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: 1. Introduction 2. The mapping process 3. Fuel cycle technology breakdown (draft) 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		Final report for publication

Contents

Foreword

Will be completed for the final report

Executive summary

Will be completed for the final report.

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 those 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

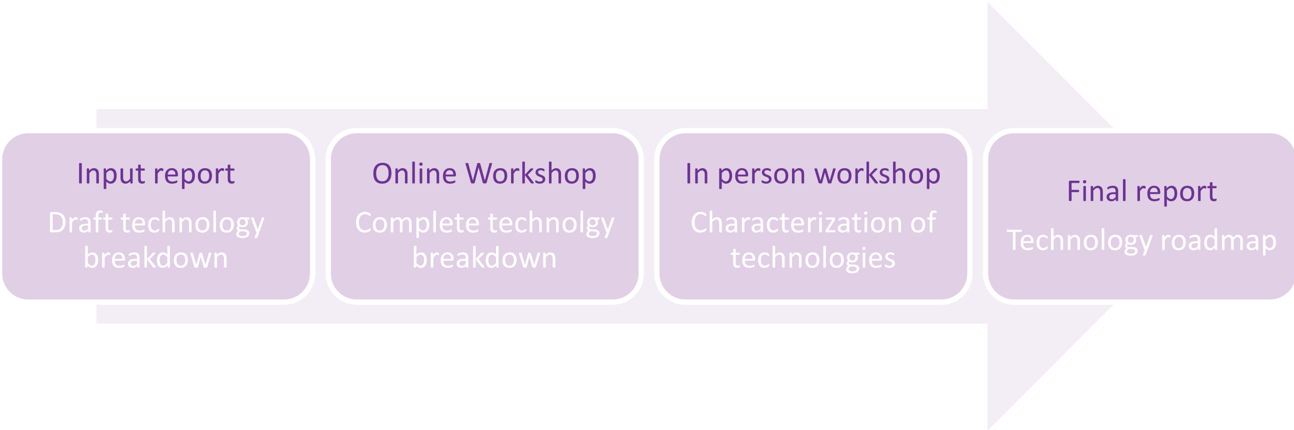
The scope of the first such mapping exercise is the fusion fuel cycle. It covers vacuum pumping, fuel purification, storage and injection, isotope separation, water detritiation, air detritiation and tritium management. Tritium breeding technologies such as blanket modules and Lithium enrichment will be the subject of a separate exercise.

The main associated event is 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 prepare 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, is 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 is the opportunity for all participants to the technology mapping exercise to come together. It typically lasts 3 to 4 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 is an exhaustive list of relevant technologies agreed between all participants in the workshop. This breakdown forms 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) is made available to participants before the in-person workshop.

2.3 In person workshop

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

- Agreement on current Technology Readiness Level (see Appendix 1 for definitions)
- Definition of the next step (eg analysis, prototype, testing, industrialization plan etc) and time permitting of the one after that.
- Quantification of the characteristics of the technology (see appendix 2 for proposed list of characteristics to be evaluated).
- A timeline with a classification of what is needed when, for the technologies considered in the technology mapping. Typical timelines can cover 5, 15 or 30 years ahead, or short, medium and long times.

The workshop is 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 provides 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, staff from Fusion for Energy and Eurofusion compile the outcome in a final report (an evolution of the input report). The report includes an overview of European capabilities in the field as well as the proposed technology roadmap detailing and prioritizing possible actions for the period until the next review (typically 2 to 3 years).
Participants are given an opportunity to comment before the final version of the report is published.

3 Fuel Cycle technology Breakdown

3.1 Fuel Cycle overview

The plasma in a fusion machine needs to be continuously fuelled by 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 directly to 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 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 of the lasers.

For plasma control purposes, additional gases are injected, and a vacuum system is required to **pump the hydrogen isotopes with the additional 'impurity' gases** as well as reaction products.

Since a very 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 impurity gases from the hydrogen 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, which is costly, especially in the face of the current shortage of tritium for civil applications. **Accelerating fuel treatment is of interest to reduce the overall 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.**

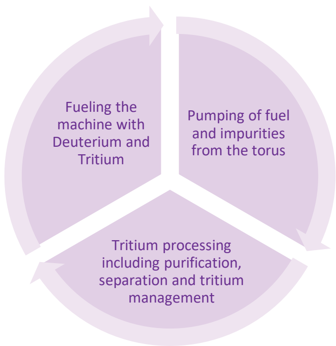
Additional duties of a fusion tritium plant will be to **store fuel**, process tritium from the breeding blankets, **air** and **water detritiation** as well as **tritium measurement and accountancy**.

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 and 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. Next to these the detritiation of gases, liquids or molten salts need to be addressed by tritium processing technologies.
This wide area of technologies is split into two sub-sections:

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

3.3 Map of individual technologies

Overview

Fuelling and storage

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

Membranes and Packing

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

Pumping

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

Tritium Management

- Cryogenic Temperature Sensor
- Instruments to measure hydrogen isotope concentrations
- Magnetic Sector Leak Detector (MSLD)
- Non-destructive Tritium detection in solids
- Process Simulation Model Validation
- Real time tritium detector for water
- Room tritium detector
- Tritium accountancy
- Tritium permeation barriers
- Tritium sealing of dismountable Flanges
- Wearable tritium detector

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 that experiments with tritium pellets are strongly needed. Testing of pellet injection system with tritium is currently not possible in Europe; an integrated test facility would need to be licensed for significant amounts of tritium, and this is not available. 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.

Pellet Source

Extruder

The technology involves creating continuously dense hydrogen ribbons (deuterium and tritium, eventually mixed with impurities for plasma control), 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. A European supply chain is currently not available, and the only suppliers are in Russia or the USA.

Pellet Cutter

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

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. A European supply chain is currently not available.

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 pellets to determine whether they can be injected into the plasma or if they must be discarded. 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 is forming a solid in the capsule and needs to be in a homogeneous geometry.

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. Injectors using gas-gun acceleration or centrifugal accelerators 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 by this in the solid materials. The hydrogen release is controlled by heating the materials to several hundred degrees Celsius. Politically 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, for which, however, no engineering solution is ready yet.

Modelling and Software Developments

Different areas of modelling with a huge variety of background could/should be developed, starting from pellet creation, pellet doping, acceleration and injection tube optimization up to the plasma/pellet interaction. No specific topic for fueling and storage is currently addressed in the technology map.

3.3.2 Pumping Technologies

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.

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. The technology is used for the Torus- Cryostat and Neutral Beam Cryopumps at ITER. The only missing improvement to have a completed product for a fusion power plant is the change to a water-resistant ceramic glue for charcoal adherence.

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 usually required 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.

Diffusion pumps

This pumping technology is based on a momentum transfer from an evaporated working fluid towards the gas molecules that shall be pumped. It pumps all gases – the lighter ones like helium and hydrogen better then heavy species and is capable to achieve low pressure.

Liquid Metal Diffusion Pumps

In this pump, the operating fluid is a liquid metal (mercury or lithium), 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.

Oil diffusion pumps with tritium compatible oils

In these pumps, oil is used as operating fluid. Oil is most used in diffusion pumps, but oils contaminate the process gas and usually are not tritium compatible as they show a quick chemical degradation. There have been investigations launched in the US to determine 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 center, 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. Currently not available as tritium compatible technology, but interesting pump type for several applications in the vacuum system of a fusion power plant. 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. A all stainless-steel pump has been developed and prototyped by ITER and is available on the European market. Compared to the scroll pumps this pump is not fully tritium compatible but can be used within some technical limitations for tritium processing.

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.

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 application a tritium compatible piston pump from a Japanese supplier is used for ITER.

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.

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

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 as well as proton-conducting membranes are additional candidates for the technology.

Packed Beds

Packed beds are used for the hydrogen removal from a gas stream with low hydrogen concentration hydrogen. The packed beds operation efficiency is driven by their accumulation and extraction efficiency. They will be used in batch operations and the regeneration and control strategy will define the final design and the technologies for cooling and heating. Their applications include hydrogen removal from primary gas coolant, from carrier gas and from glove box ventilation.
Zeolite Molecular Sieve beds, CuO beds, catalytic beds, and getter beds are different options.

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.

Equilibrators

Equilibrators are used for balancing hydrogen isotope gas streams within the Isotope Separation System of the fusion tritium plant. By this the separation efficiency of the cryogenic distillation columns can be improved. The equilibrators contain catalysts based on aluminium oxide pebbles coated with palladium.

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, but it could be fuelled with a D/T mixture, it would simplify the fuel cycle a lot, as the Isotope Separation System could be by-passed for a large part of the fueling gas. The separation of the D/T stream from the plasma exhaust gas stream can possibly be realized by cryogenic distillation.

Detritiation of water

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 case of ITER the distillation column has 48 m overall height with ~ Ø 1 m).

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 is a key point to reduce system dimensions.
To optimize the efficiency of the LPCE columns, that are using hydrophilic and hydrophobic internals, the design of the water distribution and the catalyst integration in the columns need to be evaluated and developed.

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.

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.

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 of gas to be detritiated, gas composition/chemistry and hydrogen content. There are several applications such as the detritiation systems for air ventilation, 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.

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.

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 are depending 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.

3.3.4 Tritium management

Instrumentation

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.

Room tritium detectors

The detectors function by 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 to have the applied in areas close to the tokamak.

Real time tritium detectors for water

Tritium detection in liquids for cooling water loops or tritium breeding loops are 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.

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 (10^5Gy for ITER, TBD further). 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.

Wearable tritium detectors

To date, tritium air concentration is monitored in real time by ionization chambers positioned in the working area and 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 with potential advantages for worker protection.

Non-destructive tritium detection in solids (TBD)

Magnetic Sector Leak Detector (MSLD)

MSLD’s are available from industrial suppliers in Europe. For fusion power plants it would be of big advantage to have these leak detectors compliant with the neutron radiation load (TBD) and the magnetic fields, in case of ITER of up to 300 mT +- 100 mT/s. For these environmental conditions several components in the industrial MSLD’s would need to be modified.

Cryogenic heat exchangers (Recuperators)

For the isotope separation system, the hydrogen isotopes are process in between cryogenic components operated at ~20 K and components at RT. The required heat exchangers operated between 20 K and 300 K require high efficiencies and compact designs but also require to be all stainless-steel designs. New manufacturing technologies (e.g. 3D printing) allow to optimize this technology.

Technologies for the Cryogenic Supply

Pellet Injectors and Isotope Separation by cryogenic distillation will be clients of a future power plant as both systems are required in the fuel cycle. In case cryogenic pumping is chosen as primary pumping system or for the roughing pumping system an additional cryogenic client is added.
Possible solutions are conventional refrigerator system delivering cooling power by cold helium at ~4.2 K and Turbo Brayton Cycle refrigerators that are delivering cold helium at ~16 K to 25 K (or higher). Further possibility is the use of cryocoolers that currently (2025) can deliver a cooling power of 100 W at 20 K via there cold head. The best cryogenic supply solution depends on the different cooling power requirements of each of the clients for fueling, vacuum and isotope separation.

Tritium sealing of dismountable flanges (TBD)

Software

Process gas database for hydrogen isotopes

To have a validated database for all hydrogen isotopes that covers all state phases - gaseous, liquid and solid - for the required temperature range required in the fuel is a fundamental basis for the comparison of analysis by different entities. Where it is seen as required the database should be completed or validated by experiment.

Material database for permeation

A database that sets the permeation properties for the hydrogen isotopes through bulk materials of interest for a fusion fuel cycle is fundamental. It is important also how the material and gas properties are/have been determined to be able to compare results from different entities.

Code benchmarking

For process simulation tools the benchmarking against experimental data is important for their validation. Where needed experimental 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.

Tritium accountancy

The fuel cycle of fusion plant 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.

Tritium Permeation Barriers

Hydrogen is permeating through stainless steel or other materials. This effect is used for the separation of hydrogen isotopes from other gases, but in case of cooling loops or process loops for tritium breeding, the permeation of tritium is a problem negatively effecting the fuel cycle as detritiation efforts are get demanding.

Coating technologies for permeation barriers

For a future power plant, 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 current promising coating solutions.

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.

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 117 participants whilst 86 people attended the in-person workshop. 64 public and private entities were represented.

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

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

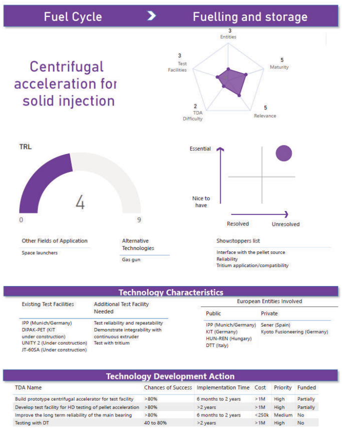
5.1 Technology dashboards

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

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

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.

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. We encourage the community to communicate updates to their Fusion for Energy or Eurofusion contact. In the future, we may publish this data 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

Summary

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

- 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 designed 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.

The UE 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.
- The EU is a major contributor to JT60SA. 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 projects being planned 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 membership 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 Focussed Energy, Gauss Fusion and Kyoto Fusioneering.

Weaknesses

The main weakness affecting the acceleration of fusion fuel cycle technology development in Europe 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 (Budapest) with IPP (Garching), CIEMAT (Madrid) and CEA (Grenoble, Cadarache) also involved to a lesser extent. In terms of supply chain, the only active actor is SENER (Spain) who supplied recently a centrifugal accelerator for JT60SA. For pellet sources, the only commercial supplier in the world is based in Russia (PELIN, St Petersburg).

Some of the tritium process technologies have not benefit from the ripple effect from ITER since they are procured from domestic agencies 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 still very immature, **there are monopolies in the supply chain** for critical components (even with high TRL) which may threaten its long-term sustainability. 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 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.

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 by F4E or EUROfusion of MoUs 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 two projects for new tritium handling facilities for fusion applications in Europe. One is proposed by CEA on its Cadarache site and the Cernavodă Tritium Removal Facility which will be operated by Nuclearelectrica SA. These 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 licence which may currently be dormant or under used by other sectors.

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 (eg Turbo Molecular Pumps, Mass Spectrometer Leak Detectors) or to limit the monopolies in for roots and scroll pumps.
- military: 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 (ie for the 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. For the Fuel Cycle area, as well as developing an EU Roadmap for Fuel Cycle activities, 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 regulations 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.

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 members 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
AsdexUpGrade	IPP (Munich)	Operating machine	N	Pellet injection
DIPAK and DIPAK-PET	KIT (Karlsruhe)	Under construction (start-up 2030)	N	Pellet injection Pumping
W7X	IPP (Greifswald)	Operating machine	N	Pellet injection
WEST	CEA (Cadarache)	Operating machine	N	Pellet injection
	HUN-REN (Budapest)	Operational	N	Pellet injection
Tritium Laboratory Karlsruhe	KIT (Karlsruhe)	Operational	Y (40g)	Tritium processing Storage Tritium detection
Pilot plant for Tritium and Deuterium Separation	ICSI (Valcea)	Operation	N	Tritium processing Storage
Tritium Removal Facility	Nuclearelectrica SA (Cernavodă)	Under construction (start-up 2028)	Y (TBC)	Tritium processing Storage
	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 Tritium processing

Facilities established in EUROfusion member country 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 Pumping Tritium processing Storage
JT60SA	Fusion for Energy (Japan – with QST)	Under upgrade (start-up 2027)	N	Pellet injection Cryopumps
AGHS	UKAEA (Culham)	Operational	Y (20 g TBC)	Pumping Tritium processing Storage
H3AT	UKAEA-ENI (Culham)	Under construction (start up 2028)	Y (TBC)	Storage Pumping Tritium processing
EUROPA	UKAEA (Culham)	Planned (Start up TBC)	Y (TBC)	Permeation

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 - Inertial fusion target delivery - Equilibrators - Cryogenic Adsorption Pumps - Turbo Molecular Pumps - Cryogenic Viscous Compressor - Metal foil pumps - Instruments to measure hydrogen isotopes concentration	- Packed beds - Liquid Ring Pumps - Liquid Metal Diffusion Pumps - Roots pumps - Cryogenic temperature sensor	- Wet scrubbers - Snail pump - Metal bellows pumps - Diffusion pumps with Tritium compatible oils - Piston pumps - Proton conductor pumps - Screw pumps - Scroll pumps

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

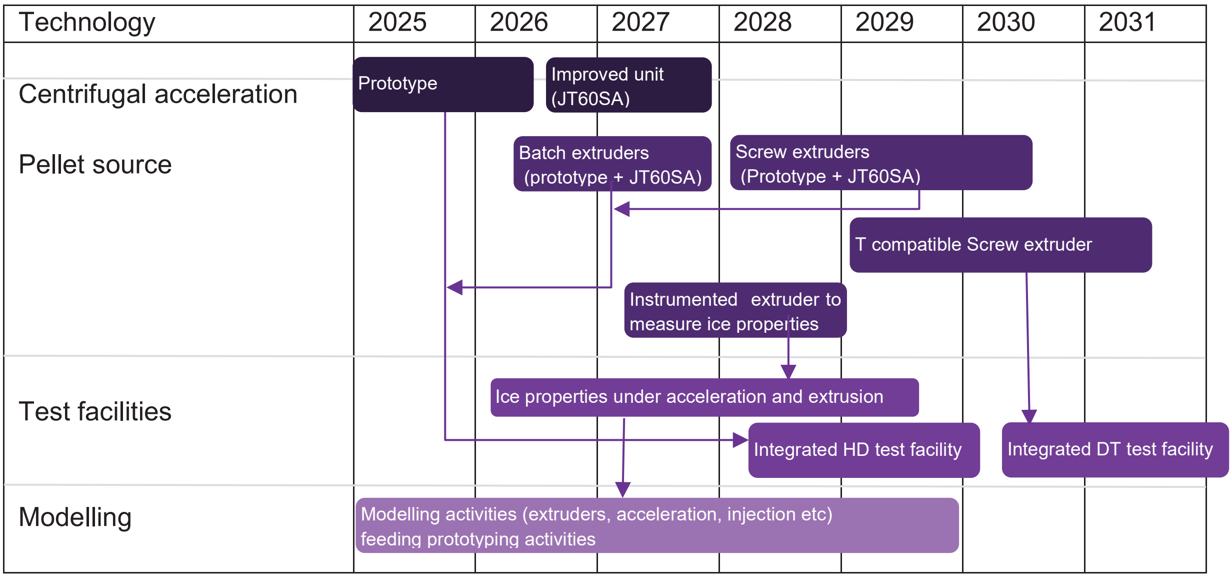
5.3 Roadmaps

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.

