / 5–15 years / >15 years | *How long until the technology is commercially viable?* |
| **Availability of test facilities** | Yes / No | *Are there existing facilities in Europe to validate the technology?* |
| **3. Interest from the Innovation Ecosystem** | | |
| *Criterion* | *Scale* | *Explanation* |
| **Interest from start-ups** | None / 1–3 interested parties / >3 interested parties | *Level of engagement from early-stage companies.* |
| **Interest from industry** | None / 1–3 interested parties / >3 interested parties | *Level of interest from established industry players.* |
| **Interest from research institutions** | None / 1–3 interested parties / >3 interested parties | *Interest from universities, national labs, and research centers.* |
| **4. Other Investment Decision-Making Factors** | | |
| *Criterion* | *Scale* | *Explanation* |
| **Market potential** | Nuclear fusion-specific / Wider market potential | *Is the technology limited to fusion, or does it have broader applications?* |
| **Competences & skills development** | Yes / No | *Will this technology enhance European expertise in fusion?* |
| **Regulatory impact** | Yes / No | *Does the technology pose significant regulatory challenges?* |
| **5. Risk, Cost, and Implementation Timeline of Next Step on Roadmap** | | |
| *Criterion* | *Scale* | *Explanation* |
| **Outcome predictability & risks** | Low risk / Medium risk / High risk | *How uncertain are the results of the next development?* |
| **Estimated development cost** | 0–500k EUR / 501k–2M EUR / >2M EUR | *Rough cost estimate for next development step.* |
| **Time to first output (once funded)** | <1 year / 1–2 years / >2 years | *Timeframe for delivering tangible results.* |

# Appendix 3: Technology dashboards

### Fuelling and storage

- Pellet Source
- Centrifugal acceleration for solid injection
- Gas-gun acceleration mechanism for solid injection
- Diagnostic System for pellet injection
- Inertial Fusion Target Delivery
- Modelling and Software Developments
- Metal Hydride Beds

### Membranes and Packing

- Column packings
- Packed Beds
- Pd-Ag Membranes
- Cryogenic distillation
- Temperature/Pressure Swing Adsorption (TSA/PSA/TCAP)
- Equilibrators
- Combined Electrolysis and Catalytic Exchange (CECE)
- Liquid Phase Catalytic Exchange (LPCE)
- Electrolyser
- Water distillation
- Vapor Phase Catalytic Exchange (VPCE)
- Wet Scrubbers
- Catalytic Reactors for Hydrogen Oxidation
- Membrane Absorption
- Quantum Sieving

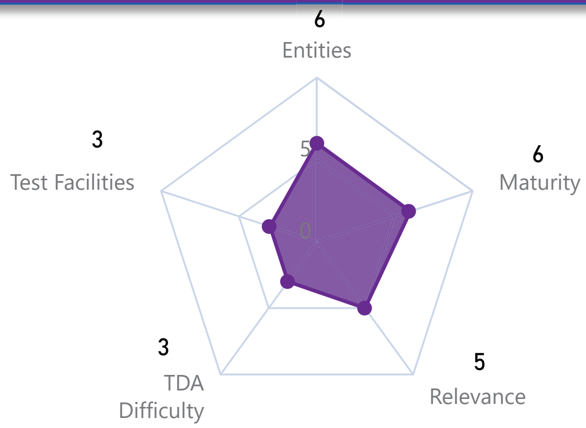
### Pumping

- Cryogenic Adsorption pumps
- Temperature Staged cryogenic condensation and adsorption pumps
- Continuous Cryogenic Diffusion Pump / Snail Pump
- Cryogenic Viscous Compressor (CVC)
- Cryogenic Temperature Sensor
- Non-Evaporable Getter (NEG) pumps
- Metal foil pump
- Proton conductor pump
- Liquid metal diffusion pump
- Liquid Ring pumps
- Oil diffusion pumps with tritium compatible oils
- Metal bellows pumps
- Scroll pumps
- Roots pumps
- Piston pumps
- Screw pumps
- Turbo Molecular Pumps and Cryogenic TMPs

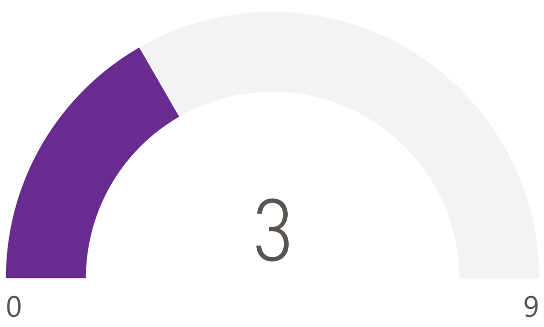
### Tritium Management

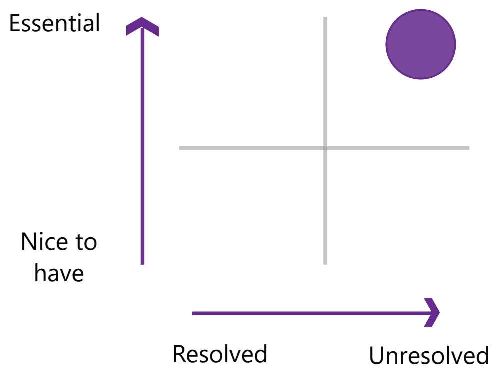
- Tritium permeation barriers
- Instruments to measure hydrogen isotope concentrations
- Non-destructive Tritium detection in solids
- Wearable tritium detector
- Room tritium detector
- Real time tritium detector for water
- Tritium sealing of dismountable Flanges
- Tritium accountancy
- Process Simulation Model Validation

# Pellet Source




TRL




**Other Fields of Application**

Laser Targets
Neutron Spallation Sources

**Alternative Technologies**

**Showstoppers list**

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
| --- | --- |
| HUN-REN (Hungary)<br>CEA Grenoble (France)<br>KIT (Germany)<br>IPP Garching (Germany)<br>Unity 2 (Canada - Under construction) | D-T validation |

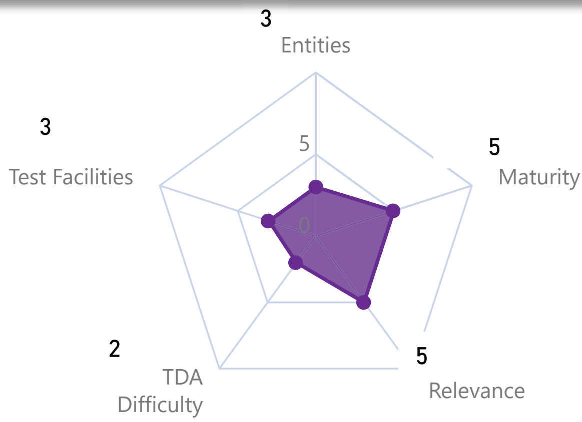
European Entities Involved

| Public | Private |
| --- | --- |
| IPP Garching (Germany)<br>CIEMAT Madrid (Spain)<br>HUN-REN (Hungary<br>CEA Grenoble (France) | |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
| --- | --- | --- | --- | --- | --- |
| Design, build and test prototype pellet extruder | 40 to 80% | 6 months to 2 years | 250k to 1M | High | Partially |
| Develop a batch piston for the production of hydrogen ice | >80% | 6 months to 2 years | 250k to 1M | High | Yes |
| Develop a vacuum-compatible electromagnetic actuator | 40 to 80% | 6 months to 2 years | 250k to 1M | Medium | No |
| Obtain mechanical properties of H isotopes ice | <40% | 6 months to 2 years | >1M | High | Partially |

# Centrifugal acceleration for solid injection

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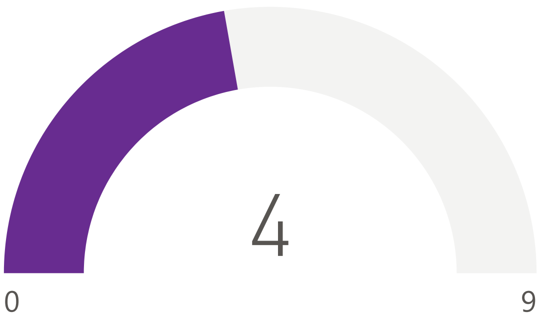
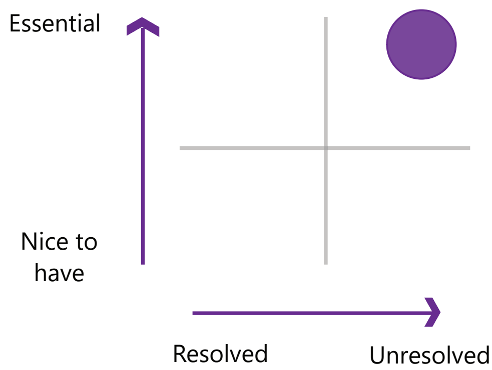



**Other Fields of Application**

Space launchers

**Alternative Technologies**

Gas gun
Rail Gun

**Showstoppers list**

Interface with the pellet source
Reliability
Tritium application/compatibility

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| IPP Garching (Germany)<br>KIT DIPAK-PET (Germany - Under construction)<br>UNITY 2 (Canada - Under construction)<br>JT-60SA (Japan - Under construction) | Test reliability and repeatability<br>Demonstrate integrability with continuous extruder<br>Test with tritium |

European Entities Involved

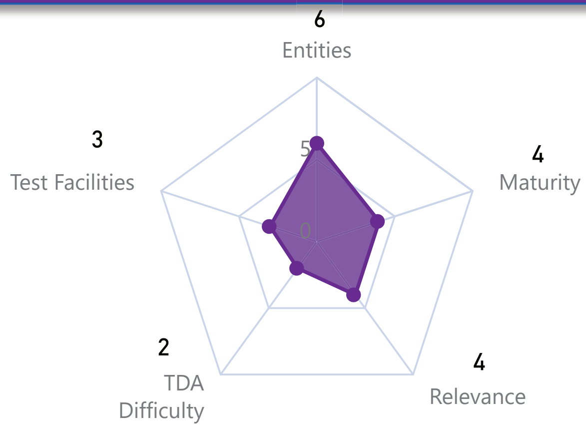
| Public | Private |
|---|---|
| IPP Garching (Germany)<br>KIT (Germany)<br>HUN-REN (Hungary)<br>DTT (Italy) | Sener (Spain)<br>Kyoto Fusioneering (Germany) |

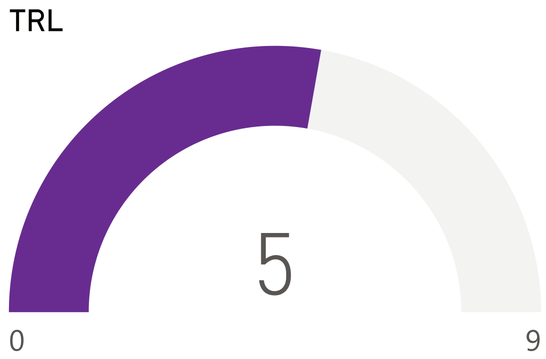
## Technology Development Actions

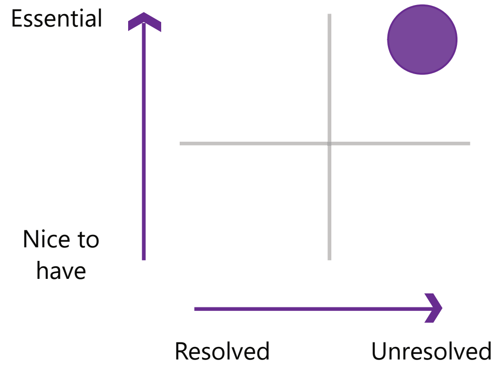
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Build prototype centrifugal accelerator for test facility | >80% | 6 months to 2 years | >1M | High | Partially |
| Develop test facility for HD testing of pellet acceleration | >80% | >2 years | >1M | High | Partially |
| Improve the long term reliability of the main bearing | >80% | 6 months to 2 years | <250k | Medium | No |
| Testing with DT | 40 to 80% | >2 years | >1M | High | No |

# Fuel Cycle › Fuelling and storage

# Gas-gun acceleration mechanism for solid injection




**Other Fields of Application**

Military
Propulsion technologies

**Alternative Technologies**

Centrifugal /
Railgun Accelerators

**Showstoppers list**

Gas load can be a strong burden on the fuel cycle
Damage to pellets
Tritium compatibility

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| IPP Greifswald (Germany)<br>KIT DIPAK-PET (Germany - Under construction)<br>UNITY 2 (Canada - Under construction) | Functional test |

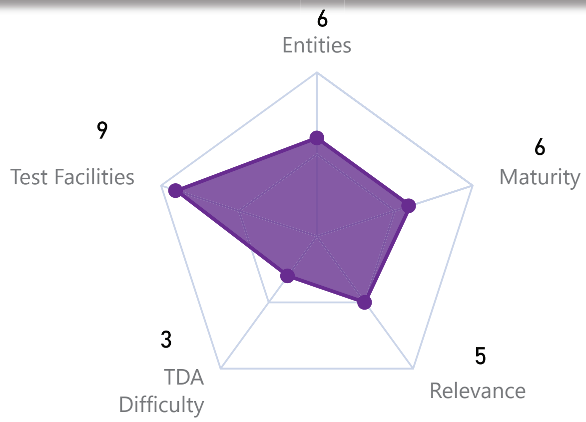
**European Entities Involved**

| Public | Private |
|---|---|
| KIT (Germany)<br>CIEMAT Madrid (Spain)<br>IPP Garching (Germany)<br>CEA Grenoble (France) | |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Build tritium compatible prototype and develop test facility | >80% | >2 years | >1M | Low | Partially |
| High Speed pellet source by gas guns and/or railguns | 40 to 80% | 6 months to 2 years | 250k to 1M | High | No |

# Diagnostic System for pellet injection

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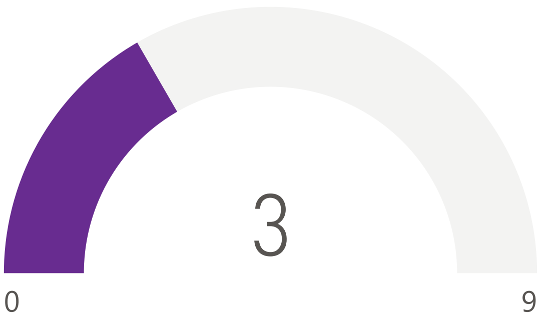
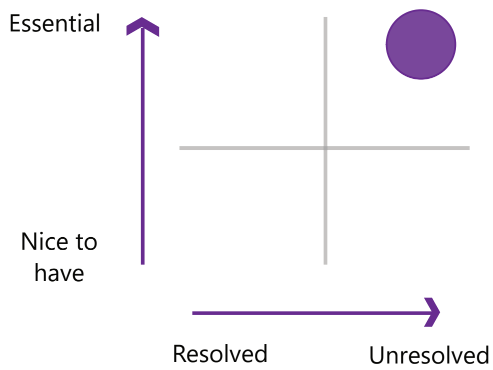



| Other Fields of Application |
|---|
| Optical monitoring |

| Alternative Technologies |
|---|
| Plasma diagnostics<br>Mirnov coils |

| Showstoppers list |
|---|
| Line of sight in the case of optical diagnostic<br>Reliability under radiated environment |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| KIT DIPAK-PET (Germany - Under construction)<br>IPP Garching/Greifswald (AUG and W7-X) | Functional test on real pellets |

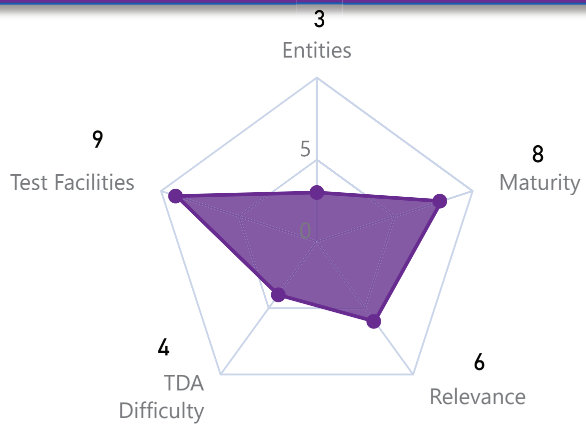
European Entities Involved

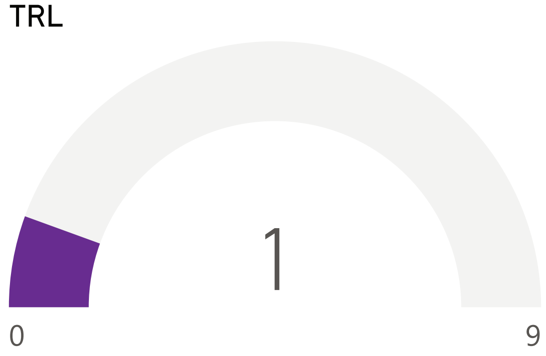
| Public | Private |
|---|---|
| Hun-REN (Hungary)<br>IPP Munich/W7-X (Germany) | |

