Tokamak Energy

Fuel Cycle – SULI PPPL

Dr. Emre Yildirim –
Assistant Chief Engineer

Presenter Slide

2015

Mechanical w/Nuclear Engineering *BEng*

2018

Materials Science (Fusion Materials) PhD

2023

PFC Development Engineer – Tokamak Energy

2024

Assistant Chief Engineer – Tritium, Power and Utitlities

© 2025 Tokamak Energy

Presenter Slide

2015

Mechanical w/Nuclear Engineering *BEng*

2018

Materials Science (Fusion Materials) PhD

2023

PFC Development Engineer – Tokamak Energy

2024

Assistant Chief Engineer – Tritium, Power and Utitlities

The biggest thing I have learnt is to be interested in what others are doing and take opportunities!

© 2025 Tokamak Energy

Talk Outline

- Why the Fuel Cycle matters
    - And its link to the plasma
- What makes up a fuel cycle?
    - Inventory and flow
    - Technologies (there are many – we will cover *some*)
- Challenges in the Fuel Cycle
    - Where are we now and where do we need to be?
- Who works on the fuel cycle?

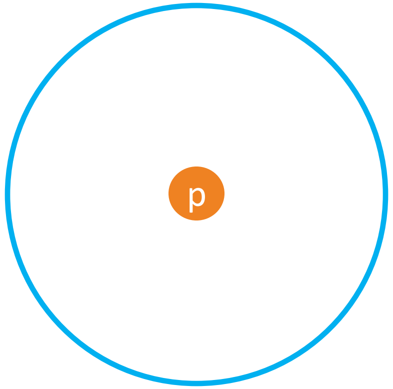
Tokamak Energy

Why the Fuel Cycle Matters

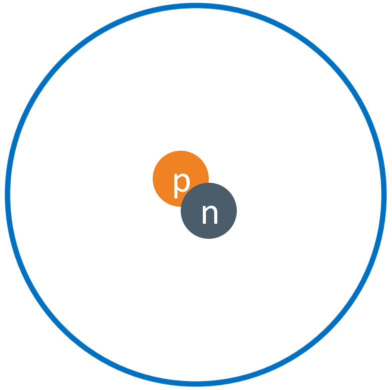
The importance of the fuel cycle

- Continuous, efficient supply
- Self-sufficiency
- Low burn fraction
- Accountancy
- Safety

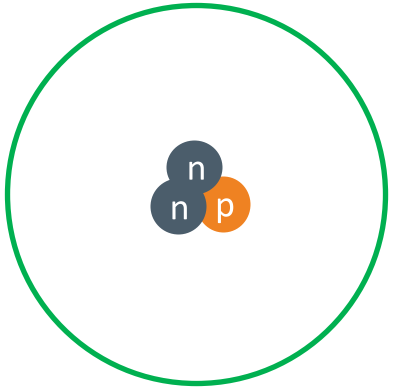
The hydrogen isotopes



- **Protium**
- Abundant
- Not used as a fusion fuel



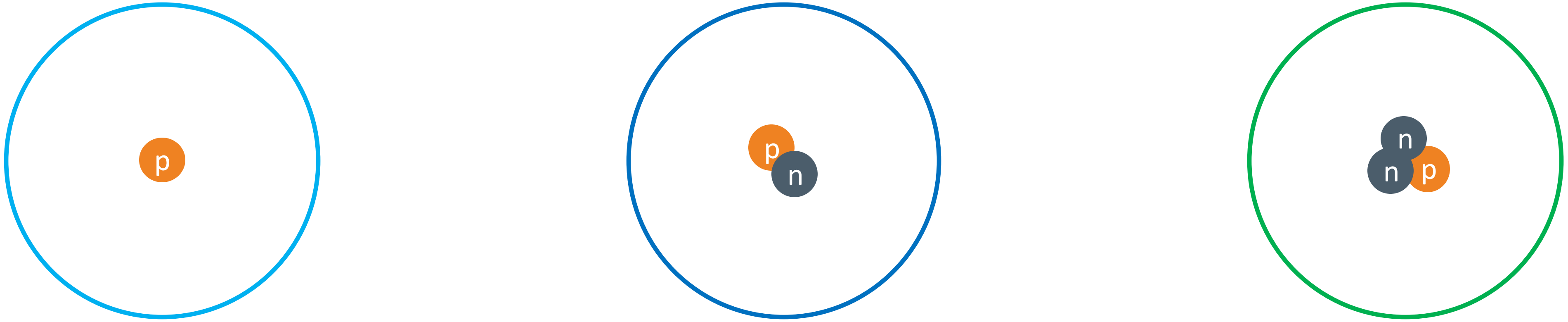
- **Deuterium**
- Naturally Occurring – 130-160 ppm in H
- Continuously consumed



- **Tritium**
- Beta emitter (18.6 keV)
- 12.3 year half life
- ~30 kg total global inventory
- Need to produce this continuously!

© 2025 Tokamak Energy

The hydrogen isotopes



Property	Hydrogen (^{1}H)	Deuterium (^{2}H or D)	Tritium (^{3}H or T)
Atomic number	1	1	1
Neutrons	0	1	2
Relative atomic mass	1.00784 u	2.01410 u	3.01605 u
Mass (kg/mol)	1.00784 g/mol	2.01410 g/mol	3.01605 g/mol
Boiling point (K)	20.271 K	23.67 K	~25 K
Radioactive?	No	No	**Yes** (β^-, t½ ≈ 12.3 yrs)
Natural abundance	>99.98%	~0.0156%	Trace (≈ 10^{-18} in nature)
Diatomic as a gas?	Yes	Yes	Yes

© 2025 Tokamak Energy

How much Tritium do we use?

$Recall$: ${}^{3}_{1}T + {}^{2}_{1}D \rightarrow {}^{1}_{0}n + {}^{4}_{2}He + 17.6\ MeV$

1,000 MW_{fus}

$$E_{reaction} = 17.6 \text{ MeV} = 17.6 \times 1.602 \times 10^{-13} \text{ J} = 2.8195 \times 10^{-12} \text{ J}$$

$$1 \times 10^{9} \text{ J s}^{-1} / 2.8195 \times 10^{-12} \text{ J reaction}^{-1} = 3.55 \times 10^{20} \text{ reactions s}^{-1}$$

M_T = 3.016 g/mol

$$3.55 \times 10^{20} \text{ atoms s}^{-1} / 6.022 \times 10^{23} \text{ atoms mol}^{-1} = 5.90 \times 10^{-4} \text{ mol s}^{-1}$$

$$5.90 \times 10^{-4} \text{ mol s}^{-1} \times 3.016 \text{ g mol}^{-1} = 1.78 \times 10^{-3} \text{ g s}^{-1}$$

~ 56.1 kg year^{-1}

© 2025 Tokamak Energy

Tritium Sources and Scarcity

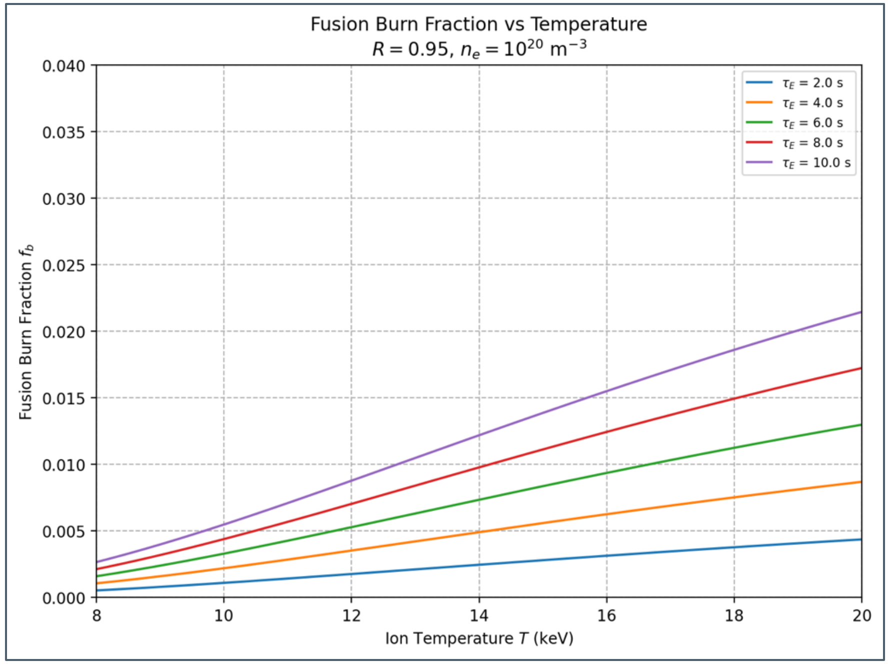
- Only current sources of tritium: Canada, South Korea and Romania
  - Through heavy water moderated fission plants
- With ~ 30 kg in commercial existence – cost is ~ 30,000+ $/g
- Tritium use in defense – highly regulated commodity
- Produced in fusion through Lithium interaction with a neutron:
  - ${}^{6}_{3}Li + {}^{1}_{0}n \rightarrow {}^{3}_{1}T + {}^{4}_{2}He + 4.78\ MeV$ (requires thermal neutron)
  - ${}^{7}_{3}Li + {}^{1}_{0}n \rightarrow {}^{3}_{1}T + {}^{4}_{2}He + {}^{1}_{0}n\ - 2.47\ MeV$ (requires high energy neutron)
  - Natural lithium is 7.5 % Li-6 and 92.5 % Li-7

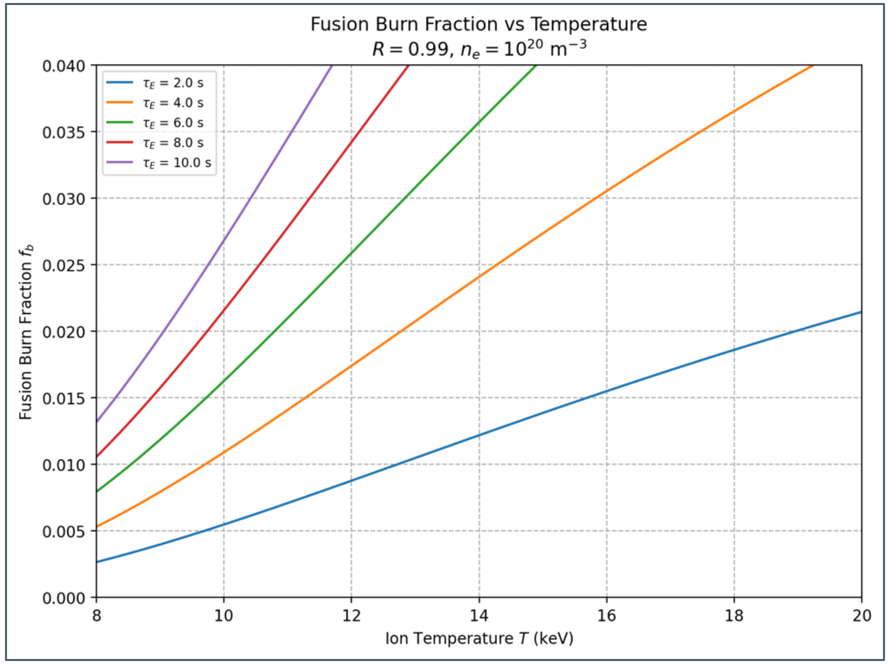
© 2025 Tokamak Energy

How much Tritium burns?

$$f_b = \frac{n\langle\sigma v\rangle\tau *}{2 + n\langle\sigma v\rangle\tau *}$$

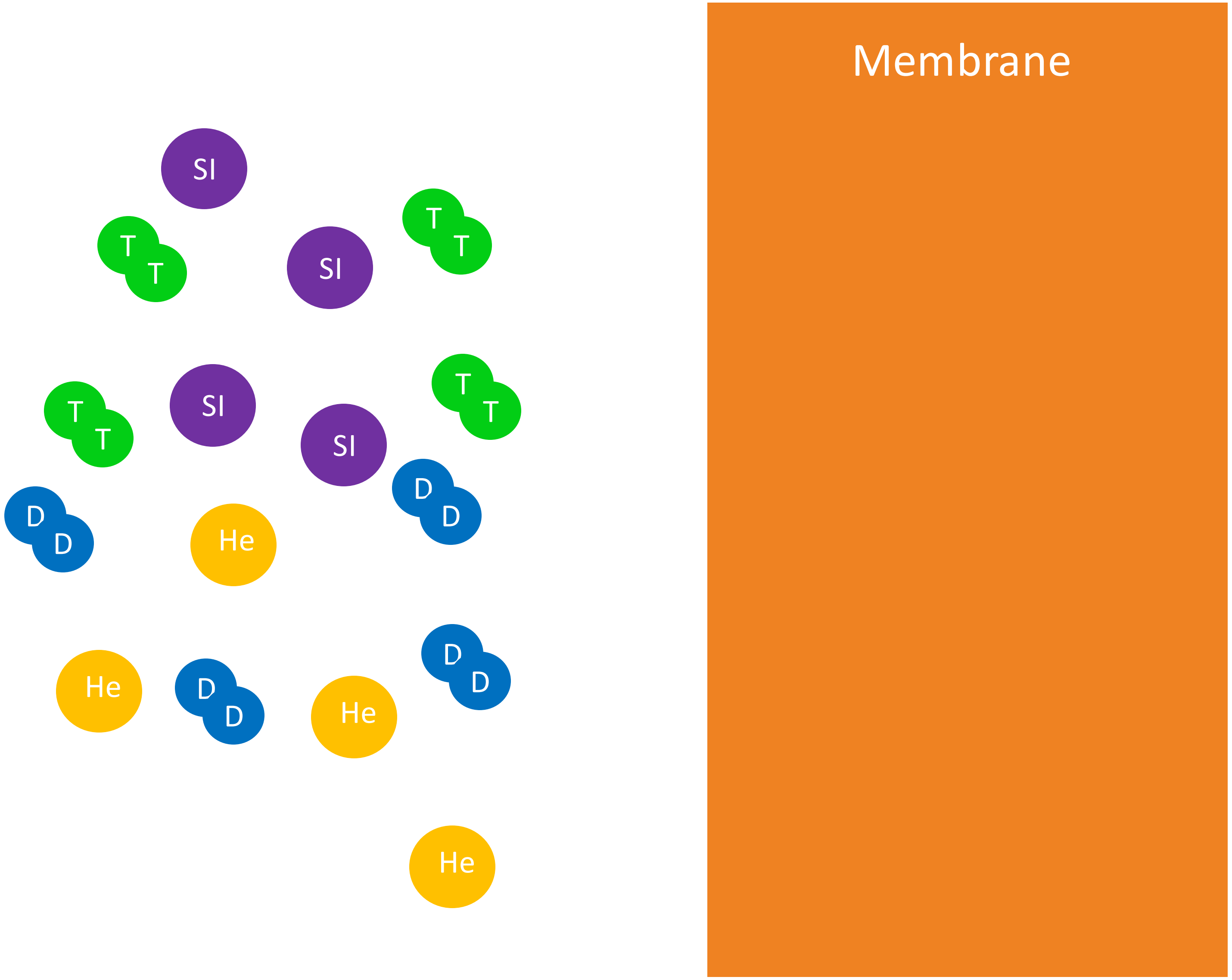
$$\tau * = \frac{\tau}{1 - R}$$





© 2025 Tokamak Energy

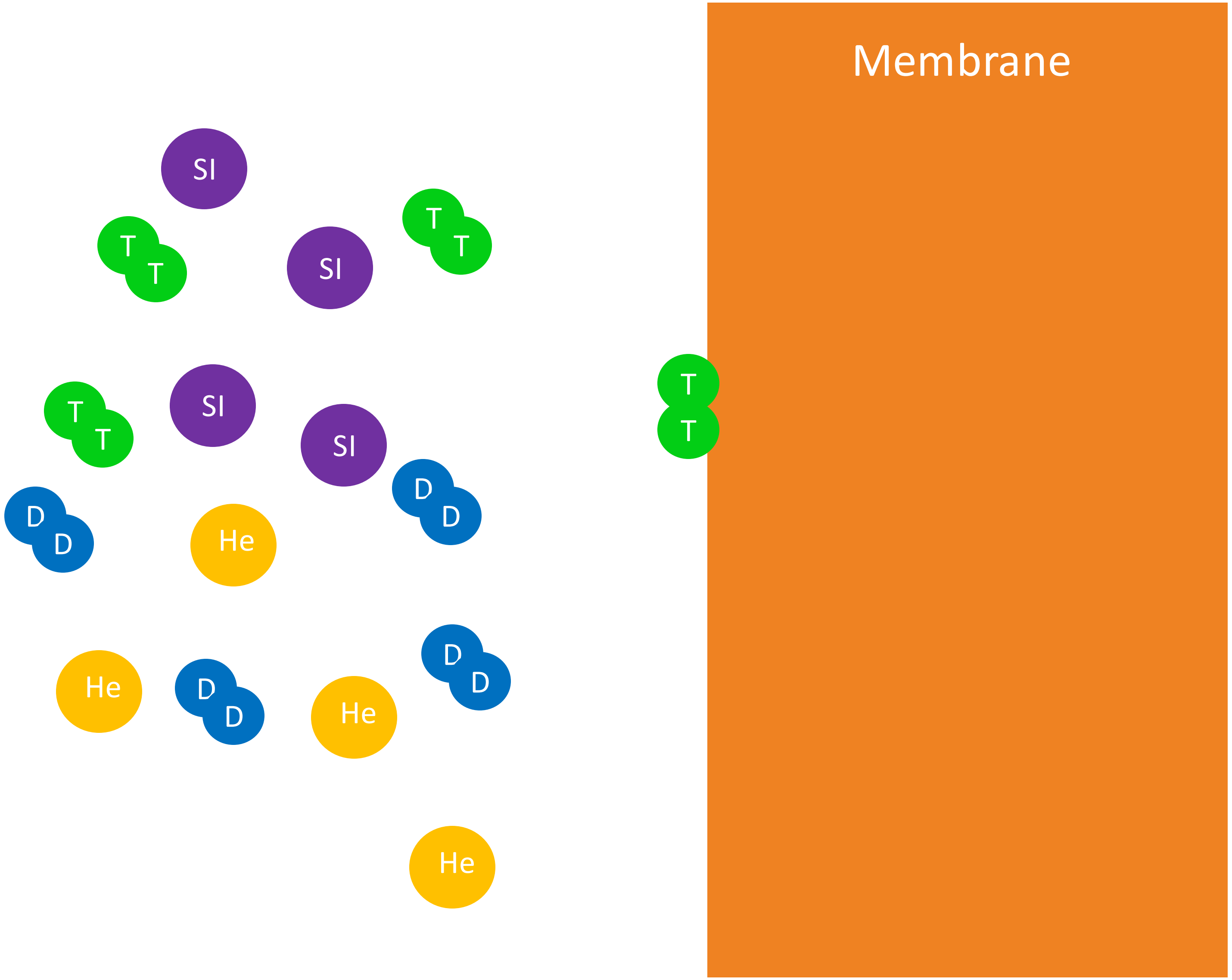
Key Concepts in the Fuel Cycle - Permeation