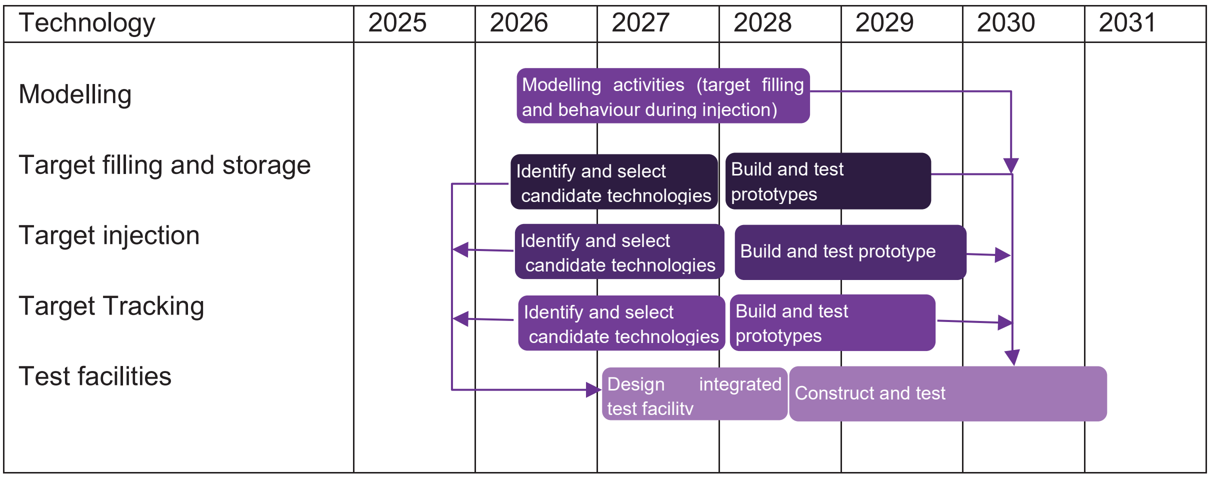
TDAs which are not fundamentally linked to other activities and can be executed independently are not included on roadmaps. This is true, for example, for the pumping area.

5.3.1 Fuelling

Pellet injection

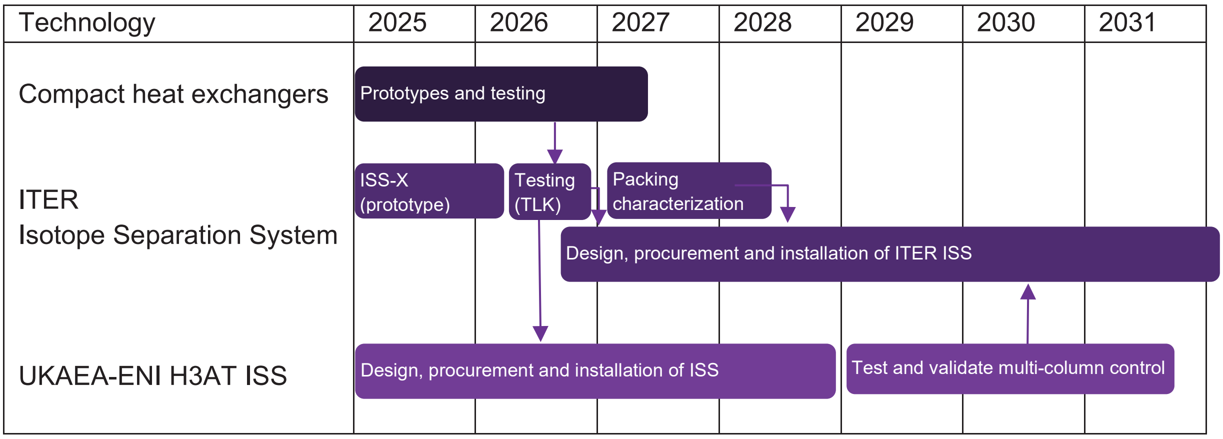


Inertial Fusion Target Delivery

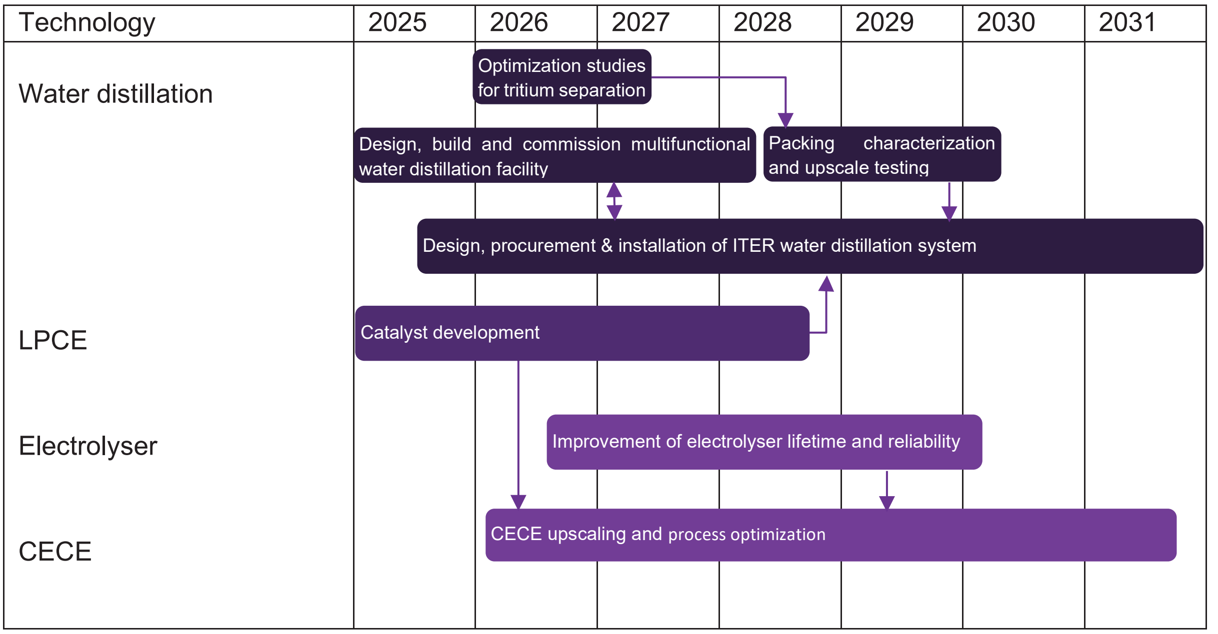


5.3.2 Membranes and packing

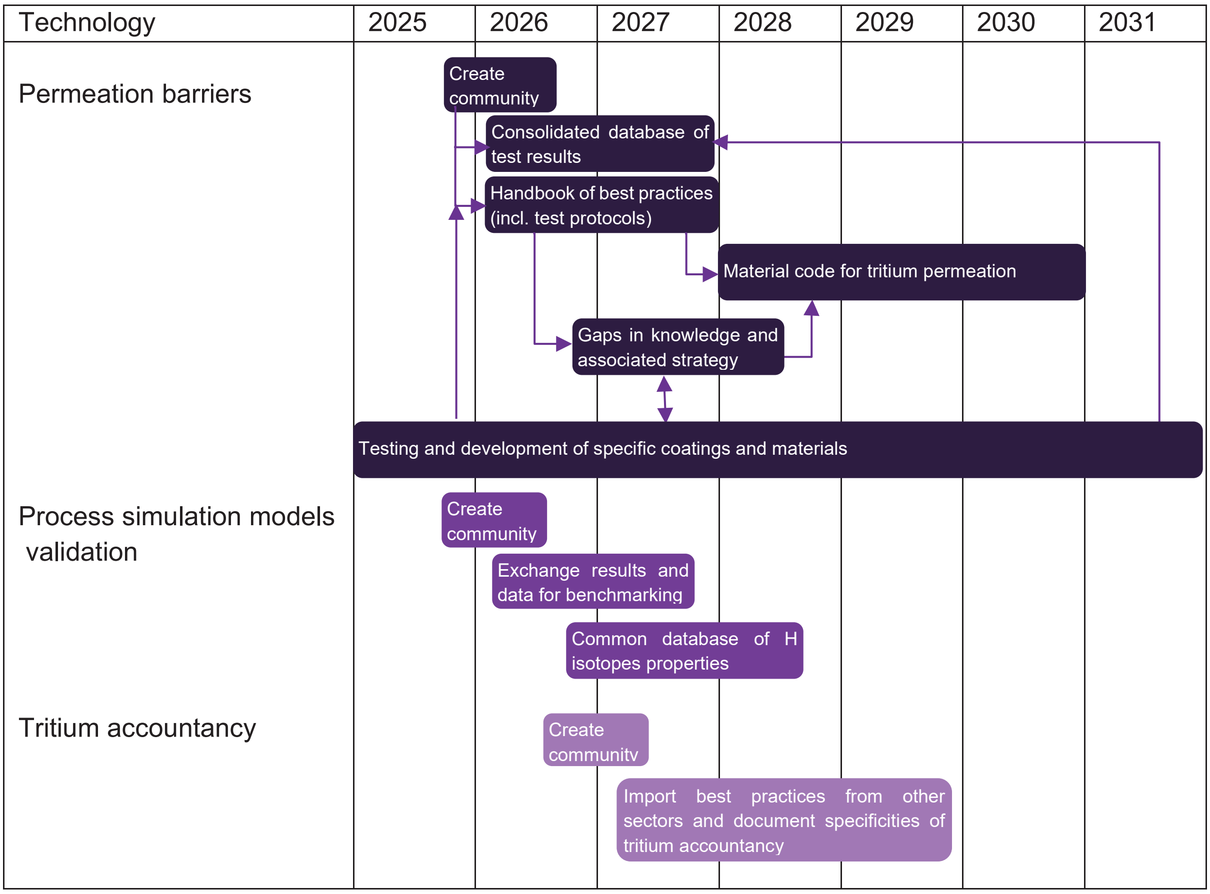
Cryogenic distillation



Water detritiation



5.3.3 Tritium management



6 Conclusion

Will be completed for the final report.

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

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[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) 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

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

Membranes and Packing

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

Pumping

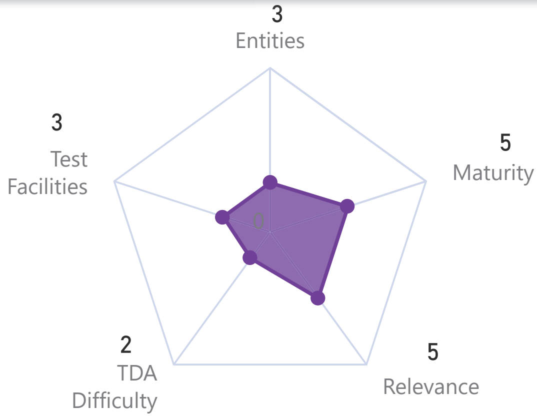
- Continuous Cryogenic Diffusion Pump / Snail Pump
- Cryogenic Adsorption pumps
- Turbo Molecular Pumps and Cryogenic TMPs
- Cryogenic Viscous Compressor (CVC)
- Liquid Ring pumps
- Liquid metal diffusion pump
- Metal bellows pumps
- Metal foil pump
- Non-Evaporable Getter (NEG) pumps
- Oil diffusion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

Tritium Management

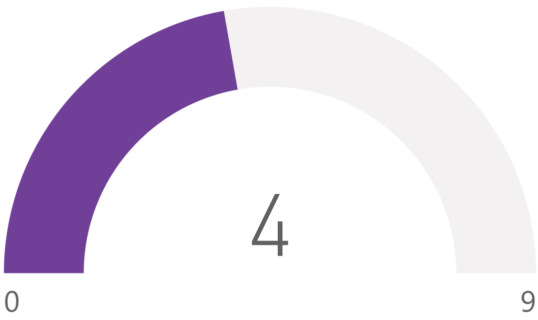
- Tritium permeation barriers
- Cryogenic Temperature Sensor
- Instruments to measure hydrogen isotope concentrations
- Non-destructive Tritium detection in solids
- Wearable tritium detector
- Process Simulation Model Validation
- Tritium accountancy
- Room tritium detector
- Real time tritium detector for water
- Tritium sealing of dismountable Flanges
- Magnetic Sector Leak Detector (MSLD) - missing

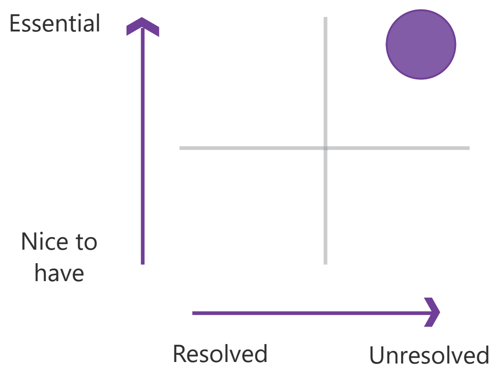
Fuel Cycle > Fuelling and storage

Centrifugal acceleration for solid injection



TRL





Other Fields of Application
Space launchers

Alternative Technologies
Gas gun

Showstoppers list
Interface with the pellet source Reliability Tritium application/compatibility

Technology Characteristics

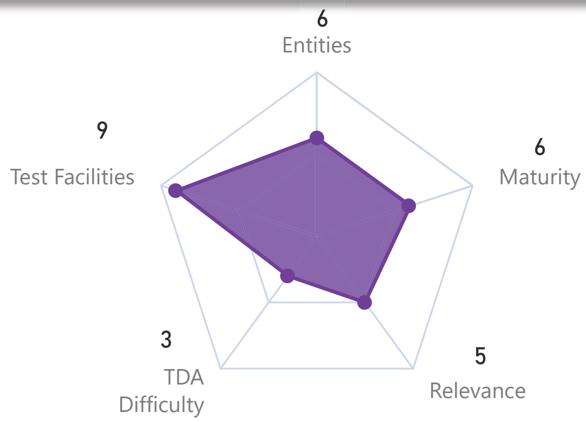
Existing Test Facilities	Additional Test Facility Needed
IPP (Munich/Germany) DIPAK-PET (KIT under construction) UNITY 2 (Under construction) JT-60SA (Under construction)	Test reliability and repeatability Demonstrate integrability with continuous extruder Test with tritium

European Entities Involved	
Public	Private
IPP (Munich/Germany) KIT (Germany) HUN-REN (Hungary) DTT (Italy)	Sener (Spain) Kyoto Fusioneering (Germany)

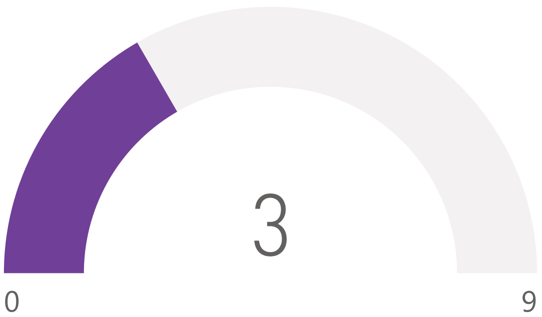
Technology Development Action

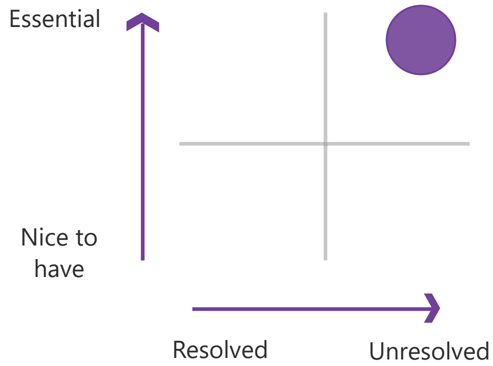
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Build prototype centrifugal accelerator for test facility	>80%	6 months to 2 years	>1M	High	Partially
Develop test facility for HD testing of pellet acceleration	>80%	>2 years	>1M	High	Partially
Improve the long term reliability of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

Diagnostic System for pellet injection



TRL





Other Fields of Application
Optical monitoring

Alternative Technologies
Plasma diagnostics Mirnov coils

Showstoppers list
Line of sight in the case of optical diagnostic Reliability under radiated environment

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
KIT DIPAK-PET (under construction) IPP (AUG and W7-X)	Functional test on real pellets

European Entities Involved

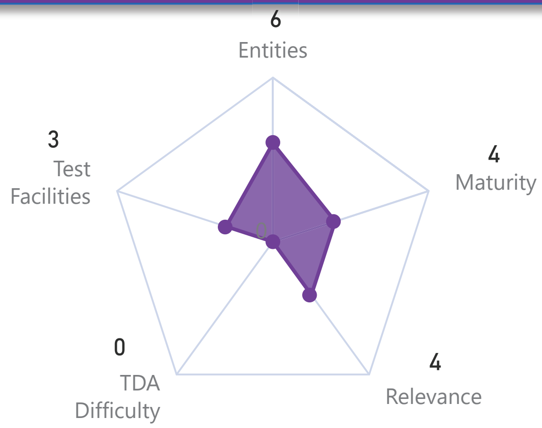
Public	Private
Hun-REN (Budapest) IPP Munich/W7-X (Germany)	