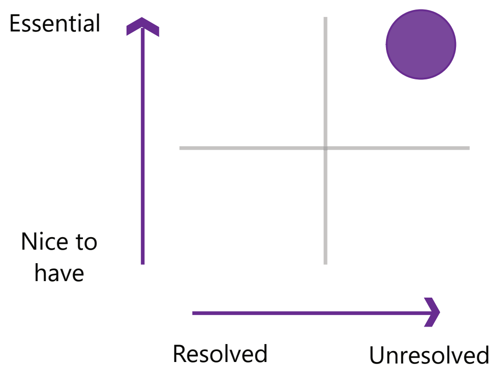
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Define technologies to detect if pellets entered the highly confined plasma | >80% | <6 months | <250k | Medium | No |
| Optical diagnostic to measure successful arrival of pellets into the vessel | <40% | >2 years | >1M | Medium | No |

# Inertial Fusion Target Delivery




Other Fields of Application

Alternative Technologies

Showstoppers list

Precision and localization of target, High repetition rate, Shape precision and durability of the pellets, Synchronization between driver and pellet injector

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| | Demonstrate feasibility of fast and repetitive filling of targets. Repeatability, precision and localization of the pellet. |

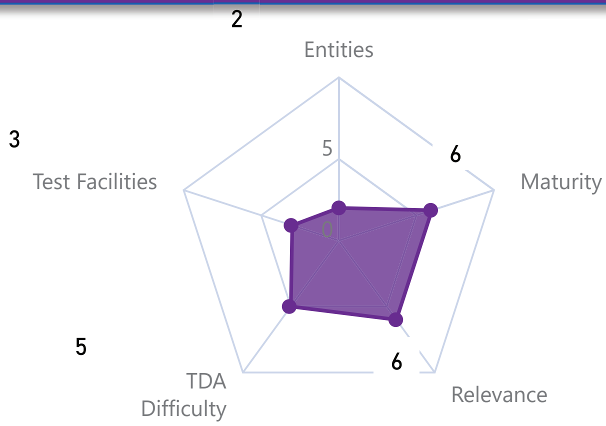
European Entities Involved

| Public | Private |
|---|---|
| ELI Prague (Czech Republic)<br>CEA Bordeaux/Dijon/Grenoble (France)<br>Fraunhofer IAF Darmstadt (Germany) | Focused Energy<br>GenF (France) |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Develop a target tracking technology | <40% | 6 months to 2 years | 250k to 1M | Low | No |
| Target filling process definition | <40% | 6 months to 2 years | <250k | High | Partially |
| Target Injection: Build and test a prototype injector | >80% | >2 years | >1M | High | No |
| Target Storage: Prepare specification for possible storage and handling solutions | >80% | <6 months | <250k | Medium | No |

# Modelling and Software Developments

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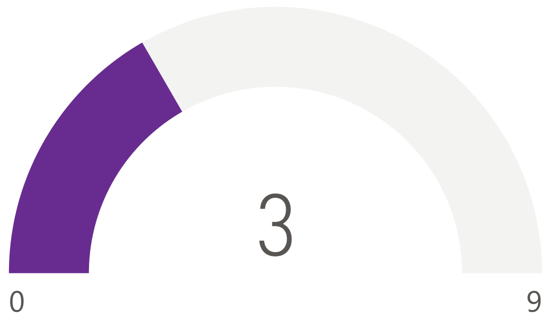
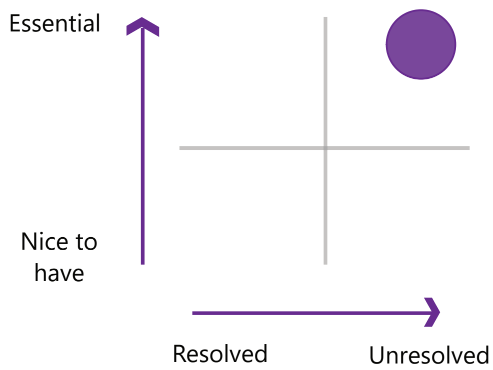



| Other Fields of Application |
|---|

| Alternative Technologies |
|---|
| Experiments |

| Showstoppers List |
|---|
| Validation of codes<br>Unknown properties of HDT ice |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| (For plasma with pellets)<br>IPP Garching AUG (Germany)<br>IPP Greifswald W-7X (Germany)<br>JT-60SA (Japan - Under construction)<br>CEA Cadarache WEST (France) | HDT ice characterization |

European Entities Involved

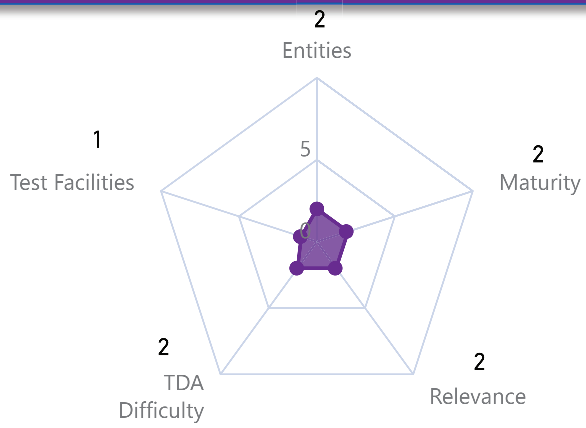
| Public | Private |
|---|---|
| CEA Cadarache/Grenoble (France)<br>HUN-REN (Hungary)<br>IPP Garching (Germany)<br>KIT (Germany)<br>ENEA Frascati (Italy)<br>DIFFER (Netherlands)<br>ONERA (France) | ENI (Italy) |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Mechanical model for behaviour of the pellets in the guide tube | >80% | <6 months | <250k | Medium | No |
| Mechanical model for pellet behaviour during acceleration | >80% | <6 months | <250k | Medium | No |
| Modelling of heating of targets through gas friction during inertial fusion injection | >80% | 6 months to 2 years | <250k | High | No |
| Modelling of the centrifugal acceleration process | >80% | <6 months | <250k | Medium | No |
| Process and thermal model of the extrusion process | >80% | <6 months | <250k | High | No |
| Model for pellet impact to the plasma | 40 to 80% | 6 months to 2 years | <250k | Medium | No |
| Test facility to characterize the mechanical properties of the various species | 40 to 80% | >2 years | >1M | High | No |

# Fuel Cycle › Fuelling and storage

# Metal Hydride Beds

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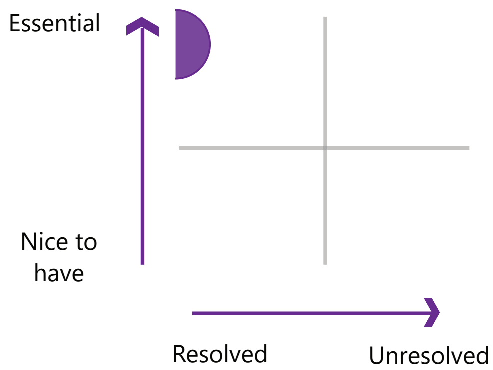



Other Fields of Application

Bulk H storage
Hydrogen generation

Alternative Technologies

Showstoppers list

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| TLK/KIT (Germany)<br>AGHS (UK)<br>H3AT (UK under construction)<br>Unity 2 (Canada under construction)<br>ICSI (Romania) | |

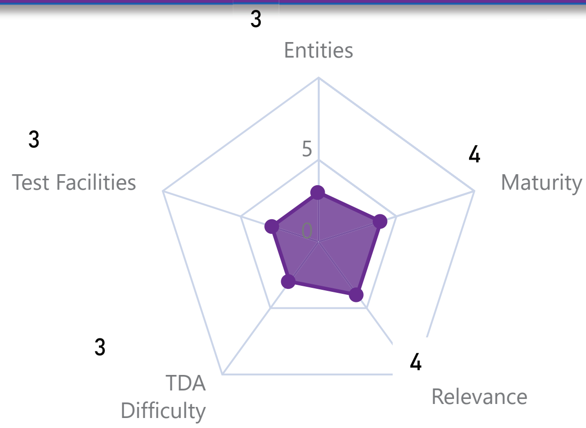
European Entities Involved

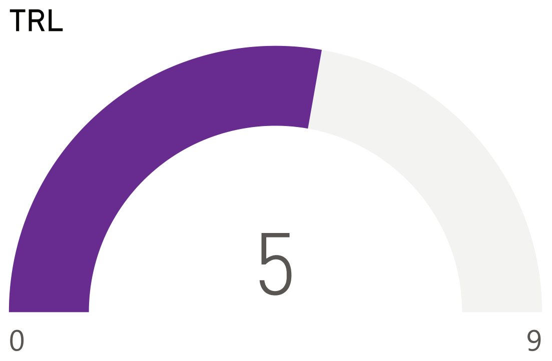
| Public | Private |
|---|---|
| TLK/KIT (Germany)<br>ENUSA (Spain)<br>CIEMAT (Spain)<br>ICSI (Romania) | Monteiro (France)<br>Alsymex (France)<br>Kyoto Fusioneering<br>SAES (Italy)<br>Urenco<br>Orano (France)<br>Eni (Italy)<br>IDONIAL (Spain)<br>FUS-ALIANZ (Spain) |

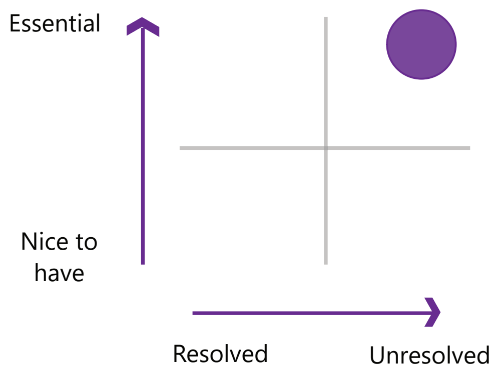
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Design, build and test prototype ZrCo transport container | >80% | 6 months to 2 years | 250k to 1M | Medium | No |
| Develop a powder metallurgy and matched sintering DU beds as T hydrides | 40 to 80% | 6 months to 2 years | <250k | High | No |

# Column packings




| Other Fields of Application |
|---|
| Gas separation<br>Fission<br>Water Purification<br>Petrochemical |

| Alternative Technologies |
|---|
| Trays |

| Showstoppers list |
|---|
| Tritium Compatibility |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| ICSI (Romania)<br>KIT/TLK (Germany)<br>CURIUM (France) | Characterise packing performance<br>Upscale testing |

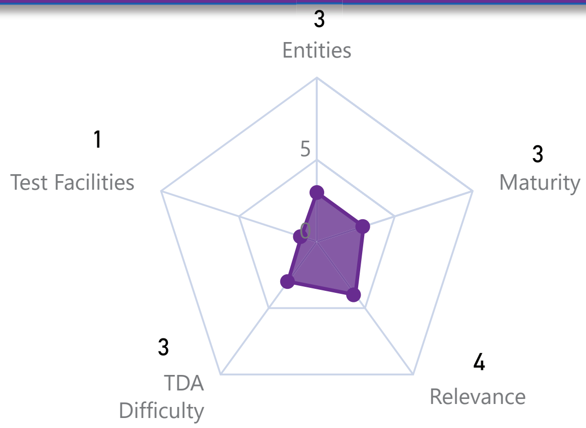
European Entities Involved

| Public | Private |
|---|---|
| ICSI (Romania)<br>KIT/TLK (Germany)<br>ENEA Frascati (Italy)<br>H3AT (under construction) | Sulzer Chemtech (Switzerland)<br>Montz (Germany)<br>ALSYMEX (France) |

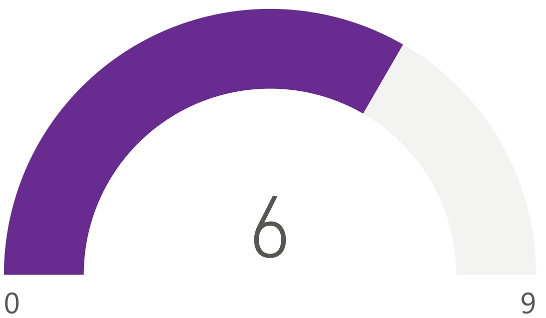
## Technology Development Actions

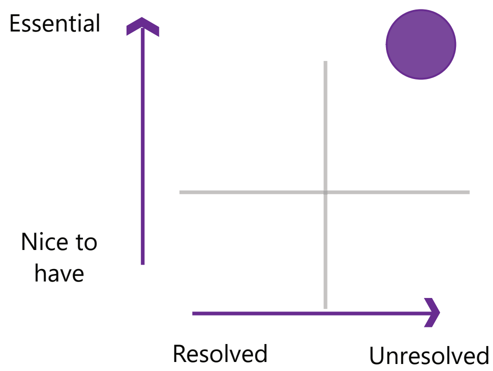
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Multifunctional Water Distillation test facility | 40 to 80% | 6 months to 2 years | 250k to 1M | High | No |
| Upscale Testing | <40% | >2 years | >1M | Medium | No |

# Packed Beds




TRL




| Other Fields of Application |
|---|
| Gas Purification<br>Chemical Plants<br>Heavy Water<br>Cryo<br>Reactors<br>Laboratory<br>Semiconductor Industry |

| Alternative Technologies |
|---|
| Membranes<br>Water Distillation |

| Showstoppers list |
|---|
| Experimental facilities needed |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| ENEA - Hydrex (Italy)<br>Smolsys (Switzerland)<br>CURIUM (France) | Test material in high pressure of inert gas and low partial pressure of tritium. Upscale test facility. |

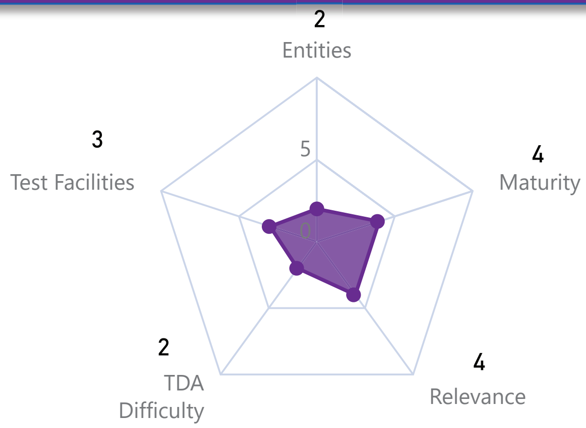
European Entities Involved

| Public | Private |
|---|---|
| ENEA (Frascati) | Sulzer Chemtech (Switzerland)<br>Saes (Italy)<br>Smolsys (Lucerne) |

## Technology Development Actions

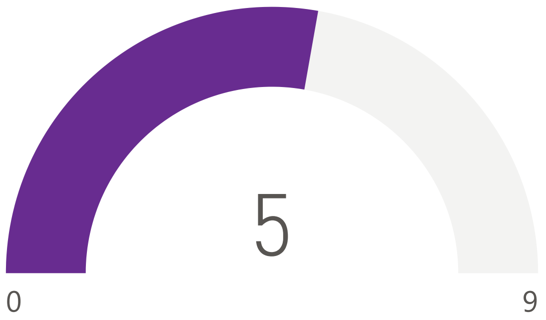
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Digital Twin technology usage for Tritium Scale Up design | <40% | 6 months to 2 years | <250k | Medium | No |
| Regeneration procedure and efficiency of the Packed Bed | >80% | >2 years | 250k to 1M | Medium | No |

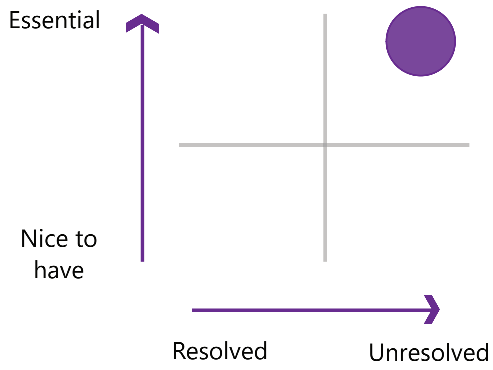
# Fuel Cycle › Membranes and packing




# Pd-Ag Membranes

TRL




### Other Fields of Application

Hydrogen fuel
Membrane reactors

### Alternative Technologies

Alternative membrane materials
Adsorption
Composite Membrane
Distillation and Catalytic Oxidation

### Showstoppers list

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
| --- | --- |
| UKAEA Culham (UK)<br>University of Bath (UK)<br>ENEA Frascati (Italy)<br>ICSI (Romania)<br>CURIUM (France) | Separation performance<br>Life expectancy<br>Poisoning |

European Entities Involved

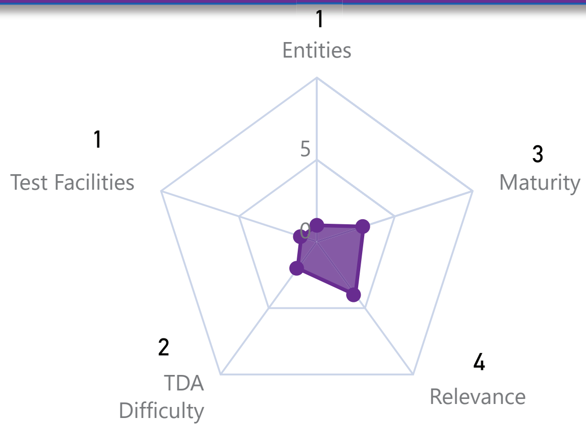
| Public | Private |
| --- | --- |
| UKAEA Culham (UK)<br>KIT/TLK (Germany)<br>ENEA Frascati (Italy)<br>TNO (NL)<br>ICSI (Romania)<br>CEA Cadarache (France - Under construction) | Tecnalia<br>Kyoto Fusioneering |