© 2025 Tokamak Energy Private and Confidential

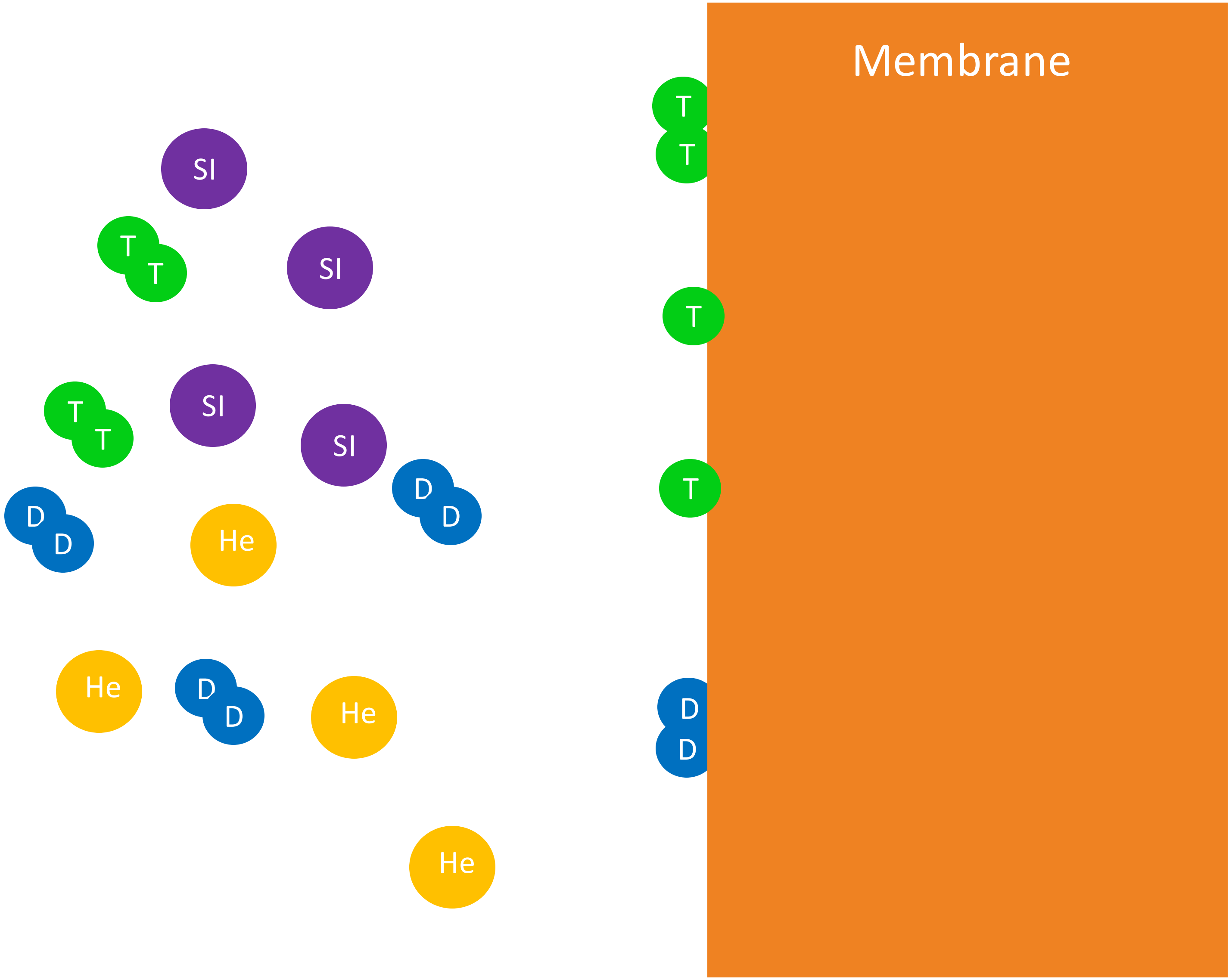
Key Concepts in the Fuel Cycle - Permeation

Adsorption



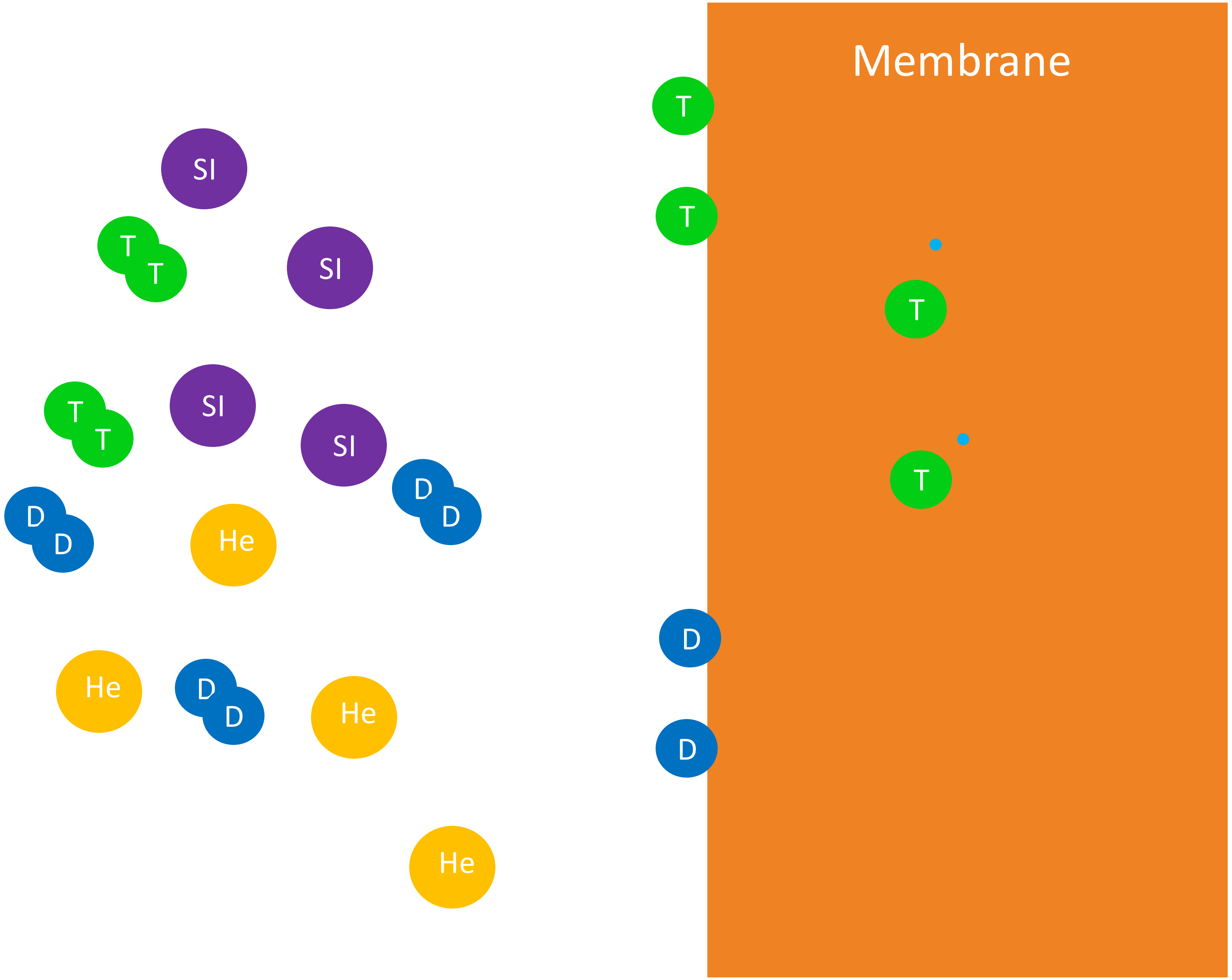
Key Concepts in the Fuel Cycle - Permeation

Dissociation



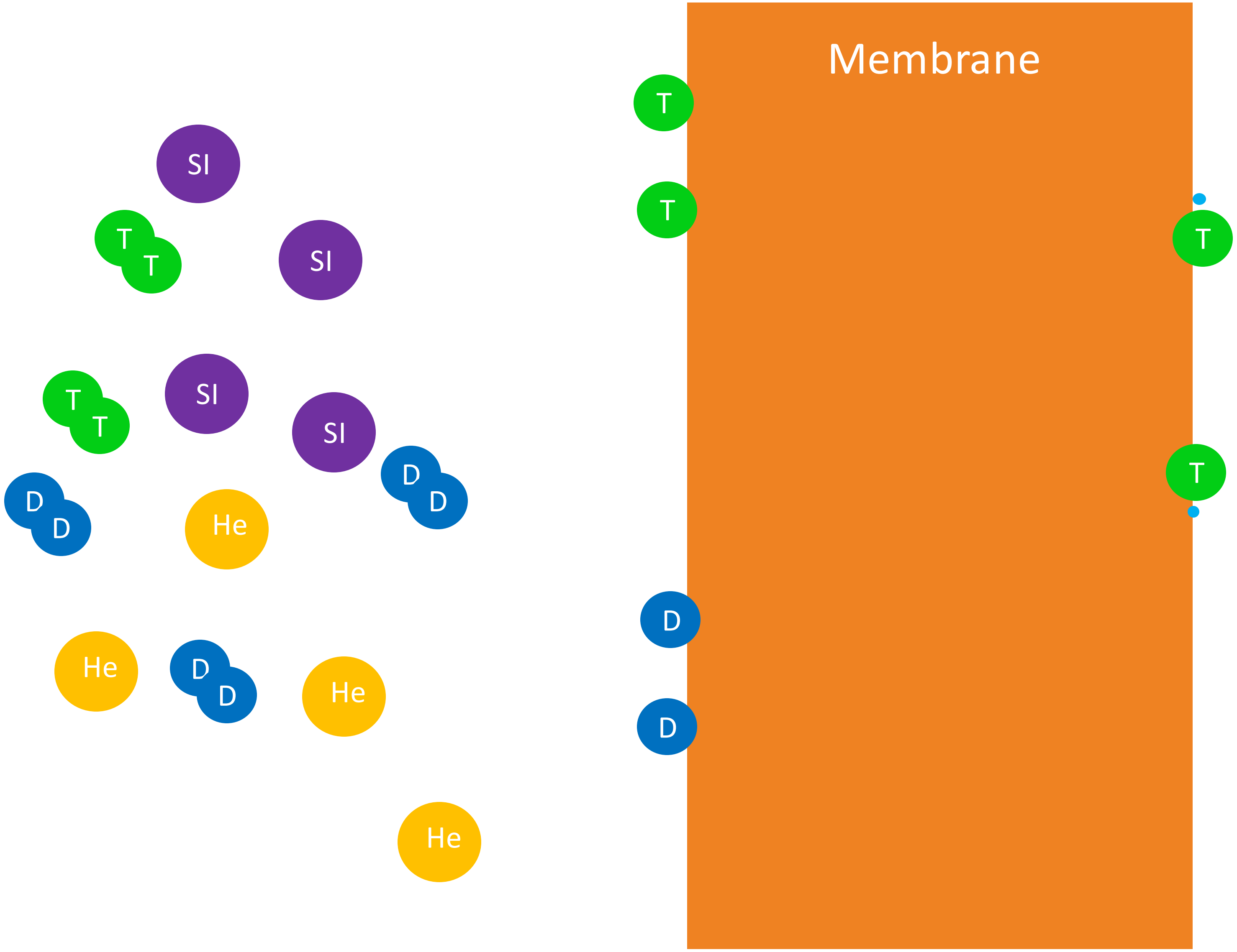
Key Concepts in the Fuel Cycle - Permeation

Ionization



Key Concepts in the Fuel Cycle - Permeation

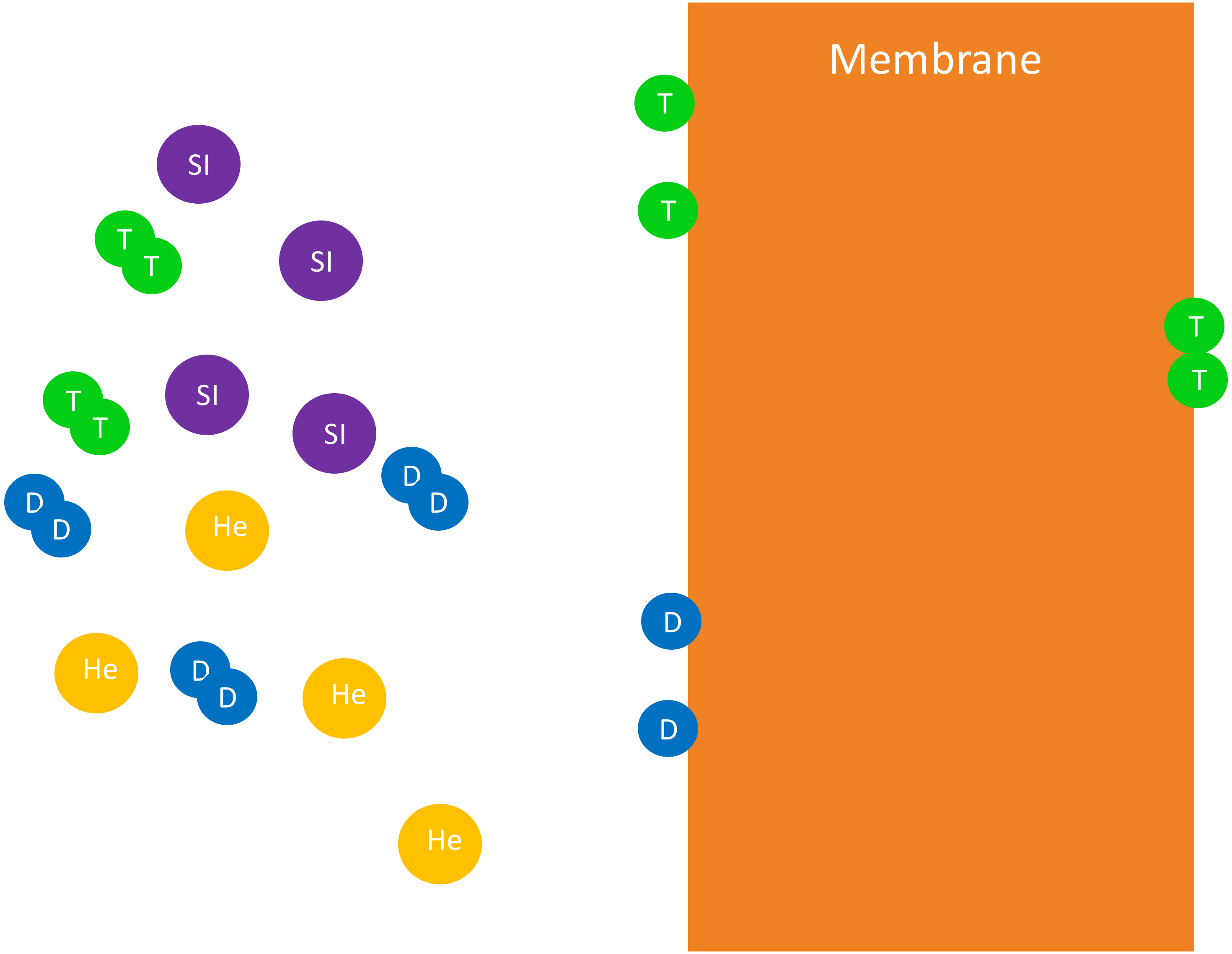
Diffusion



© 2025 Tokamak Energy

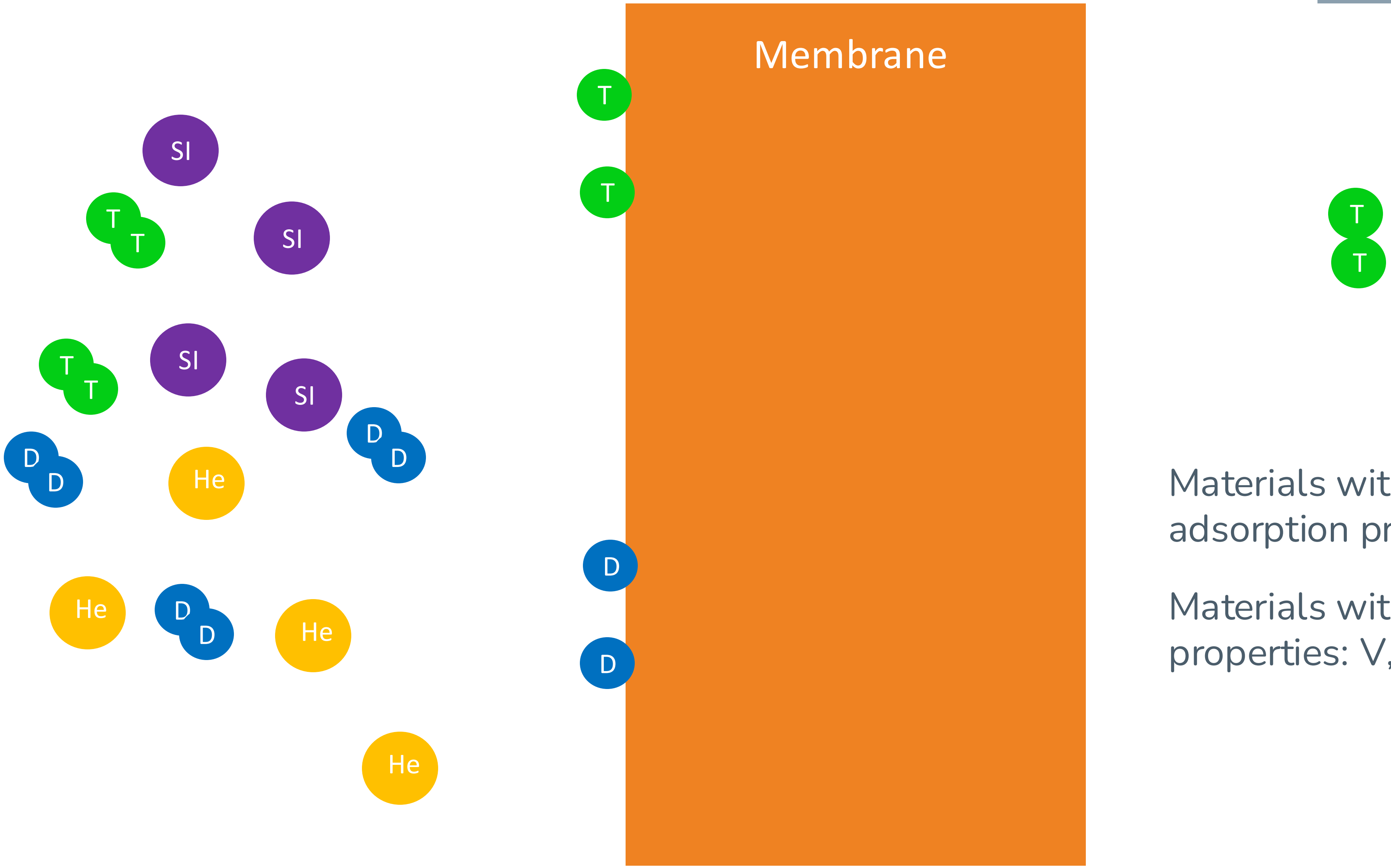
Key Concepts in the Fuel Cycle - Permeation

Recombination



Key Concepts in the Fuel Cycle - Permeation

Desorption



Materials with good adsorption properties: Pd

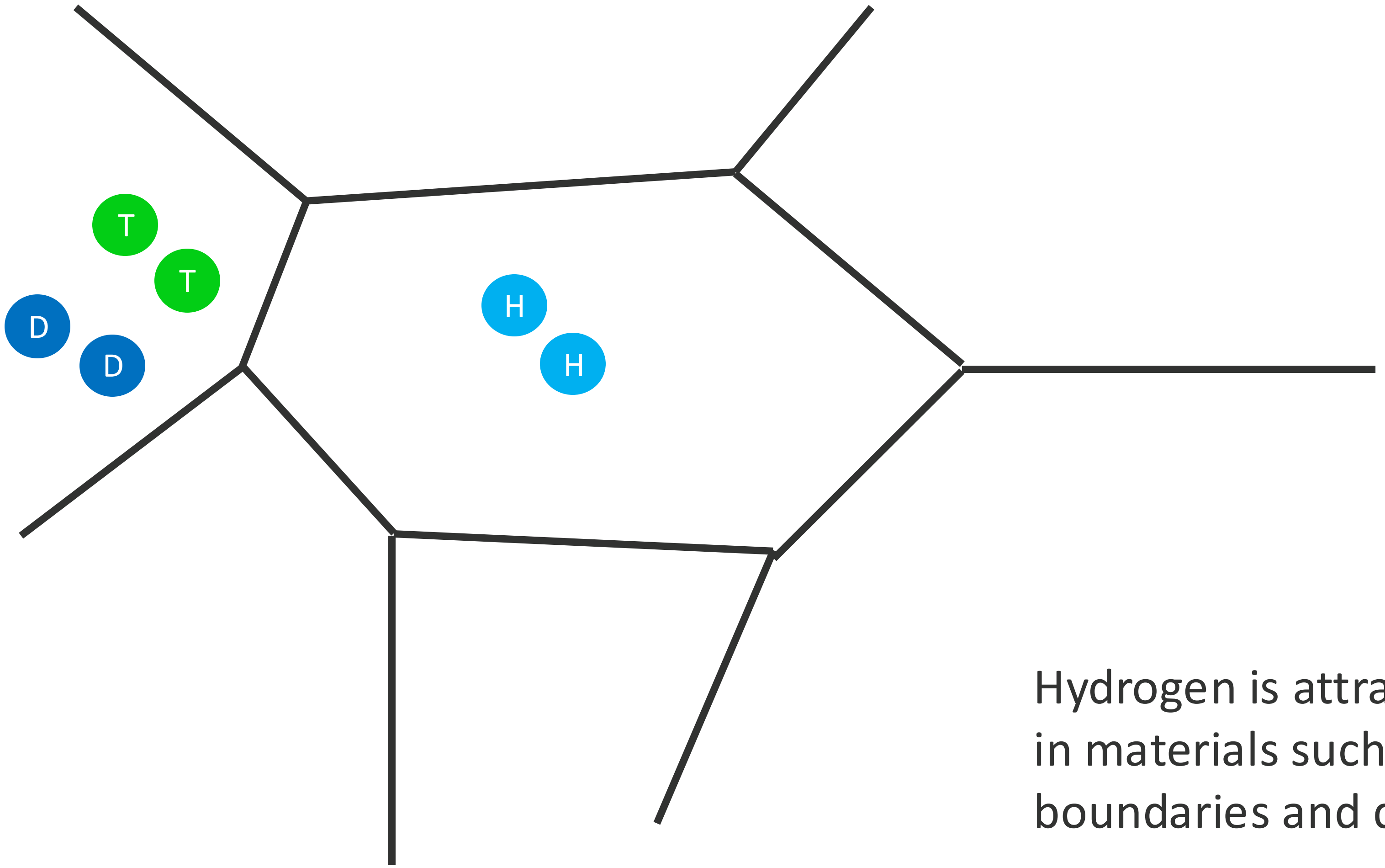
Materials with fast diffusive properties: V, Ta, Ti