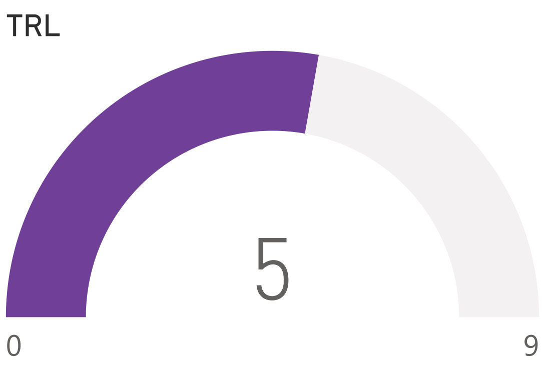
Technology Development Action

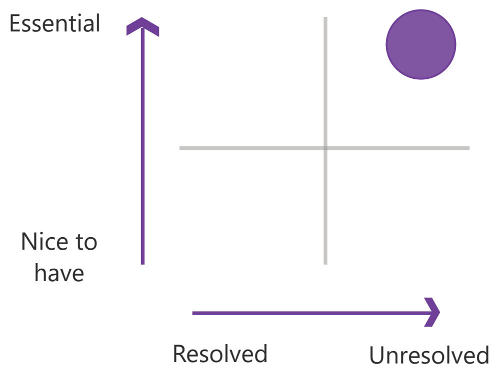
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Define technologies to detect if pellets entered the highly confined plasma	>80%	<6 months	<250k	Medium	No
Optical diagnostic to measure successful arrival of pellets into the vessel	<40%	>2 years	>1M	Medium	No

Fuel Cycle > Fuelling and storage

Gas-gun acceleration mechanism for solid injection







Other Fields of Application
Military Propulsion technologies

Alternative Technologies
Centrifugal 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) KIT DIPAK-PET (Under construction) UNITY 2 (Canada under construction)	Functional test

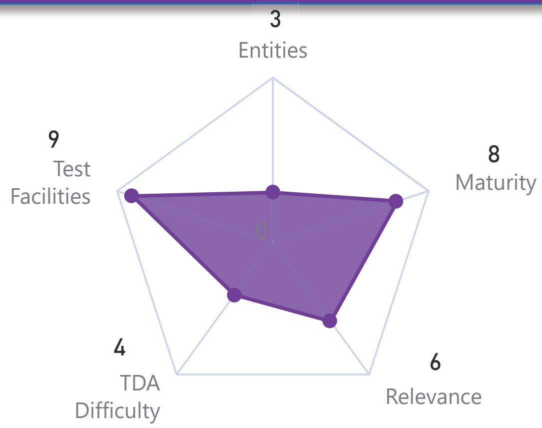
European Entities Involved	
Public	Private
KIT (Karlsuhe) CIEMAT (Madrid) IPP (Garching) CEA (Grenoble)	

Technology Development Action

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Build tritium compatible prototype and develop test facility	>80%	>2 years	>1M	Low	Partially

Fuel Cycle > Fuelling and storage

Inertial Fusion Target Delivery



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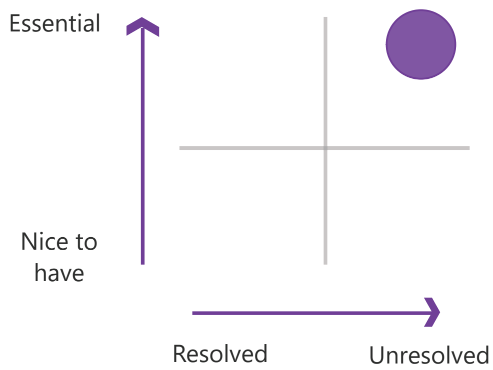


Other Fields of Application	Alternative Technologies

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.

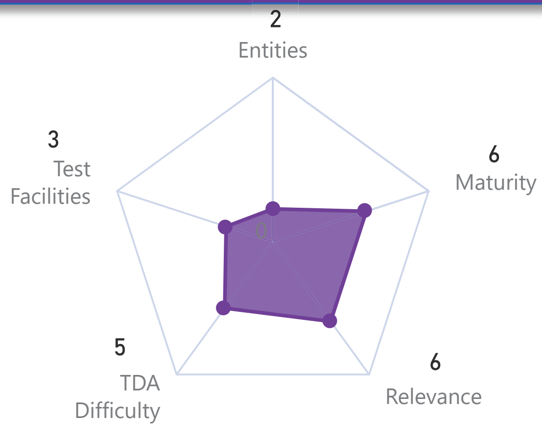
European Entities Involved

Public	Private
ELI (Prague) CEA (Bordeaux Dijon Grenoble) Fraunhofer IAF (Darmstadt)	Focused Energy (Germany)

Technology Development Action

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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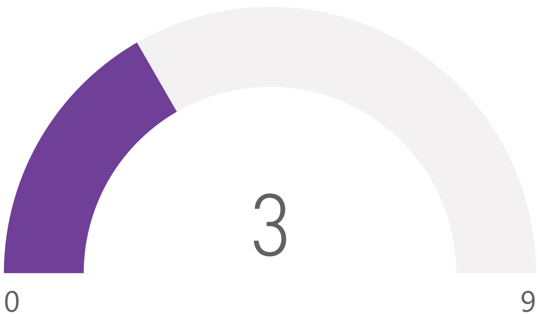
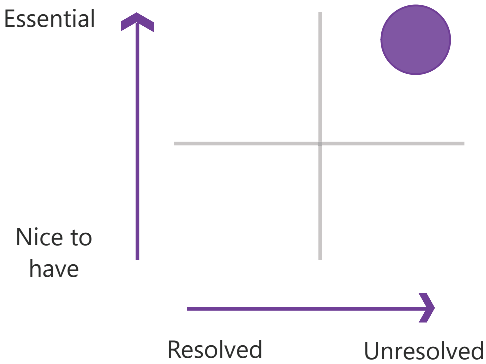




Other Fields of Application	Alternative Technologies	Showstoppers List
	Experiments	Validation of codes Unknown properties of HDT ice

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
(For plasma with pellets) AUG (Munich) W7-X (Greifswald) JT-60SA (Under construction) WEST (Cadarache)	HDT ice characterization

European Entities Involved

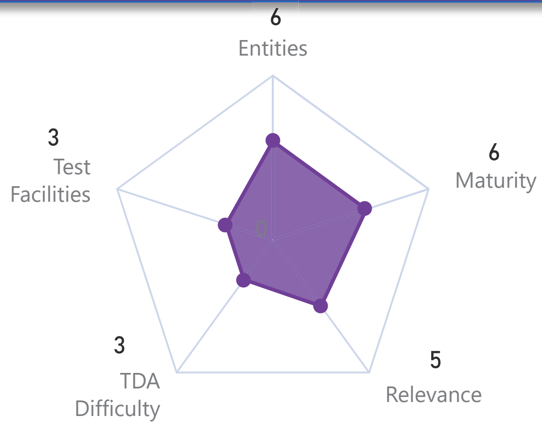
Public	Private
CEA (Cadarache & Grenoble) HUN-REN (Budapest) IPP (Garching) KIT (Germany) ENEA (Frascati) DIFFER (Netherlands) ONERA (France)	ENI (Italy)

Technology Development Action

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
Model for pellet impact to the plasma	40 to 80%	6 months to 2 years	<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
Test facility to characterize the mechanical properties of the various species of pellets	40 to 80%	>2 years	>1M	High	No

Fuel Cycle > Fuelling and storage

Pellet Source



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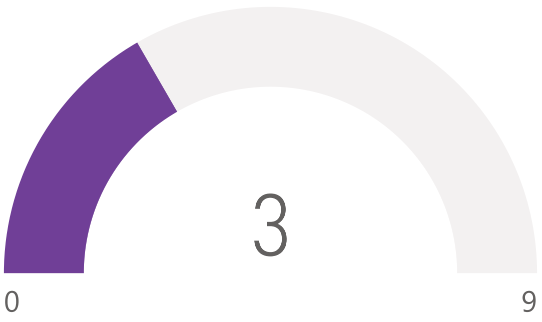
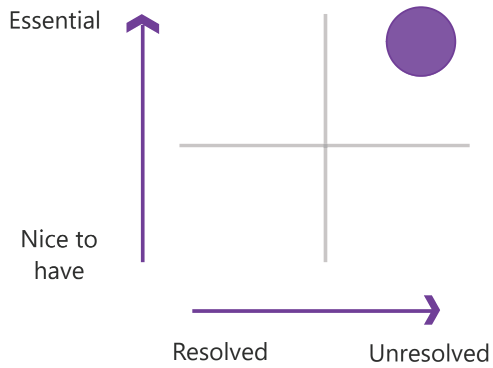




Other Fields of Application

Laser Targets
Neutron Spallation Sources

Alternative Technologies

Showstoppers list

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
HUN-REN (Budapest) CEA France (Grenoble) KIT (Karlsruhe) IPP (Garching) Unity 2 (Canada)	D-T validation

European Entities Involved

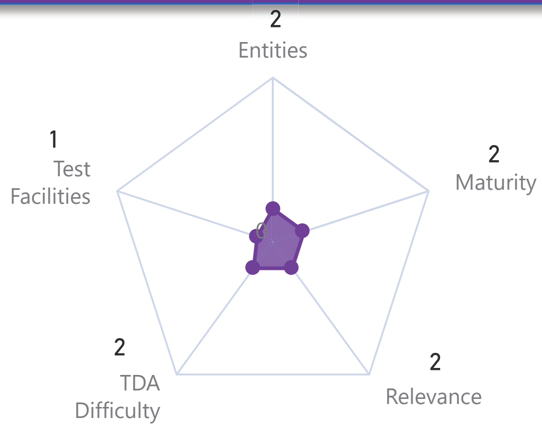
Public	Private
IPP CIEMAT HUN-REN CEA	

Technology Development Action

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Build prototype and test it in a cryogenic and vacuum environment (+ Tritium as second step)	40 to 80%	6 months to 2 years	250k to 1M		
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	No

Fuel Cycle > Fuelling and storage

Metal Hydride Beds



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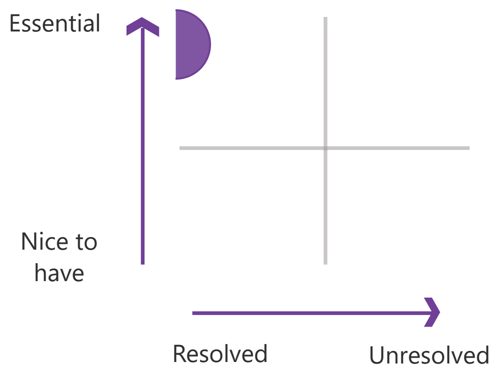


Other Fields of Application

Bulk H storage
Hydrogen generation

Alternative Technologies

Showstoppers list

Technology Characteristics

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

European Entities Involved

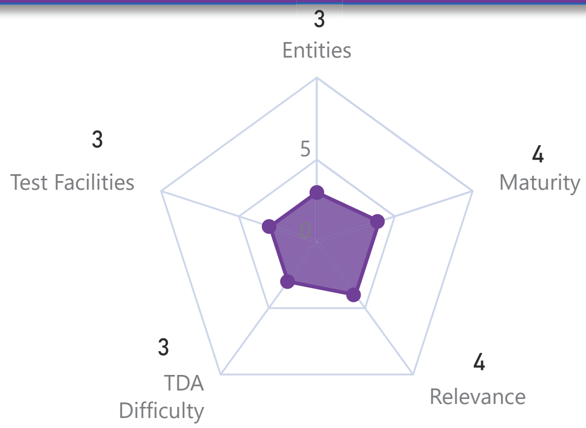
Public	Private
TLK/KIT (Germany) ENUSA (Spain) CIEMAT (Spain) ICSI (Romania)	Monteiro (France) Alsymex (France) Kyoto Fusioneering SAES (Italy) Urenco Orano (France) Eni (Italy) IDONIAL (Spain) FUS-ALIANZ (Spain)

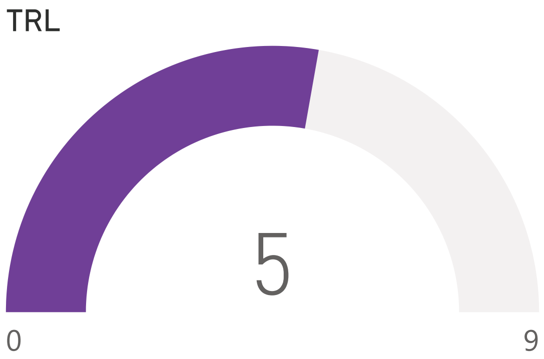
Technology Development Action

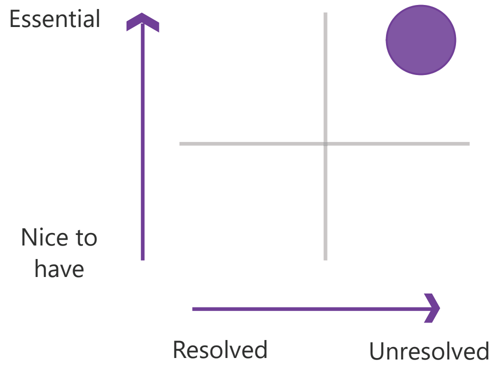
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Design, build and test prototype ZrCo transport container	>80%	6 months to 2 years	250k to 1M	Medium	No
Develop a powder metallurgy and matched sintering DU beds as T hydrides	40 to 80%	6 months to 2 years	<250k	High	No

Fuel Cycle > Membranes and packing

Column packing







Other Fields of Application
Gas separation Fission Water Purification Petrochemical

Alternative Technologies
Trays

Showstoppers list
Tritium Compatibility

Technology Characteristics

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

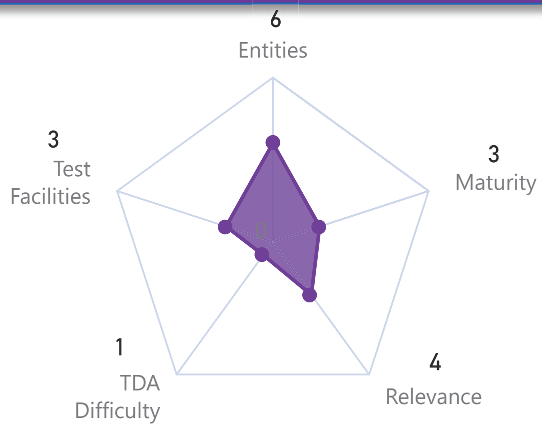
European Entities Involved

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

Technology Development Action

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

Combined Electrolysis and Catalytic Exchange (CECE)



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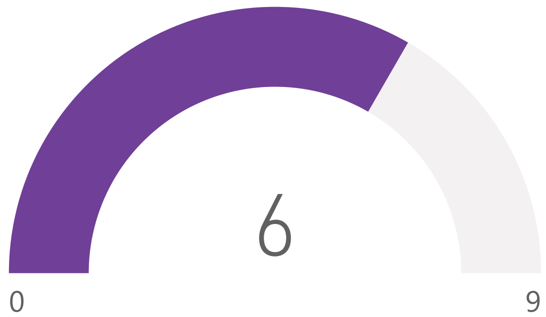
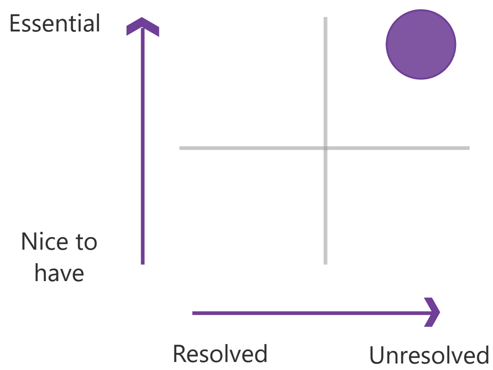




Other Fields of Application
Fission Hydrogen

Alternative Technologies
Water distillation with LPCE or electrolyser

Showstoppers list
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) KIT/TLK (Germany)	Upscale of prior test setups. Process investigation optimization and benchmarking of modeling.