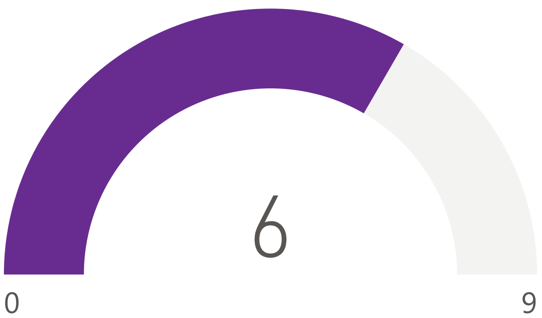
## Technology Development Actions

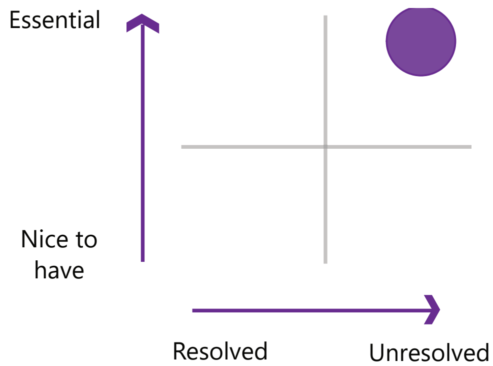
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
| --- | --- | --- | --- | --- | --- |
| Development of Pd-Ag membrane reactor/catalyst | 40 to 80% | 6 months to 2 years | 250k to 1M | High | No |
| Industrialization of membrane modules | >80% | 6 months to 2 years | 250k to 1M | Medium | No |

# Fuel Cycle › Membranes and packing

# Cryogenic distillation




| Other Fields of Application |
| --- |
| Fission<br>Gas separation<br>Medical industry<br>Chemical and steel manufacturing<br>Electronics |

| Alternative Technologies |
| --- |
| TSA<br>PSA<br>Membranes |

| Showstoppers List |
| --- |
| Large Inventory<br>Energy consumption |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
| --- | --- |
| KIT/TLK (Germany)<br>ICSI (Romania)<br>UKAEA H3AT (UK -under construction)<br>UKAEA AGHS (UK)<br>CURIUM (France) | |

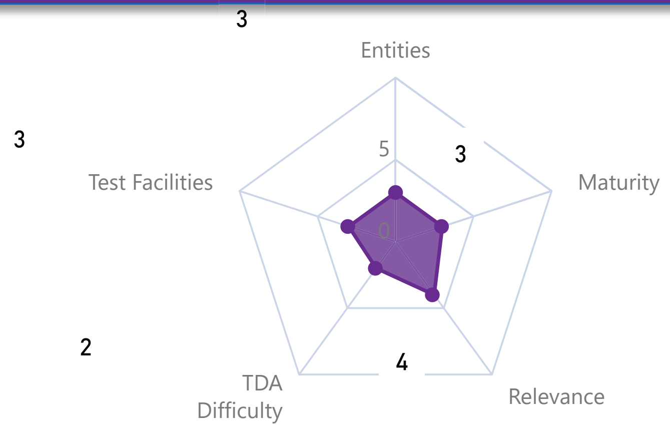
European Entities Involved

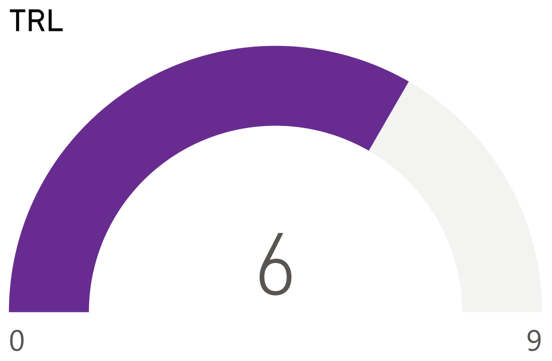
| Public | Private |
| --- | --- |
| UKAEA Culham ()UK<br>KIT/TLK (Germany)<br>ITER<br>ICSI (Romania)<br>ENEA (Italy)<br>CEA Cadarache (France - Under Construction) | Air Liquide (France)<br>Linde (Switzerland)<br>Research Instruments (Germany)<br>Absolut System (France)<br>Polaris (Italy)<br>ALSYMEX (France)<br>Eni (Italy) |

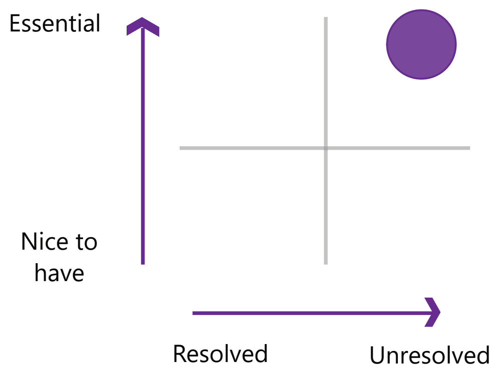
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
| --- | --- | --- | --- | --- | --- |
| Develop cryogenic distillation for D,T separation from the plasma exhaust | 40 to 80% | 6 months to 2 years | 250k to 1M | Low | No |
| Development of compact heat exchangers and copper-SS joining techniques | >80% | 6 months to 2 years | 250k to 1M | Medium | No |
| Packing performances assessment testing | >80% | 6 months to 2 years | 250k to 1M | Low | No |
| Testing of the dynamic operation of multiple columns (control loops) | >80% | 6 months to 2 years | 250k to 1M | High | Yes |

# Temperature/Pressure Swing Adsorption (TSA/TCAP)




### Other Fields of Application

Hydrogen
Separation
Carbon Adsorption

### Alternative Technologies

Cryo distillation
PSA
Membranes
Gas Chromatography

### Showstoppers List

Capacity
Control
Efficiency
Large Inventory
Throughput
Batch
Slow performance

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| MAIA (KIT)<br>HESTIA (KIT)<br>Air Liquide Innov. campus (France)<br>CURIUM (France)<br>ALSYMEX (France)<br>H3AT-UKAEA (UK - under construction) | Upscaling test facility (in long-term) |

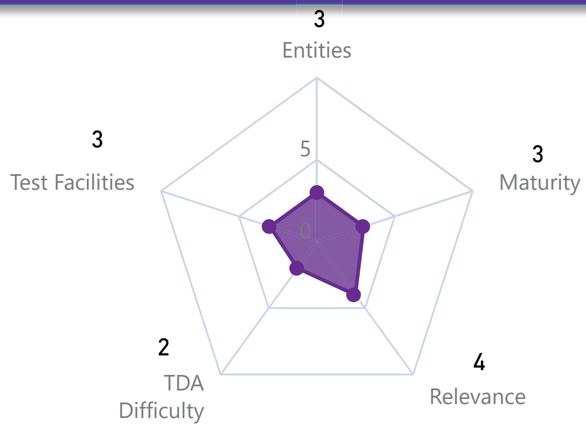
European Entities Involved

| Public | Private |
|---|---|
| KIT (Germany)<br>ENEA Frascati (Italy)<br>CEA Cadarache (France - Under Construction) | Air Liquide<br>Linde |

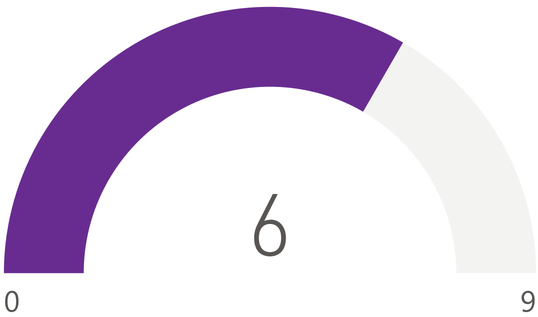
## Technology Development Actions

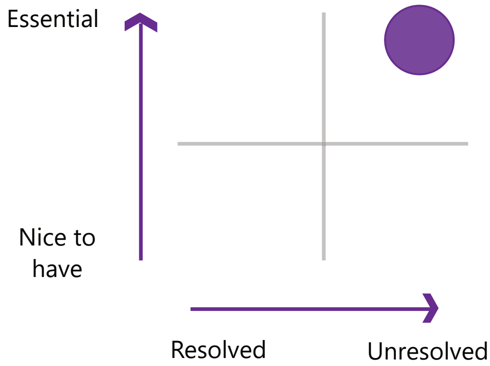
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Characterization of adsorption properties of tritium for different adsorbents | >80% | 6 months to 2 years | 250k to 1M | Low | No |
| Investigate TSA/TCAP for H/DT rebalancing | 40 to 80% | 6 months to 2 years | 250k to 1M | High | No |

# Equilibrators




TRL




| Other Fields of Application |
|---|
| Chemical Plants |

| Alternative Technologies |
|---|
| Packing Distillation |

| Showstoppers List |
|---|
| Catalyst Performance<br>Availability of Testing Equipment |

## Technology Characteristics

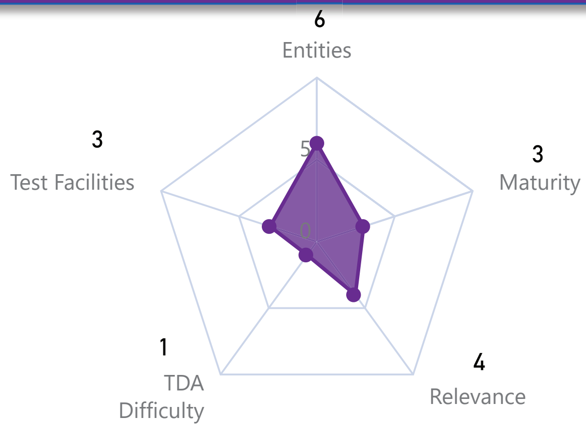
| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| CURIUM (France)<br>H3AT (UKAEA under construction) | To test catalyst performance |

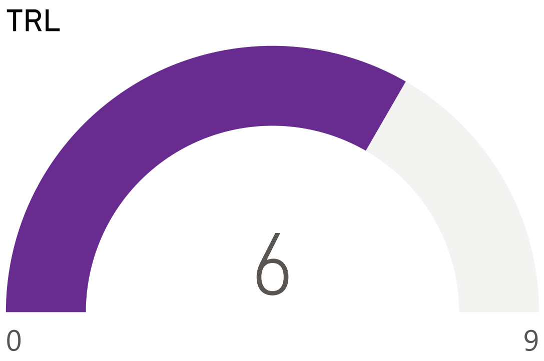
| European Entities Involved | |
|---|---|
| Public | Private |
| KIT (Karlsruhe)<br>ICSI (Valcea) | ALSYMEX |

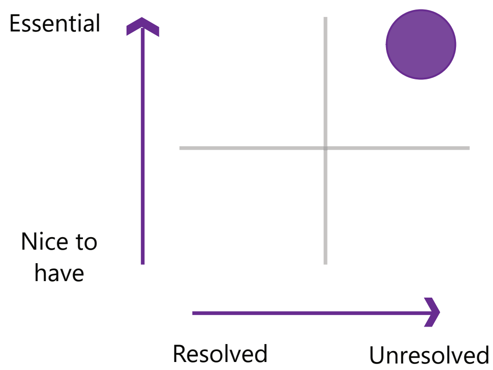
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| R&D and testing of new catalyst solutions for equilibrators | 40 to 80% | 6 months to 2 years | <250k | Medium | No |

# Combined Electrolysis and Catalytic Exchange (CECE)




| Other Fields of Application | Alternative Technologies | Showstoppers list |
|---|---|---|
| Fission<br>Hydrogen | Water distillation with LPCE or electrolyser | Electrolyzer robustness/lifetime, Electrolyte management, Energy demand, Complexity of operation, process complexity and economical demands |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| ICSI (Romania)<br>KIT/TLK (Germany) | Upscale of prior test setups. Process investigation<br>optimization and benchmarking of modeling. |

European Entities Involved

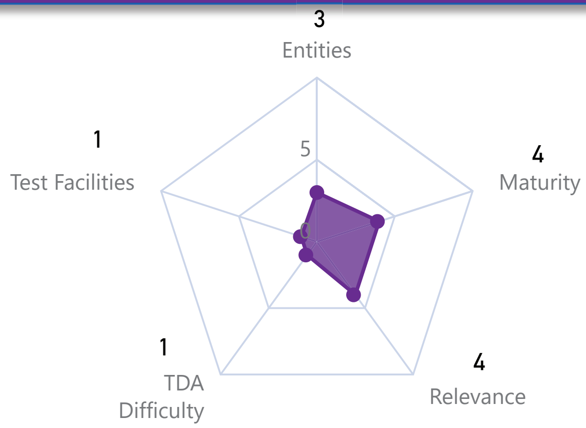
| Public | Private |
|---|---|
| ENEA (Italy)<br>KIT/TLK (Germany)<br>ICSI (Romania)<br>CEA Cadarache (France - Under construction) | |

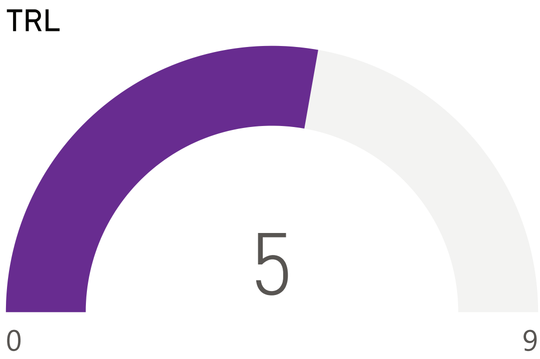
## Technology Development Actions

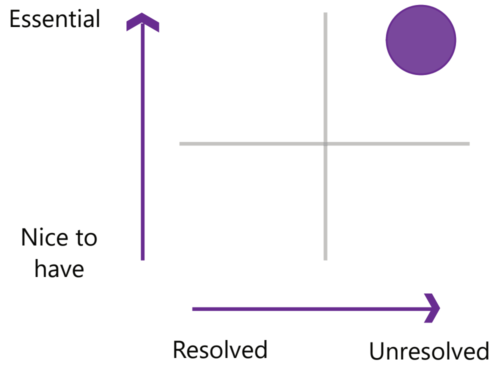
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Upscale CECE technology | 40 to 80% | >2 years | >1M | | |

# Fuel Cycle › Membranes and packing

# Liquid Phase Catalytic Exchange (LPCE)




| Other Fields of Application | Alternative Technologies | Showstoppers List |
|---|---|---|
| Fission<br>Reactive distillation | Water distillation<br>Membrane reactor | Catalyst performance<br>Packing characterization<br>Maintenance |

## Technology Characteristics

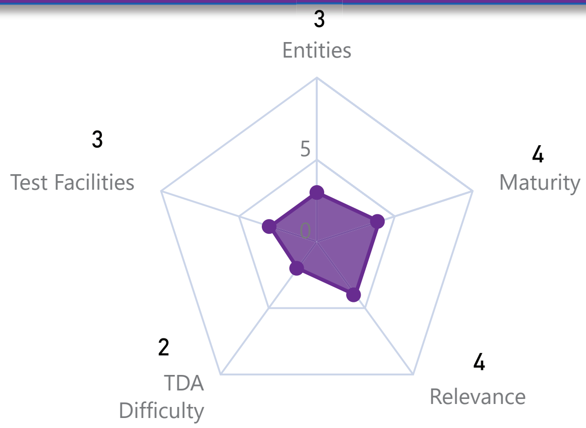
| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| ICSI (Romania)<br>KIT/TLK (Germany)<br>JET - AGHS (Culham)<br>CURIUM (France) | Upscale test facility |

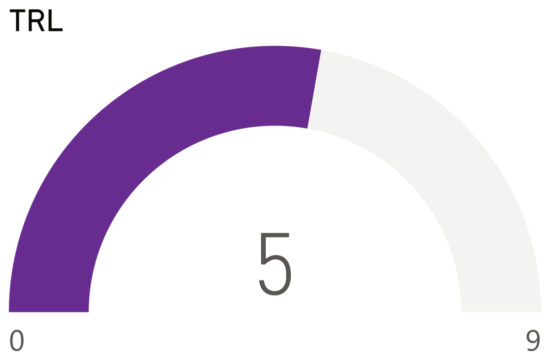
| European Entities Involved | |
|---|---|
| **Public** | **Private** |
| ICSI (Valcea)<br>KIT/TLK (Karlsruhe)<br>ENEA (Frascati)<br>CEA Cadarache - Future tritium process test facility for 2031 (France) | Eiffage SPG |

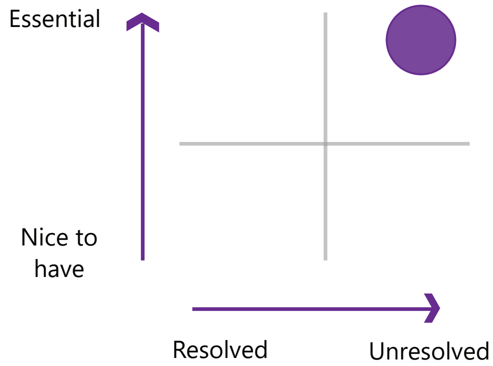
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| LPCE Catalyst development for Tritium | >80% | >2 years | >1M | Medium | Partially |