© 2025 Tokamak Energy

Key Concepts in the Fuel Cycle – Isotopic Differences

- Difference in mass leads to:
  - Differences in boiling points
  - Difference in diffusivity through materials
- Isotopic exchange can also occur
  - Tritium will prefer to be in bigger polar molecules like water vs. staying in HT form
  - This process is instantaneous
- These can help us separate out these molecules

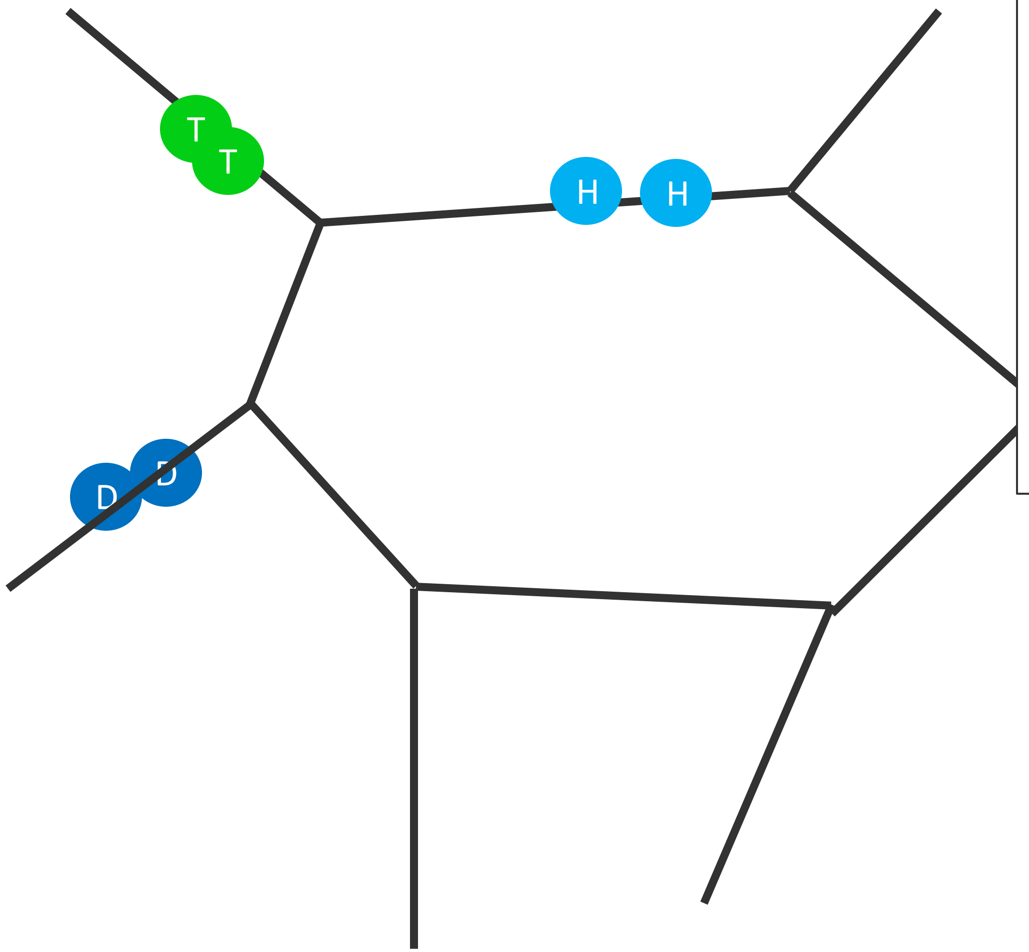
Key Concepts in the Fuel Cycle – Hydrogen Embrittlement

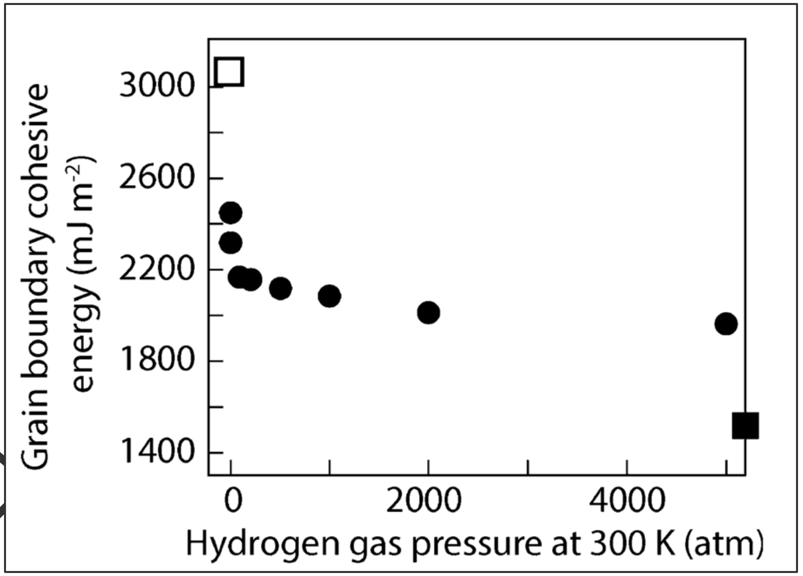


Hydrogen is attracted to *sinks* in materials such as grain boundaries and defects

© 2025 Tokamak Energy

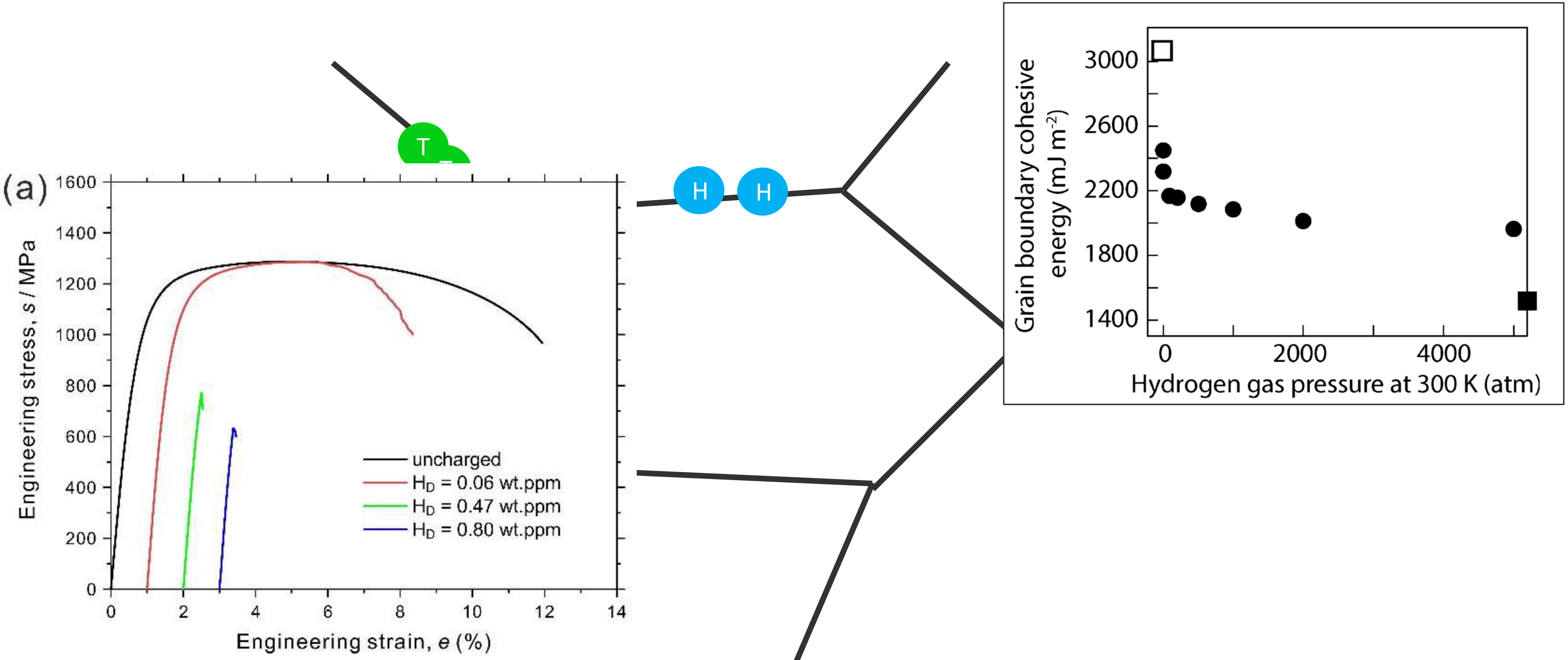
Key Concepts in the Fuel Cycle – Hydrogen Embrittlement





Robertson, I. A. *et al.*,"Hydrogen Embrittlement Understood", *JOM* 67(5), 1036–1046 (2015).

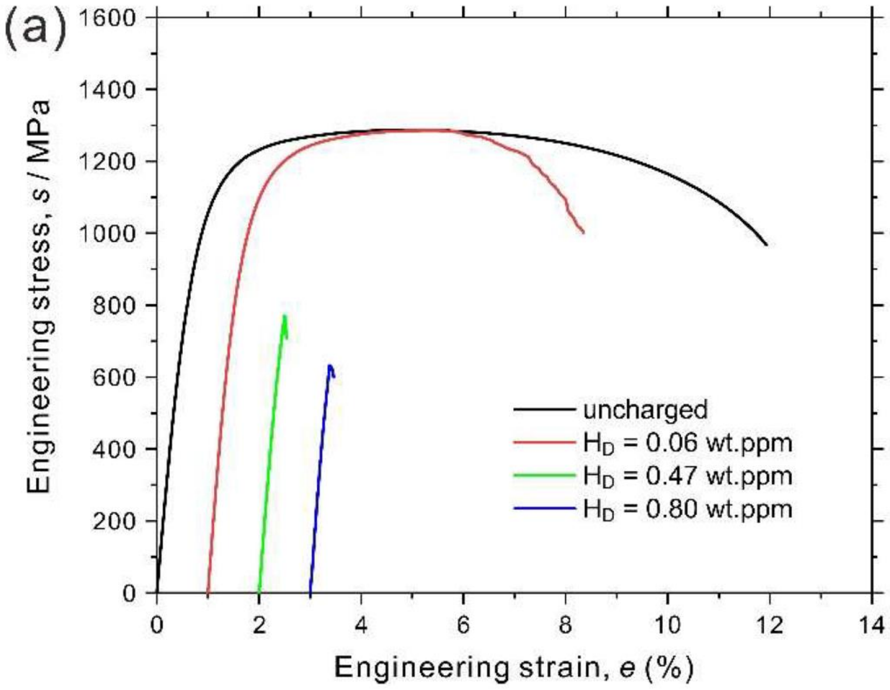
Key Concepts in the Fuel Cycle – Hydrogen Embrittlement

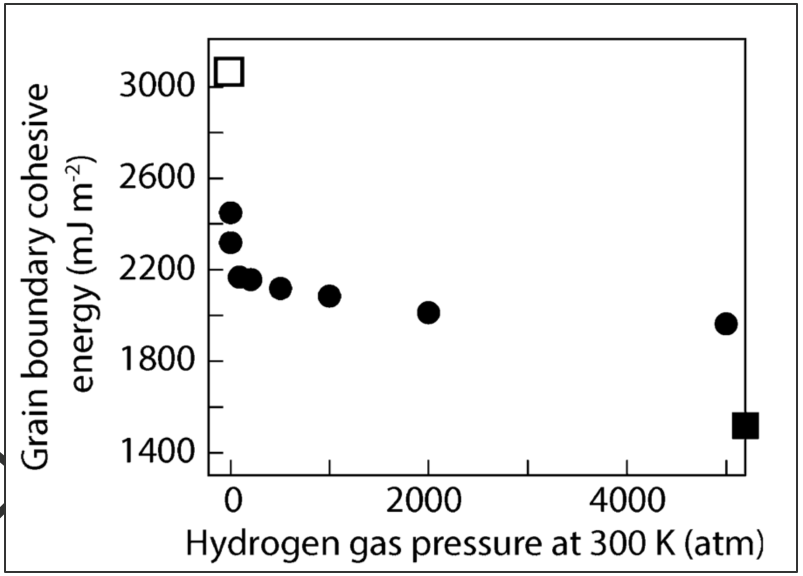


Shibata, A. et al."Hydrogen-Related Fracture Behavior under Constant Loading Tensile Test in As-Quenched Low-Carbon Martensitic Steel", *Metals* 12(3), 440 (2022).

© 2025 Tokamak Energy

Key Concepts in the Fuel Cycle – Hydrogen Embrittlement





Mechanism	Description
Hydride formation	Brittle metal hydrides form inside grains
Decohesion	H weakens atomic bonds at grain boundaries
Dislocation interaction	H enhances crack growth at stress concentrators

© 2025 Tokamak Energy

Key Concepts in the Fuel Cycle – Polymer Challenges

- Polymers (in general) are not preferred for tritium service but are normally needed in seals, gaskets, O-rings, valves, flexible tubing
- Tritium can degrade the material properties causing cracking and leaking through loss of elasticity

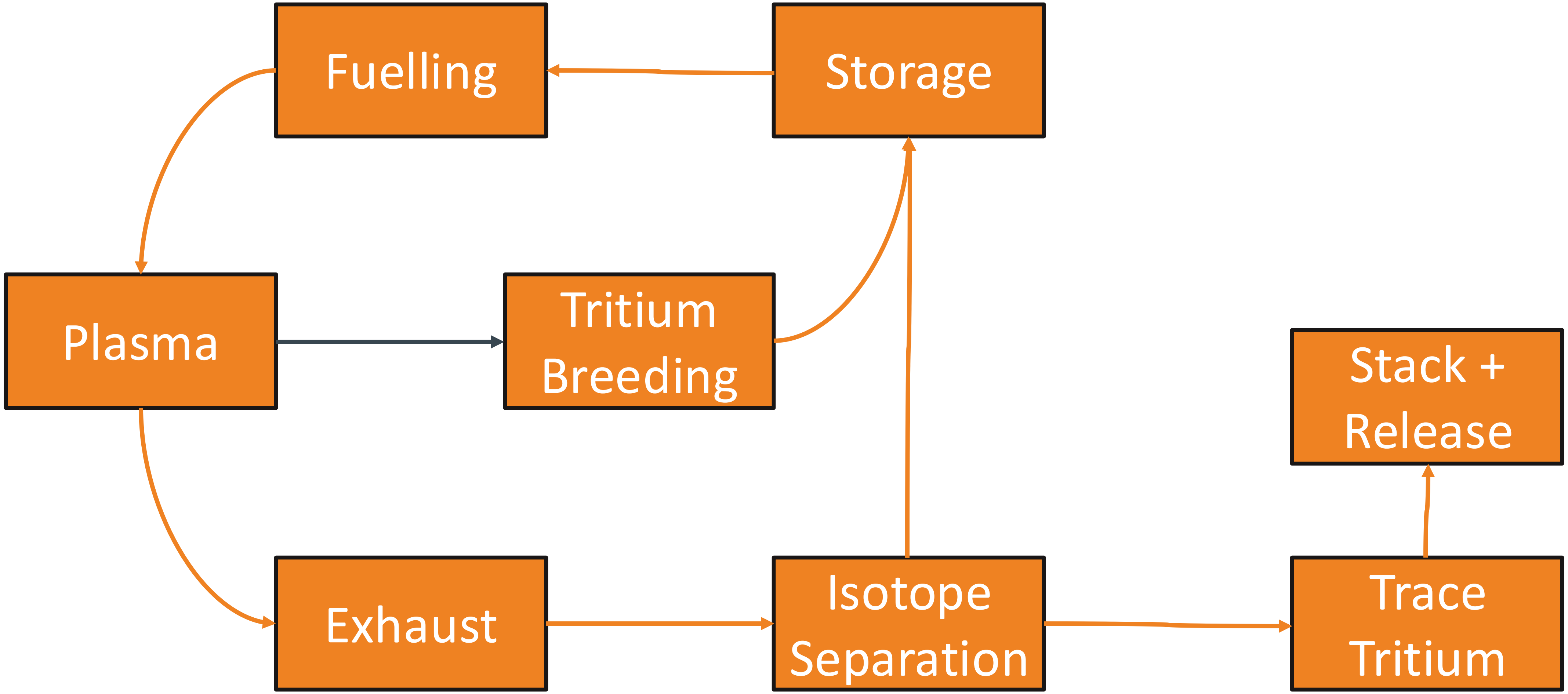
Effect	Mechanism
Radiolysis	Tritium beta decay releases ~5.7 keV -> ionizes/breaks chemical bonds
Gas evolution	Formation of H_2, CH_4, and other small molecules → blistering, pressure build-up
Embrittlement	Chain scission lowers molecular weight → brittle fracture
Crosslinking	Radiation-induced bonding between chains → stiffens material
Swelling and cracking	From accumulated gas or uneven degradation

© 2025 Tokamak Energy

Tokamak Energy

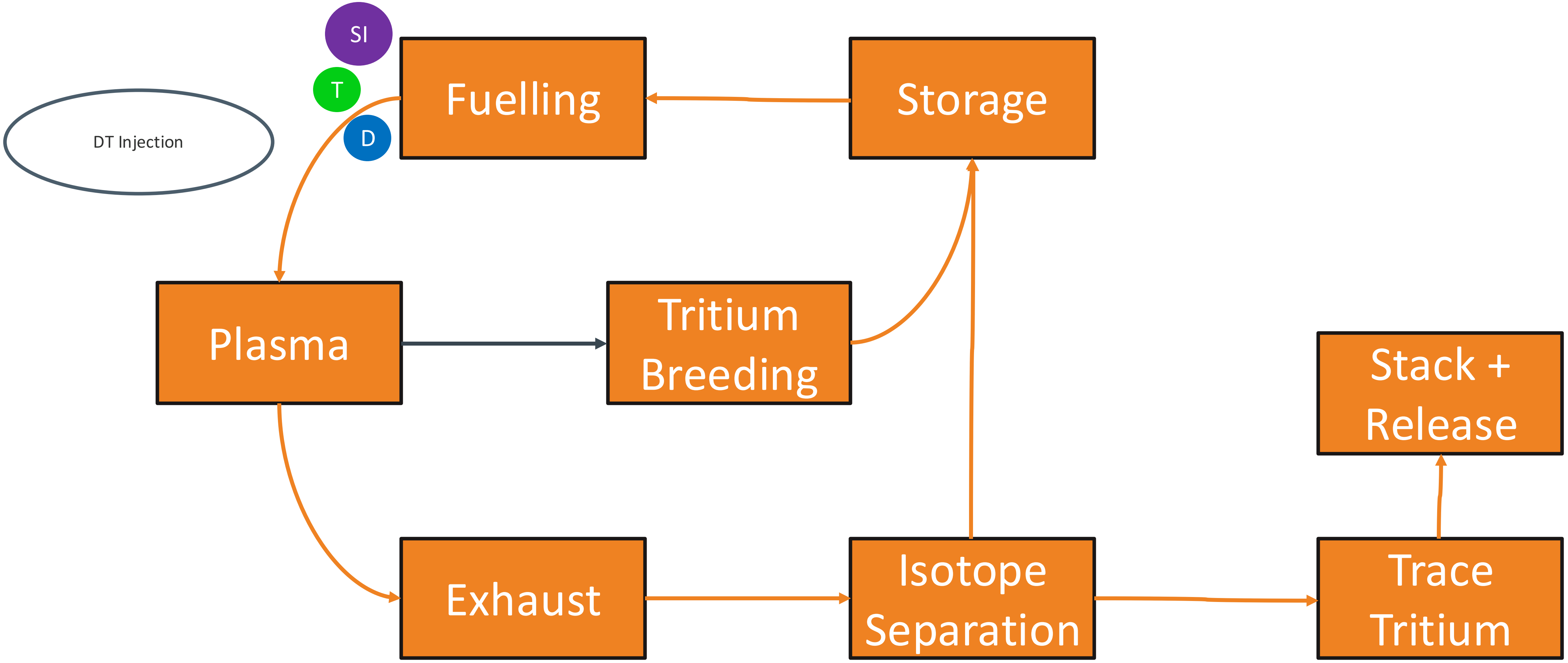
What makes up a fuel cycle?