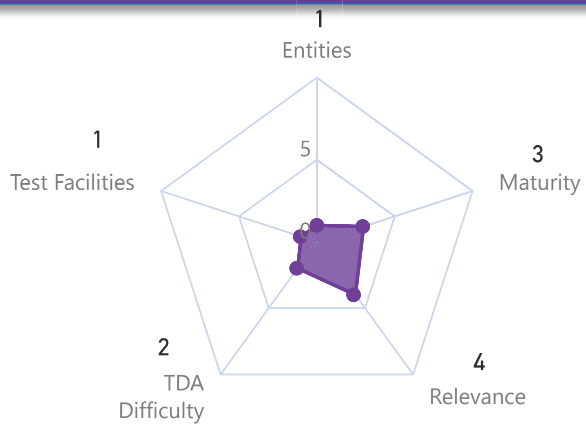
European Entities Involved

Public	Private
ENEA (Italy) KIT/TLK (Germany) ICSI (Romania) CEA Cadarache - Future tritium process test facility for 2031 (France)	

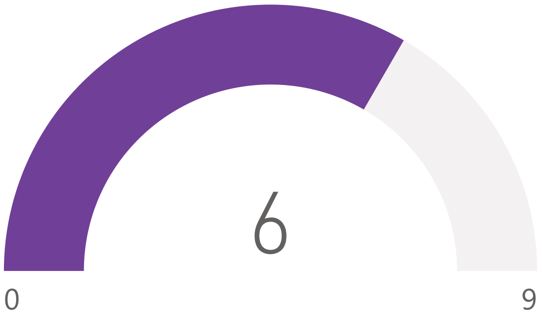
Technology Development Action

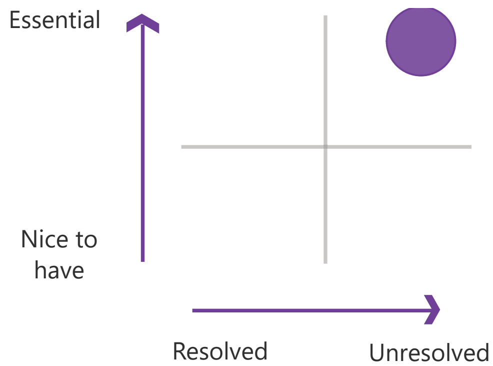
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Upscale CECE technology	40 to 80%	>2 years	>1M		

Fuel Cycle › Membranes and packing



Cryogenic distillation





Other Fields of Application

Fission
Gas separation
Medical industry
Chemical and steel manufacturing
Electronics

Alternative Technologies

TSA
PSA
Membranes

Showstoppers List

Large Inventory
Energy consumption

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
KIT/TLK (Germany) ICSI (Romania) UKAEA H3AT (Culham under construction) UKAEA AGHS (Culham) CURIUM (France)	

European Entities Involved

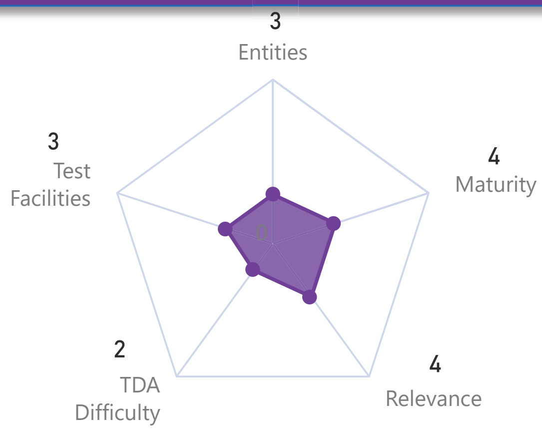
Public	Private
UKAEA (Culham) KIT/TLK (Germany) ITER ICSI (Romania) ENEA (Italy) CEA Cadarache - Future tritium process test facility for 2031 (France)	Air Liquide (France) Linde (Switzerland) Research Instruments (Germany) Absolut System (France) Polaris (Italy) ALSYMEX (France) Eni (Italy)

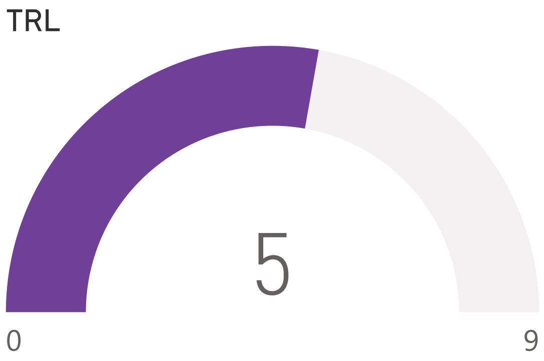
Technology Development Action

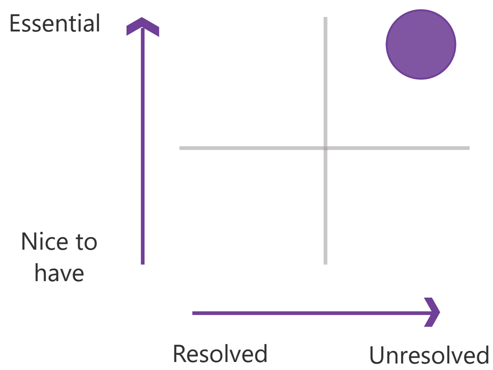
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Develop cryogenic distillation for D,T separation from the plasma exhaust	40 to 80%	6 months to 2 years	250k to 1M	Low	No
Development of compact heat exchangers and copper-SS joining techniques	>80%	6 months to 2 years	250k to 1M	Medium	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

Fuel Cycle > Membranes and packing

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) H3AT (Culham under construction) KIT/TLK (Germany) CURIUM (France) Unity 2 (Canada under construction)	Tritium long term operation Roe collection and exchange

European Entities Involved

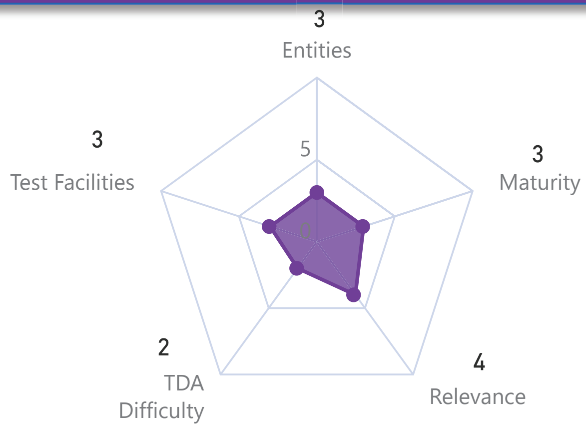
Public	Private
ICSI (Valcea) UKAEA (Culham) KIT (Karlsruhe) CEA Cadarache - Future tritium process test facility for 2031 (France)	Kyoto Fusioneering (Germany) Kraftanlagen Heidelberg (Germany) Veolia Water Technologies (France) ELOGEN GTT (France) Eni (Italy)

Technology Development Action

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

Equilibrators



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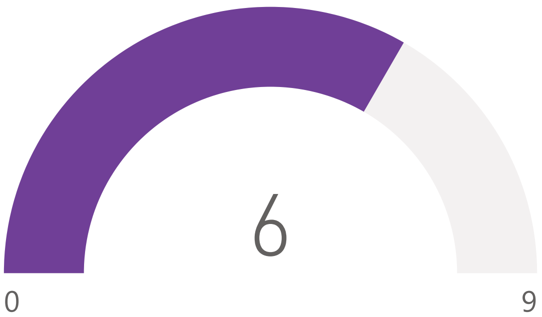
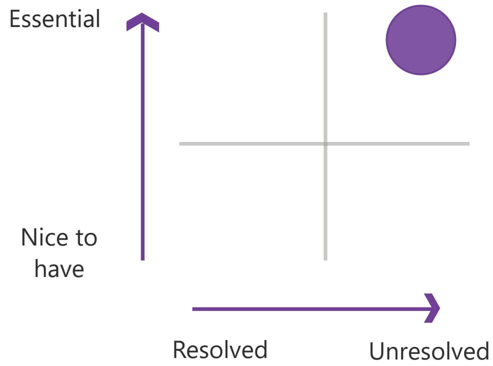




Other Fields of Application
Chemical Plants

Alternative Technologies
Packing Distillation

Showstoppers List
Catalyst Performance Availability of Testing Equipment

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
CURIUM (France) H3AT (UKAEA under construction)	To test catalyst performance

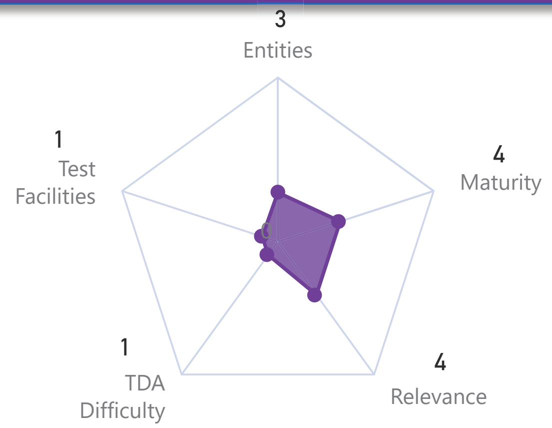
European Entities Involved	
Public	Private
KIT (Karlsruhe) ICSI (Valcea)	ALSYMEX

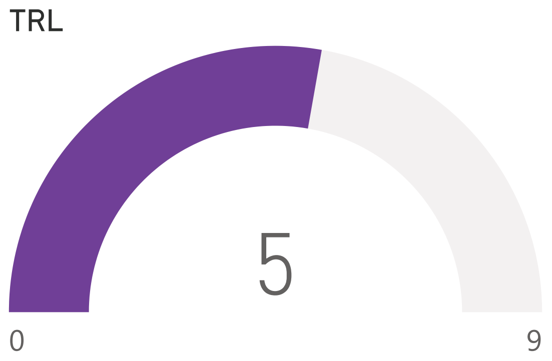
Technology Development Action

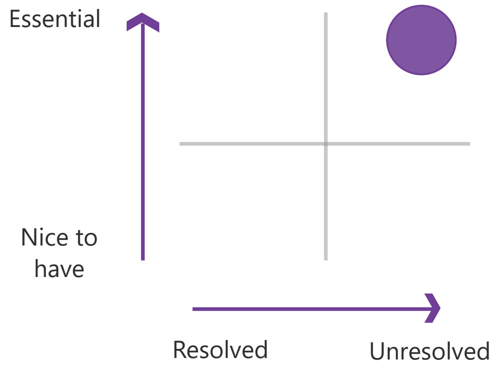
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
R&D and testing of new catalyst solutions for equilibrators	40 to 80%	6 months to 2 years	<250k	Medium	No

Fuel Cycle > Membranes and packing

Liquid Phase Catalytic Exchange (LPCE)







Other Fields of Application
Fission Reactive distillation

Alternative Technologies
Water distillation Membrane reactor

Showstoppers List
Catalyst performance Packing characterization Maintenance

Technology Characteristics

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

European Entities Involved

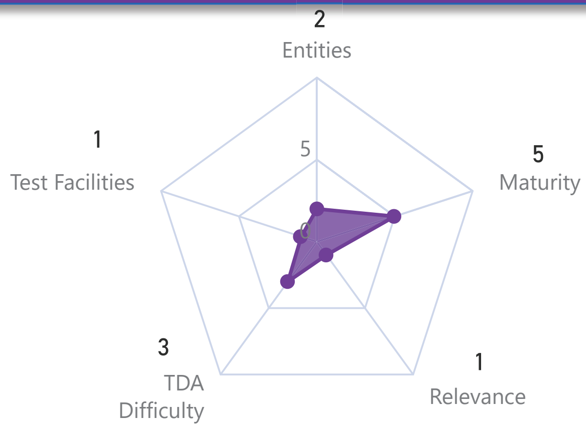
Public	Private
ICSI (Valcea) KIT (Karlsruhe) ENEA (Frascati) CEA Cadarache - Future tritium process test facility for 2031 (France)	VEOLIA SPG Eiffage

Technology Development Action

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

Fuel Cycle › Membranes and packing

Membrane Absorption



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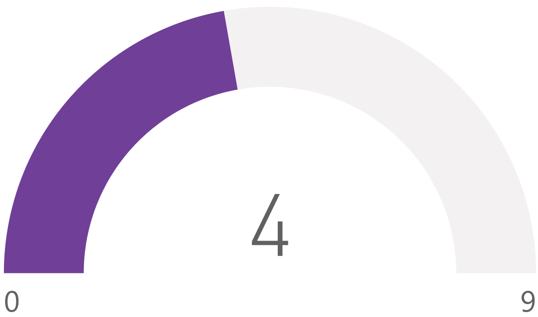
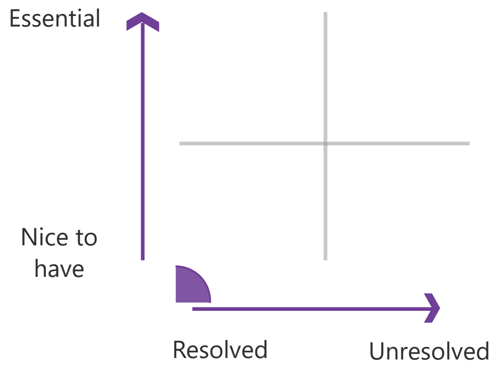




Other Fields of Application
Hydrogen Gas Separation

Alternative Technologies
Packings Cryo separation

Showstoppers List
Capacity Batch Process High Process Control and Safety demand

Technology Characteristics

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

European Entities Involved

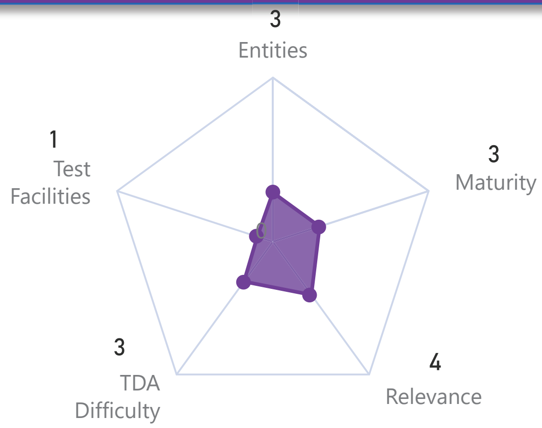
Public	Private
ENEA (Frascati) Univ of Calabria UKAEA (Culham) University of Bath and Rochester (UK) TNO (Netherlands)	Tecnalia

Technology Development Action

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

Fuel Cycle > Membranes and packing

Packed Beds



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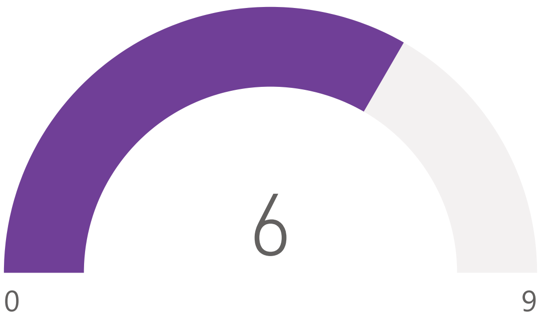
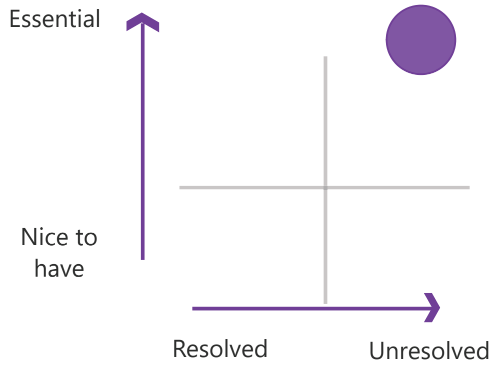




Other Fields of Application

Gas Purification
Chemical Plants
Heavy Water
Cryo
Reactors
Laboratory
Semiconductor Industry

Alternative Technologies

Membranes
Water Distillation

Showstoppers list

Experimental facilities needed

Technology Characteristics

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

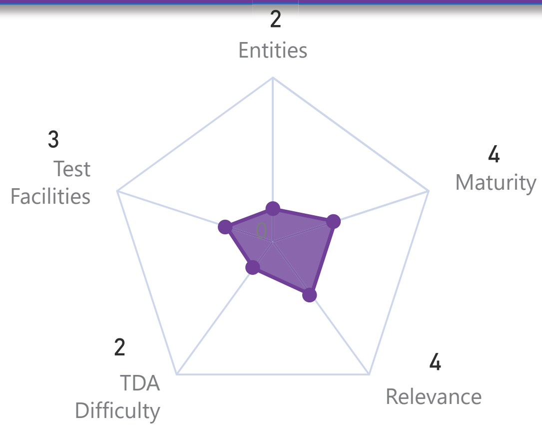
European Entities Involved	
Public	Private
ENEA (Frascati)	Sulzer Chemtech (Switzerland) Saes (Italy) Smolsys (Lucerne)

Technology Development Action

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



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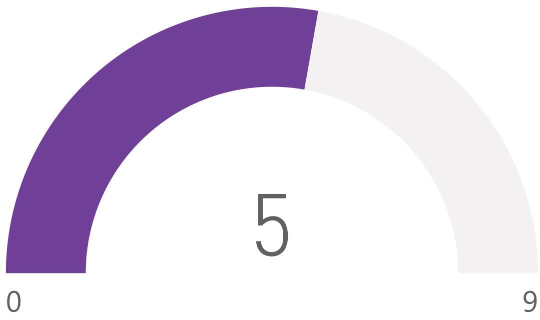
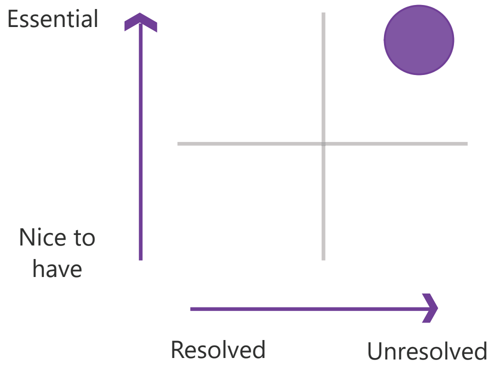




Other Fields of Application
Hydrogen fuel Membrane reactors

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) University of Bath (UK) ENEA (Frascati) ICSI (Romania) CURIUM (France)	Separation performance Life expectancy Poisoning

European Entities Involved

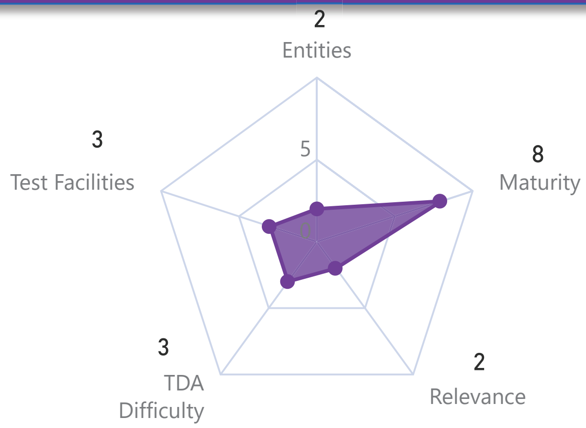
Public	Private
UKAEA (Culham) KIT (Karlsruhe) ENEA (Frascati) TNO (NL) ICSI (Romania) CEA Cadarache - Future tritium process test facility for 2031 (France)	Tecnalia Kyoto Fusioneering

Technology Development Action

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Development of Pd-Ag membrane reactor/catalyst (air-like)	40 to 80%	6 months to 2 years	250k to 1M	High	No
industrialization of membranes modules (shape, joining, compatibility with environment, etc.)	>80%	6 months to 2 years	250k to 1M	Medium	No

Fuel Cycle › Membranes and packing

Quantum sieving



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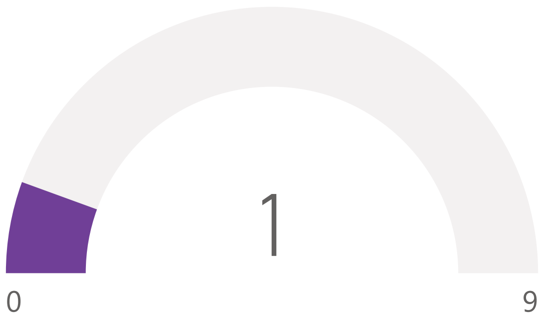
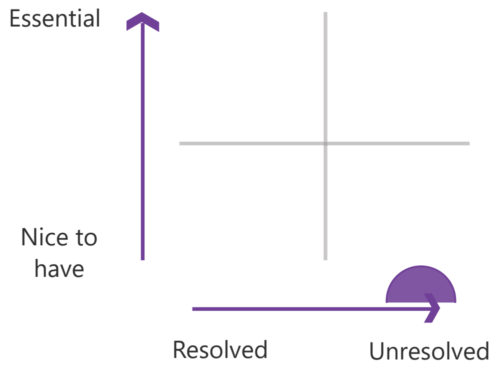