# Electrolyser




**Other Fields of Application**

Fission
Hydrogen

**Alternative Technologies**

Water distillation plus LPCE

**Showstoppers list**

High energy consumption
Lifetime
Tritium compatibility

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| ICSI (Romania)<br>H3AT (Culham under construction)<br>KIT/TLK (Germany)<br>CURIUM (France)<br>Unity 2 (Canada under construction) | Tritium long term operation<br>Roe collection and exchange |

**European Entities Involved**

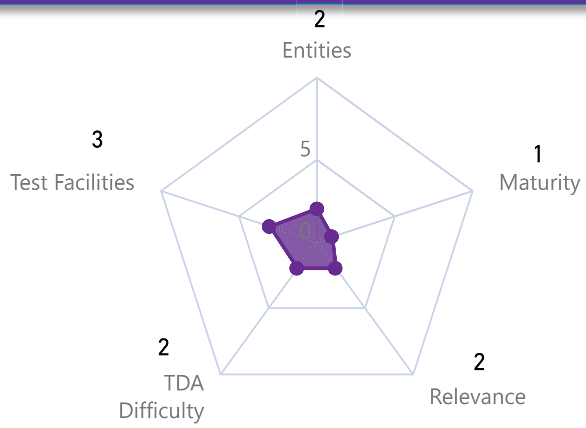
| Public | Private |
|---|---|
| ICSI (Valcea)<br>UKAEA (Culham)<br>KIT (Karlsruhe)<br>CEA Cadarache - Future tritium process test facility for 2031 (France) | Kyoto Fusioneering (Germany)<br>Kraftanlagen Heidelberg (Germany)<br>Veolia Water Technologies (France)<br>ELOGEN GTT (France)<br>Eni (Italy) |

## Technology Development Actions

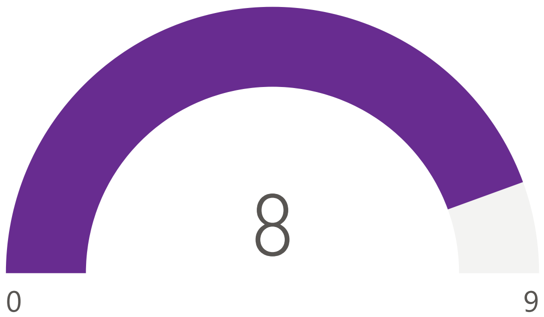
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Test electrolyzer materials with tritium to improve lifetime and reliability. | 40 to 80% | >2 years | >1M | Medium | No |

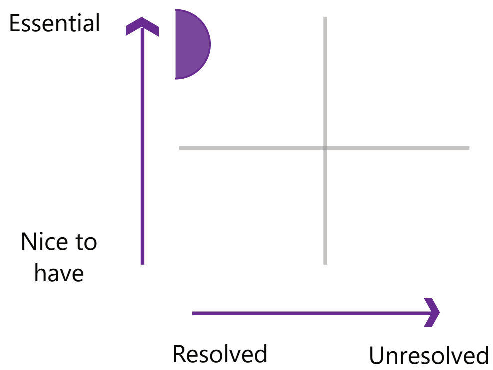
# Fuel Cycle › Membranes and packing

# Water distillation




TRL




**Other Fields of Application**

Fission
Water purification
Desalination

**Alternative Technologies**

Membranes
LPCE
CECE

**Showstoppers list**

Column size
Energy intensive
High inventory
Packing performance in relevant conditions

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| ICSI (Romania)<br>CURIUM (France) | Packing characterization<br>Performance<br>Operability and Maintenance<br>Integration with other type of processes. |

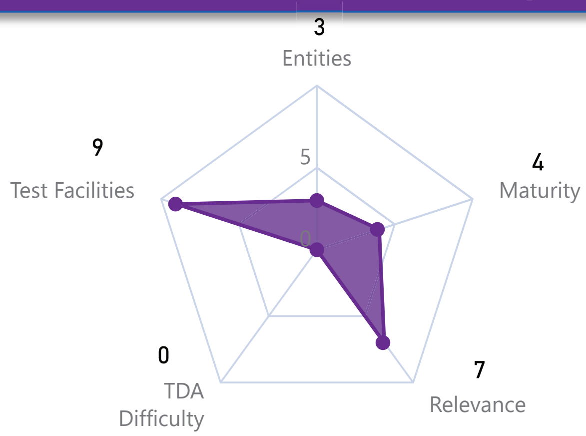
**European Entities Involved**

| Public | Private |
|---|---|
| ICSI Valcea (Romania)<br>ENEA Frascati (Italy)<br>CEA Cadarache (France - Under construction) | Effiage SPG<br>Sulzer<br>Koch-glitsch<br>Montz<br>Kraftanlagen Heidelberg<br>ALSYMEX<br>MONTEIRO |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Development of heat pump compatible with fusion environment | >80% | 6 months to 2 years | 250k to 1M | | No |
| Water Distillation optimization for tritium separation | >80% | >2 years | >1M | Medium | No |

# Vapor Phase Catalytic Exchange (VPCE)

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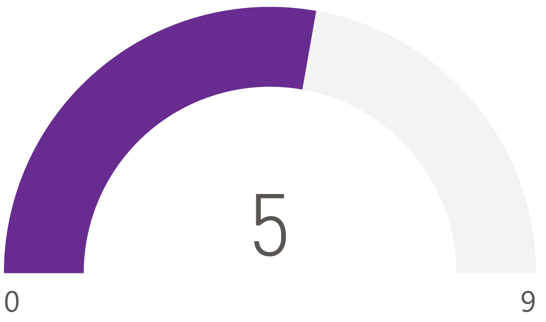
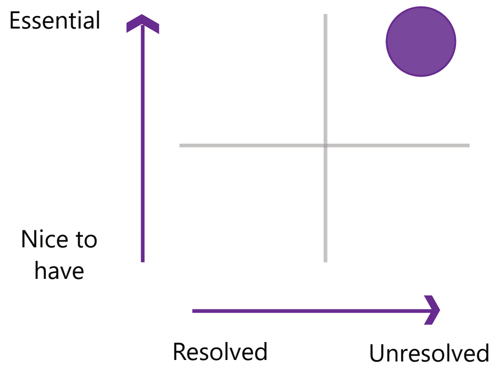



| Other Fields of Application |
|---|
| |

| Alternative Technologies |
|---|
| LPCE<br>CECE<br>Water distillation |

| Showstoppers list |
|---|
| Catalyst and packing<br>Operation temperature |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| CEA Cadarache (France)<br>KIT/TLK (Germany<br>UKAEA-AGS (UK)<br>CURIUM (France) | Depends on the level<br>Qualification program (Detritiation) |

European Entities Involved

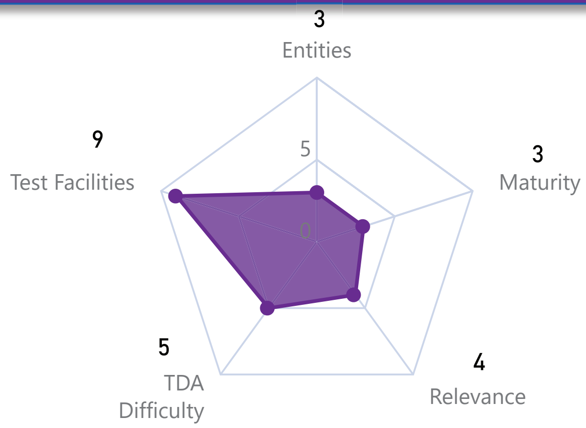
| Public | Private |
|---|---|
| ENEA<br>KIT<br>UKAEA<br>CEA Cadarache - (France - Under construction) | Eiffage SPG |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|

# Fuel Cycle › Membranes and packing

# Wet scrubbers

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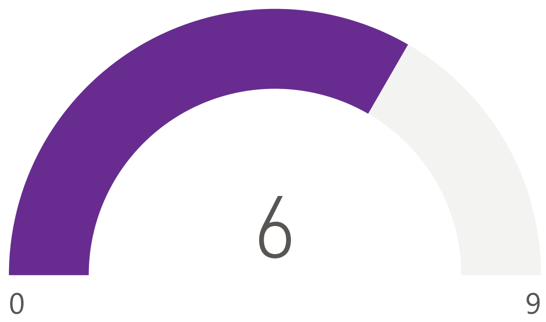
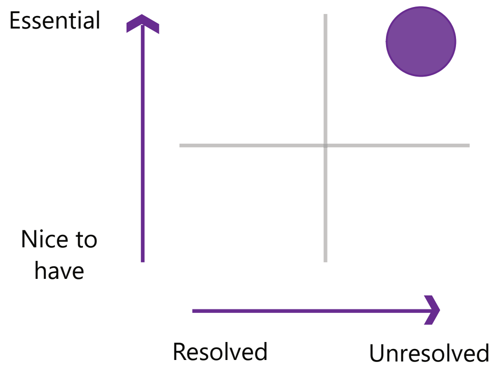



| Other Fields of Application |
| --- |
| Air purification needs using water trickle beds |

| Alternative Technologies |
| --- |

| Showstoppers list |
| --- |

## Technology Characteristics

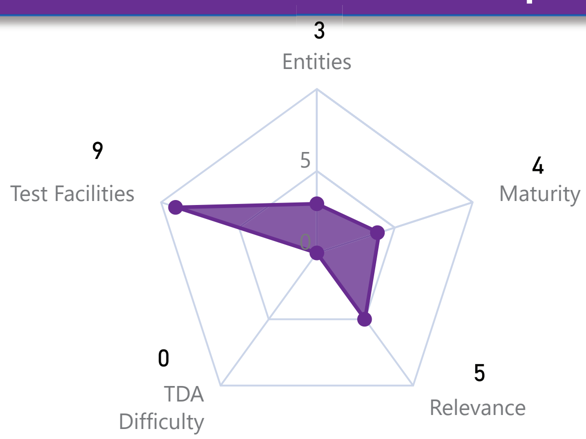
| Existing Test Facilities | Additional Test Facility Needed |
| --- | --- |

European Entities Involved

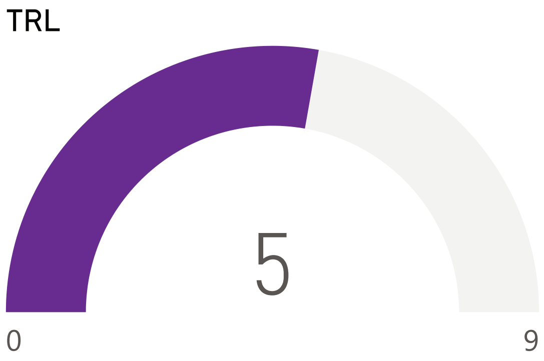
| Public | Private |
| --- | --- |
| Eni Spa | Eni<br>Eiffage SPG |

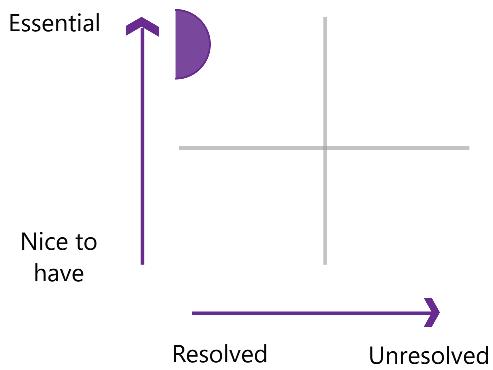
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
| --- | --- | --- | --- | --- | --- |
| Air detritiation wet scrubber development | >80% | 6 months to 2 years | 250k to 1M | High | No |
| Wet Scrubber Optimization | 40 to 80% | <6 months | <250k | High | No |




# Catalytic Reactors for Hydrogen Oxidation




| Other Fields of Application | Alternative Technologies |
|---|---|

| Showstoppers list |
|---|

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|

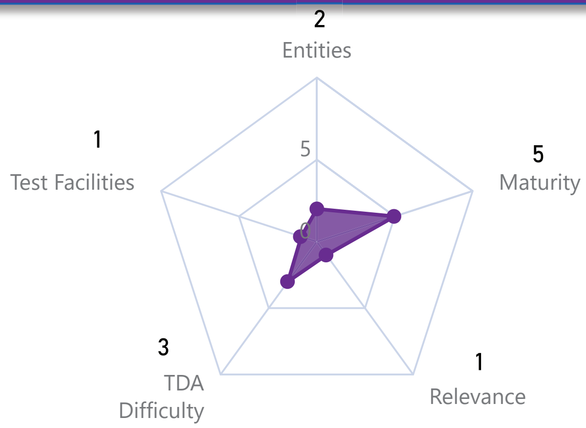
European Entities Involved

| Public | Private |
|---|---|
| ENEA | Eni<br>Eiffage SPG |

## Technology Development Actions

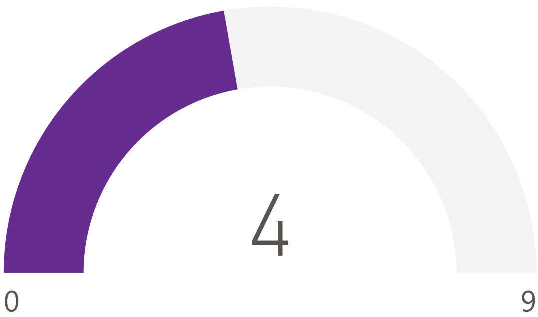
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|

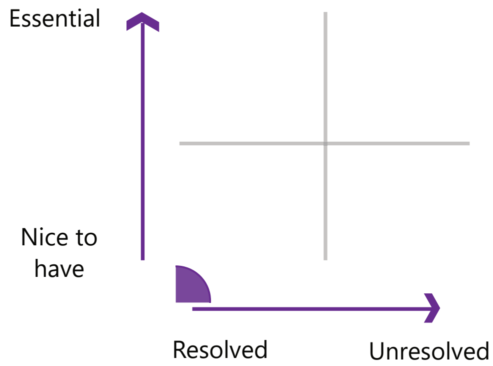
# Fuel Cycle › Membranes and packing




## Membrane Absorption

TRL




| Other Fields of Application | Alternative Technologies | Showstoppers List |
|---|---|---|
| Hydrogen<br>Gas Separation | Packings<br>Cryo separation | Capacity<br>Batch Process<br>High Process Control and Safety demand |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| UKAEA (Culham)<br>University of Bath (UK)<br>ENEA (Frascati)<br><br>CURIUM (France) | Adsoption process to be characterized for fusion process |

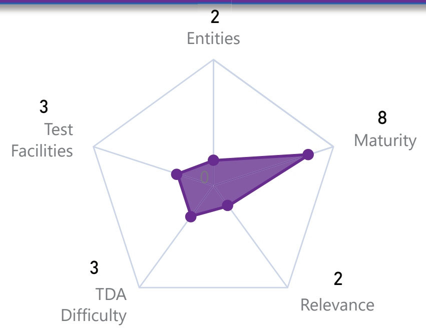
European Entities Involved

| Public | Private |
|---|---|
| ENEA (Frascati)<br>Univ of Calabria<br>UKAEA (Culham)<br>University of Bath and Rochester (UK)<br>TNO (Netherlands) | Tecnalia |

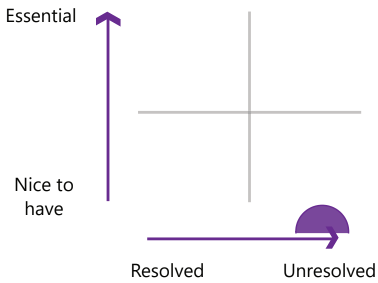
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Characterise adsorption function and develop its feasibility within the fuel cycle | 40 to 80% | 6 months to 2 years | 250k to 1M | Low | No |

# Quantum sieving








| Other Fields of Application |
|---|
| Fission<br>Gas separation |

| Alternative Technologies |
|---|
| Cryo distillation<br>Pd Membranes<br>Metal Foil pump |

| Showstoppers list |
|---|
| Manufacturability<br>Control |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| Univ of Bath (UK)<br>UKAEA<br>NPL (London)<br>Liverpool University (UK)<br>Bimo Tech<br>VTT Technical Research Centre of Finland<br>CURIUM (France) | Characterise material<br>process control<br>performance<br>chemistry compatibility<br>reproducibility<br>scale-up |

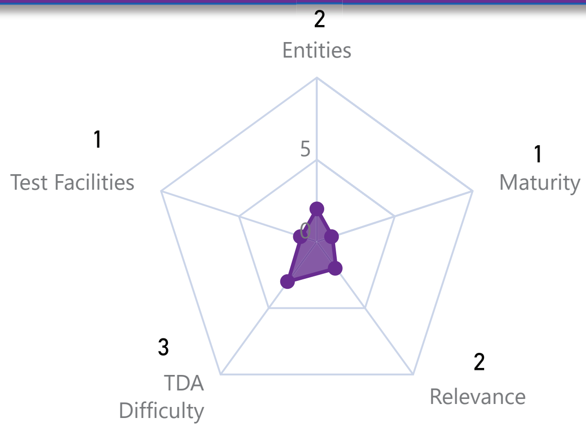
European Entities Involved

| Public | Private |
|---|---|
| Univ of Bath (UK)<br>UKAEA<br>NPL (London)<br>Liverpool University (UK)<br>VTT Technical Research Centre of Finland | Tecnalia (Spain)<br>Atkins (UK)<br>BIMO Tech |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Develop scalable materials and techniques for quantum sieving for efficient hydrogen isotope separation. | 40 to 80% | 6 months to 2 years | 250k to 1M | Low | No |