Simplified Block-Flow Diagram



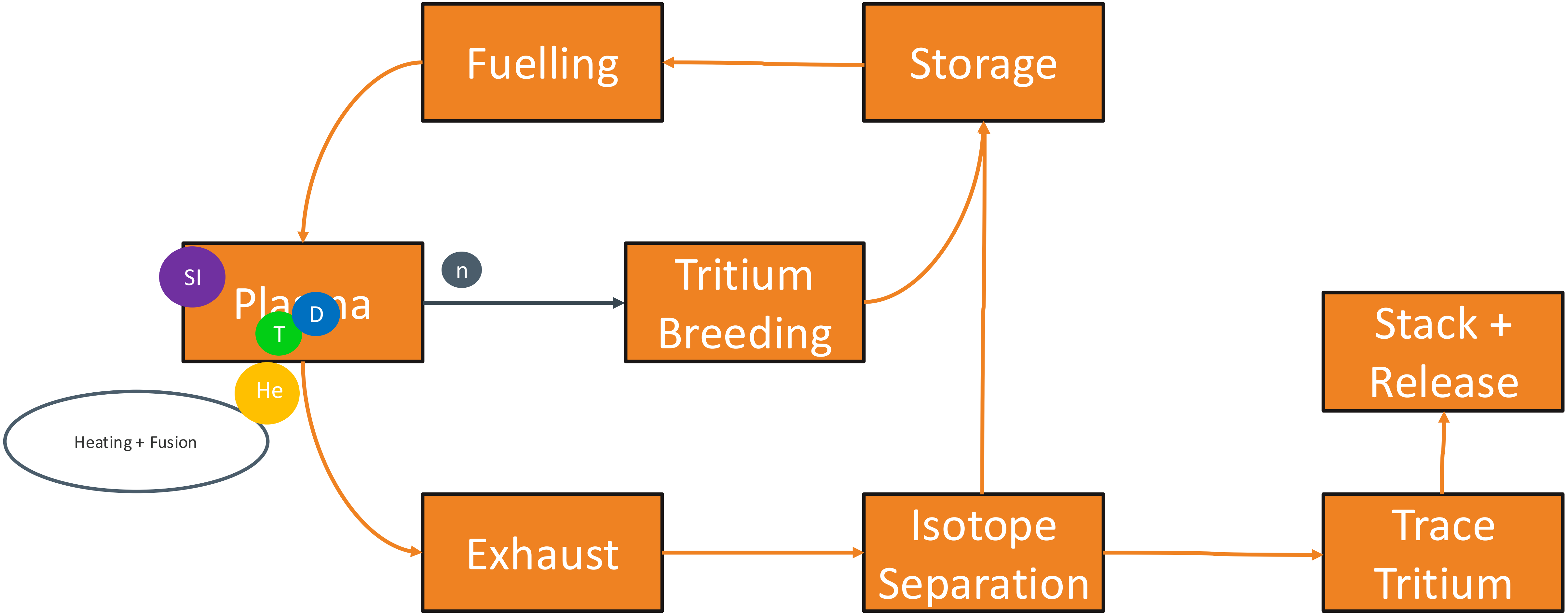
© 2025 Tokamak Energy

Simplified Block-Flow Diagram



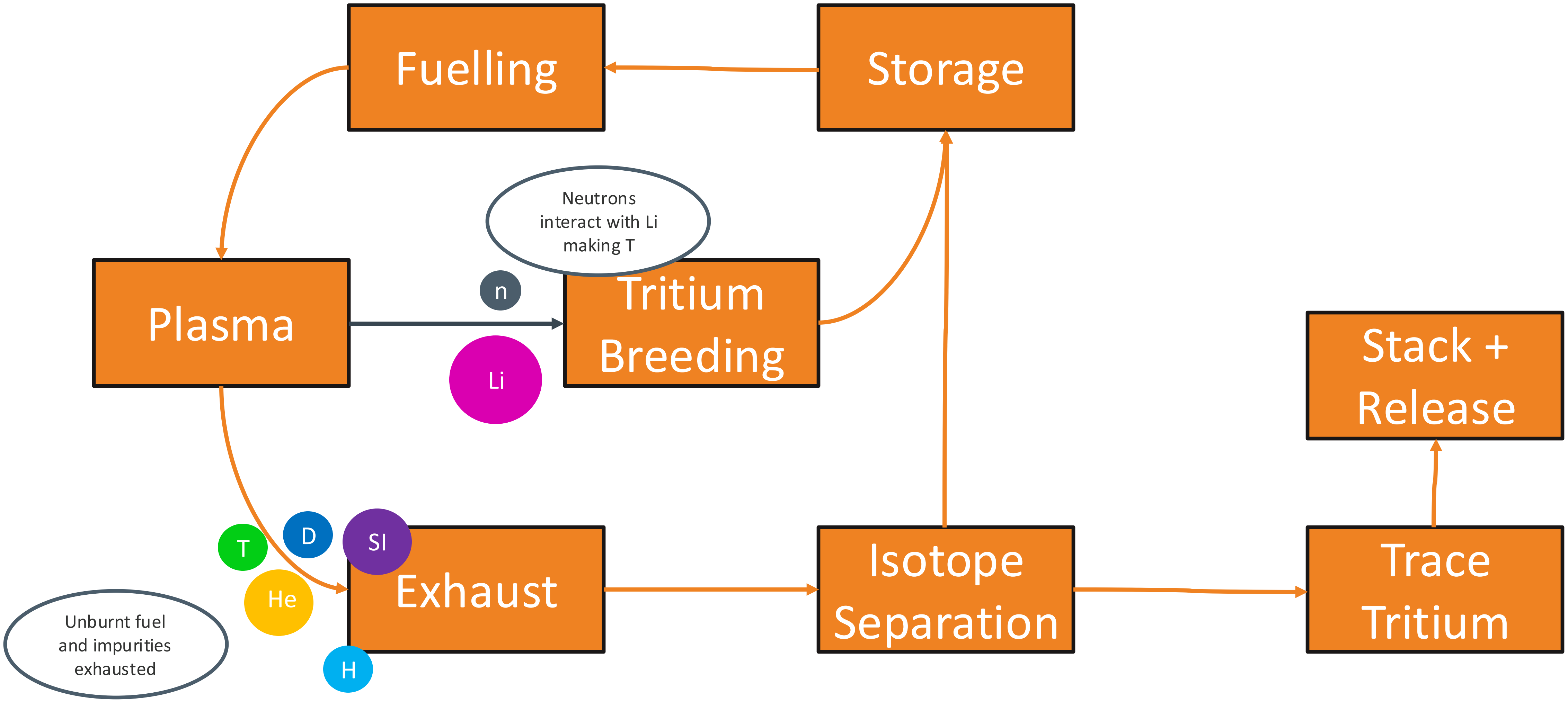
© 2025 Tokamak Energy

Simplified Block-Flow Diagram



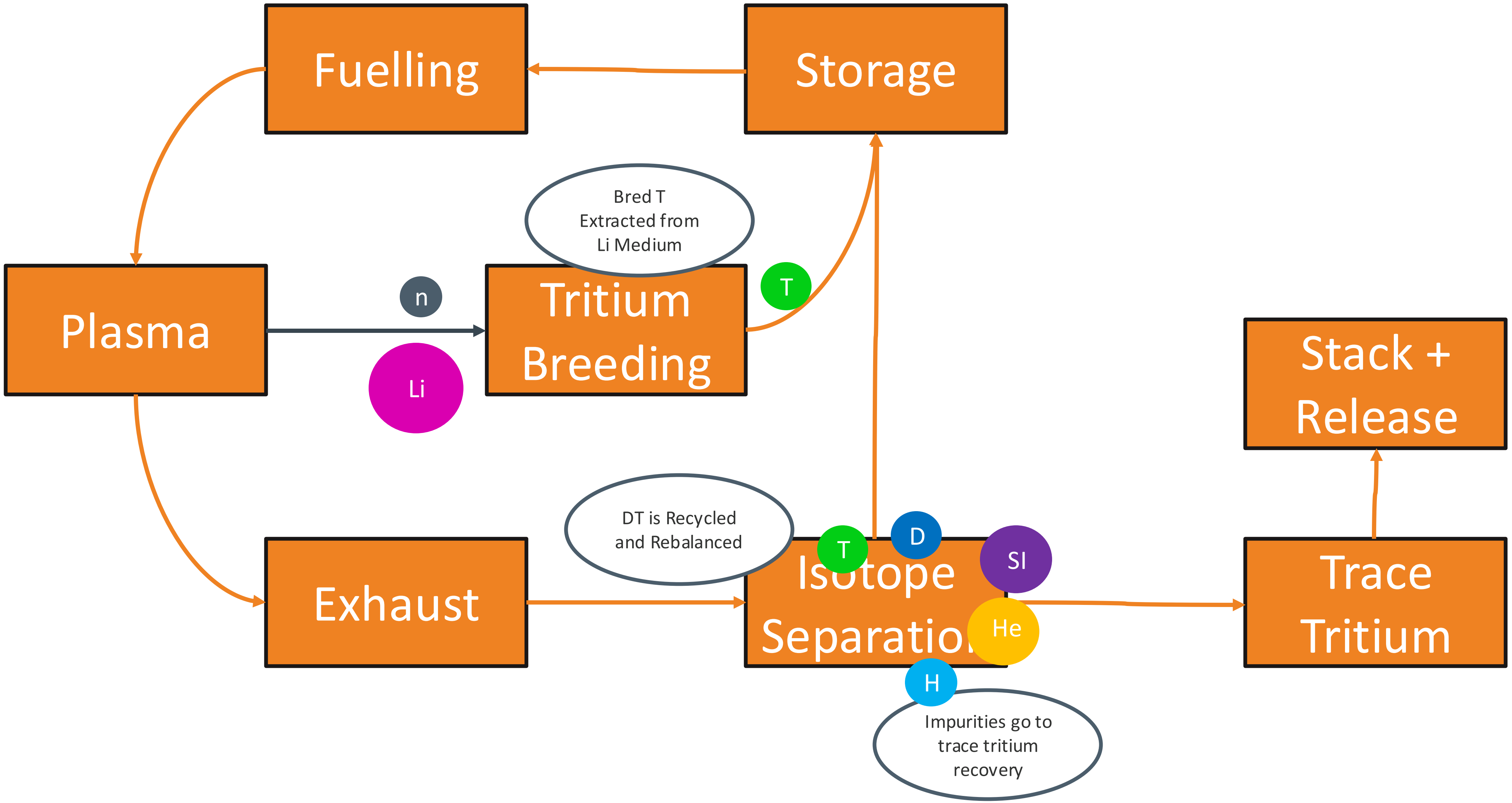
© 2025 Tokamak Energy

Simplified Block-Flow Diagram



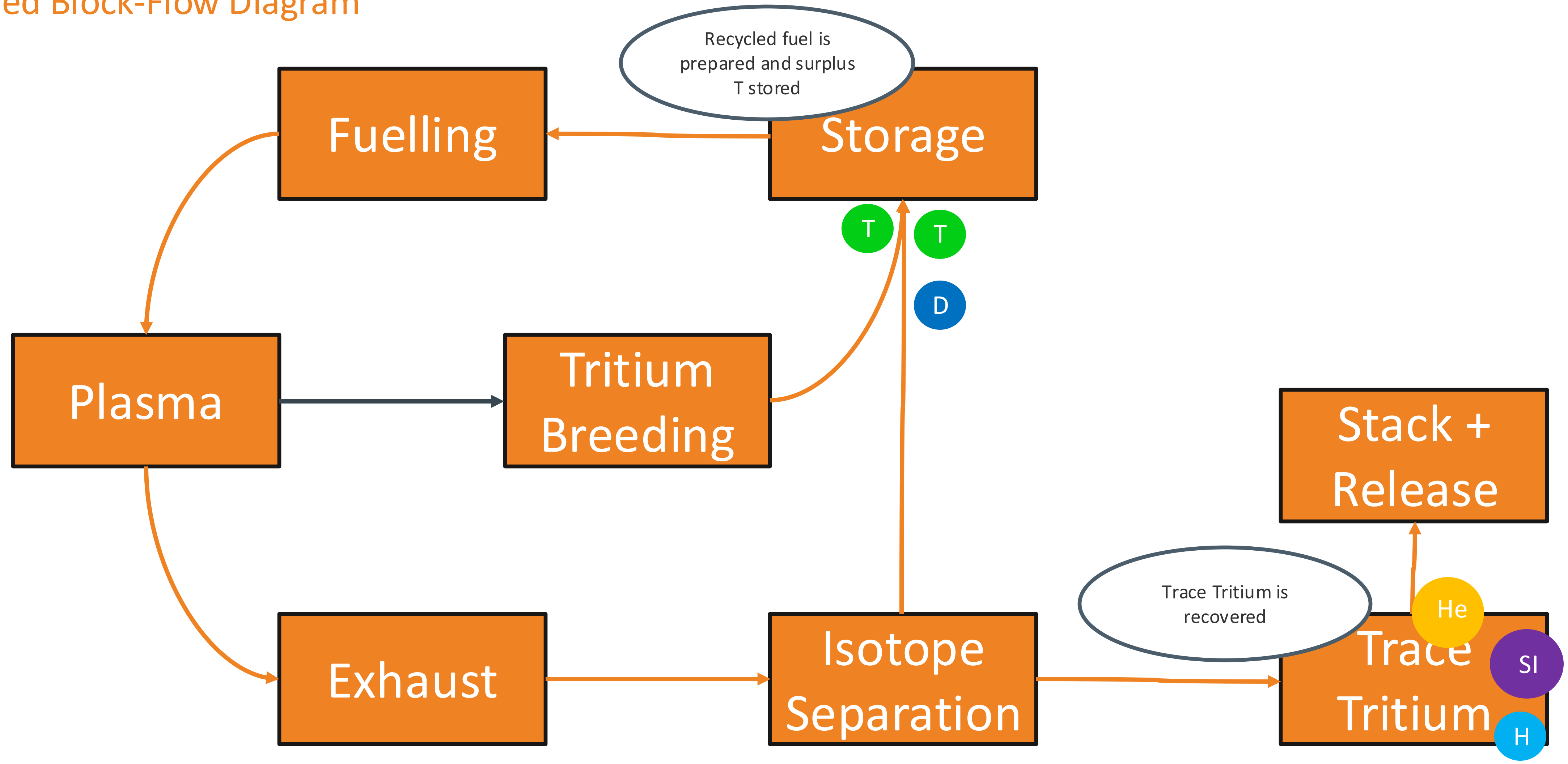
© 2025 Tokamak Energy

Simplified Block-Flow Diagram



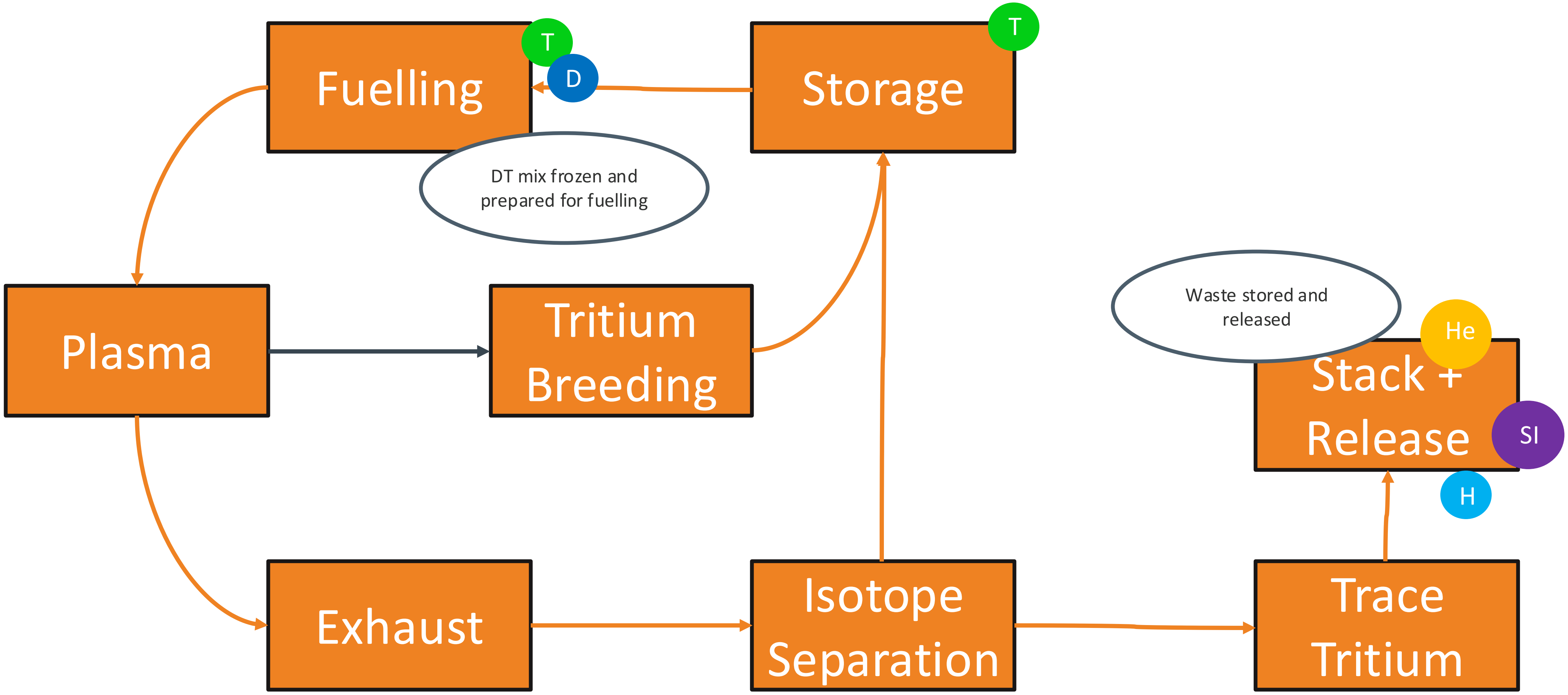
© 2025 Tokamak Energy

Simplified Block-Flow Diagram



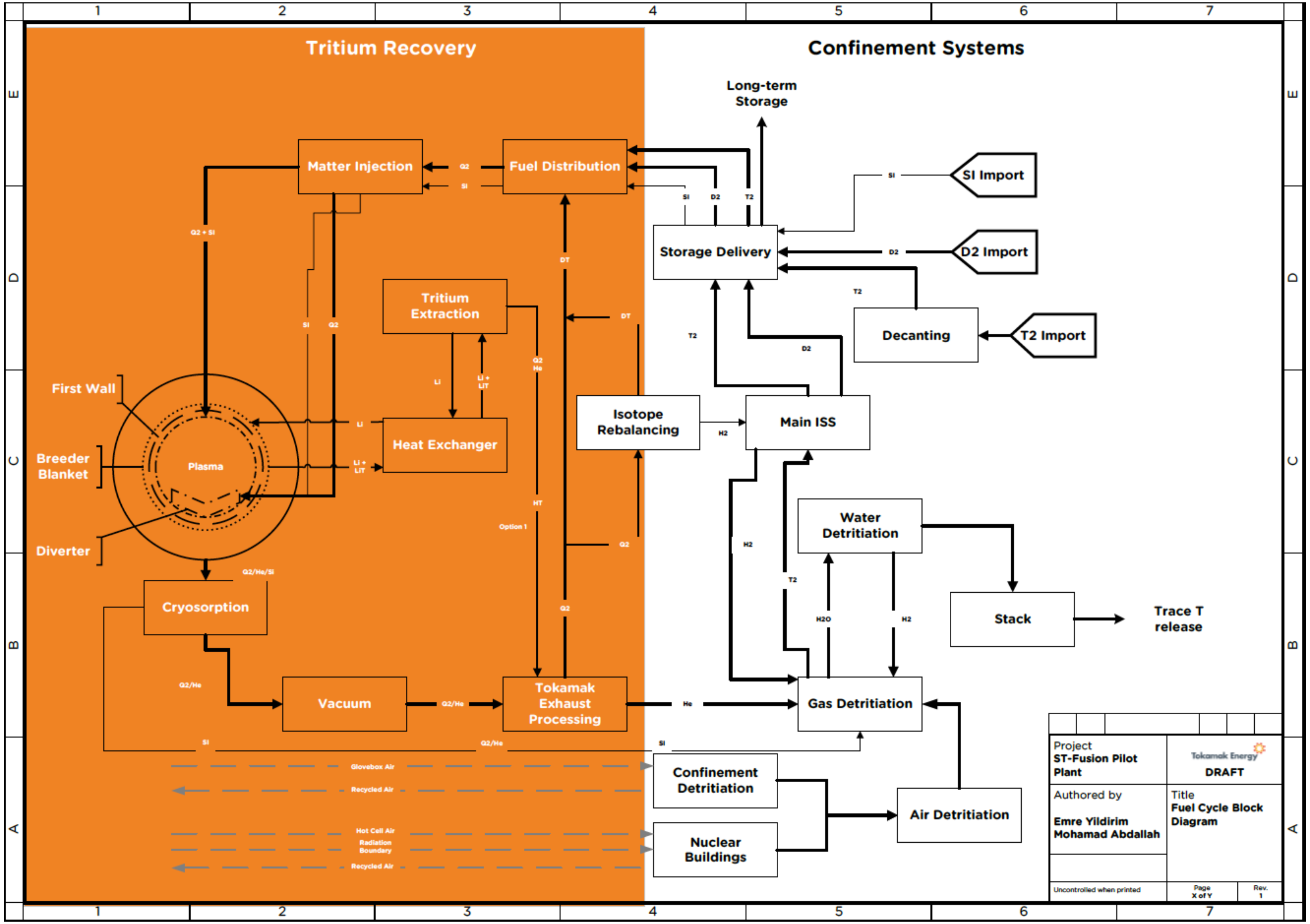
© 2025 Tokamak Energy

Simplified Block-Flow Diagram



© 2025 Tokamak Energy

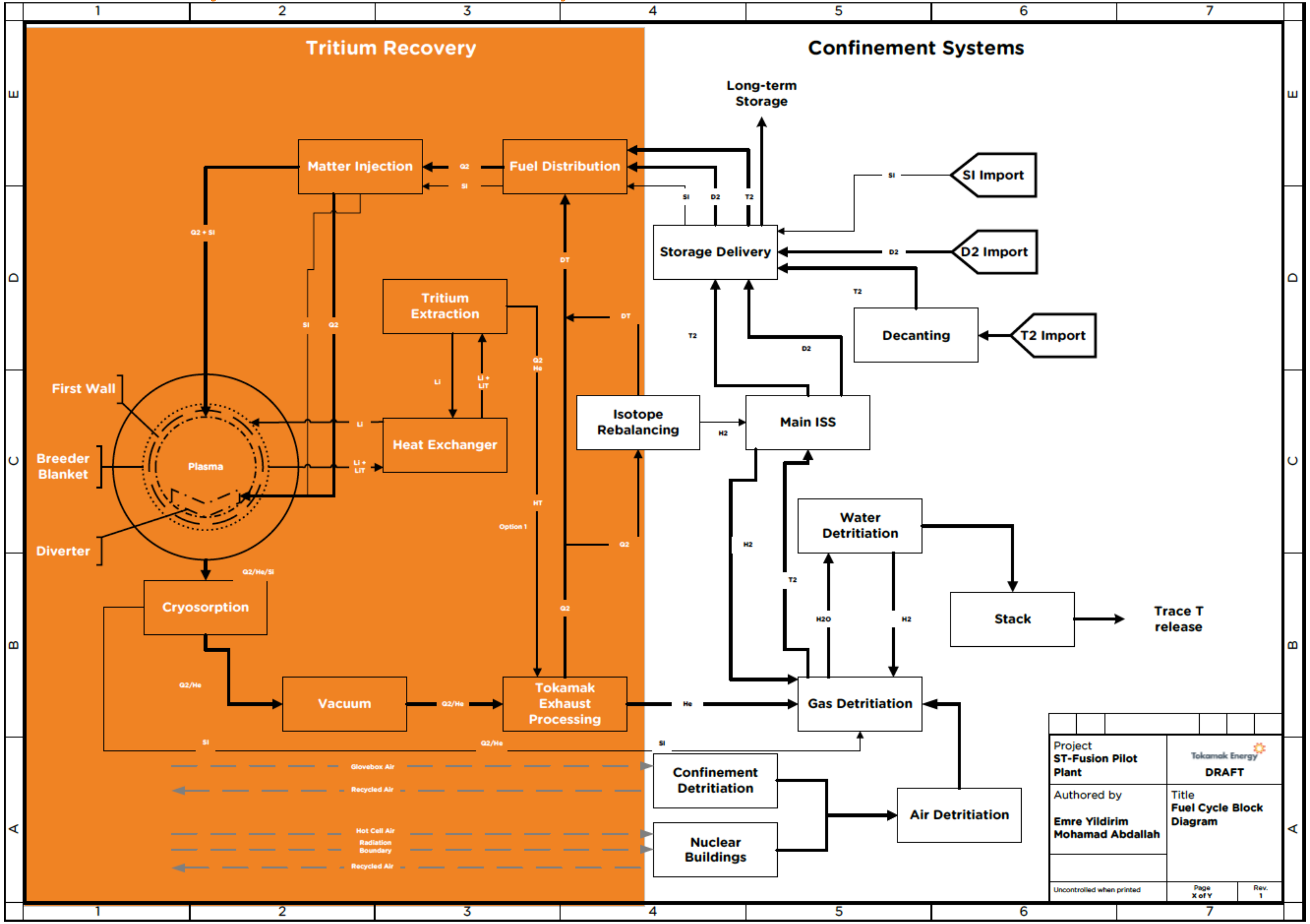
As always – there is always more!



And this is still just a Block Flow Diagram!

© 2025 Tokamak Energy

As always – there is always more!



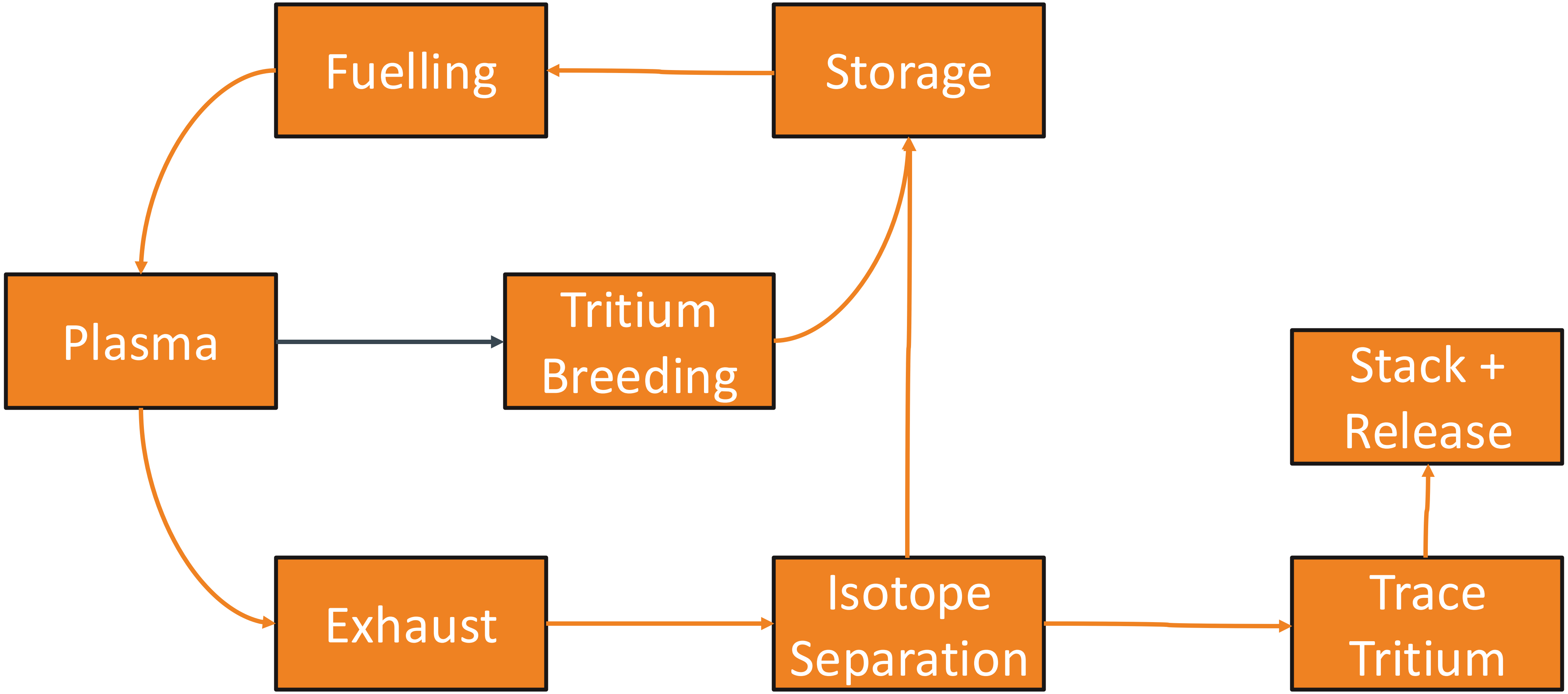
Questions:

The first wall and divertor are on this diagram – why? *Hint: remember your PMI lecture*

Why are we interested in highlighting heat exchangers in the fuel cycle?

Where could the need for air detritiation system come from?

© 2025 Tokamak Energy



© 2025 Tokamak Energy

Fuelling

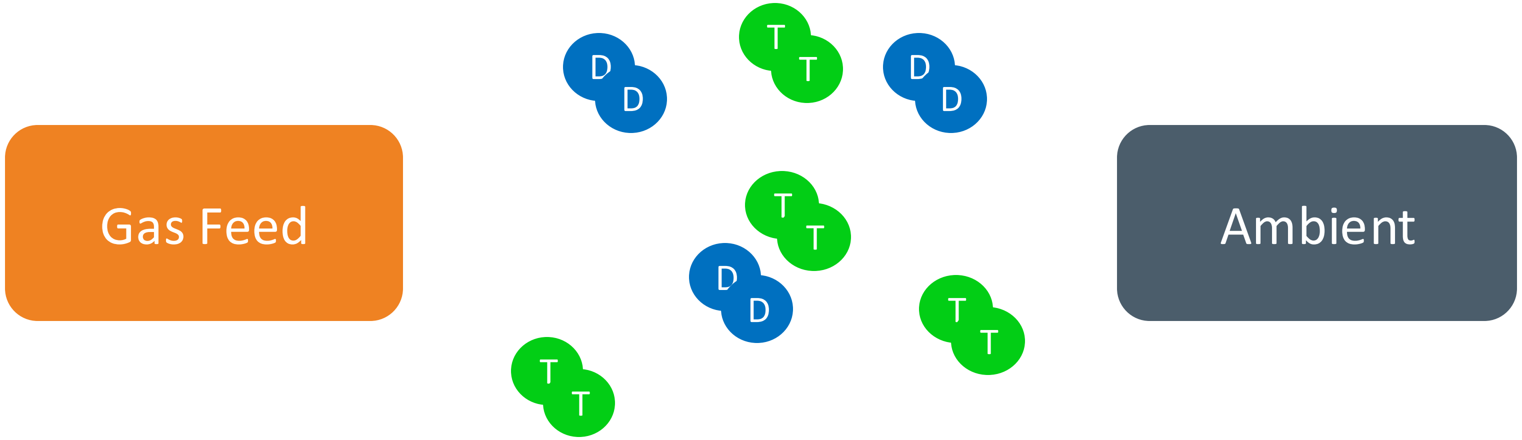
- Fueling controls the fusion power out and allows for the fusion reaction to be maintained