Other Fields of Application

Fission
Gas separation

Alternative Technologies

Cryo distillation
Pd Membranes
Metal Foil pump

Showstoppers list

Manufacturability
Control

Technology Characteristics

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

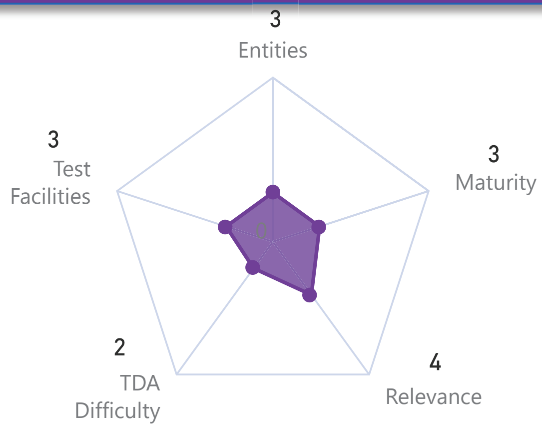
European Entities Involved

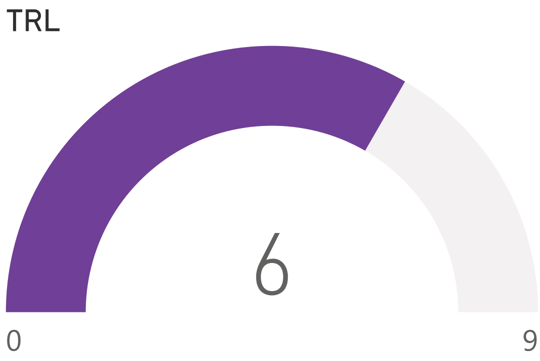
Public	Private
Univ of Bath (UK) UKAEA NPL (London) Liverpool University (UK) VTT Technical Research Centre of Finland	Tecnalia (Spain) Atkins (UK) BIMO Tech

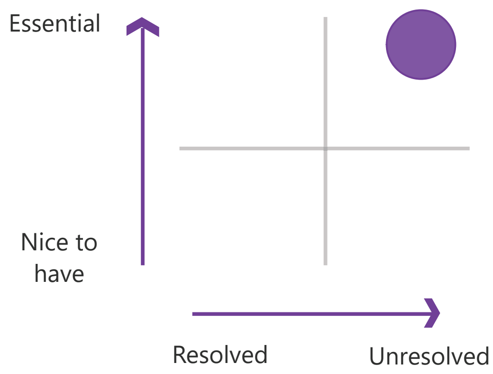
Technology Development Action

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

Temperature/Pre... 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

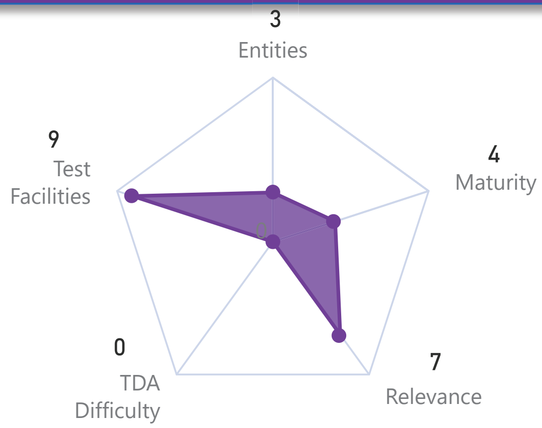
Existing Test Facilities	Additional Test Facility Needed
MAIA (KIT) HESTIA (KIT) Air Liquide Innov. campus (France) CURIUM (France) ALSYMEX (France) H3AT (UKAEA) under construction	Upscaling test facility (in long-term)

European Entities Involved	
Public	Private
KIT (Karlsruhe) ENEA (Frascati) CEA Cadarache - Future tritium process test facility for 2031 (France)	Air Liquide Linde

Technology Development Action

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Characterization of adsoprtion of T by/for different materials	>80%	6 months to 2 years	250k to 1M	Low	No
Investigate TSA for H/DT rebalancing using existing proto to see if reqs. (e.g. throughput vs separation) can be met	40 to 80%	6 months to 2 years	250k to 1M	High	No

Vapor Phase Catalytic Exchange (VPCE)



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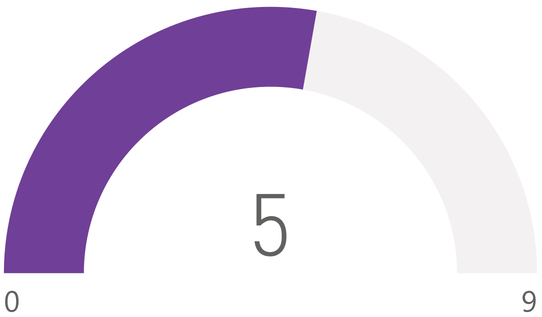
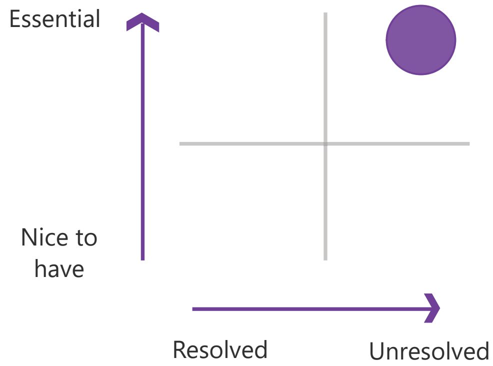




Other Fields of Application

Alternative Technologies

LPCE
CECE
Water distillation

Showstoppers list

Catalyst and packing
Operation temperature

Technology Characteristics

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

European Entities Involved

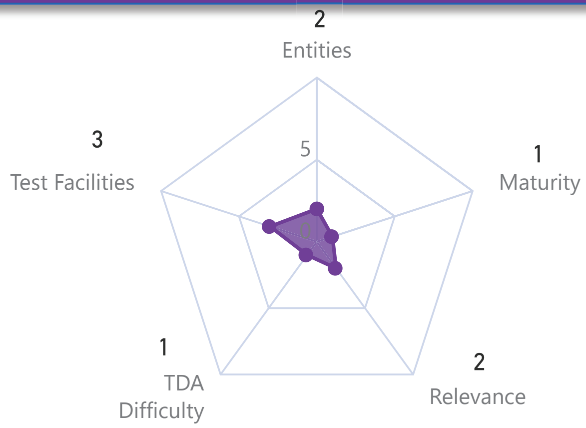
Public	Private
ENEA KIT UKAEA CEA Cadarache - Future tritium process test facility for 2031 (France)	SPG-Eiffage

Technology Development Action

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded

Fuel Cycle > Membranes and packing

Water distillation



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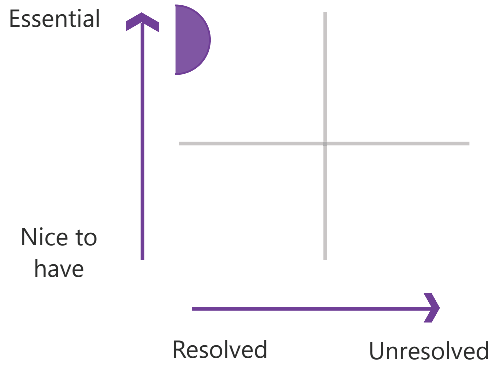


Other Fields of Application
Fission Water purification Desalination

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) CURIUM (France)	Packing characterization Performance Operability and Maintenance Integration with other type of processes.

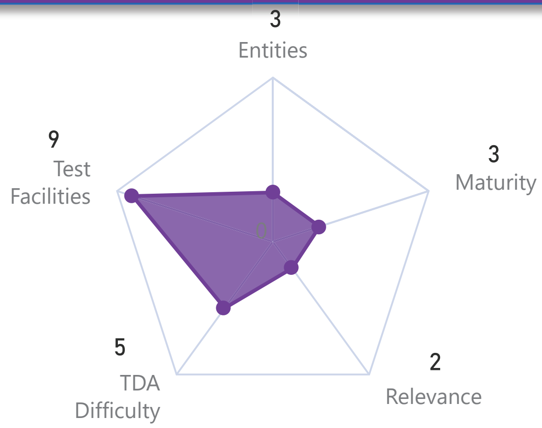
European Entities Involved

Public	Private
ICSI (Valcea) ENEA (Frascati) CEA Cadarache - Future tritium process test facility for 2031 (France)	SPG - Effiage Sulzer Koch-glitsch Montz Kraftanlagen Heidelberg ALSYMEX MONTEIRO

Technology Development Action

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Water Distillation optimization for tritium separation	>80%	>2 years	>1M	Medium	No

Wet scrubbers



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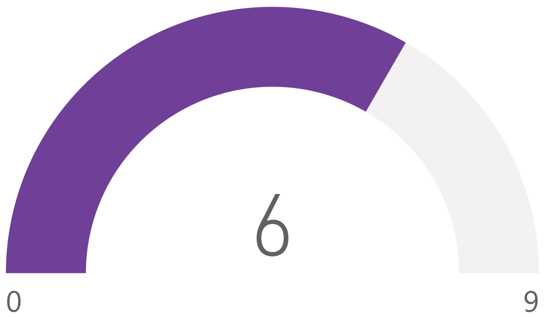
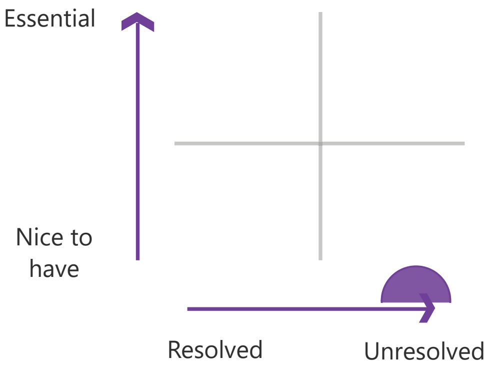




Other Fields of Application
Air purification needs using water trickle beds

Alternative Technologies

Showstoppers list

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed

European Entities Involved

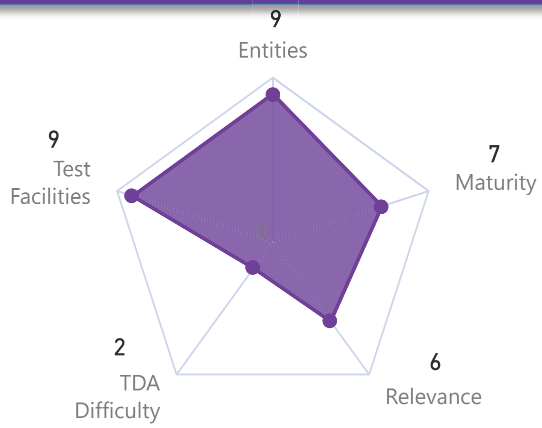
Public	Private
Eni Spa	Eni (Italy

Technology Development Action

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

Fuel Cycle › Pumping

Continuous Cryogenic Diffusion Pump / Snail Pump



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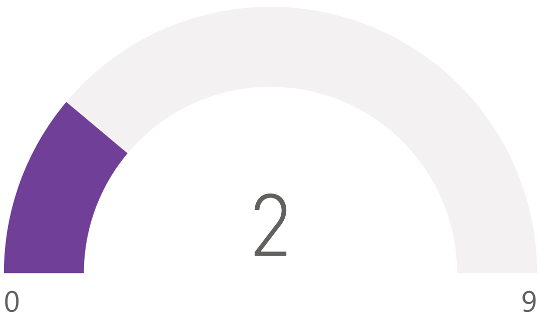
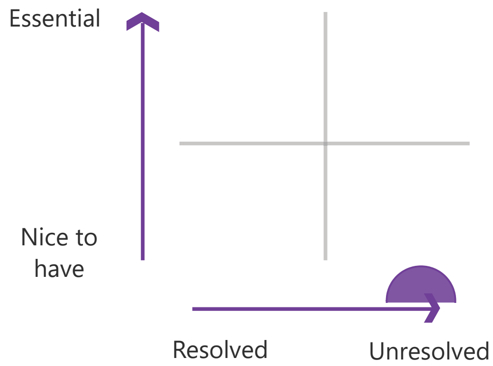




Other Fields of Application

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

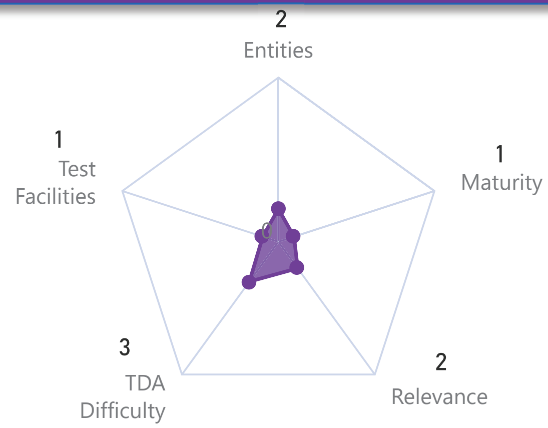
European Entities Involved

Public	Private

Technology Development Action

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

Cryogenic Adsorption pumps



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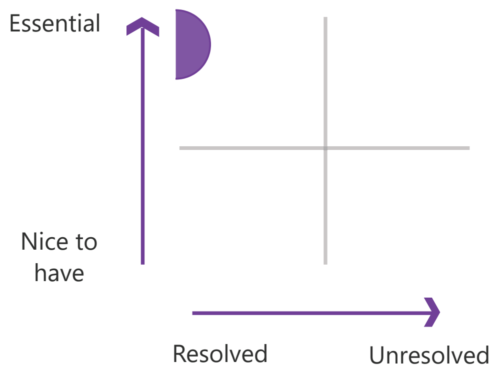


Other Fields of Application
Semiconductor solar process Aerospace High energy physics

Alternative Technologies
NEG pumps Foil pumps Diffusion pumps Turbo MP

Showstoppers list
Tritium inventory and hydrogen safety Scale up-helium cost

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
ITER	

European Entities Involved

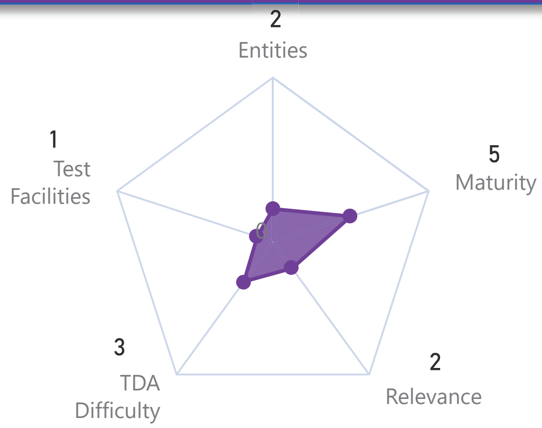
Public	Private
ITER KIT (Germany) DTT (Italy)	Research Instruments ALSYMEX Kyoto Fusioneering Absolut System SDMS AVS HSR AG Balzers

Technology Development Action

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

Fuel Cycle > Pumping

Turbo Molecular Pump and Cryogenic TMP



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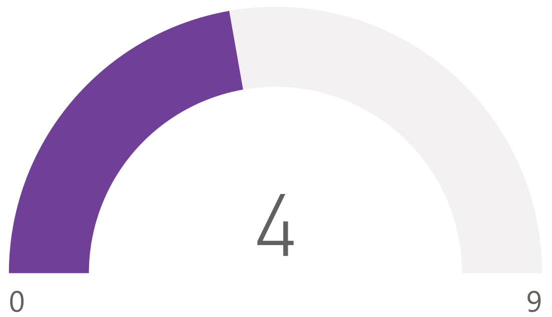
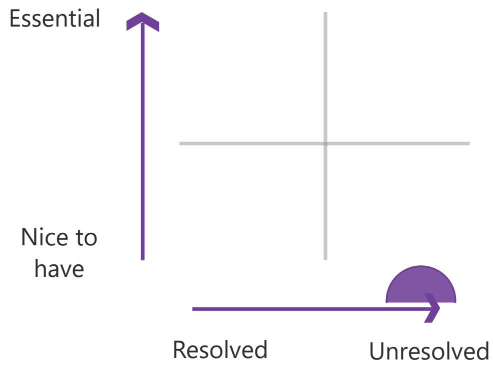




Other Fields of Application

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)	

European Entities Involved

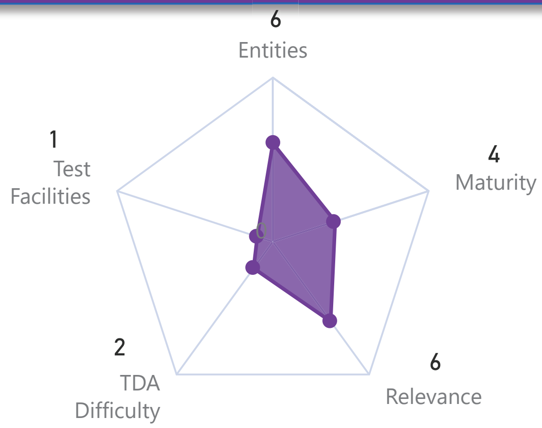
Public	Private
ITER CEA (Grenoble)	ALCEN/ALSYMEX+IRELEC Pfeiffer, Edwards, Inficon, Agilent, Busch, Oerlikon

Technology Development Action

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

Fuel Cycle › Pumping

Cryogenic Viscous Compressor (CVC)