# Cryogenic Adsorption pumps

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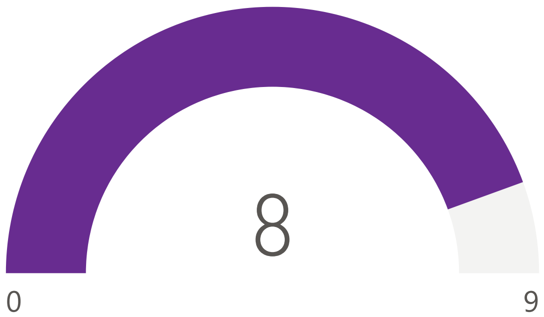
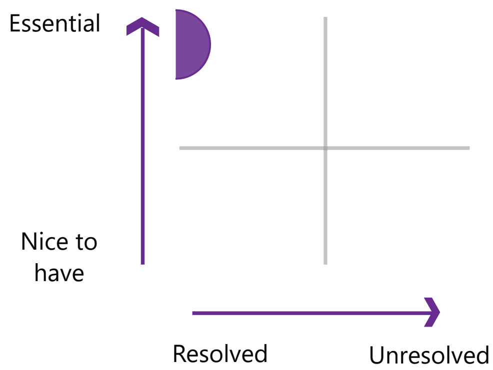



| Other Fields of Application | Alternative Technologies | Showstoppers list |
|---|---|---|
| Semiconductor<br>solar process<br>Aerospace<br>High energy physics | NEG pumps<br>Foil pumps<br>Diffusion pumps<br>Turbo MP | Tritium inventory and hydrogen safety<br>Scale up-helium cost |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| ITER | |

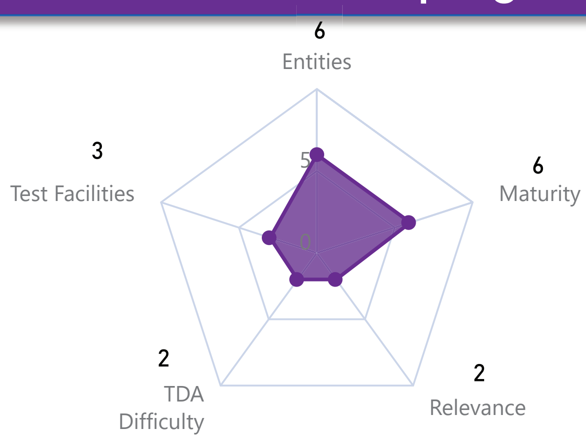
European Entities Involved

| Public | Private |
|---|---|
| ITER<br>KIT (Germany)<br>DTT (Italy) | Research Instruments<br>ALSYMEX<br>Kyoto Fusioneering<br>Absolut System<br>SDMS<br>AVS<br>HSR AG Balzers |

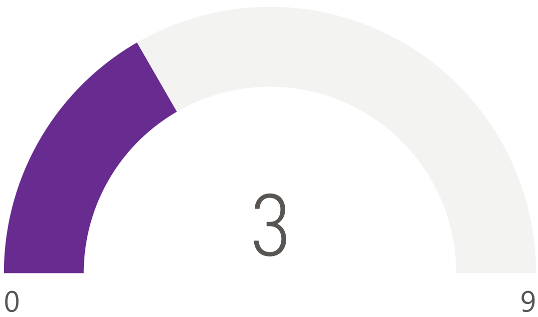
## Technology Development Actions

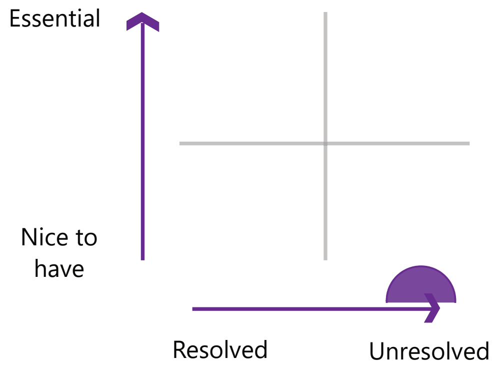
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Develop water resistant glue for charcoal | >80% | 6 months to 2 years | <250k | Medium | No |
| Prototype a cryopump panel with carbon nanotube cryosorption media | <40% | 6 months to 2 years | 250k to 1M | Low | No |
| Tritium accountancy at cryopump sorption panels | <40% | >2 years | >1M | Medium | No |

# Temperature Staged cryogenic condensation and adsorption pumps




TRL




| Other Fields of Application |
|---|
| Hydrogen |

| Alternative Technologies |
|---|
| TMPs<br>Cryosorption<br>NEG<br>Metal foil pump<br>proton conductor pump |

| Showstoppers list |
|---|

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| ITER | Investigate separation capabilities of the pumps |

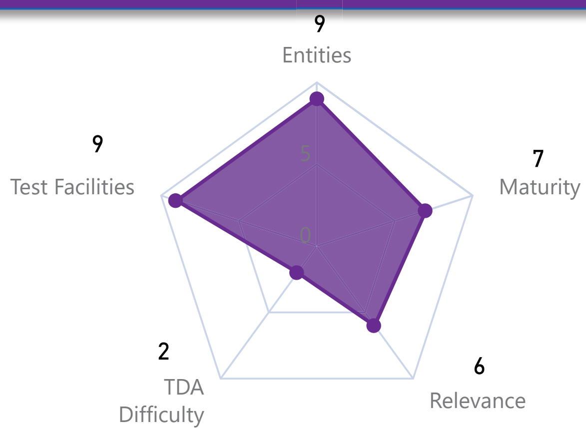
European Entities Involved

| Public | Private |
|---|---|
| CEA Grenoble (France)<br>CERN<br>KIT (Germany)<br>ITER | |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Detailed study of a temperature staged cryopump | 40 to 80% | 6 months to 2 years | 250k to 1M | Low | No |

# Continuous Cryogenic Diffusion Pump / Snail Pump

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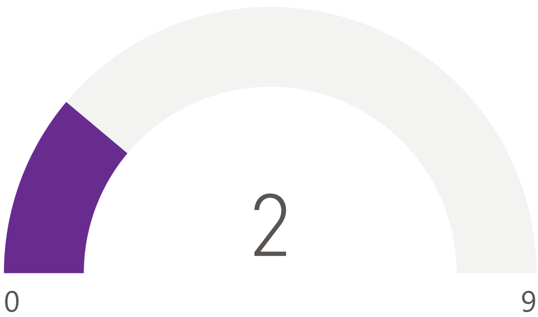
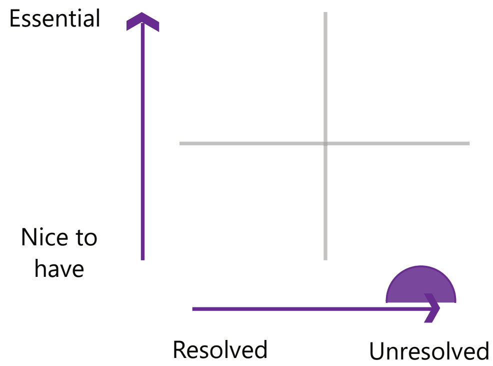



Other Fields of Application

Alternative Technologies

For plasma pumping and at high TRL ITER like Cryopumps only

Showstoppers list

Scale-up
Moving parts reliability

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
| --- | --- |

European Entities Involved

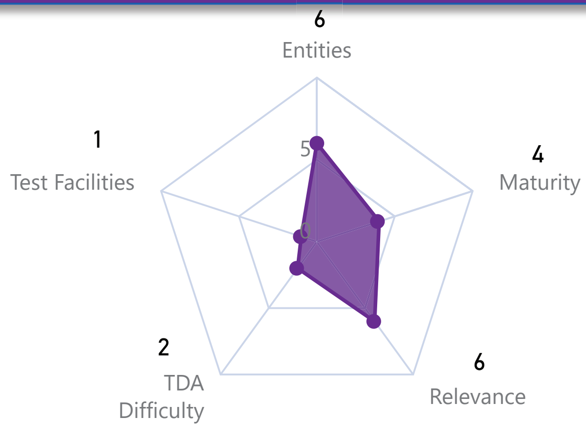
| Public | Private |
| --- | --- |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
| --- | --- | --- | --- | --- | --- |
| Develop a snail pump in Europe | <40% | >2 years | >1M | Low | No |

# Fuel Cycle > Pumping

# Cryogenic Viscous Compressor (CVC)

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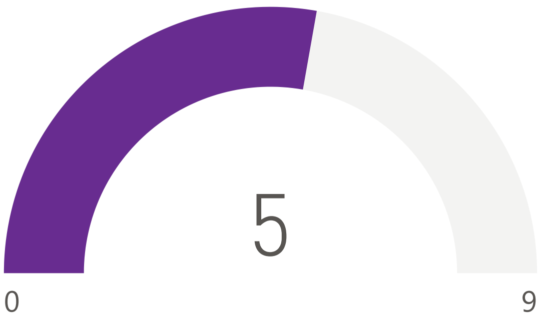
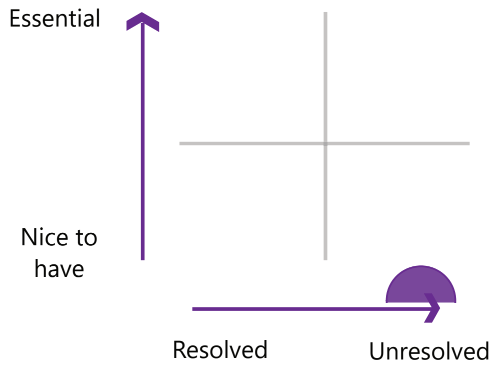



| Other Fields of Application | Alternative Technologies | Showstoppers list |
|---|---|---|
| | Tritium compatible mechanical pumps<br>Metal foil pumps<br>Conventional pumps scroll roots | Large tritium inventories<br>Regeneration technology<br>Explosion protection limits |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| CEA Grenoble (France) | |

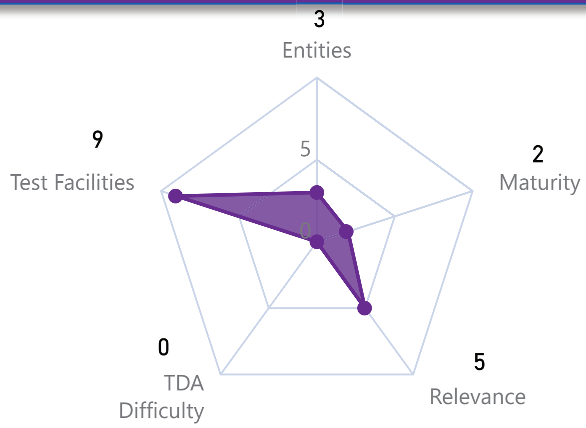
European Entities Involved

| Public | Private |
|---|---|
| ITER<br>CEA Grenoble (France) | |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Investigate the use of the CVC technology in a fusion fuel cycle and define associated requirements | 40 to 80% | 6 months to 2 years | <250k | Low | No |

# Cryogenic Temperature Sensor

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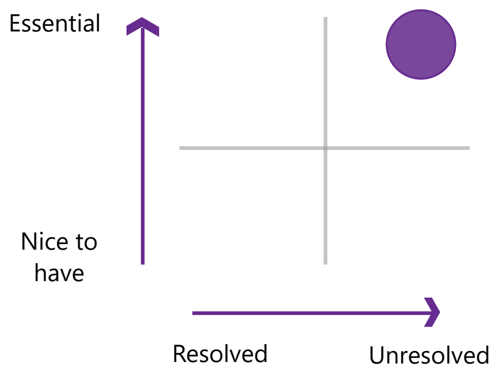



| Other Fields of Application |
|---|
| Accelerators |

| Alternative Technologies |
|---|
| Use of room temperature systems |

| Showstoppers List |
|---|

## Technology Characteristics

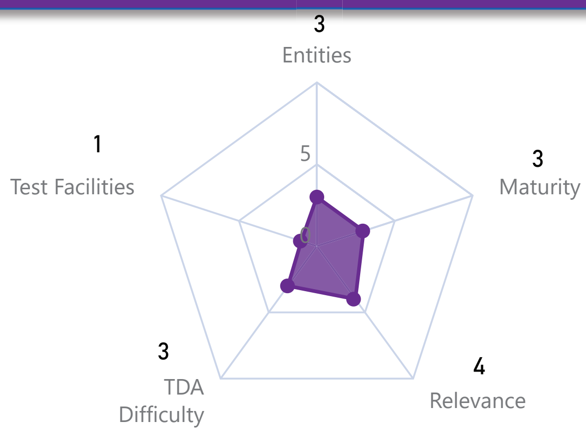
| Existing Test Facilities | Additional Test Facility Needed |
|---|---|

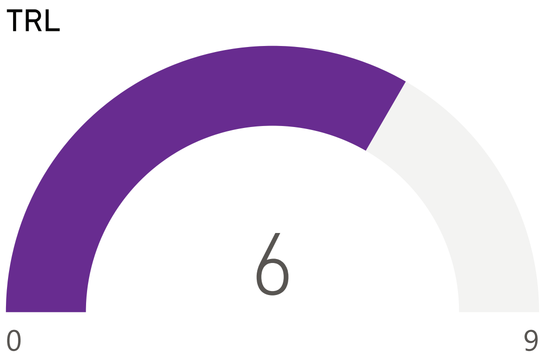
| European Entities Involved | |
|---|---|
| Public | Private |
| ITER | Fraco-Term (PL) |

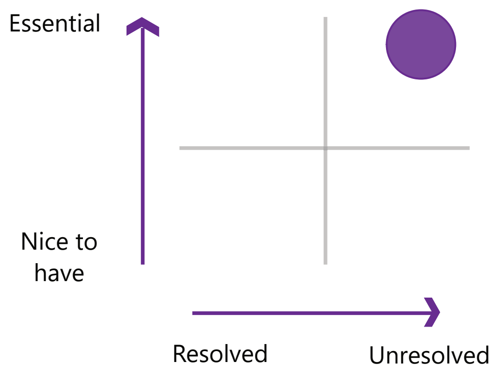
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Qualify operation range of Fraco-term TVOs to 500K, radiation hardness and magnetic field compliance | | 6 months to 2 years | <250k | Low | No |

# Non-Evaporable Getter (NEG) pumps




| Other Fields of Application |
|---|
| Accelerators<br>Hydrogen |

| Alternative Technologies |
|---|
| Cryopumps<br>TMP<br>diffusion pumps<br>other getter pumps |

| Showstoppers list |
|---|
| No pumping of noble gases<br>Regeneration temperature |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| Saes Getters (Italy)<br>Spider RFX Padova (Italy)<br>DIPAK KIT (Germany) | Radiation and tritium compatibility |

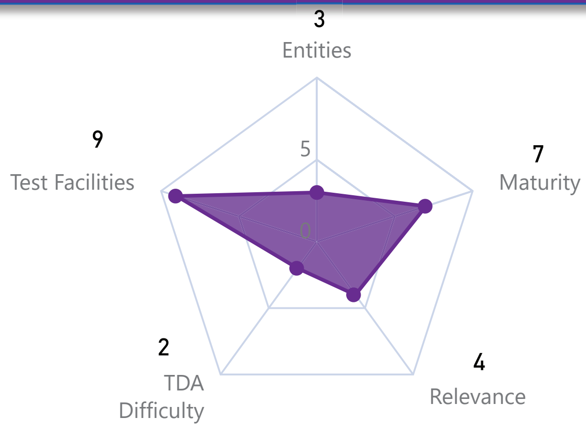
European Entities Involved

| Public | Private |
|---|---|
| KIT (Germany)<br>RFX (Italy)<br>IPP Garching (Germany)<br>CERN | SAES Getter (Italy) |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Getter pump material research to improved robustness | 40 to 80% | 6 months to 2 years | 250k to 1M | Low | No |
| Getter Pump qualification for prove compatibility with radiation and tritium (2 tasks). | 40 to 80% | 6 months to 2 years | 250k to 1M | Low | No |
| High Pressure Characterization of Getter Beds | >80% | >2 years | 250k to 1M | Low | No |
| Successfuly validate an stage pumping system by simulation/computation | 40 to 80% | 6 months to 2 years | <250k | High | No |

# Metal foil pump

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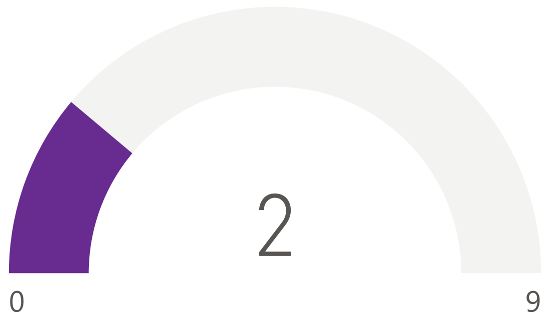
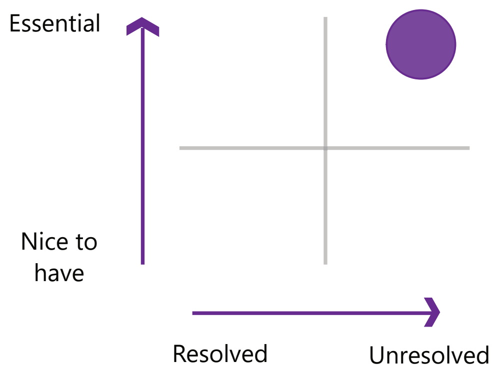