- Fueling must penetrate the core plasma – to allow as much of it to fuse as possible
- Fuel that does not make it to the core adds to the pumped flux out of the tokamak and must be recycled fast

Method	Description	Pros	Cons
Gas Puffing	Injects gas near plasma edge	Simple, robust, low-cost	Low fuelling efficiency (η), most fuel stays at the edge
Pellet Injection	High-speed frozen D/T pellets fired into plasma	Penetrates deeper, improves η and β	Cryo systems required, some mass loss during ablation
Neutral Beam Injection	High-energy neutral atoms (D or T) injected into core	Also heats plasma, can drive current	Requires ultra-pure gas, high tritium losses, complex system

© 2025 Tokamak Energy

Fuelling

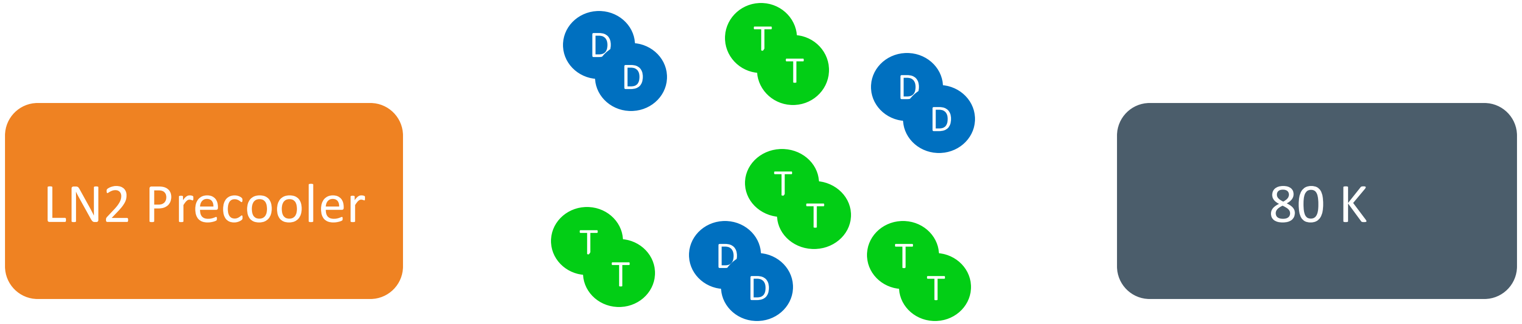
Pellet Injection – Pellet Injectors!



© 2025 Tokamak Energy

Fuelling

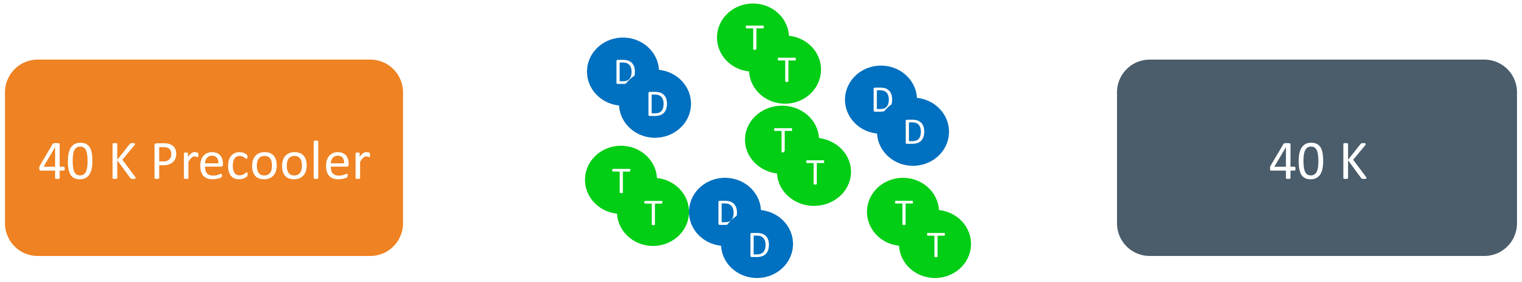
Pellet Injection – Pellet Injectors!



© 2025 Tokamak Energy

Fuelling

Pellet Injection – Pellet Injectors!

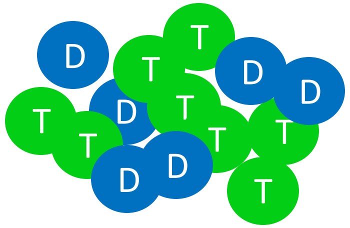


© 2025 Tokamak Energy

Fuelling

Pellet Injection – Pellet Injectors!

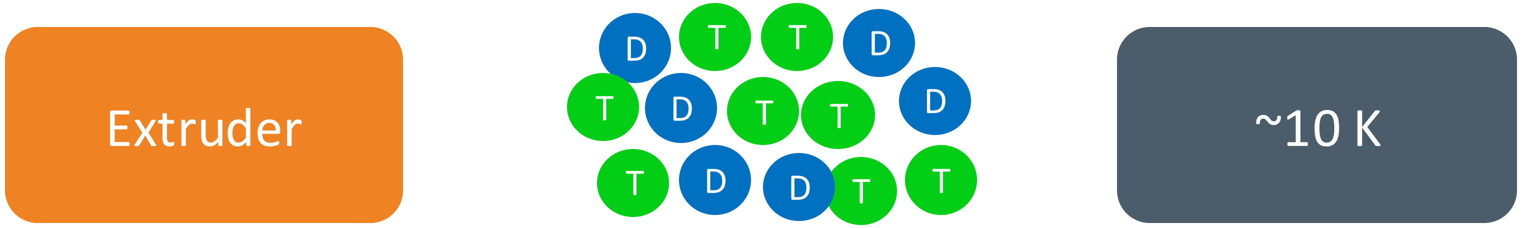
Liquifier



20 K

Fuelling

Pellet Injection – Pellet Injectors!