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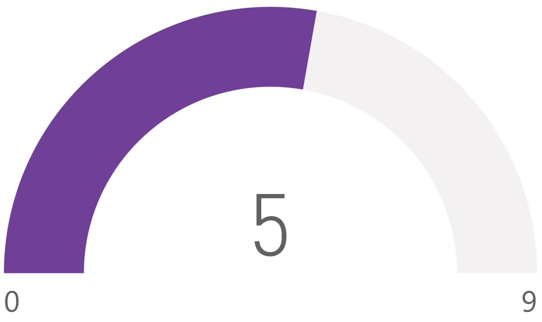
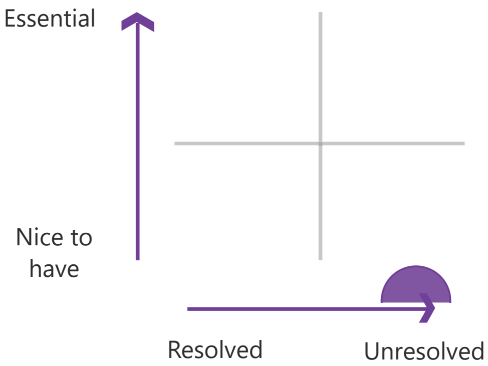




Other Fields of Application	Alternative Technologies	Showstoppers list
	Tritium compatible mechanical pumps Metal foil pumps Conventional pumps scroll roots	Large tritium inventories Regeneration technology Explosion protection limits

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
CEA (Grenoble)	

European Entities Involved

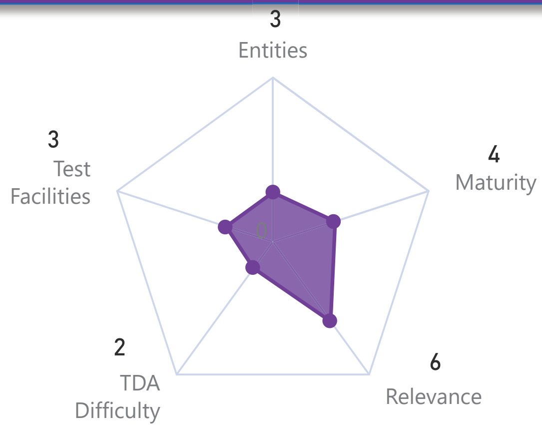
Public	Private
ITER CEA (Grenoble)	

Technology Development Action

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

Fuel Cycle > Pumping

Liquid Ring pumps



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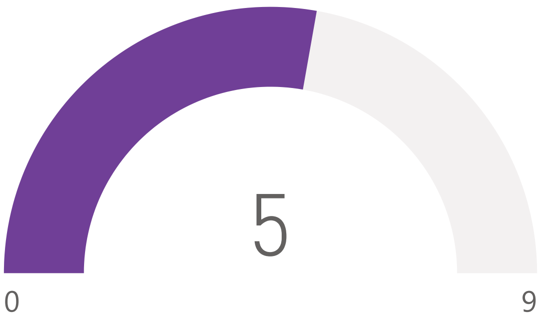
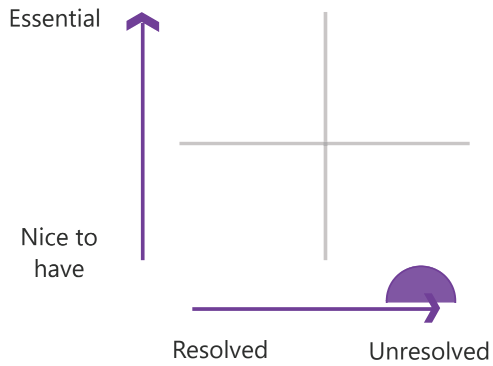




Other Fields of Application

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 under construction) UKAEA (Rochester) Unity-2 (Canada under construction)	Tritium test bench

European Entities Involved

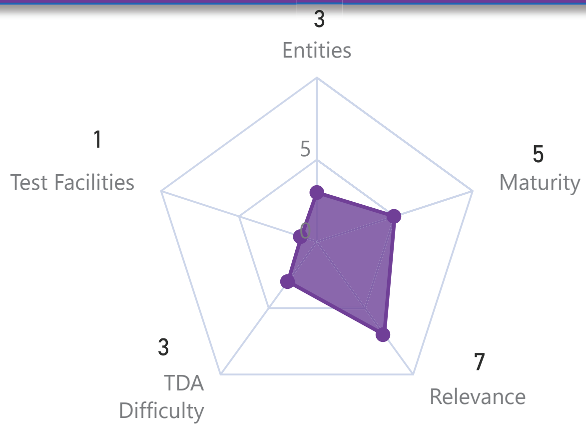
Public	Private
KIT	Vakuo GmbH Nash Friatec AG Hermetic

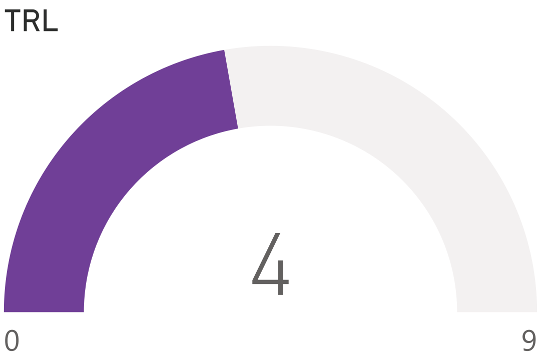
Technology Development Action

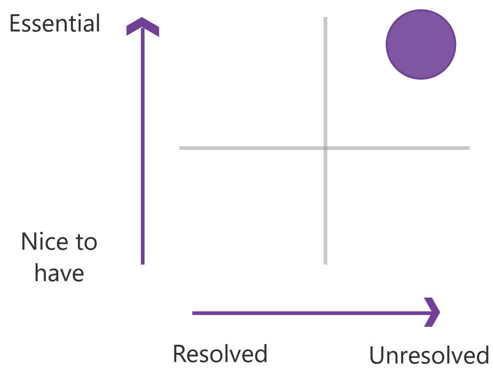
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Find an alternative to mercury	40 to 80%	6 months to 2 years	<250k		No
Qualify the mercury liquid ring pump to fusion requirements	>80%	6 months to 2 years	>1M	Medium	No

Fuel Cycle > Pumping

Liquid metal diffusion pump







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 Karlsruhe under construction)	

European Entities Involved

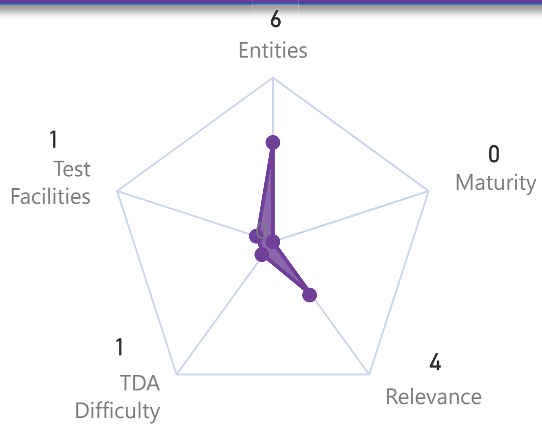
Public	Private
KIT (Karlsruhe)	Kyoto Fusioneering

Technology Development Action

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

Fuel Cycle › Pumping

Metal bellows pumps



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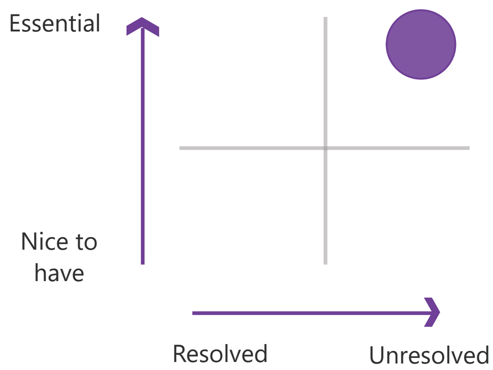


Other Fields of Application	Alternative Technologies	Showstoppers list
Aerospace Petrochemical		

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
KIT - Tritium Laboratory Karlsruhe (Germany) UKAEA (Rochester UK) Unity-2 (Canada under construction)	

European Entities Involved

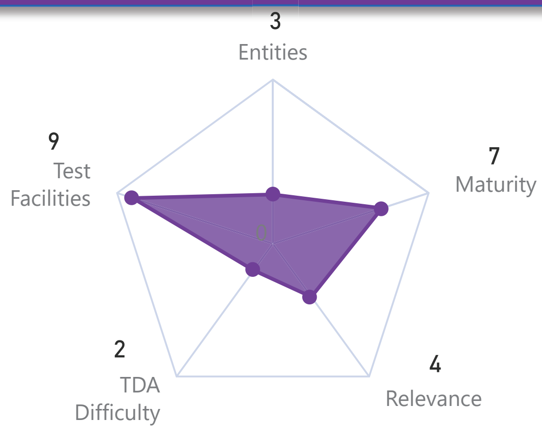
Public	Private

Technology Development Action

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

Fuel Cycle > Pumping

Metal foil pump



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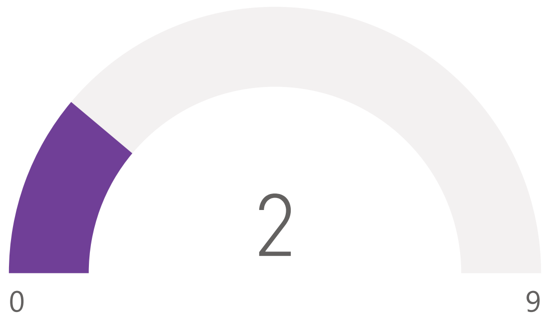
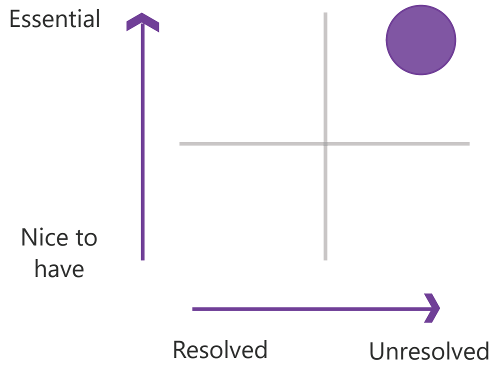




Other Fields of Application
Hydrogen industry Semiconductors

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 under construction) H3AT (UK under construction) UNITY-2 (Canada under construction).	Upscale development and testing Test performance and operation Testing with Tritium

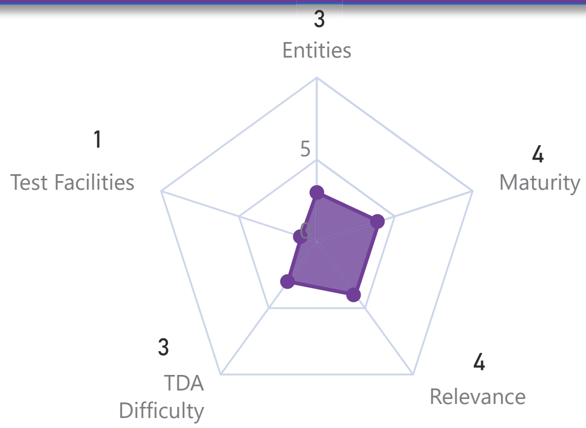
European Entities Involved	
Public	Private
KIT University of Stuttgart	Kyoto Fusioneering Eni (Italy)

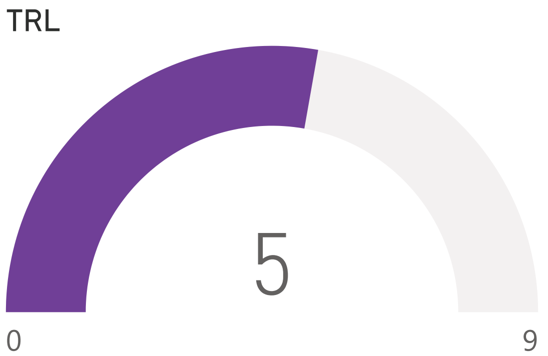
Technology Development Action

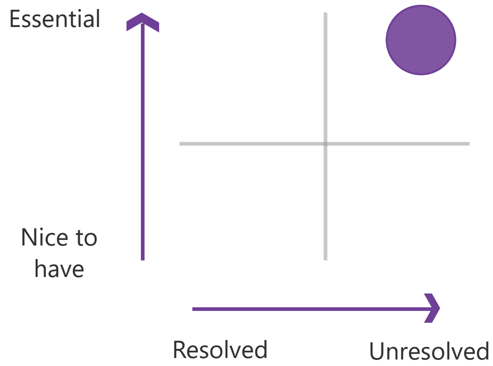
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Develop atomic H2 production sources	40 to 80%	6 months to 2 years	250k to 1M	Medium	No
Performance and operation qualification (1° qualification step)	40 to 80%	6 months to 2 years	250k to 1M	Medium	Partially
Prototype the Metal Foil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

Fuel Cycle > Pumping

Non-Evaporable Getter (NEG) pumps







Other Fields of Application
Accelerators Hydrogen

Alternative Technologies
Cryopumps TMP diffusion pumps other getter pumps

Showstoppers list
No pumping of noble gases Regeneration temperature

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
Saes Getters (Milan) Spider (RFX Padova) DIPAK (KIT Karlsruhe)	Radiation and tritium compatibility

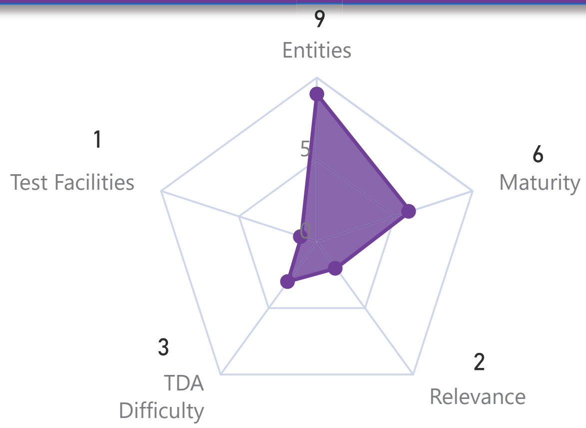
European Entities Involved

Public	Private
KIT RFX IPP CERN	SAES Getter

Technology Development Action

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

Oil diffusion pumps with tritium compatible oils



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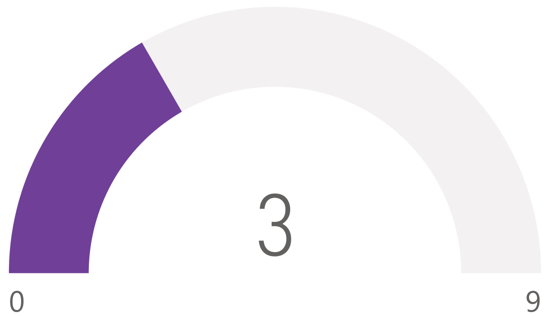
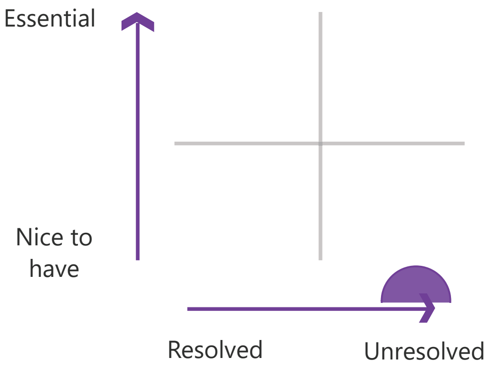




Other Fields of Application

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

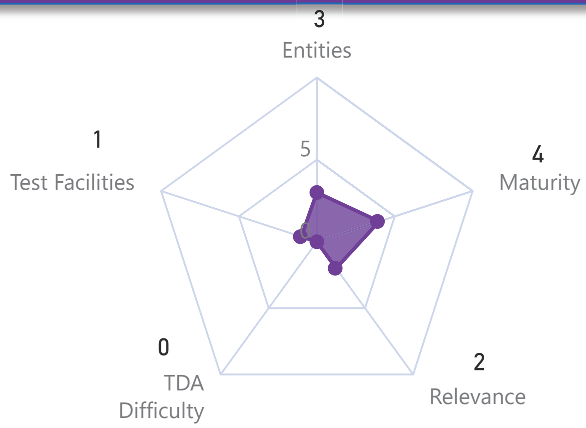
European Entities Involved

Public	Private

Technology Development Action

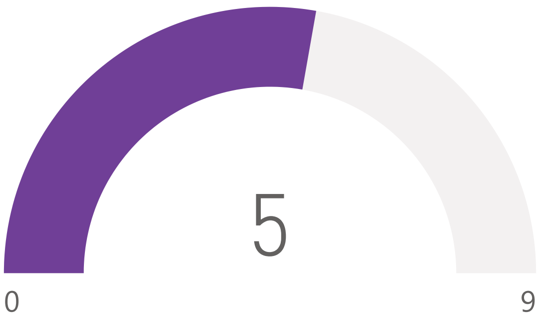
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Design optimization to exclude any oil back flow to the process/system for compliance with requirements	40 to 80%	6 months to 2 years	<250k	Low	No
Develop oil that is tritium compatible	<40%	>2 years	250k to 1M	Low	No

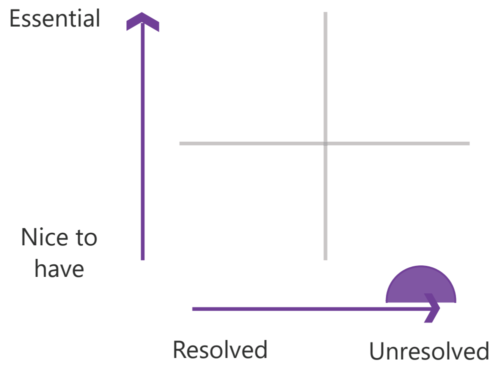
Fuel Cycle › Pumping



Piston pumps

TRL





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

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
KIT - Tritium Laboratory Karlsruhe (TLK) UKAEA (Rochester) Unity-2 (Canada under construction)	

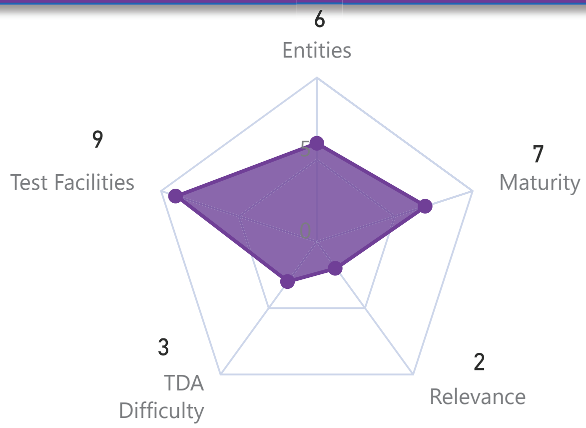
European Entities Involved	
Public	Private
Kyoto Fusioneering	Kyoto Fusioneering