**Other Fields of Application**

Hydrogen industry
Semiconductors

**Alternative Technologies**

Proton conductor pumps,
Cryosorption pumps

**Showstoppers list**

Reliability and maintenance in environment

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| DIPAK KIT (Germany - Under construction)<br>H3AT (UK - Under construction)<br>UNITY-2 (Canada - Under construction). | Upscale development and testing<br>Test performance and operation<br>Testing with Tritium |

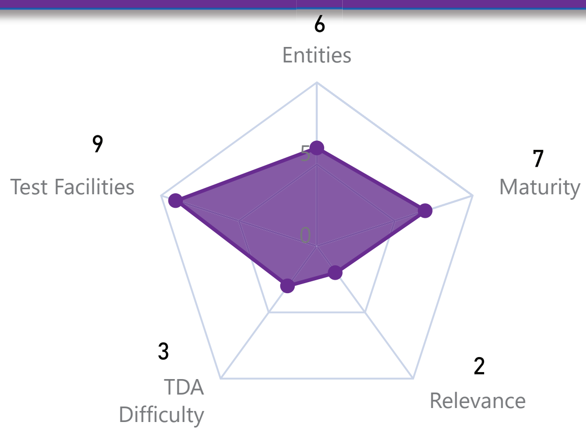
European Entities Involved

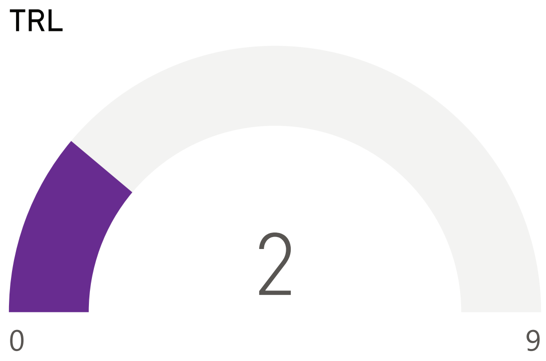
| Public | Private |
|---|---|
| KIT<br>University of Stuttgart | Kyoto Fusioneering<br>Eni (Italy) |

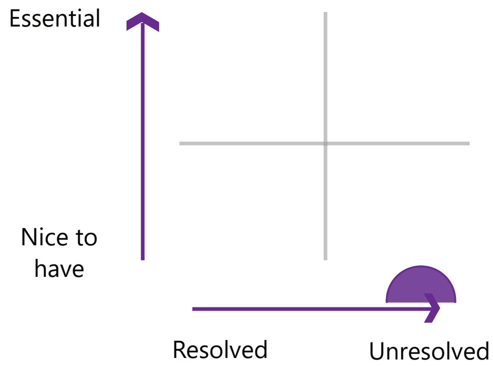
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Develop atomic H2 production sources | 40 to 80% | 6 months to 2 years | 250k to 1M | Medium | No |
| Performance and operation qualification (1° qualification step) | 40 to 80% | 6 months to 2 years | 250k to 1M | Medium | Partially |
| Prototype the Metal Foil Pump | >80% | >2 years | >1M | Medium | Partially |
| Qualification with tritium (second qualification step) | 40 to 80% | 6 months to 2 years | 250k to 1M | Medium | Partially |

# Proton conductor pump




| Other Fields of Application |
|---|
| Pure hydrogen separation<br>H2 purification<br>Petrochemical |

| Alternative Technologies |
|---|
| Metal foil<br>quantum sieving |

| Showstoppers list |
|---|
| Reliability<br>Compatibility with operational conditions<br>Maintenance |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|

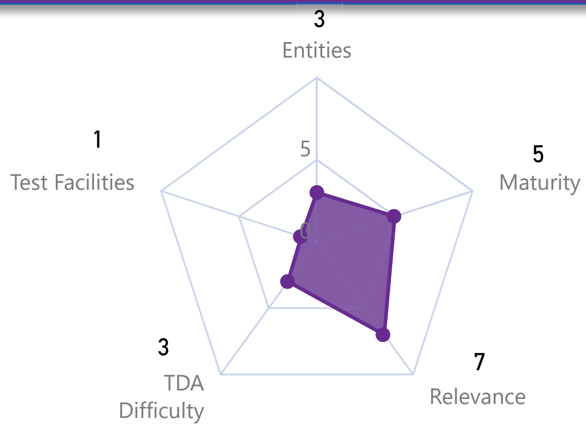
European Entities Involved

| Public | Private |
|---|---|
| Kyoto Fusioneering | |

## Technology Development Actions

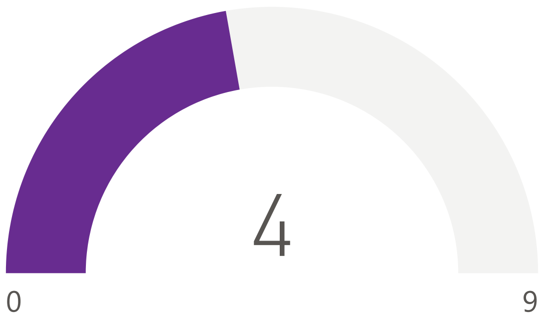
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Assess the feasibility of a proton conductor pump for the fusion fuel cycle | >80% | <6 months | <250k | Low | No |

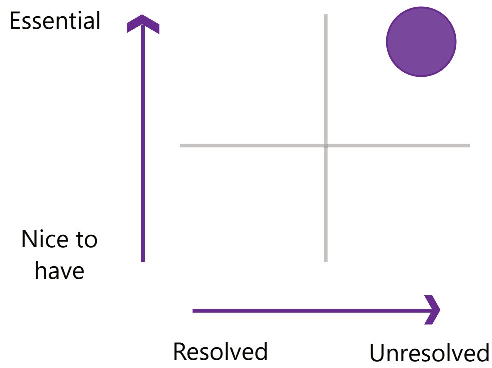
# Fuel Cycle › Pumping




# Liquid metal diffusion pump

TRL




### Other Fields of Application

### Alternative Technologies

Cryopumps
TMP
other diffusion pumps,

### Showstoppers list

Mercury regulation EU 852/2027 for protection of health and environment
Mercury contamination of other systems in the fusion power plant

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| DIPAK KIT (Germany - Under construction) | |

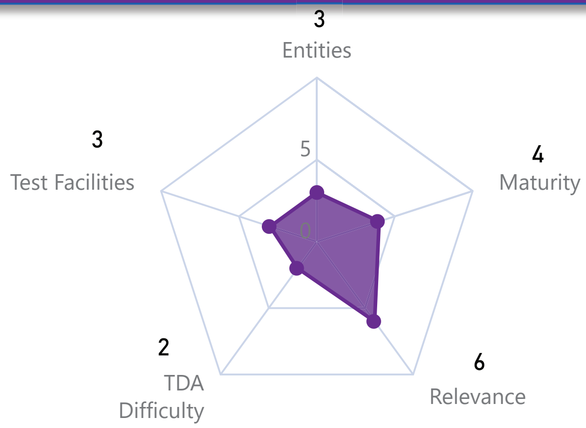
European Entities Involved

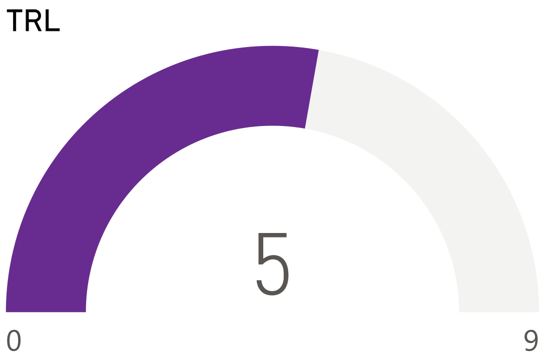
| Public | Private |
|---|---|
| KIT (Germany) | Kyoto Fusioneering |

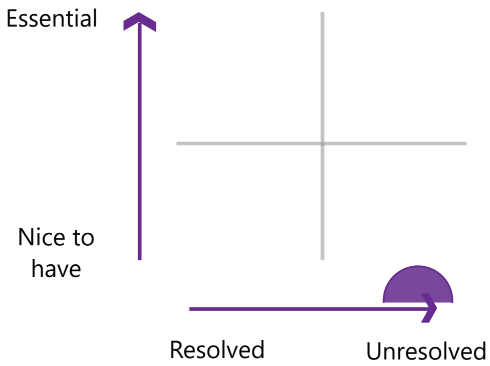
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Demonstrate compatibility with a plasma protection systems (DMS) | 40 to 80% | <6 months | <250k | High | No |
| Develop liquid lithium diffusion pump | 40 to 80% | 6 months to 2 years | 250k to 1M | Medium | Yes |
| Performance and operation demonstration in a relevant environment | >80% | >2 years | >1M | Medium | No |
| Proof that there is no mercury back flow into the torus | 40 to 80% | 6 months to 2 years | <250k | High | No |

# Liquid Ring pumps




### Other Fields of Application

### Alternative Technologies

Mechanical displacement pumps (all metal SS, Octa 1500 by Pfeiffer qualified by ITER US)

### Showstoppers list

Pump liquid not compatible with fusion process gases

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| DIPAK KIT (Germany - Under construction)<br>UKAEA Rochester (UK)<br>Unity-2 (Canada - Under construction) | Tritium test bench |

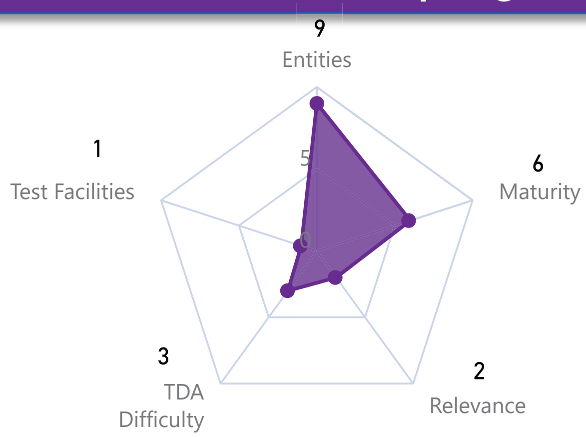
European Entities Involved

| Public | Private |
|---|---|
| KIT | Vakuo GmbH<br>Nash<br>Friatec AG<br>Hermetic |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Find an alternative to mercury | 40 to 80% | 6 months to 2 years | <250k | | No |
| Qualify the mercury liquid ring pump to fusion requirements | >80% | 6 months to 2 years | >1M | Medium | No |

# Oil diffusion pumps with tritium compatible oils

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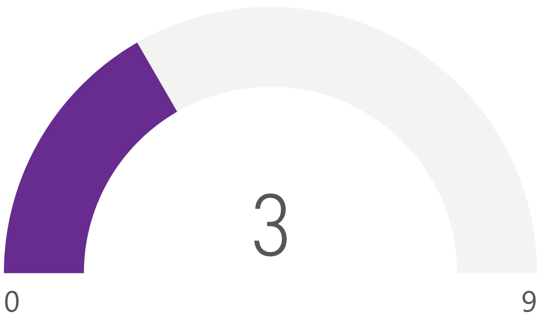
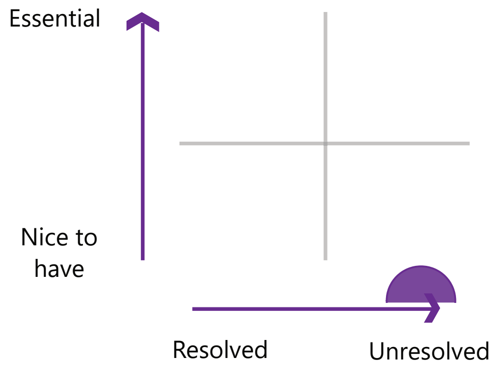



**Other Fields of Application**

Petrochemicals
semiconductors,

**Alternative Technologies**

Cryopump
TMP
NEGs

**Showstoppers list**

Oil in the process
Contamination of plasma
Tritium compatibility
Degradation of oil

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
| --- | --- |

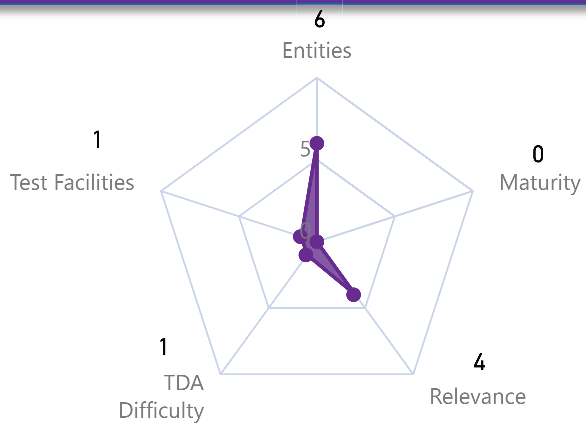
European Entities Involved

| Public | Private |
| --- | --- |

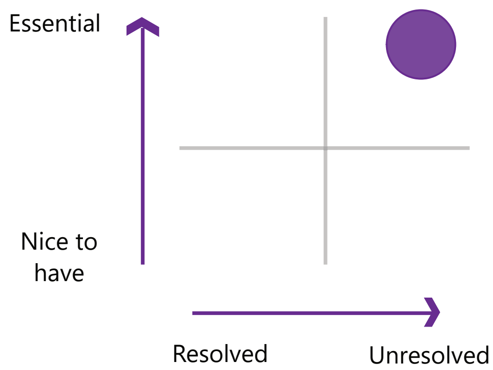
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
| --- | --- | --- | --- | --- | --- |
| Design optimization to exclude any oil back flow to the process/system for compliance with requirements | 40 to 80% | 6 months to 2 years | <250k | Low | No |
| Develop oil that is tritium compatible | <40% | >2 years | 250k to 1M | Low | No |

# Metal bellows pumps








### Other Fields of Application

Aerospace
Petrochemical

### Alternative Technologies

### Showstoppers list

## Technology Characteristics

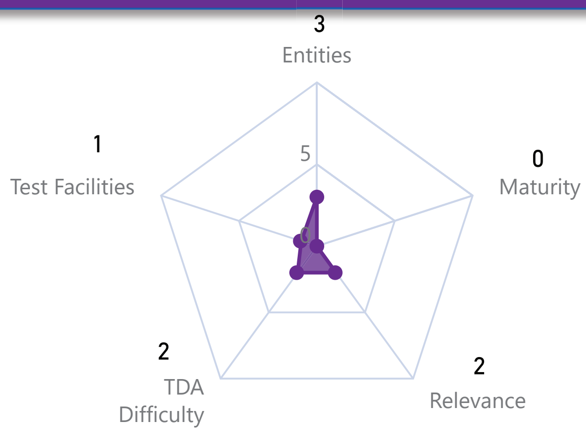
| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| KIT/TLK (Germany)<br>UKAEA Rochester (UK)<br>Unity-2 (Canada - Under construction) | |

| European Entities Involved | |
|---|---|
| Public | Private |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Certify existing internationally available pumps to European Market | >80% | 6 months to 2 years | 250k to 1M | Medium | No |

# Scroll pumps

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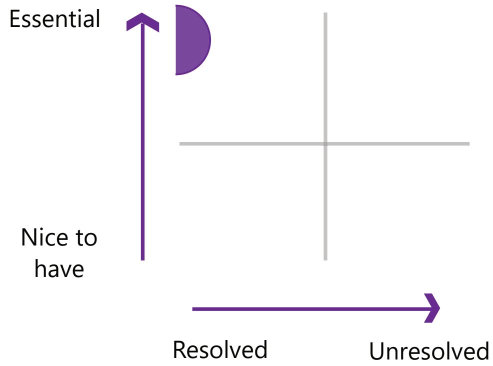



**Other Fields of Application**

Process industry
Accelerators

**Alternative Technologies**

**Showstoppers list**

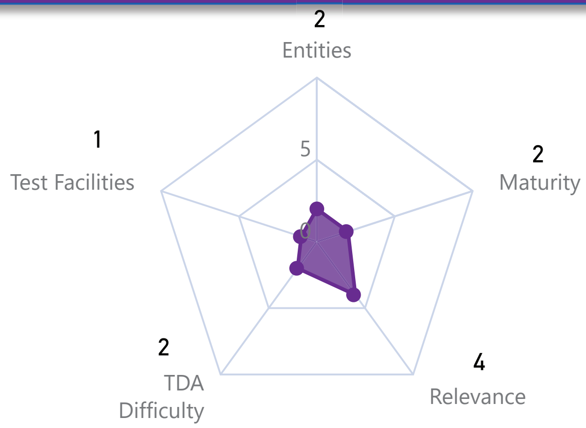
## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed | European Entities Involved: Public | European Entities Involved: Private |
|---|---|---|---|
| KIT - (Germany)<br>UKAEA Rochester (UK)<br>Unity-2 (Canada - Under construction) | | | EUMECA (150 m3/hr and 15 m3/hr qualified by ITER) |