Fuelling

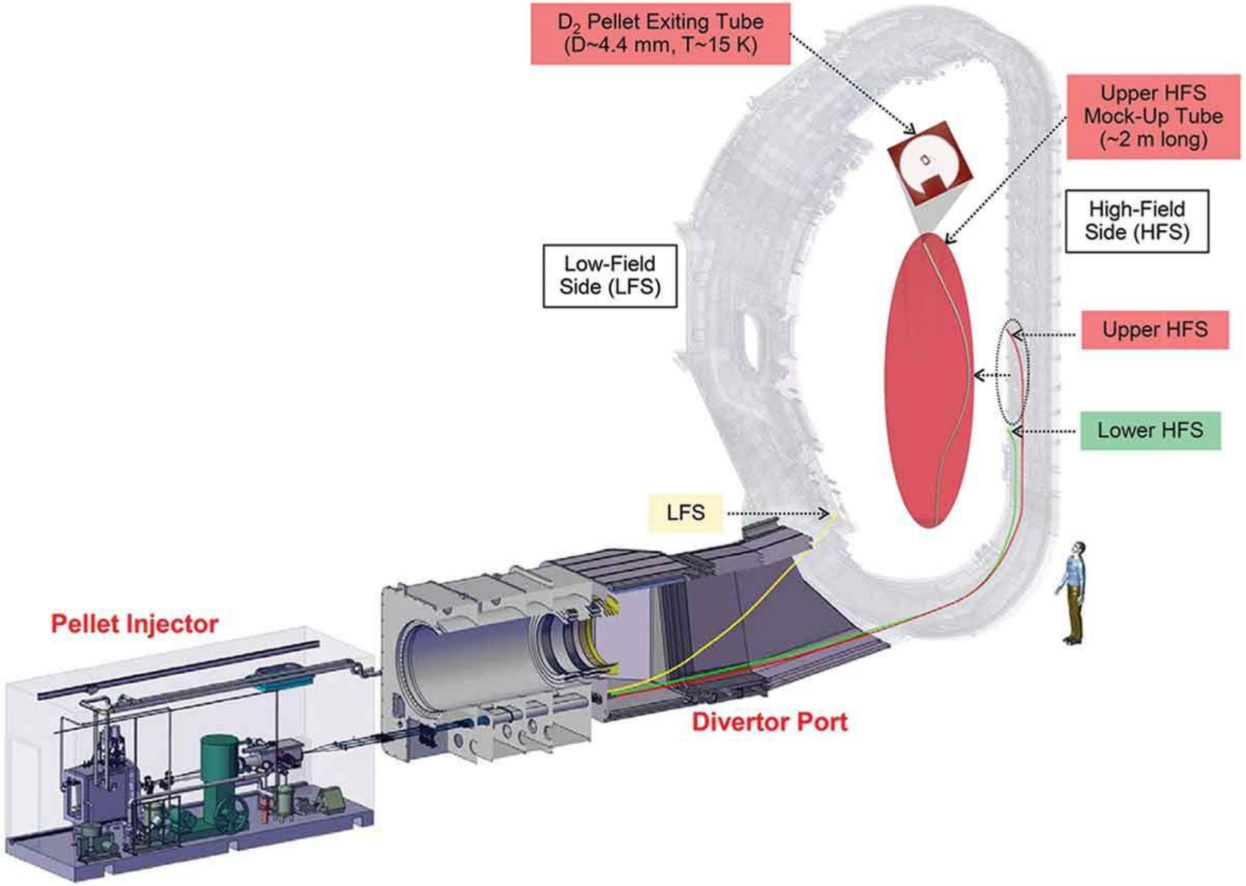
Frozen Pellets → Cutter → Acceleration → Guiding Tube → Plasma

Type	How It Works	Speed
Gas gun	High-pressure gas propels pellet down a barrel (like a cannon)	~300–1000 m/s
Centrifugal launcher	Rotating arm flings pellet into guide tube	Up to ~1000 m/s

© 2025 Tokamak Energy

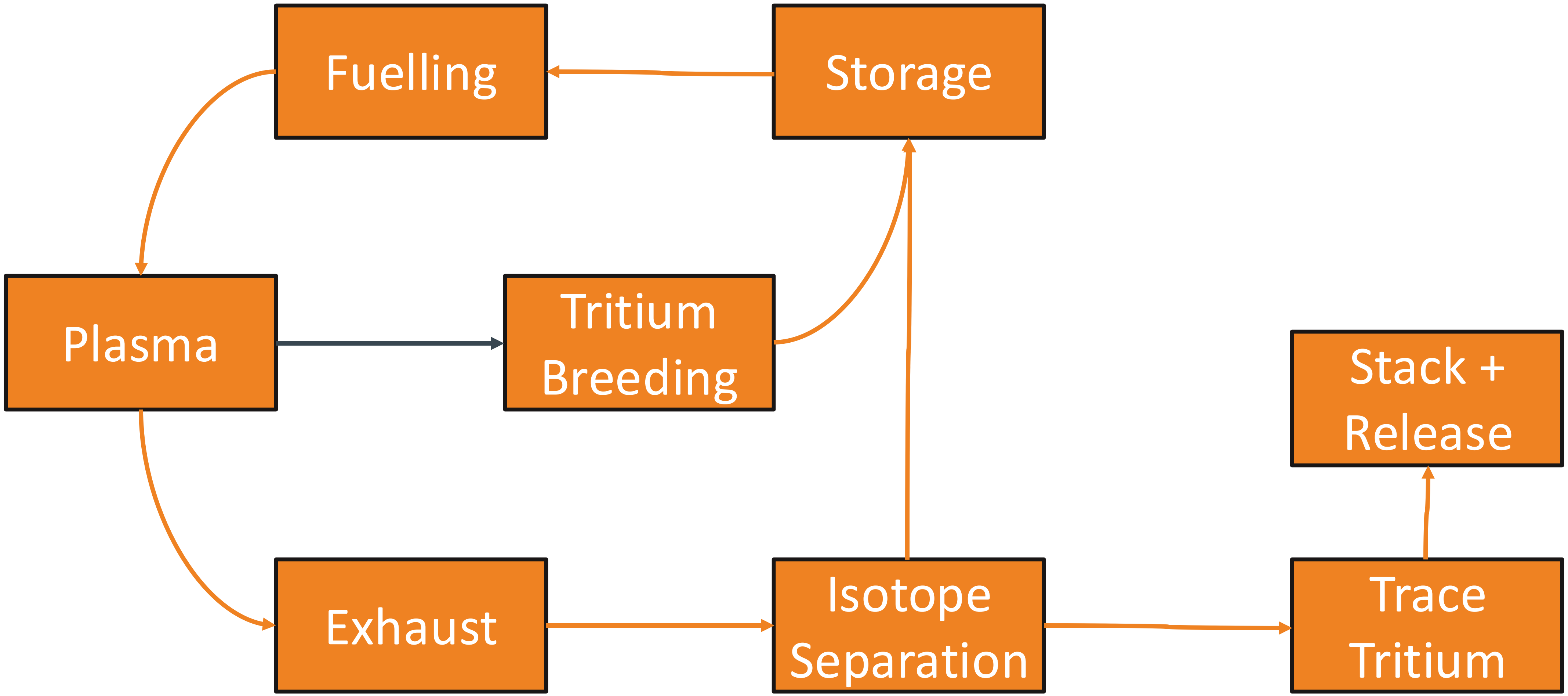
Fuelling

- There are large uncertainties around fueling efficiencies, with these range from ~10-90 %
- Fueling is critical for the fuel cycle requirements, but is more critical for the plasma itself
  - Aids control of plasma burn
  - Aids control of density profiles
  - Poor fueling could also contribute to things like L-H transitions
- The pellet mass, injection speed and geometry are all parameters to tweak
  - Often the ExB drift is the biggest parameter - mean high field side fueling is a must to improve efficacy and fusion burn



Combs, S. K., & Baylor, L. R. (2018). Pellet-Injector Technology—Brief History and Key Developments in the Last 25 Years. *Fusion Science and Technology*, *73*(4), 493–518.

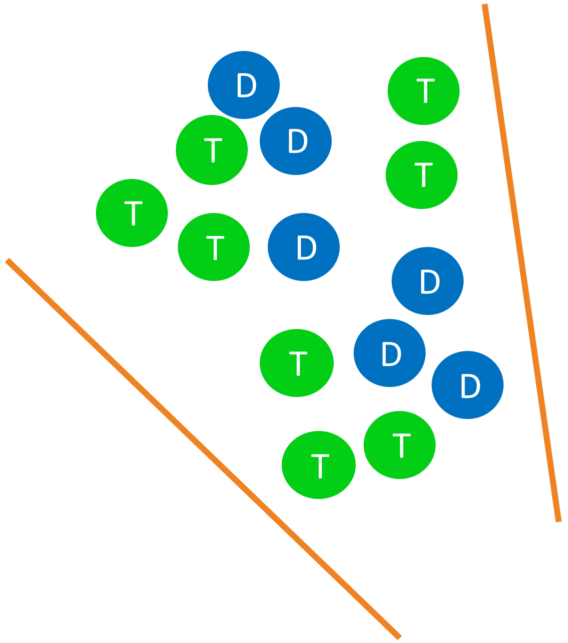
© 2025 Tokamak Energy


Fuelling
Storage
Plasma
Tritium Breeding
Stack + Release
Exhaust
Isotope Separation
Trace Tritium

Exhaust

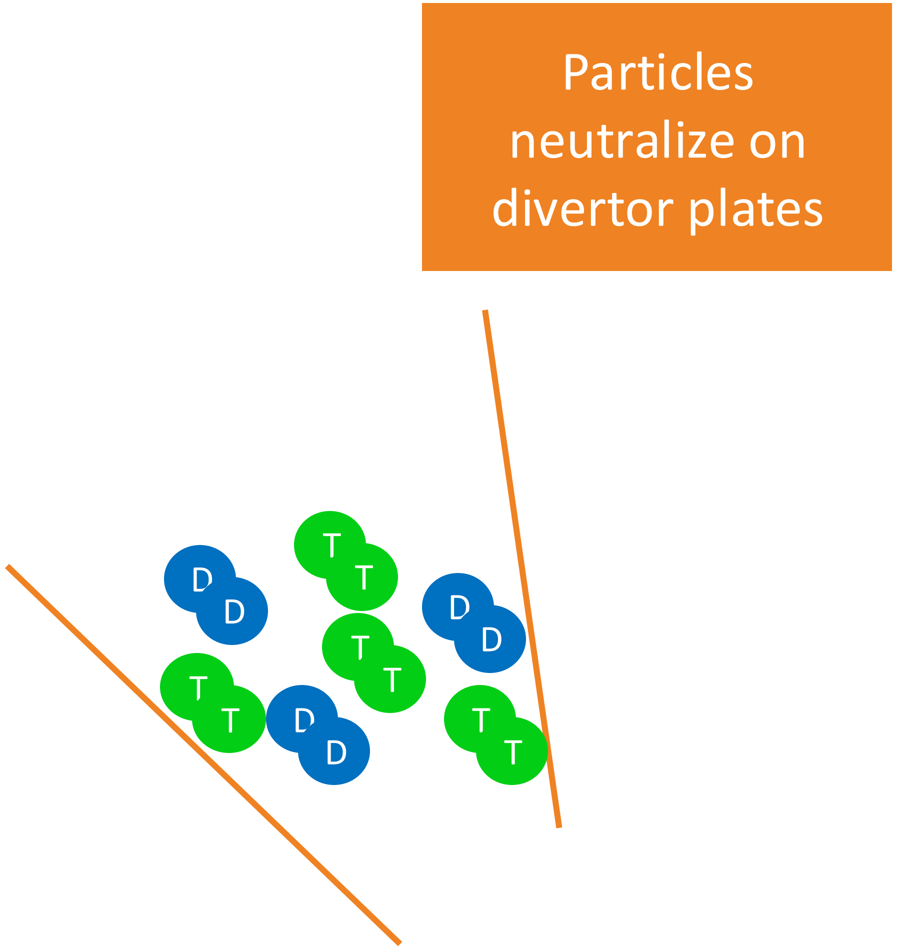
Exhaust – Vacuum Systems

- Vacuum acts to reduce the pressure at inlet
- Molecules move from high pressure to low pressure
- (usually) pressure is then increased after pump [compression ratio]
- This allows us to pump the species that have reached the SOL and been accelerated to the divertor to reduce pressure build up in the chamber



© 2025 Tokamak Energy

Exhaust



Exhaust – Vacuum Systems

- Vacuum acts to reduce the pressure at inlet
- Molecules move from high pressure to low pressure
- (usually) pressure is then increased after pump [compression ratio]
- This allows us to pump the species that have reached the SOL and been accelerated to the divertor to reduce pressure build up in the chamber

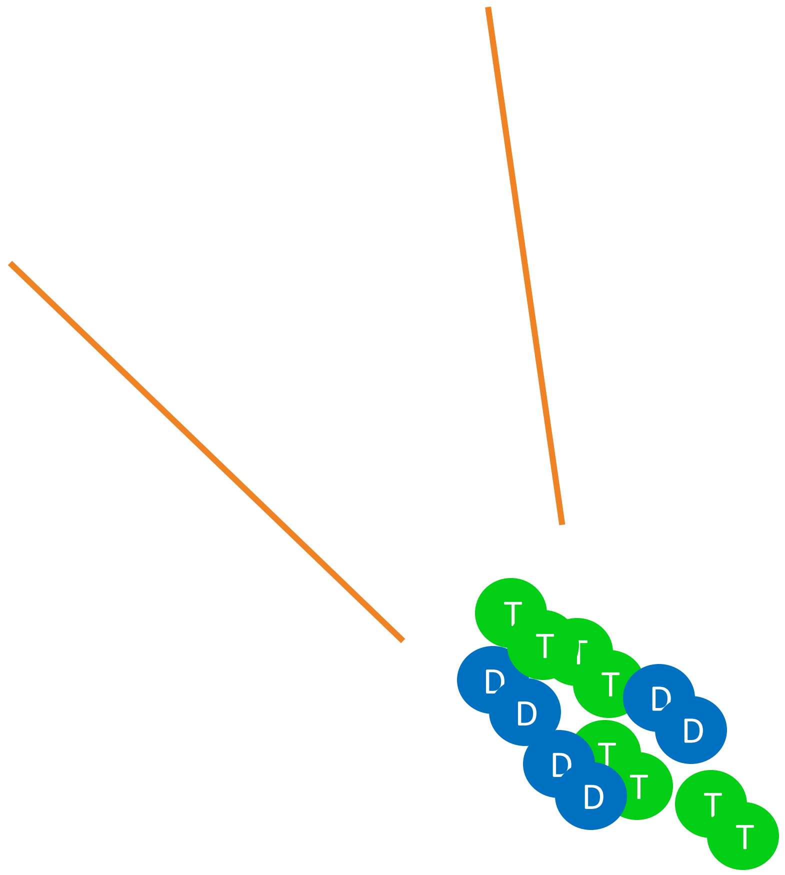
© 2025 Tokamak Energy

Exhaust

Vacuum Pumps pump out particles

Exhaust – Vacuum Systems

- Vacuum acts to reduce the pressure at inlet
- Molecules move from high pressure to low pressure
- (usually) pressure is then increased after pump [compression ratio]
- This allows us to pump the species that have reached the SOL and been accelerated to the divertor to reduce pressure build up in the chamber



© 2025 Tokamak Energy

Exhaust

Exhaust Pumping

- Pump out unburnt hydrogen isotopes, He ash and impurities (both intentional such as Ar and residual such as W particles)
- Key to maintain a ‘clean’ plasma
- Depends on:
  - Conductance [C] - How easily gas flows through a duct or pipe to reach the pump (divertor geometry), in L/s
  - Pumping Speed [S] - The rate at which the pump *can remove gas* (pump type and design), typically in L/s or m^3/s

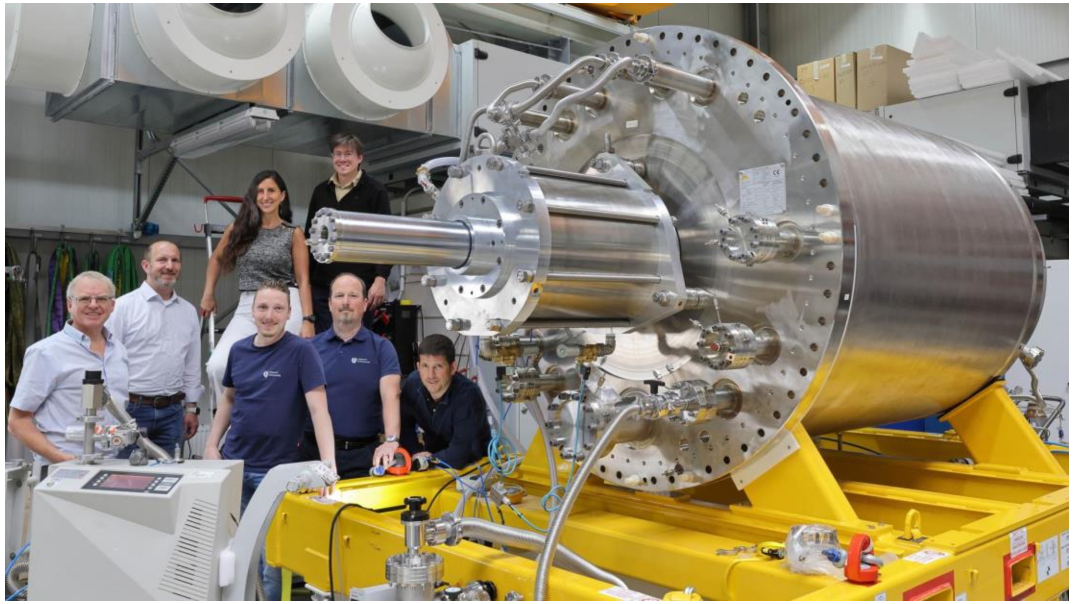
Pump Type	Operating Pressure Range (mbar)	Notes
Roughing Pumps	1e3 to 1e-1	Rotary vane or scroll; used for initial pump-down
Roots Blower	1e2 to 1e-2	Boosts flow between roughing and high-vacuum stages
Turbomolecular Pumps	1e-3 to 1e-9	Requires backing pump; excellent for high vacuum
Cryopumps	1e-3 to 1e-9	Ideal for hydrogen isotopes; based on cryocondensation/sorption
Diffusion Pumps	1e-3 to 1e-7	Oil-based; used less in fusion due to contamination concerns

NB: we use lots of these pumps all around the fuel cycle!

© 2025 Tokamak Energy

Exhaust

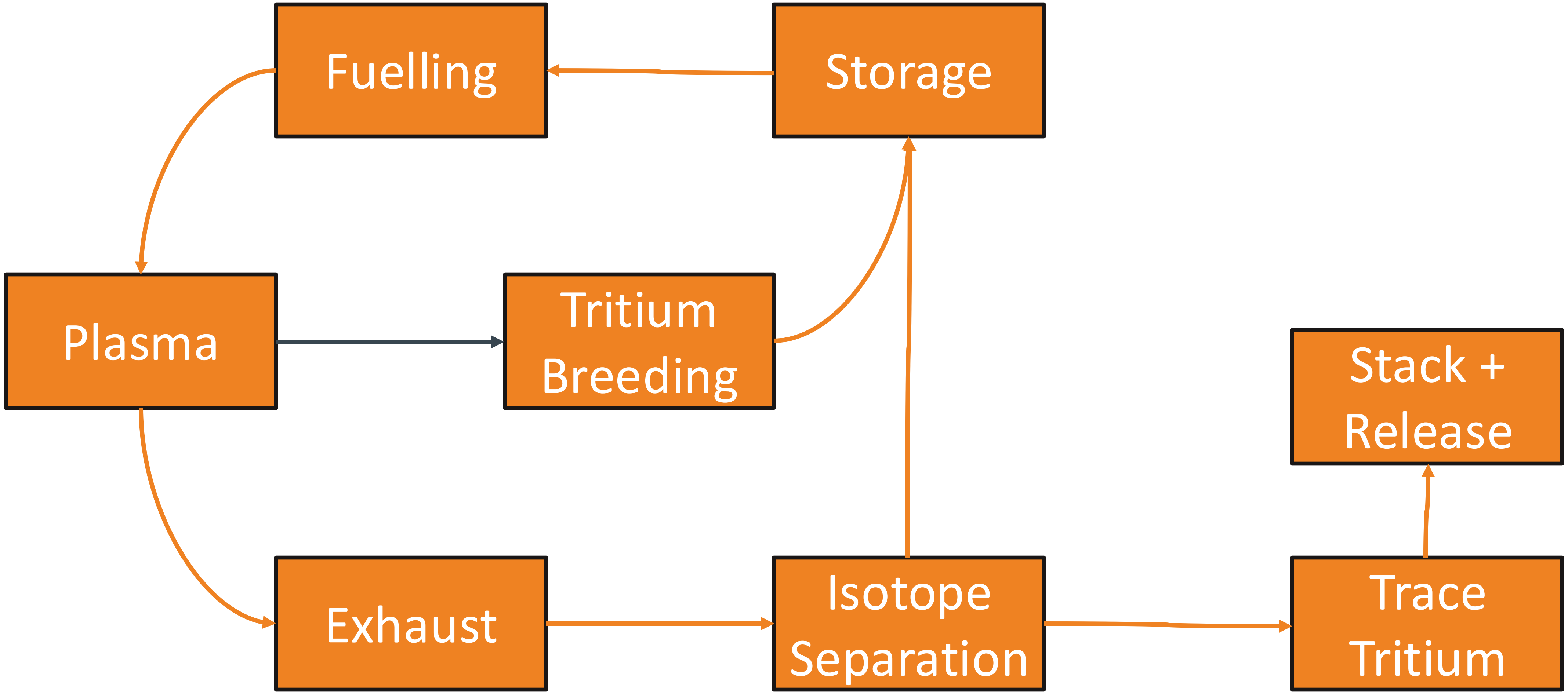
Exhaust Pumping



ITER Website

Pump Type	Operating Pressure Range (mbar)	Notes
Roughing Pumps	1e3 to 1e-1	Rotary vane or scroll; used for initial pump-down
Roots Blower	1e2 to 1e-2	Boosts flow between roughing and high-vacuum stages
Turbomolecular Pumps	1e-3 to 1e-9	Requires backing pump; excellent for high vacuum
Cryopumps	1e-3 to 1e-9	Ideal for H_2, He, and T_2; based on cryocondensation/sorption
Diffusion Pumps	1e-3 to 1e-7	Oil-based; used less in fusion due to contamination concerns