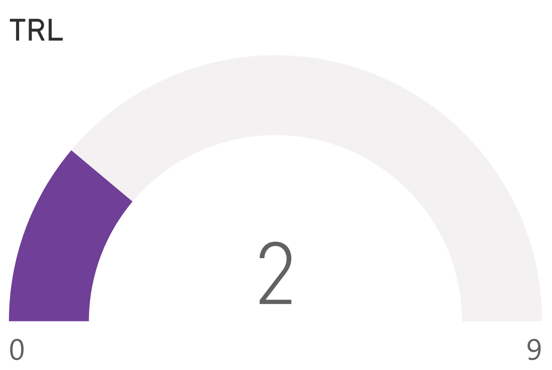
Technology Development Action

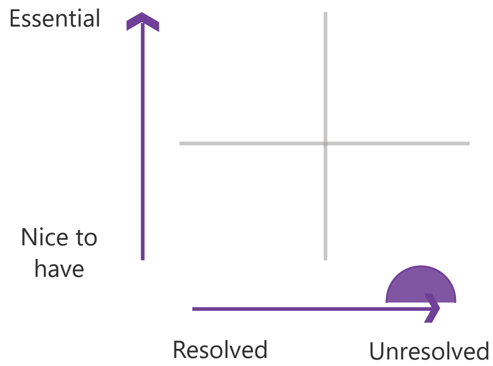
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded

Fuel Cycle > Pumping

Proton conductor pump







Other Fields of Application
Pure hydrogen separation H2 purification Petrochemical

Alternative Technologies
Metal foil quantum sieving

Showstoppers list
Reliability Compatibility with operational conditions Maintenance

Technology Characteristics

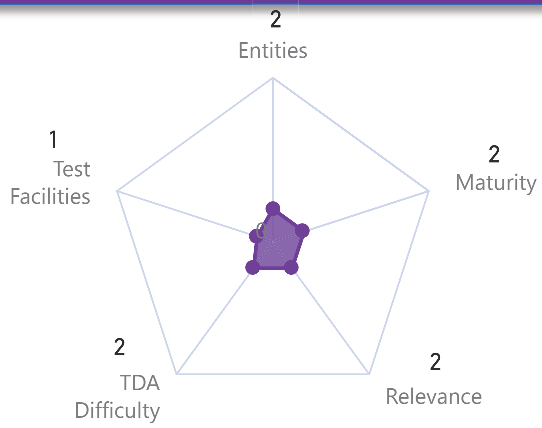
Existing Test Facilities	Additional Test Facility Needed

European Entities Involved	
Public	Private
Kyoto Fusioneering	

Technology Development Action

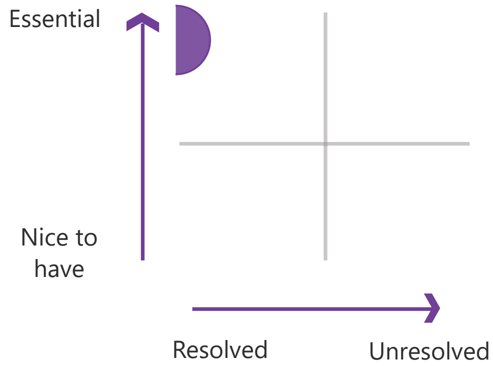
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Assess the feasibility of a proton conductor pump for the fusion fuel cycle	>80%	<6 months	<250k	Low	No

Fuel Cycle > Pumping



Roots pumps

TRL



Other Fields of Application	Alternative Technologies	Showstoppers list
Accelerators Semiconductor	CVC screw	

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
KIT - Tritium Laboratory Karlsruhe (TLK) UKAEA (Culham) Unity-2 (Canada under construction)	

European Entities Involved

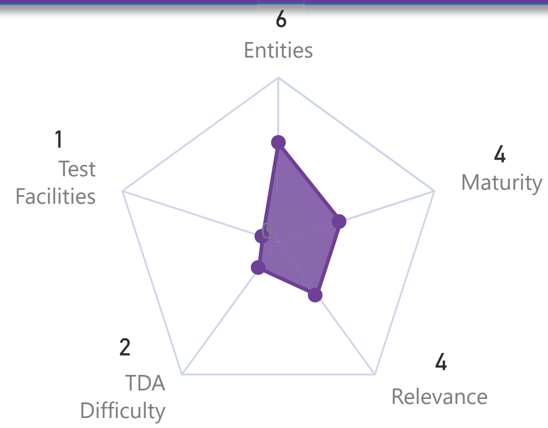
Public	Private
ITER	Pfeiffer (OCTA 1500 SS all metal - qualified by ITER US) Edwards Busch Vacuum solutions Leybold

Technology Development Action

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

Screw pumps



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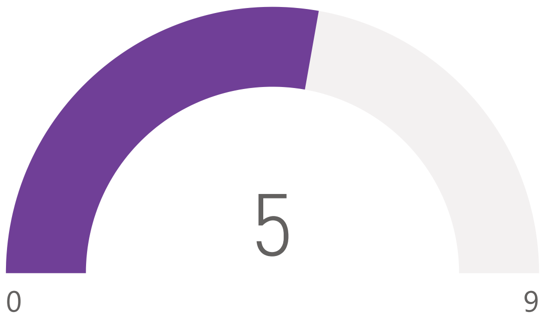
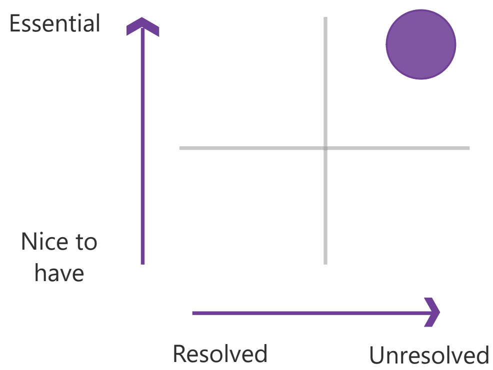




Other Fields of Application

Accelerators
Semiconductor

Alternative Technologies

Showstoppers list

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
KIT - Tritium Laboratory Karlsruhe (Germany) UKAEA (Culham Rochester) Unity-2 (Canada under construction)	

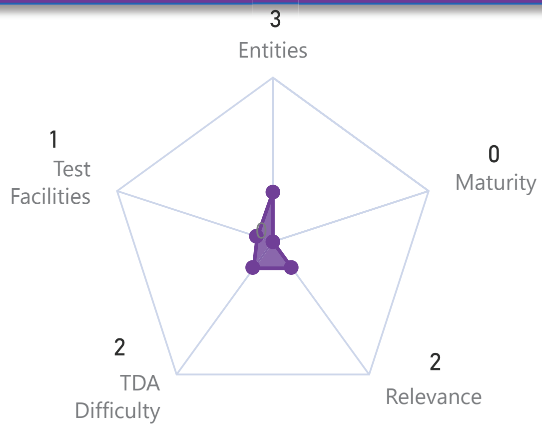
European Entities Involved

Public	Private

Technology Development Action

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

Scroll pumps



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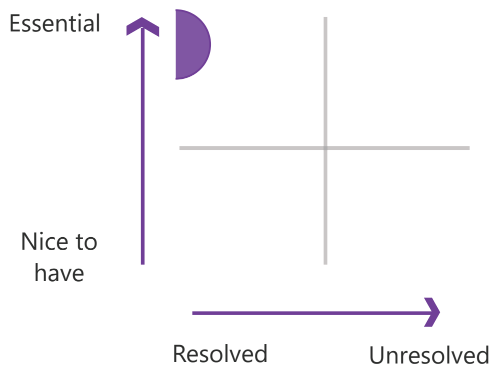


Other Fields of Application
Process industry Accelerators

Alternative Technologies

Showstoppers list

Technology Characteristics

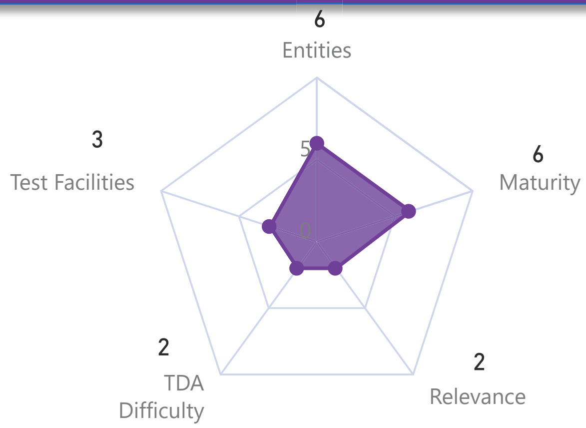
Existing Test Facilities	Additional Test Facility Needed	European Entities Involved	
		Public	Private
KIT - Tritium Laboratory Karlsruhe (TLK) UKAEA (Rochester) Unity-2 (Canada under construction)			EUMECA (150 m3/hr and 15 m3/hr qualified by ITER)

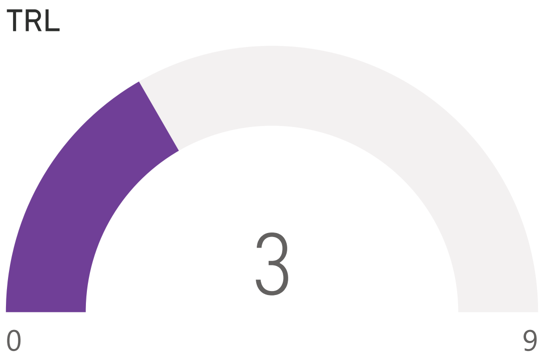
Technology Development Action

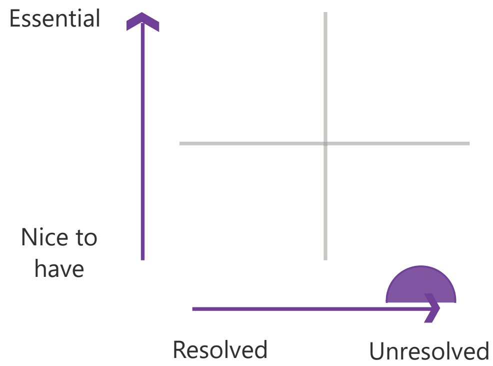
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Develop tritium compatible tip seal to improve pumping performances	>80%	6 months to 2 years	<250k	Low	No
Diversify the supply chain for tritium compatible scroll pump	>80%	>2 years	250k to 1M	Medium	No

Fuel Cycle › Pumping

Temperature Staged cryogenic condensation and adsorption pumps







Other Fields of Application

Hydrogen

Alternative Technologies

TMPs
Cryosorption
NEG
Metal foil pump
proton conductor pump

Showstoppers list

Technology Characteristics

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

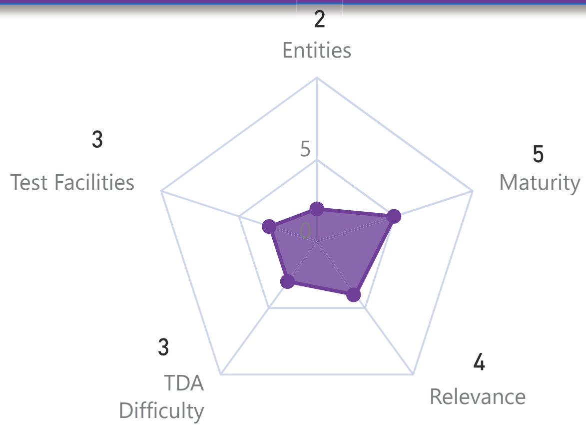
European Entities Involved

Public	Private
CEA (Grenoble) CERN KIT ITER	

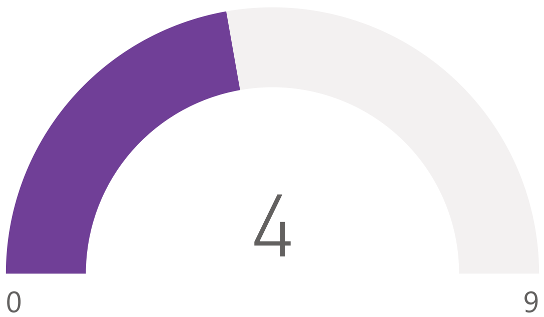
Technology Development Action

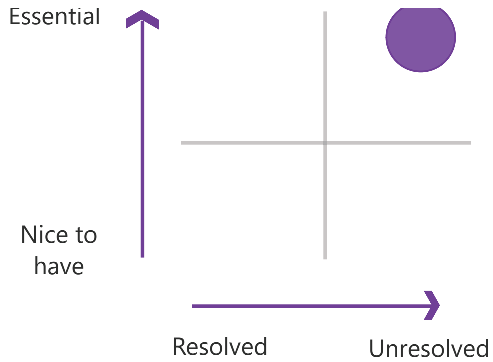
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Detailed study of a temperature staged cryopump	40 to 80%	6 months to 2 years	250k to 1M	Low	No

Tritium permeation barriers



TRL





Other Fields of Application
Fission Fast breeders H related technologies space waste
Hydrogen production Fission

Alternative Technologies
Base material selection Healing under irradiation
Return on experience from operation

Showstoppers list
Lack of coordination in the field Missing and inconsistent data Lack of experimental facilities
Regulatory issues Limited relevant permeation test facility Complex shapes of components Resistance to harsh environment

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
CURIUM (France)	
UKAEA (Culham) CURIUM (France)	Permeation measurements
Max Plank Institutes (Germany) Fraunhofer Institute (Germany)	Permeation testing

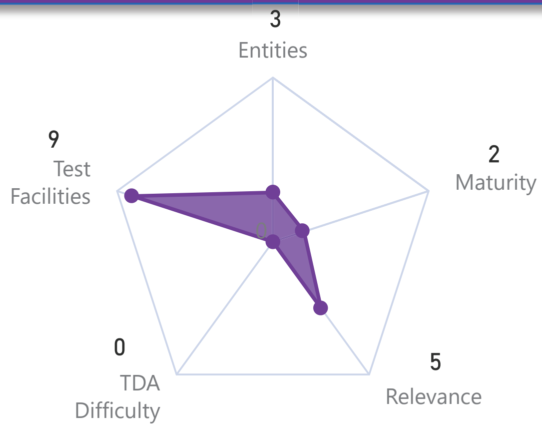
European Entities Involved

Public	Private
UKAEA (Culham) CEN-SCK (Belgium) VTT (Finland) CEA (Saclay and Cadarache) Fraunhofer Institute (Germany) ICSI (Romania)	Amentum (France), Kyoto Fusioneering (Tokyo, Japan), Orano (France)
CEA (Grenoble) CERN University of Latvia (Riga) Fraunhofer Institute (Dresden) UKAEA (Culham)	BIMO Tech Kyoto Fusioneering (Germany) Eni Spa (Italy)

Technology Development Action

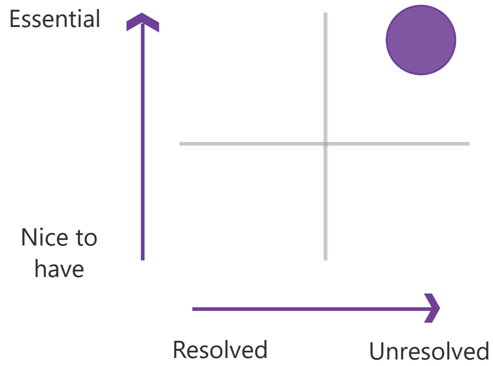
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Amendment of material codes to cover tritium permeation (or develop specific code)	>80%	>2 years	250k to 1M	Low	No
Consolidation of existing data in database	>80%	6 months to 2 years	<250k	High	Partially
Create a community for permeation 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	40 to 80%	>2 years	>1M	High	No

Fuel Cycle › Tritium management



Cryogenic Temperature Sensor

TRL



Other Fields of Application
Accelerators

Alternative Technologies
Use of room temperature systems

Showstoppers List

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed

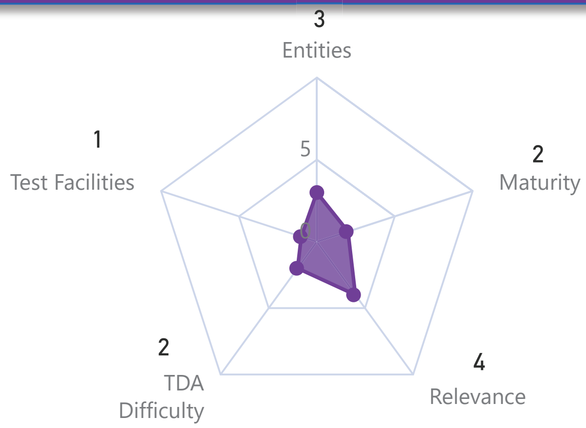
European Entities Involved	
Public	Private
ITER	Fraco-Term (PL)

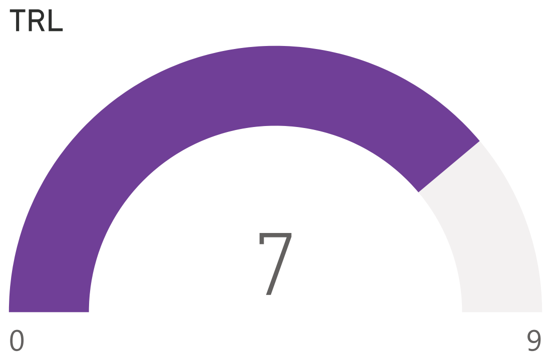
Technology Development Action

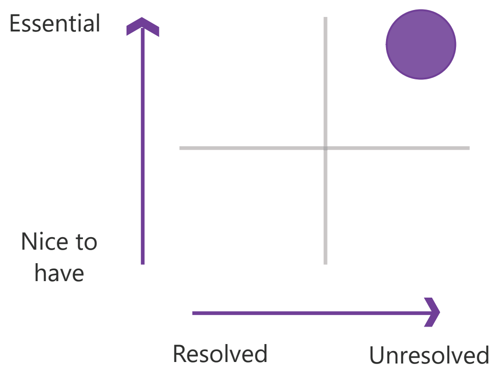
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Qualify operation range of Fraco-term TVOs to 500K, radiation hardness and magnetic field compliance		6 months to 2 years	<250k	Low	No