## Technology Development Actions

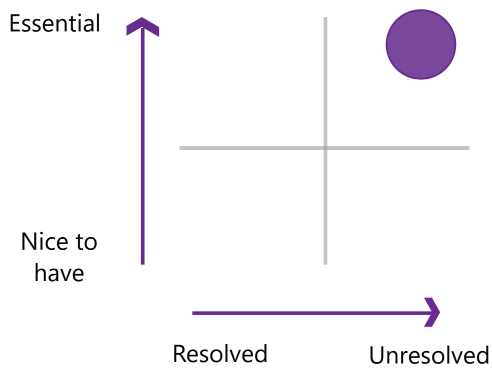
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Develop tritium compatible tip seal to improve pumping performances | >80% | 6 months to 2 years | <250k | Low | No |
| Diversify the supply chain for tritium compatible scroll pump | >80% | >2 years | 250k to 1M | Medium | No |

# Fuel Cycle › Pumping




# Roots pumps

TRL


| Other Fields of Application | Alternative Technologies | Showstoppers list |
|---|---|---|
| Accelerators<br>Semiconductor | CVC<br>screw | |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| KIT (Germany)<br>UKAEA Culham (UK)<br>Unity-2 (Canada - Under construction) | |

European Entities Involved

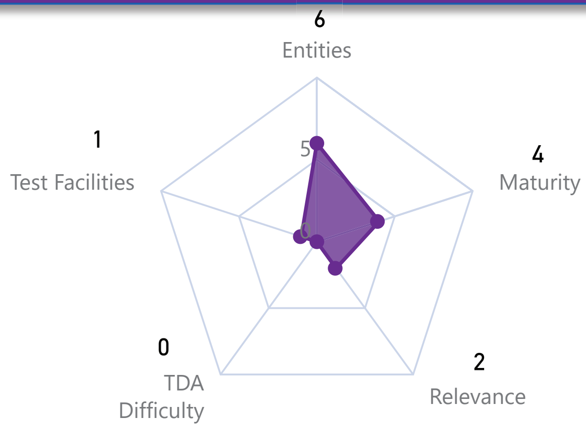
| Public | Private |
|---|---|
| ITER | Pfeiffer (OCTA 1500 SS all metal)<br>Edwards<br>Busch<br>Vacuum solutions<br>Leybold |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Determine the Roots pump tritium compatibility | >80% | 6 months to 2 years | >1M | Medium | Yes |
| Industrialize tritium compatible roots pumps | >80% | 6 months to 2 years | <250k | Medium | Partially |

## Fuel Cycle › Pumping

# Piston pumps

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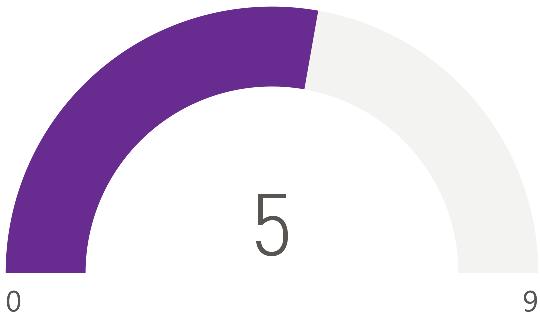
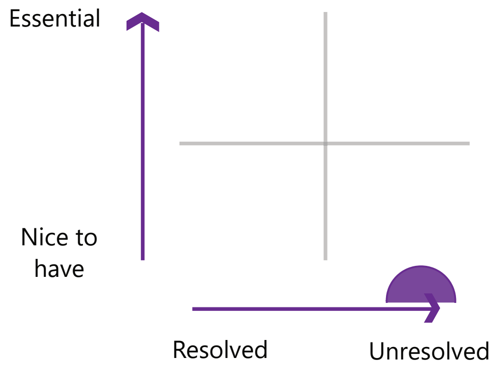



| Other Fields of Application | Alternative Technologies | Showstoppers list |
|---|---|---|
| Petrochemical | Mechanical displacement pumps | |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| KIT (Germany)<br>UKAEA Rochester (UK)<br>Unity-2 (Canada - Under construction) | |

European Entities Involved

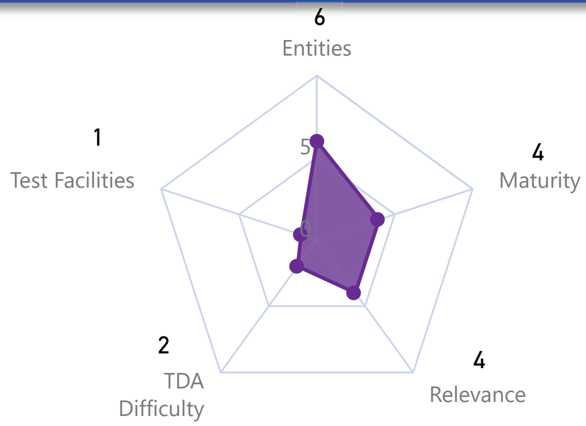
| Public | Private |
|---|---|

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|

# Fuel Cycle › Pumping

# Screw pumps

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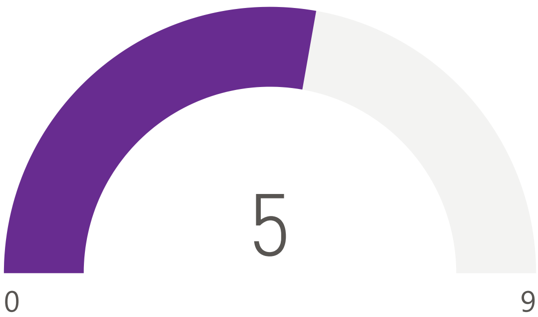
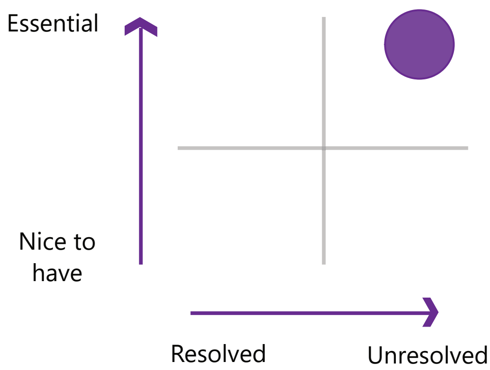



### Other Fields of Application

Accelerators
Semiconductor

### Alternative Technologies

### Showstoppers list

## Technology Characteristics

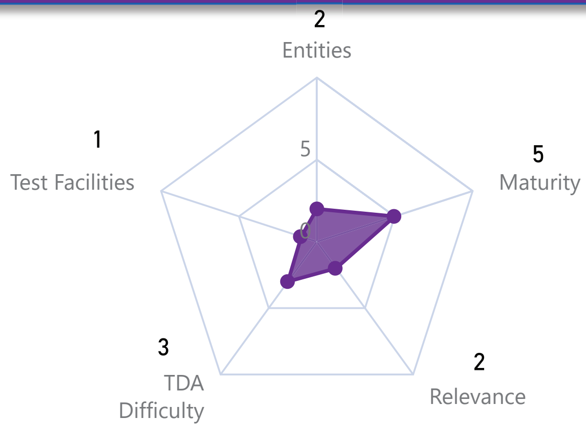
| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| KIT (Germany)<br>UKAEA Culham/Rochester (UK)<br>Unity-2 (Canada - Under construction) | |

| European Entities Involved | |
|---|---|
| Public | Private |

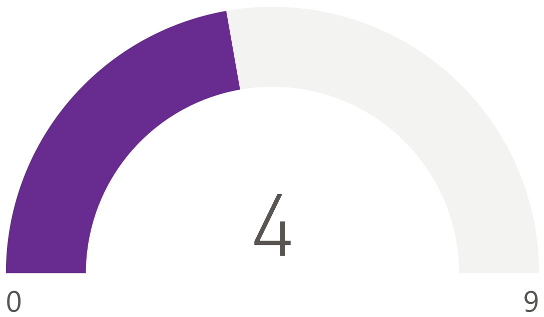
## Technology Development Actions

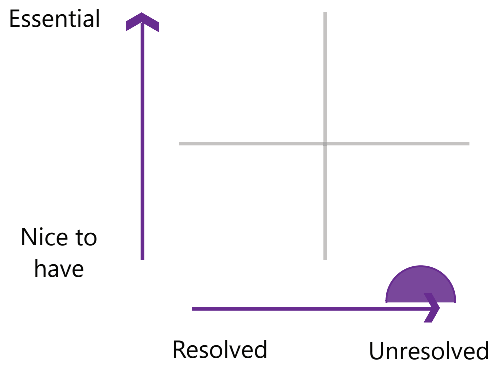
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Develop a tritium compatible single shaft screw pump | >80% | 6 months to 2 years | >1M | Medium | No |
| Screw pump purge gas alternative | 40 to 80% | 6 months to 2 years | 250k to 1M | Low | No |

# Turbo Molecular Pump and Cryogenic TMP




TRL




## Other Fields of Application

Semiconductors
Chemical Vapour Deposition
Coating
High energy physics
space

## Alternative Technologies

Cryo-adsorption Pumps not continuous
Snail/Diffusion pumps
Metal Foil pumps

## Showstoppers list

Magnetic field compatibility

## Technology Characteristics

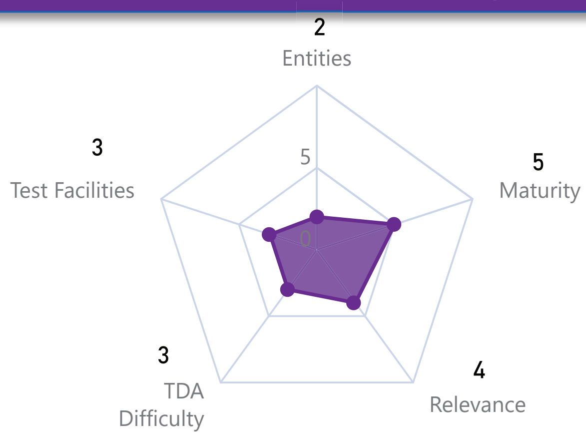
| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| CEA Grenoble (France) | |

European Entities Involved

| Public | Private |
|---|---|
| ITER<br>CEA Grenoble (France) | ALCEN/ALSYMEX+IRELEC<br>Pfeiffer, Edwards, Inficon, Agilent, Busch, Oerlikon |

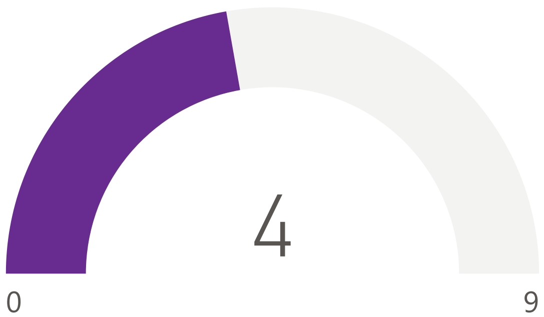
## Technology Development Actions

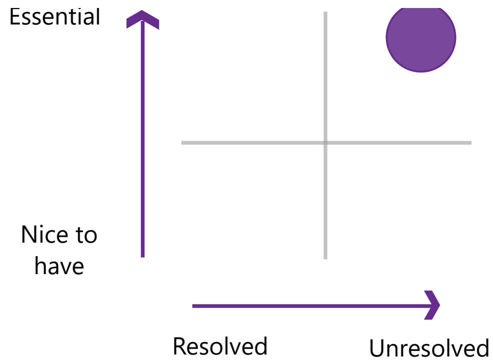
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Academic study for TMP and cryo TMP Tokamak operation environment | >80% | <6 months | <250k | Low | No |
| Develop TMP with a rotor and MagLev suspension working at cryogenic temperatures | 40 to 80% | 6 months to 2 years | 250k to 1M | Low | No |
| Development of a magnetic field, ionizing radiation and tritium-compatible TMP | 40 to 80% | 6 months to 2 years | >1M | Medium | No |




# Tritium permeation barriers

TRL




### Other Fields of Application

Hydrogen production
Fission
Space
Waste

### Alternative Technologies

Base material selection
Healing under irradiation
Return of experience from operation

### Showstoppers list

Regulatory issues
Complex shapes of components
Resistance to harsh environment
In consistent data and limited test facilities

## Technology Characteristics

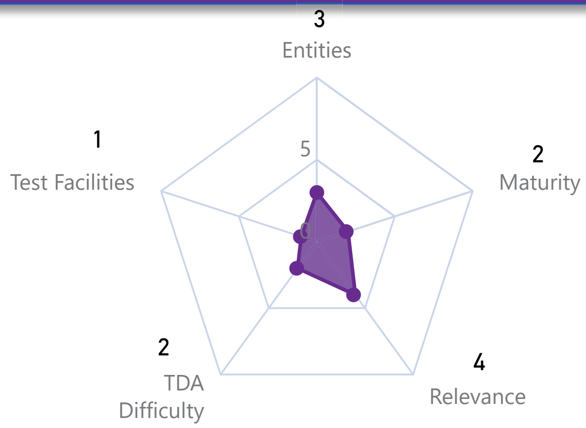
| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| CURIUM (France) | |
| UKAEA Culham (UK)<br>CURIUM (France)<br>IPP Garching (Germany)<br>Fraunhofer IWS Dresden (Germany) | Permeation testing |

| European Entities Involved | |
|---|---|
| Public | Private |
| CEA Saclay/Cadarache (France)<br>CERN<br>University of Latvia (Riga)<br>Fraunhofer IWS Dresden<br>UKAEA Culham (UK)<br>IPP Garching (Germany)<br>CEN-SCK (Belgium)<br>VTT (Finland)<br>ICSI Valcea (Romania) | BIMO Tech (Poland)<br>Kyoto Fusioneering (Europe)<br>Eni Spa (Italy)<br>Amentum (France)<br>Orano (France) |

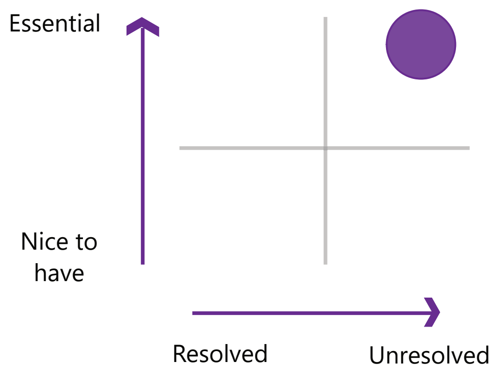
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Amendment of material codes to cover tritium permeation (or develop specific code) | >80% | >2 years | 250k to 1M | Low | No |
| Consolidation of existing data in database | >80% | 6 months to 2 years | <250k | High | Partially |
| Create a community for permeation material testing | >80% | <6 months | <250k | High | Yes |
| Creation of a handbook of best practices for tritium permation | 40 to 80% | 6 months to 2 years | <250k | Medium | No |
| Creation of a reference document for testing protocols | >80% | 6 months to 2 years | <250k | High | Yes |
| Develop specific material to limit permeation (eg EUROPERM, micro-structured concrete etc) | 40 to 80% | >2 years | >1M | High | No |

# Instruments to measure hydrogen isotope concentrations




TRL


## Other Fields of Application

Hydrogen economy
Heavy water production
Fission

## Alternative Technologies

Raman
mass spectrometry
ion chambers
scintillation
gas chromatography and proportional counters

## Showstoppers List

Online measuring in high flows
not for fuel cycle
memory effects
SMF
Magnetic field conditions
neutron sensitiveness
compatibility with activated PEGs and some compounds (depending on technique)

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| KIT/TLK (Germany)<br>UKAEA Culham (UK) | |

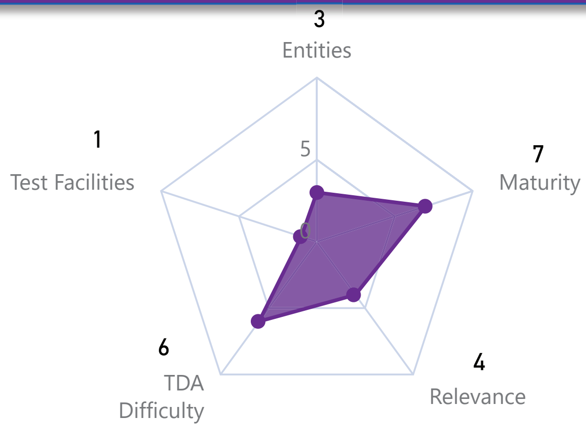
| European Entities Involved | |
|---|---|
| Public | Private |
| CEA Cadarche (France)<br>KIT/TLK (Germany) | SMOLSYS (Switzerland)<br>IS Instruments Ltd (UK) |

## Technology Development Actions

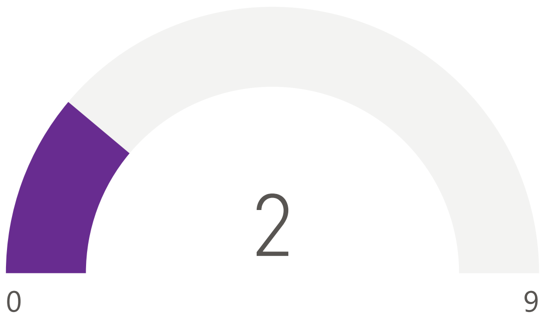
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Improvement of response time and improvement of the sensitivity for low concentrations | 40 to 80% | 6 months to 2 years | 250k to 1M | High | No |
| Industrialization of Raman Spectroscopy Detector | >80% | >2 years | 250k to 1M | Medium | Partially |