© 2025 Tokamak Energy



© 2025 Tokamak Energy

Isotope Separation

Separating hydrogen isotopes from other gases

Separate Tritium from other hydrogen isotopes

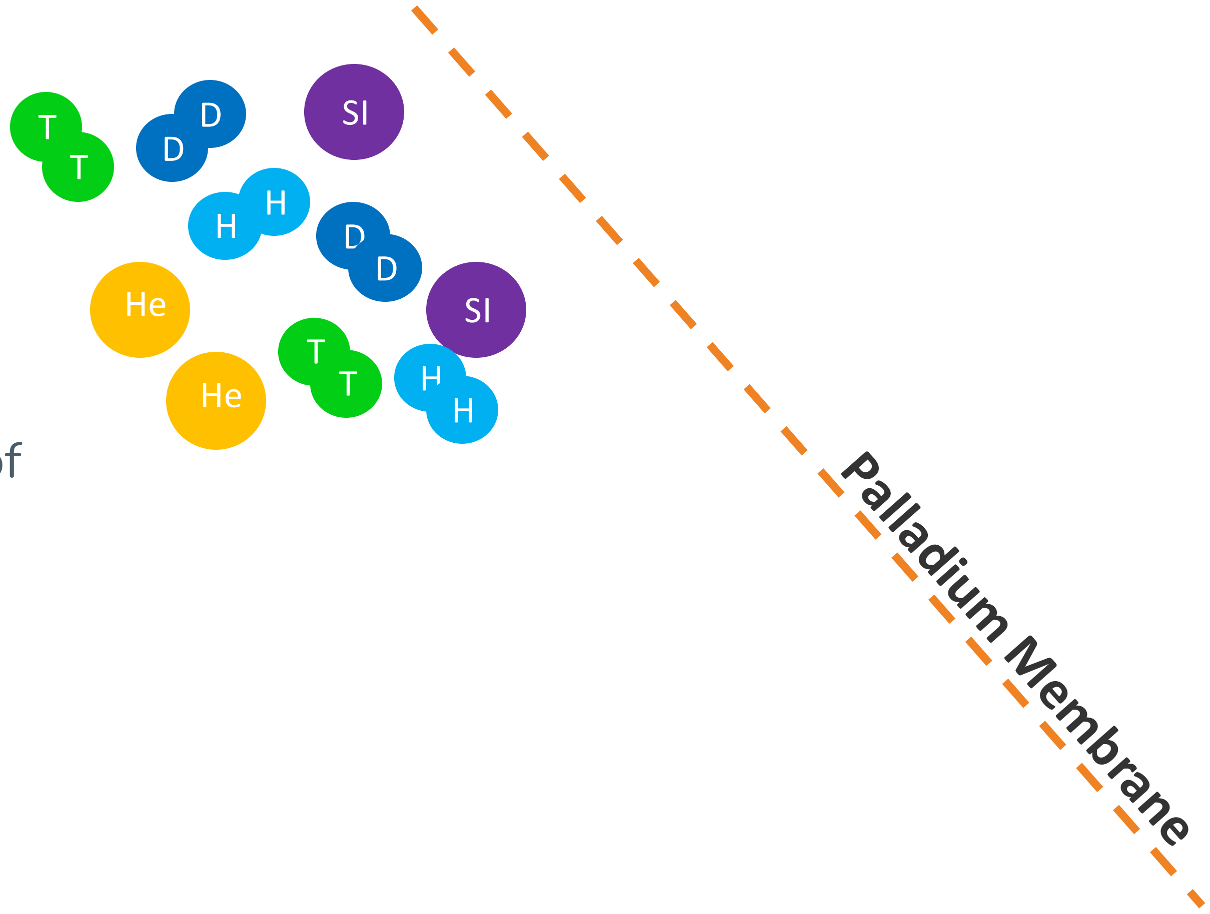
© 2025 Tokamak Energy

Isotope Separation

Separating hydrogen isotopes from other gases

Palladium Diffusers

- Allows H_2, D_2 and T_2 to pass through selectively blocking other gases
- Operate continuously (limitation is lifetime of the membrane)
- High temperature (>300°C), pressure gradient across membrane, thin membrane



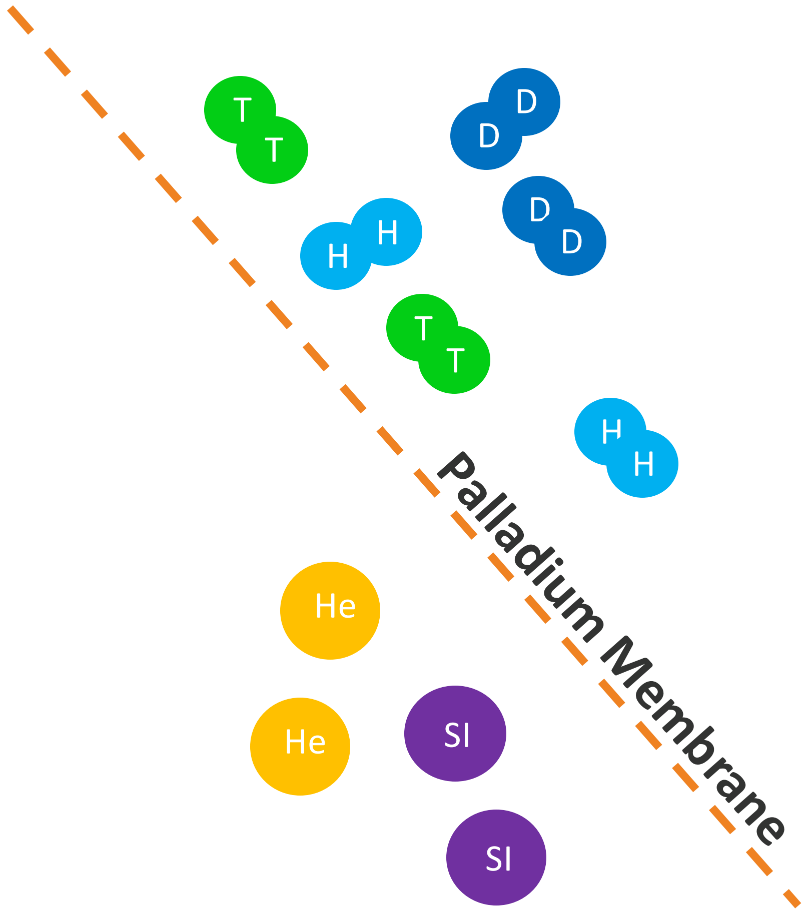
© 2024 Tokamak Energy Private and Confidential

Isotope Separation

Separating hydrogen isotopes from other gases

Palladium Diffusers

Challenge	Notes
Embrittlement	Use Pd-Ag (or other Pd based) alloys to resist cracking
Contaminants	CO, H_2O can poison membrane
Cost	Pd is rare and expensive
Throughput limits	Temperature and surface area limited



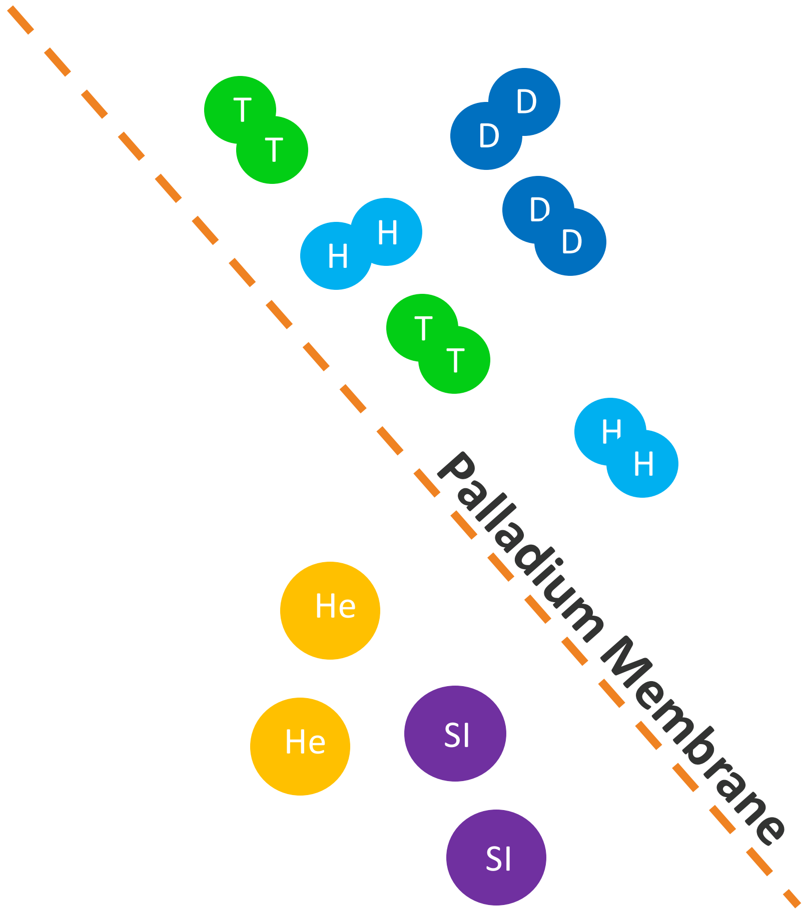
© 2024 Tokamak Energy Private and Confidential

Isotope Separation

Separating hydrogen isotopes from other gases

Palladium Diffusers

Challenge	Notes
Embrittlement	Use Pd-Ag (or other Pd based) alloys to resist cracking
Contaminants	CO, H_2O can poison membrane
Cost	Pd is rare and expensive
Throughput limits	Temperature and surface area limited

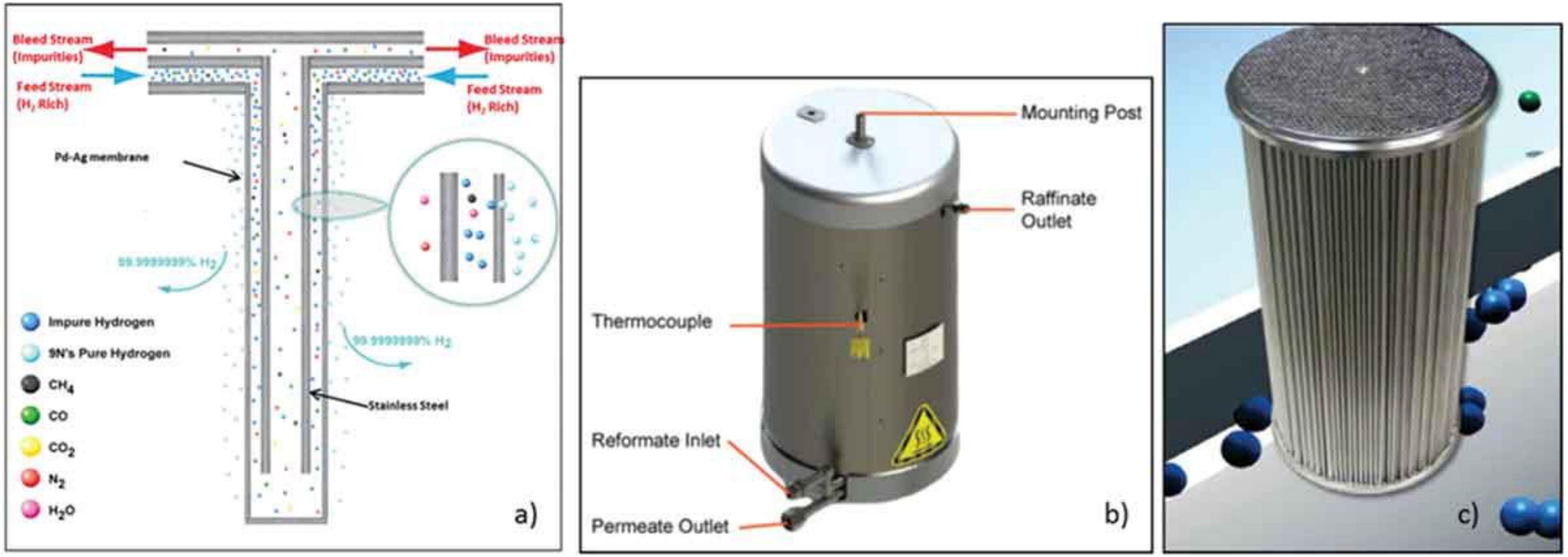


© 2024 Tokamak Energy Private and Confidential

Isotope Separation

Separating hydrogen isotopes from other gases

Palladium Diffusers - example



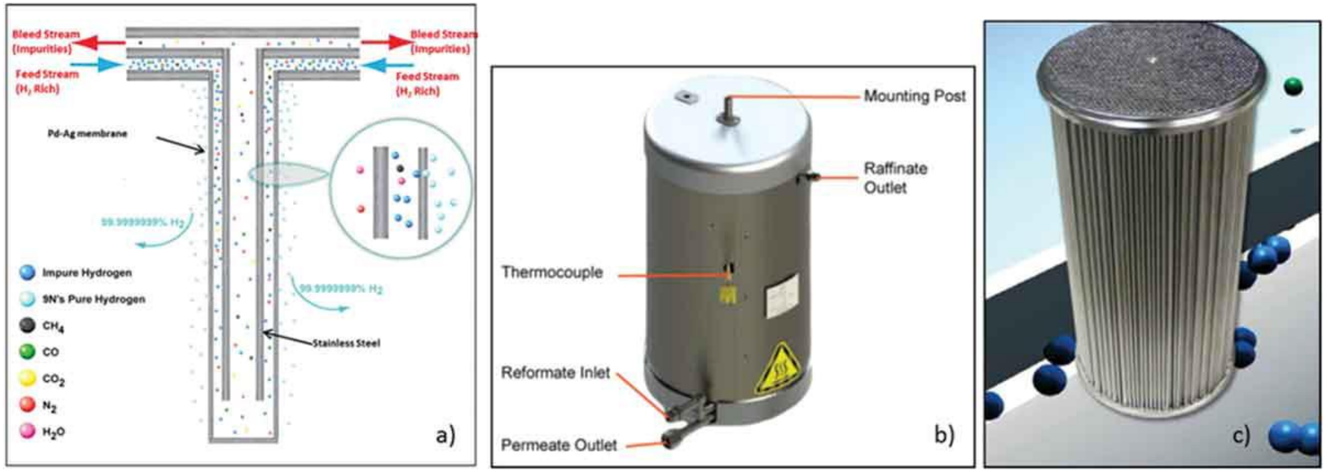
Morgan, G. A., Hodge, B. J., & Poore, A. S. (2021). *Performance Testing of a Palladium-Silver Diffuser for Tritium Processing*. Fusion Science and Technology, 77(6), 497–506.

Isotope Separation

Separating hydrogen isotopes from other gases

Palladium Diffusers - example

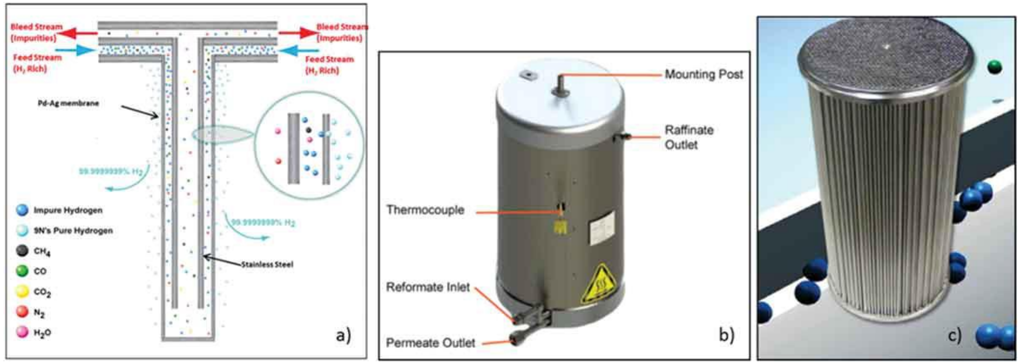
Parameter	Value
Temperature	400°C
Feed pressure	700–1140 Torr (~0.9–1.5 bar)
Feed gas compositions	96%, 50%, 2% H_2 (balance N_2)
Flow rates tested	100 – 3000 sccm
Membrane material	Pd-Ag alloy (microchannel tubes)
Membrane surface area	634 cm^2
Tube design	Inside-out flow, ~300 µm wall gap



Morgan, G. A., Hodge, B. J., & Poore, A. S. (2021). *Performance Testing of a Palladium-Silver Diffuser for Tritium Processing*. Fusion Science and Technology, 77(6), 497–506.

© 2024 Tokamak Energy Private and Confidential

Isotope Separation

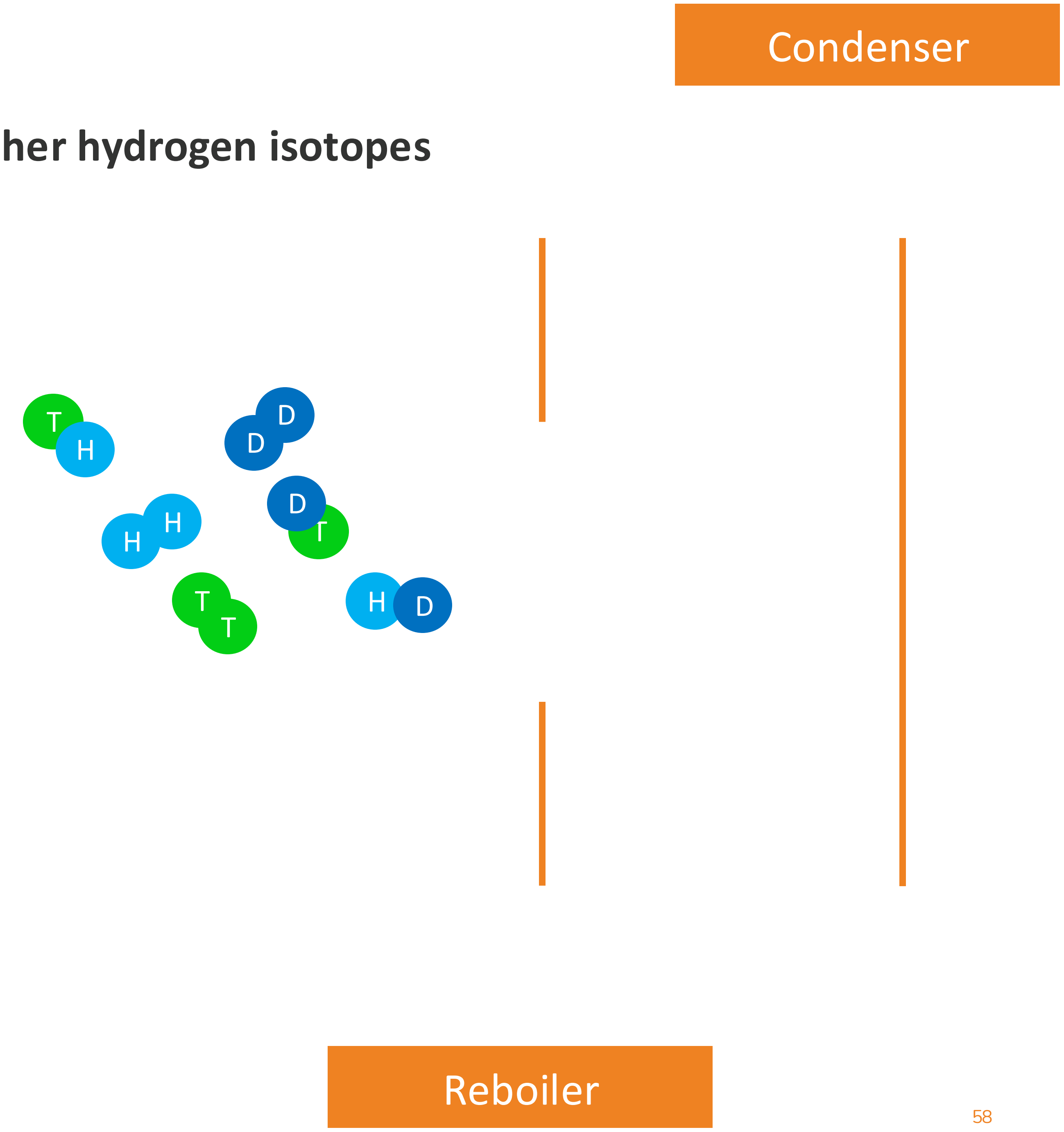


Separating hydrogen isotopes from other gases

Separate Tritium from other hydrogen isotopes

Isotope Separation

Separate Tritium from other hydrogen isotopes



Cryo Distillation Columns

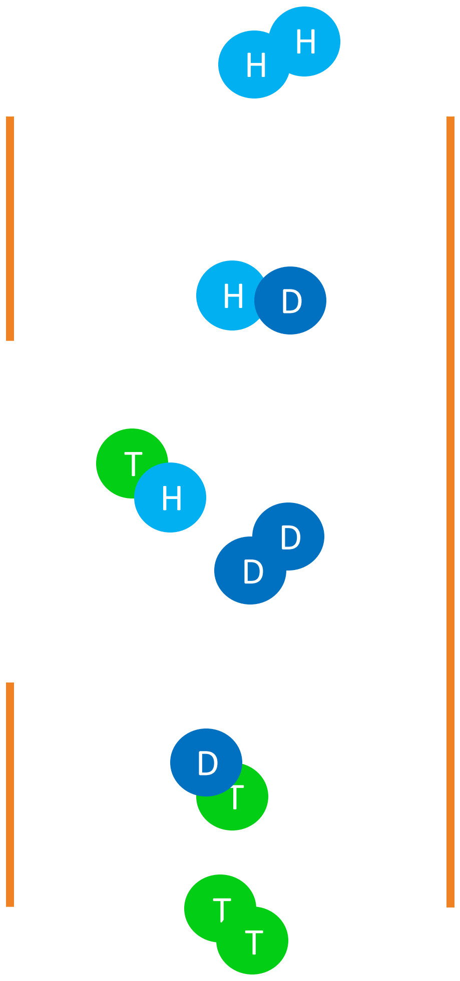
- A cryogenic distillation column separates hydrogen isotopes (H_2, D_2, T_2) based on boiling point differences at very low temperatures.
- The top product is gas enriched in lighter isotopes (HH, HT), while the bottom is liquid enriched in tritium
- Multiple stages required