Fuel Cycle > Tritium management

Instruments to measure hydrogen isotope concentrations







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
TLK (Germany) UKAEA (Culham)	

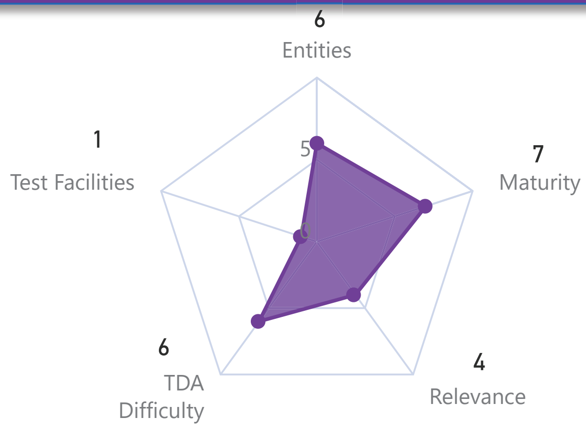
European Entities Involved	
Public	Private
CEA Cadarche (France) KIT/TLK (Germany)	SMOLSYS (Suisse) IS Instruments Ltd (UK)

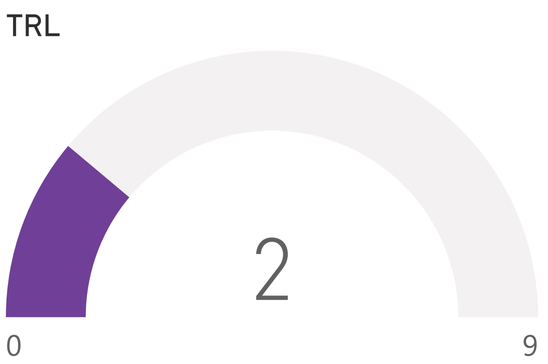
Technology Development Action

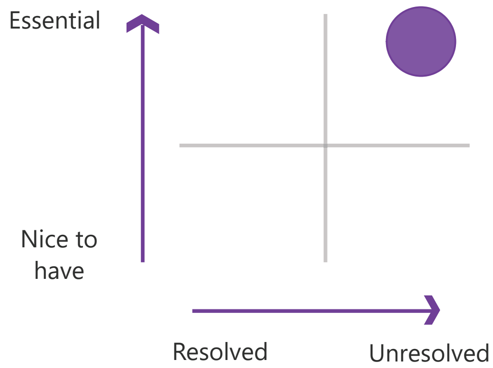
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Improvement of response time and improvement of the sensitivity for low concentrations	40 to 80%	6 months to 2 years	250k to 1M	High	No
Industrialization of Raman Spectroscopy Detector	>80%	>2 years	250k to 1M	Medium	Partially

Fuel Cycle > Tritium management

Non-destructive Tritium detection in solids







Other Fields of Application
Fission Radwaste

Alternative Technologies
Destructive methods

Showstoppers list
Difficulty in detecting low-energy beta particles

Technology Characteristics

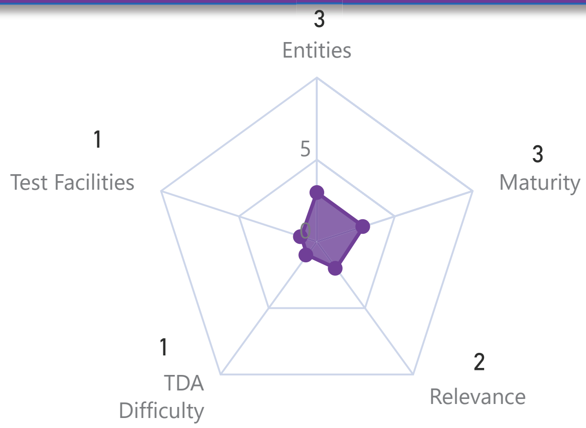
Existing Test Facilities	Additional Test Facility Needed
CURIUM (France) CEA Cadarache (France) Forschungszentrum Juelich (Germany)	

European Entities Involved	
Public	Private
CEA Cadarache - Future tritium process test facility for 2031 (France) Forschungszentrum Juelich (Germany)	

Technology Development Action

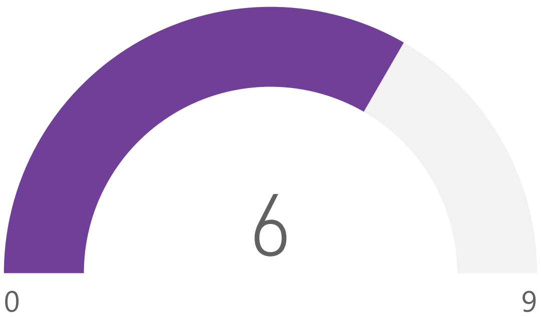
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Analyse to define the methods for non-destructive tritium measurements in solids.	>80%	<6 months	<250k	Medium	No

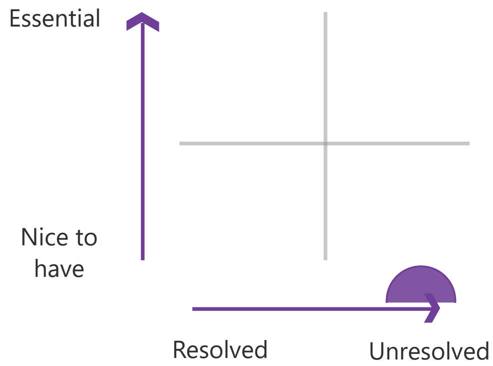
Fuel Cycle > Tritium management



Wearable tritium detector

TRL





Other Fields of Application
Fission Radwaste

Alternative Technologies
ex post analysis room monitors

Showstoppers list
Size limitation Online-measuring

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed
CURIUM (France) KIT/TLK (Germany)	

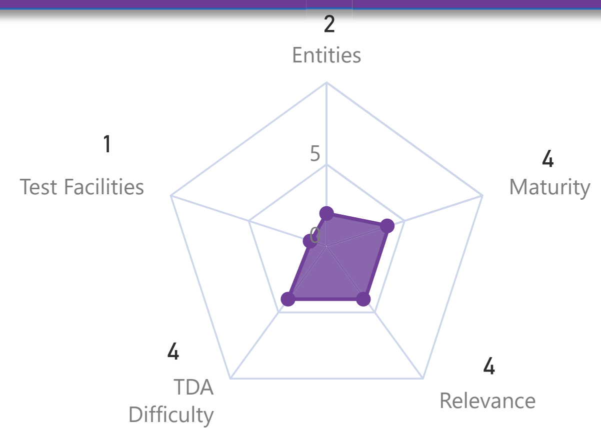
European Entities Involved	
Public	Private
ENEA (frascati) CIEMAT (Madrid) CEA (Cadarache)	Mirion Tekniker Else Nuclear

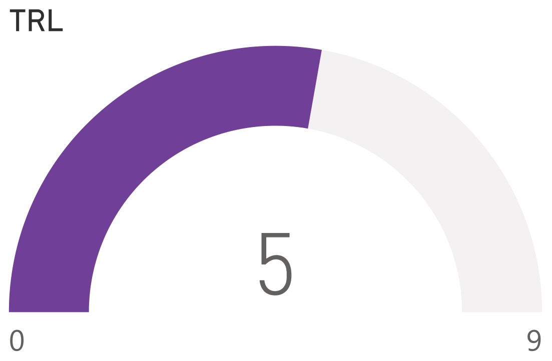
Technology Development Action

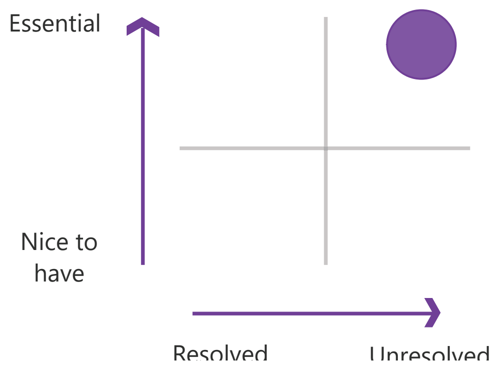
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Develop a prototype wearable tritium detector	>80%	6 months to 2 years	250k to 1M	Low	Yes

Fuel Cycle > Tritium management

Process Simulation Mode Validation







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) Unity 2 (Canada under construction) DIPAC (Germany under construction)	

European Entities Involved

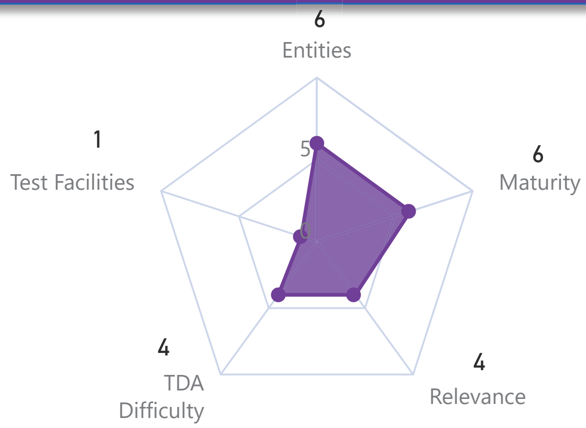
Public	Private
ITER ENEA UKAEA,	ENI (Milan) RINA (Genoa) Impresarios Agrupados (Madrid) Atkins Realis Polaris (Minsito) Kraftenlagen (Heildelberg) MONTEIRO

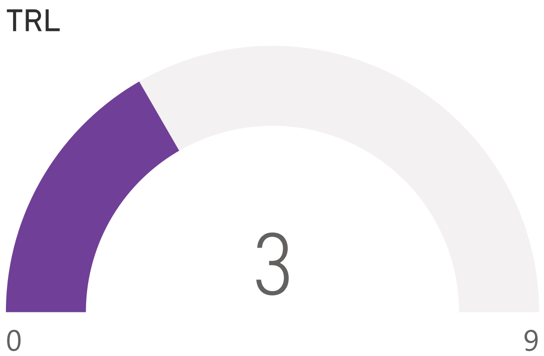
Technology Development Action

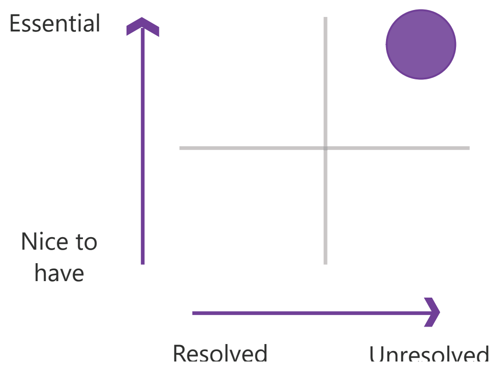
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Create a community for tritium process simulation	>80%	<6 months	<250k	Medium	Yes
Create and populate database for H isotope properties	40 to 80%	6 months to 2 years	250k to 1M	High	No
Exchange results and data for benchmarking.	>80%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

Fuel Cycle > Tritium management

Tritium accountancy







Other Fields of Application	Alternative Technologies	Showstoppers list
Fission Radwaste		Lack of tools Lack of experimental data Lack of reliable and accurate in-situ instrumentation for high flow measurements

Technology Characteristics

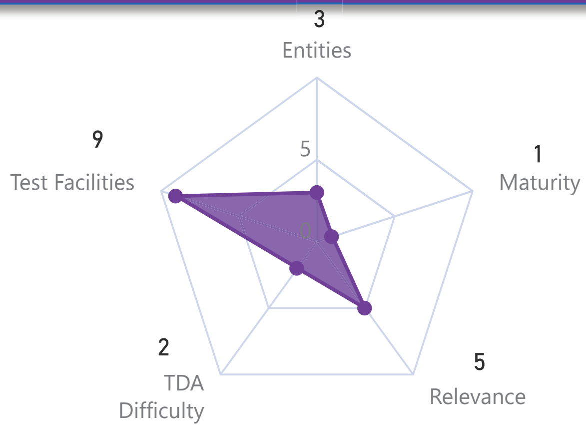
Existing Test Facilities	Additional Test Facility Needed	European Entities Involved: Public	European Entities Involved: Private
KIT/TLK (Germany)		University of Manchester UKAEA ITER KIT/TLK	

Technology Development Action

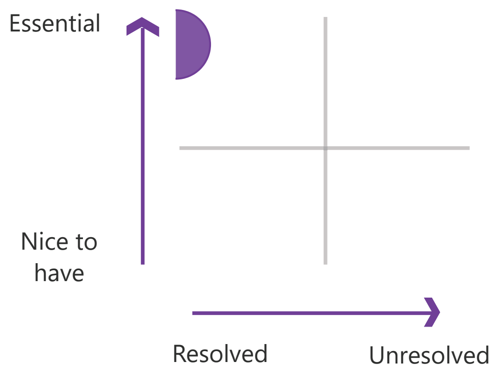
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Create a community	>80%	<6 months	<250k	Medium	No
Import best practice from JET DTE2/3 and fission fuel accountancy and create a reference document including specificities for tritium accountancy,	>80%	6 months to 2 years	<250k	Medium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

Fuel Cycle › Tritium management

Room tritium detector



TRL



Other Fields of Application

Alternative Technologies

Showstoppers List

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed

European Entities Involved

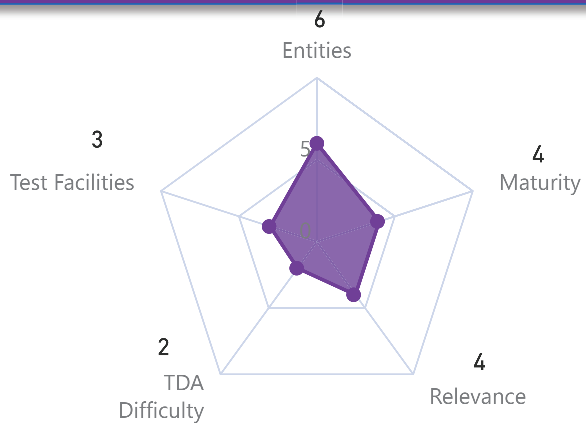
Public	Private
CEA Cadarache (France) KIT/TLK (Germany) UKAEA (UK)	Tyne Overhoff Mirion

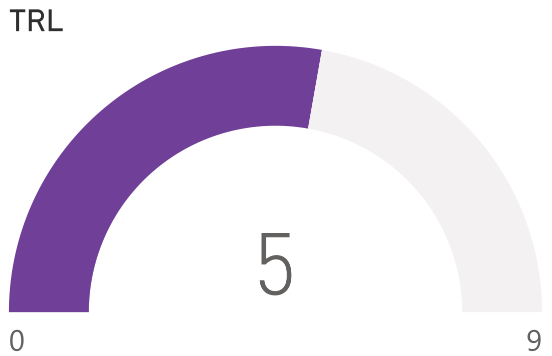
Technology Development Action

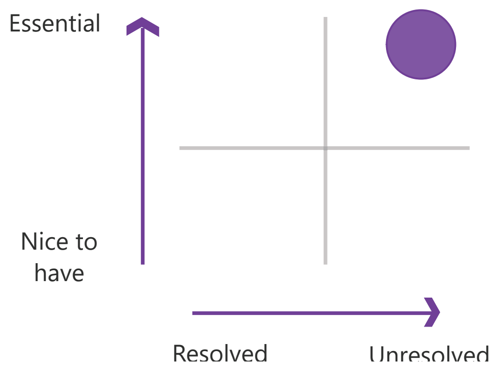
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
For real time process measurements create a tritium performance and calibration test bench (for high concentration)	>80%	6 months to 2 years	>1M	Low	Partially

Fuel Cycle > Tritium management

Real time tritium detector for water







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

Technology Characteristics

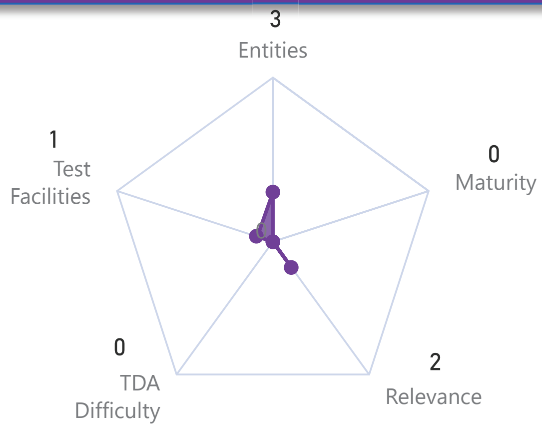
Existing Test Facilities	Additional Test Facility Needed	European Entities Involved	
		Public	Private
CURIUM (France) KIT/TLK (Germany)	Compatibility with neutron flux magnetic field	CEA Cadarache - Future tritium process test facility for 2031 (France)	

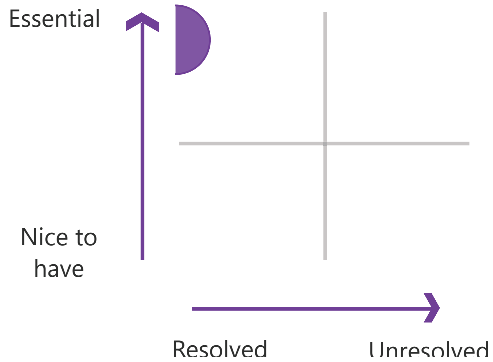
Technology Development Action

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





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
		CEA (France) Technetics (France)	Technetics (France) SPG Eiffage (Joint S)

Technology Development Action

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded

Fusion for Energy

The European Joint Undertaking for ITER and the Development of Fusion Energy
C/ Josep Pla 2,
Torres Diagonal Litoral
Edificio B3
08019 Barcelona
Spain

Tel: +34 933 201 800
E-mail: info@f4e.europa.eu

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EUROfusion

The European Consortium for the Development of Fusion Energy
Boltzmannstr. 2
85748 Garching / Munich
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Email: contact@euro-fusion.org

euro-fusion.org