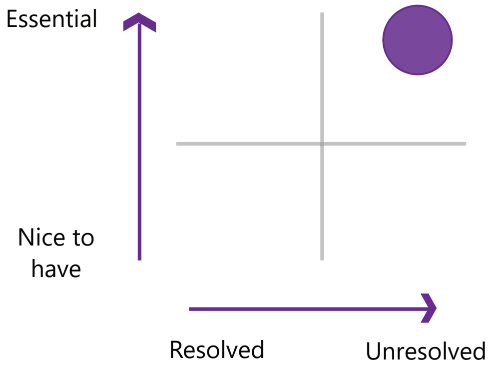
# Fuel Cycle > Tritium management

# Non-destructive Tritium detection in solids




TRL




| Other Fields of Application |
|---|
| Fission<br>Radwaste |

| Alternative Technologies |
|---|
| Destructive methods |

| Showstoppers list |
|---|
| Difficulty in detecting low-energy beta particles |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| CURIUM (France)<br>CEA Cadarache (France)<br>Forschungszentrum Juelich (Germany) | |

European Entities Involved

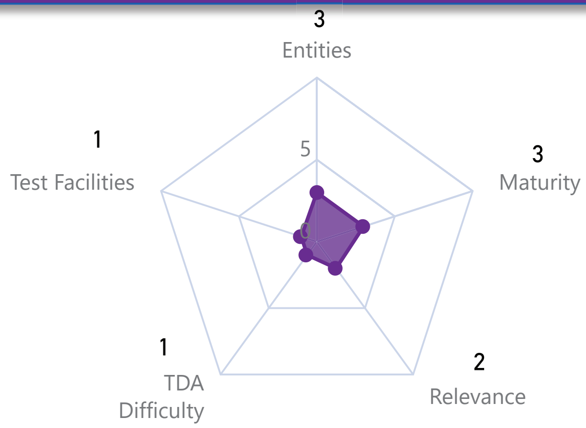
| Public | Private |
|---|---|
| CEA Cadarache - Future tritium process test facility for 2031 (France)<br>Forschungszentrum Juelich (Germany) | KEP Technologies EMEA |

## Technology Development Actions

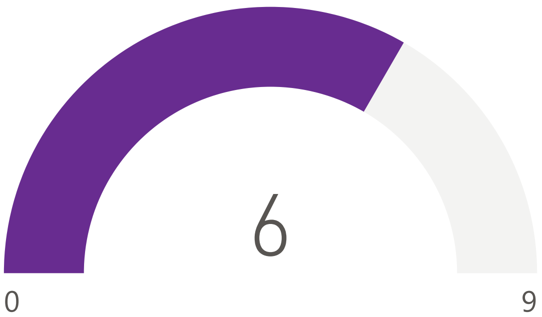
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Analyse to define the methods for non-destructive tritium measurements in solids. | >80% | <6 months | <250k | Medium | No |

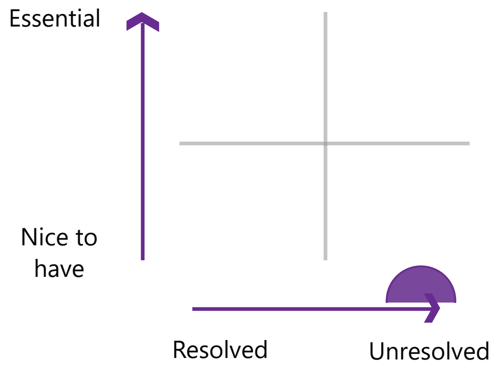
# Fuel Cycle › Tritium management

# Wearable tritium detector




TRL




| Other Fields of Application |
|---|
| Fission<br>Radwaste |

| Alternative Technologies |
|---|
| ex post analysis<br>room monitors |

| Showstoppers list |
|---|
| Size limitation<br>Online-measuring |

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| CURIUM (France)<br>KIT/TLK (Germany) | |

European Entities Involved

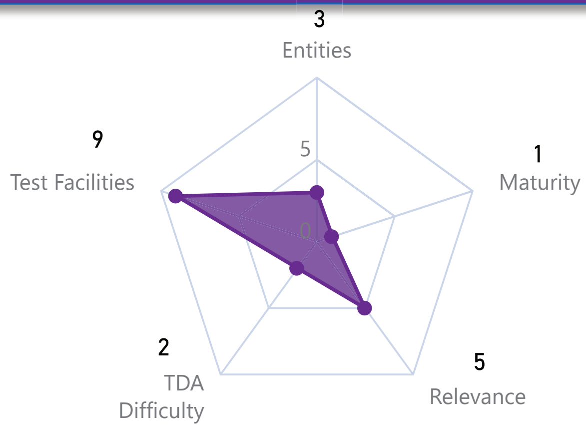
| Public | Private |
|---|---|
| ENEA Frascati (Italy)<br>CIEMAT Madrid (Spain)<br>CEA Cadarache (France) | Mirion<br>Tekniker<br>Else Nuclear |

## Technology Development Actions

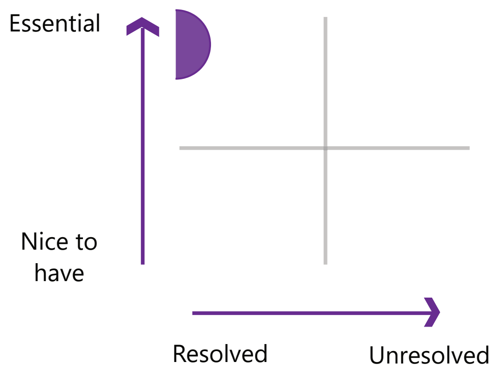
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Develop a prototype wearable tritium detector | >80% | 6 months to 2 years | 250k to 1M | Low | Yes |

# Fuel Cycle › Tritium management

# Room tritium detector








| Other Fields of Application | Alternative Technologies | Showstoppers List |
|---|---|---|

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|

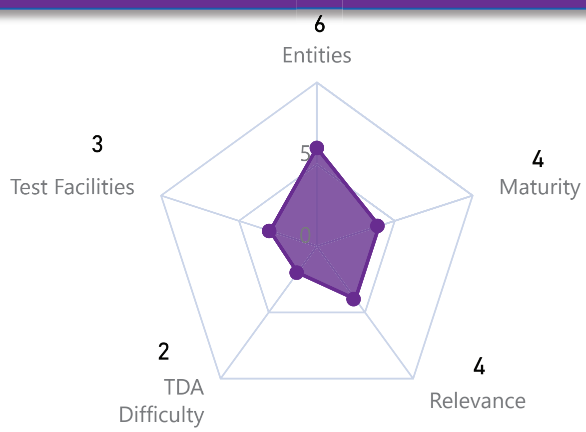
European Entities Involved

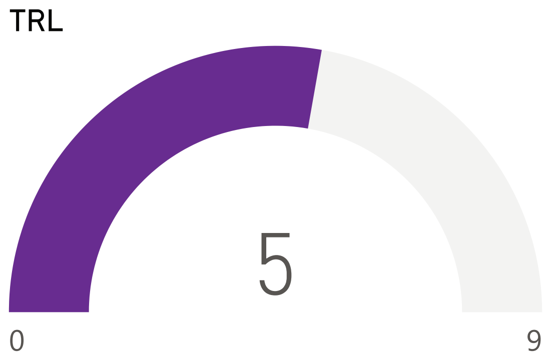
| Public | Private |
|---|---|
| CEA Cadarache (France)<br>KIT/TLK (Germany)<br>UKAEA (UK) | Mirion<br>Berthold |

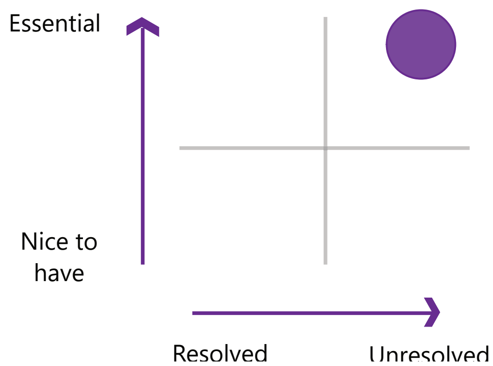
## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| For real time process measurements create a tritium performance and calibration test bench (for high concentration) | >80% | 6 months to 2 years | >1M | Low | Partially |

# Real time tritium detector for water




| Other Fields of Application | Alternative Technologies | Showstoppers list |
|---|---|---|
| Fission<br>CANDU<br>waste | | Size<br>Memory effects (especially in low level measurements) |

## Technology Characteristics

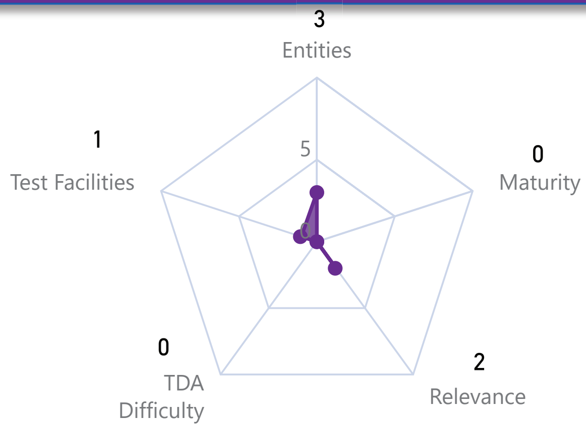
| Existing Test Facilities | Additional Test Facility Needed | European Entities Involved | |
|---|---|---|---|
| | | Public | Private |
| CURIUM (France)<br>KIT/TLK (Germany) | Compatibility with neutron flux magnetic field | CEA Cadarache - (France - Under construction) | |

## Technology Development Actions

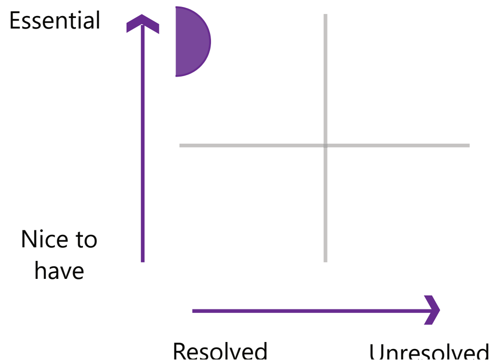
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Design, build and test a European prototype detector for tritium in water | 40 to 80% | 6 months to 2 years | 250k to 1M | | No |

Fuel Cycle › Tritium management

# Tritium sealing of dismountable flanges




TRL


| Other Fields of Application | Alternative Technologies | Showstoppers list |
|---|---|---|
| Fission | VCR for sizes smaller 1" | |

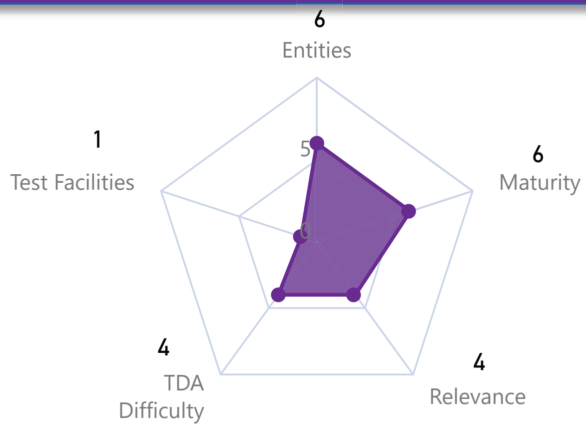
## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed | European Entities Involved | |
|---|---|---|---|
| | | Public | Private |
| Maestral Lab (CEA & Technetics) | | CEA (France)<br>Technetics (France) | Technetics (France)<br>SPG Eiffage (Joint S) |

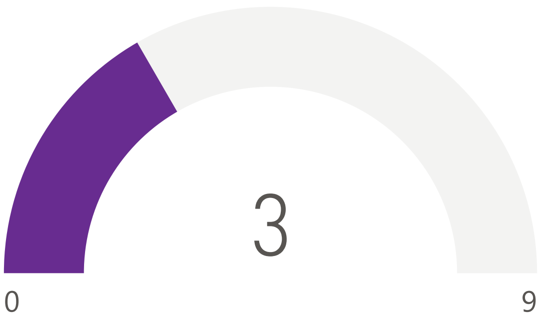
## Technology Development Actions

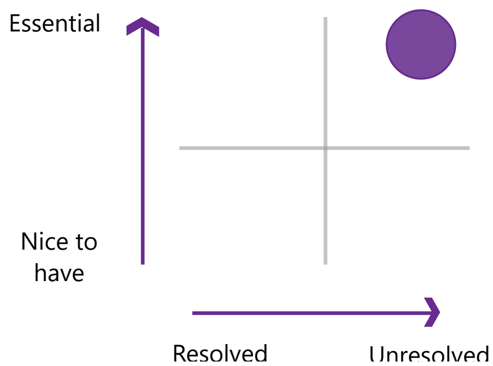
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|

# Tritium accountancy




TRL




| Other Fields of Application |
|---|
| Fission<br>Radwaste |

| Alternative Technologies |
|---|
| |

| Showstoppers list |
|---|
| Lack of tools<br>Lack of experimental data<br>Lack of reliable and accurate in-situ instrumentation for high flow measurements |

## Technology Characteristics

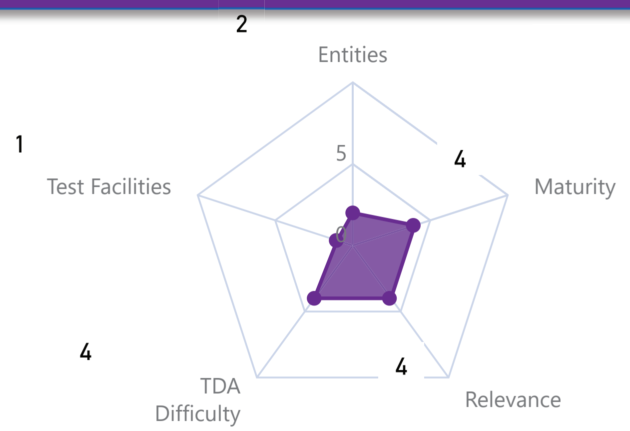
| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| KIT/TLK (Germany) | |

European Entities Involved

| Public | Private |
|---|---|
| University of Manchester (UK)<br>UKAEA (UK)<br>ITER<br>KIT/TLK (Germany) | |

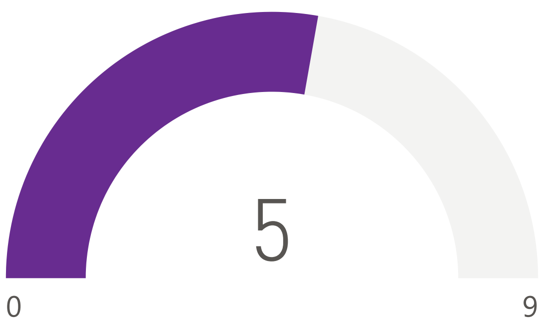
## Technology Development Actions

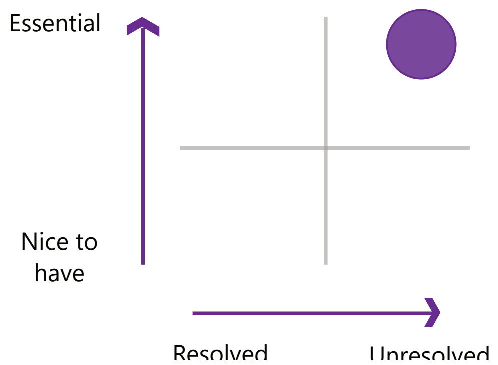
| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Create a community | >80% | <6 months | <250k | Medium | No |
| Import best practice from JET DTE2/3 and fission fuel accountancy and create a reference document including specificities for tritium accountancy, | >80% | 6 months to 2 years | <250k | Medium | No |




# Process Simulation Model Validation

TRL




**Other Fields of Application**

Other tritium systems
H economy
Fission
Petrochemical

**Alternative Technologies**

**Showstoppers list**

Lack of experimental data for validation

## Technology Characteristics

| Existing Test Facilities | Additional Test Facility Needed |
|---|---|
| H3AT (UK - Under construction)<br>Unity 2 (Canada - Under construction)<br>DIPAC KIT (Germany - Under construction) | |

**European Entities Involved**

| Public | Private |
|---|---|
| ITER<br>ENEA (Italy)<br>UKAEA (UK) | ENI (Milan)<br>RINA (Genoa)<br>Impresarios Agrupados (Madrid)<br>Atkins Realis<br>Polaris (Minsito)<br>Kraftenlagen (Heildelberg)<br>MONTEIRO |

## Technology Development Actions

| TDA Name | Chances of Success | Implementation Time | Cost | Priority | Funded |
|---|---|---|---|---|---|
| Create a community for tritium process simulation | >80% | <6 months | <250k | Medium | Yes |
| Create and populate database for H isotope properties | 40 to 80% | 6 months to 2 years | 250k to 1M | High | No |
| Exchange results and data for benchmarking. | >80% | <6 months | <250k | Medium | No |

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