© 2024 Tokamak Energy Private and Confidential

Condenser ~20 K

Isotope Separation

Separate Tritium from other hydrogen isotopes



Cryo Distillation Columns

- A cryogenic distillation column separates hydrogen isotopes (H_2, D_2, T_2) based on boiling point differences at very low temperatures.
- The top product is gas enriched in lighter isotopes (HH, HT), while the bottom is liquid enriched in tritium
- Multiple stages required

Full Reflux

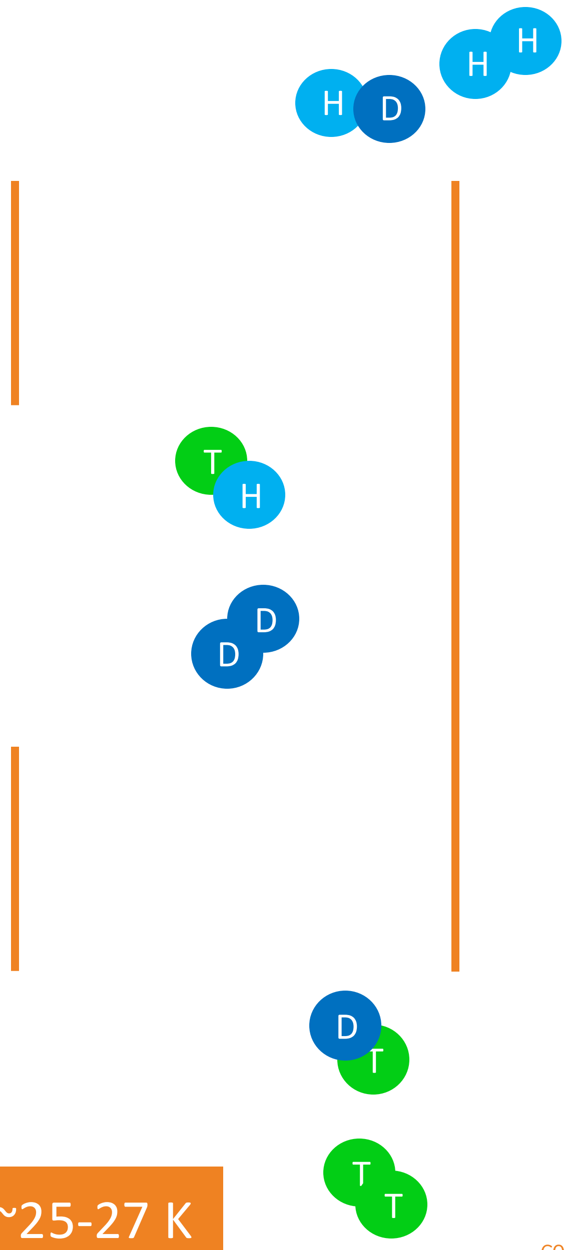
Align and stabilize the isotopologue concentration gradient – no product removal

Reboiler ~25-27 K

© 2024 Tokamak Energy Private and Confidential

Isotope Separation

Separate Tritium from other hydrogen isotopes

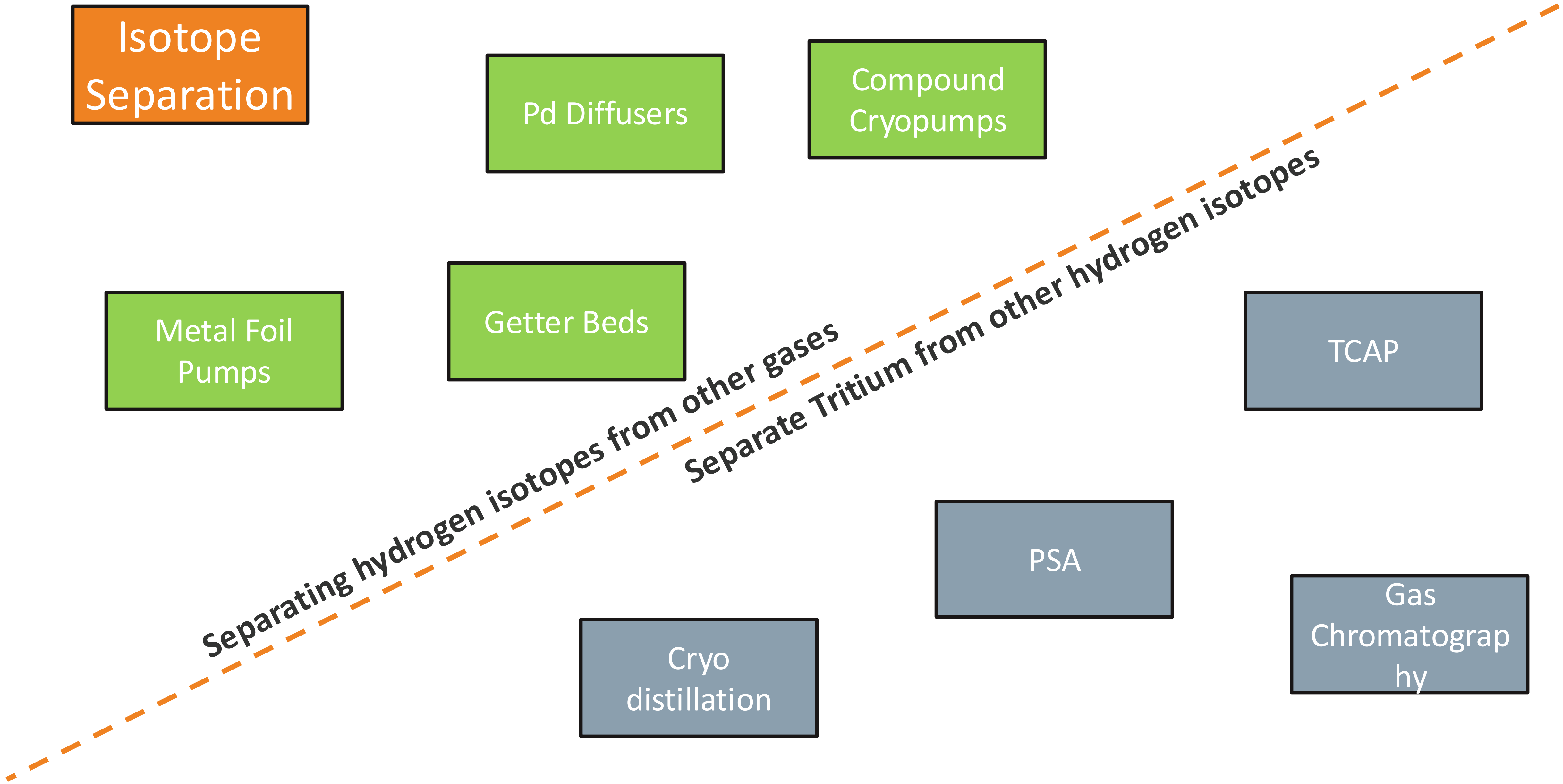


Cryo Distillation Columns

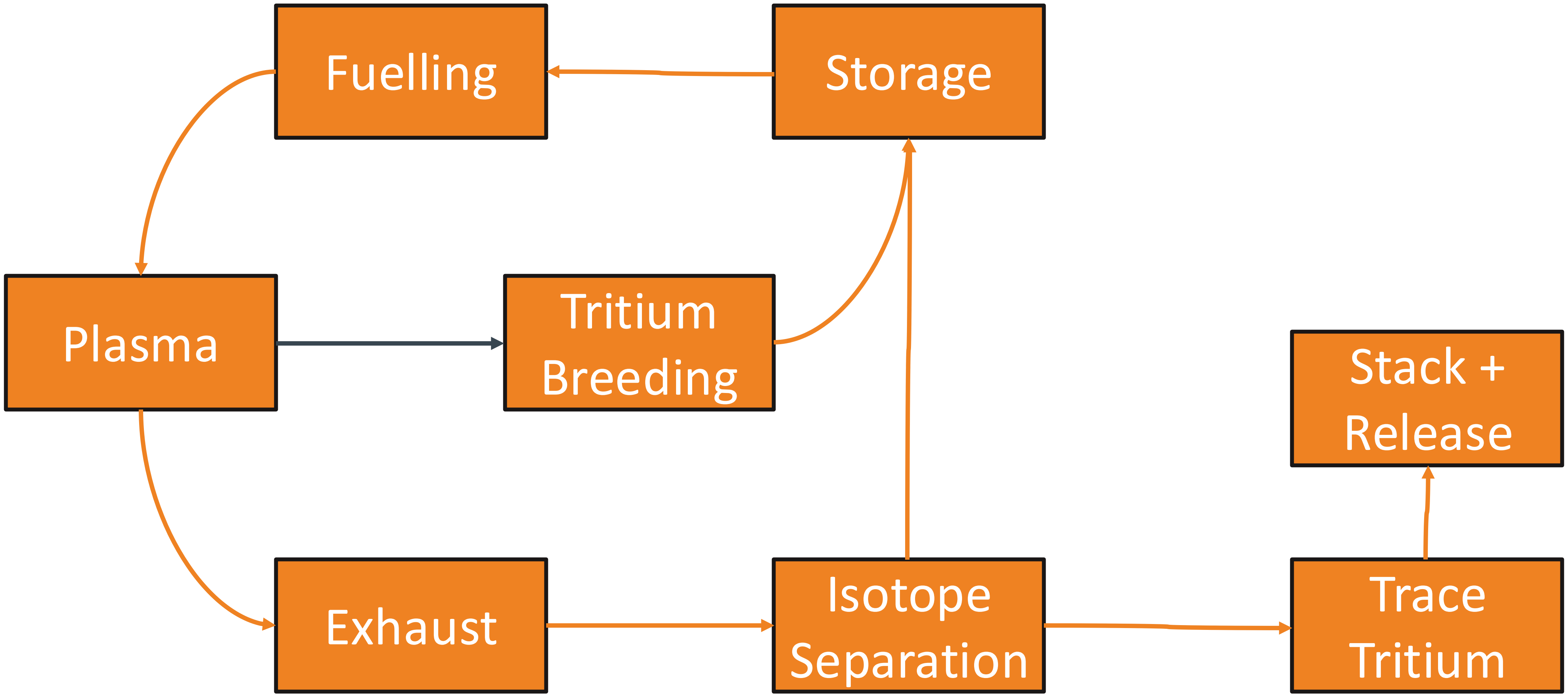
- A cryogenic distillation column separates hydrogen isotopes (H_2, D_2, T_2) based on boiling point differences at very low temperatures.
- The top product is gas enriched in lighter isotopes (HH, HT), while the bottom is liquid enriched in tritium
- Multiple stages required

Partial Reflux

Start tapping off the top and bottom products (a fraction of the condensate reused as per reflux ratio)



© 2024 Tokamak Energy Private and Confidential



© 2024 Tokamak Energy Private and Confidential

Tritium Breeding

Breed Tritium from Lithium Compounds (more in Lane's Talk!)

$$^{7}_{3}Li + ^{1}_{0}n \rightarrow ^{3}_{1}H + ^{4}_{2}He + ^{1}_{0}n$$

High energy neutrons

$$^{6}_{3}Li + ^{1}_{0}n \rightarrow ^{3}_{1}H + ^{4}_{2}He$$

Thermal neutrons

© 2024 Tokamak Energy Private and Confidential

Tritium Breeding

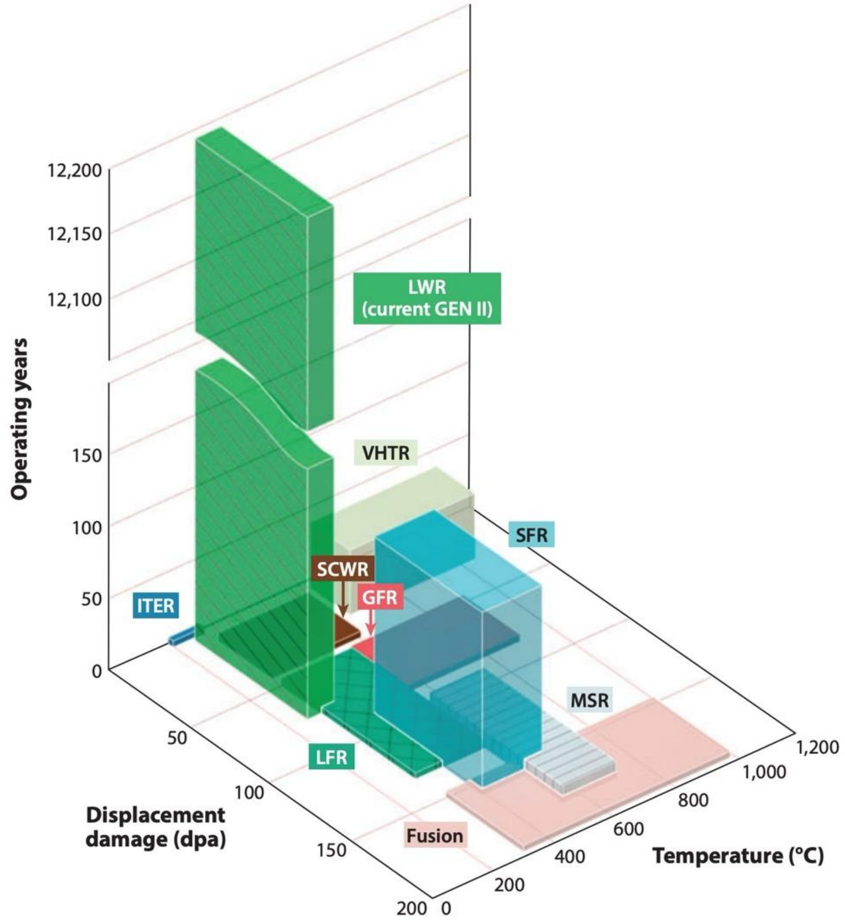
Breed Tritium from Lithium Compounds (more in Lane's Talk!)

Liquid

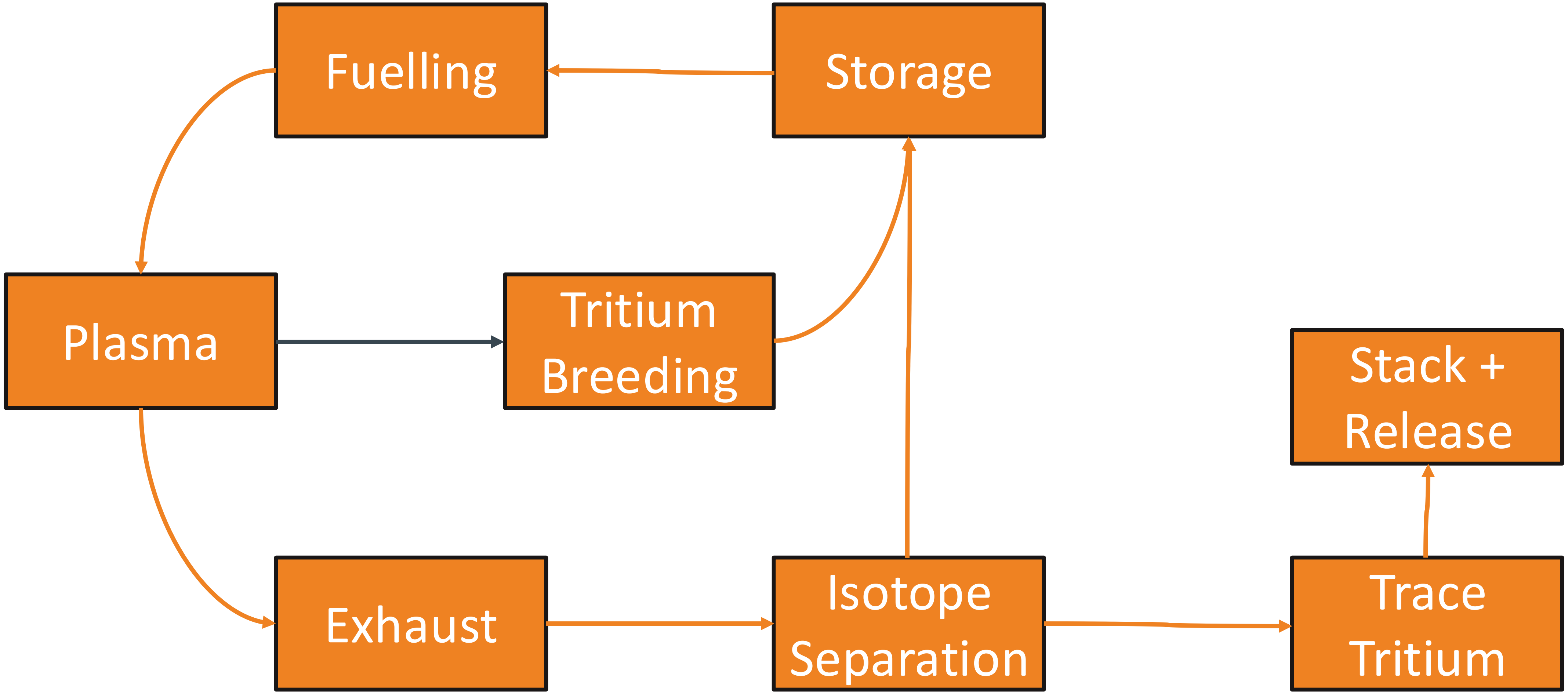
- Breeder: Li, Li/Pb, Molten Salt
- Coolant: Breeder, Water, Helium, Molten Salt
- Multiplier: Li-7, Be, Pb

Solid

- Breeder: Lithium Oxides, Ternary Oxides, Other
- Coolant: Water, Helium
- Multiplier: Be, Pb



Zinkle & Snead (2014) *Designing Radiation Resistance in Materials for Fusion Energy, Annu. Rev. Mater. Res.*, 44, 241–267



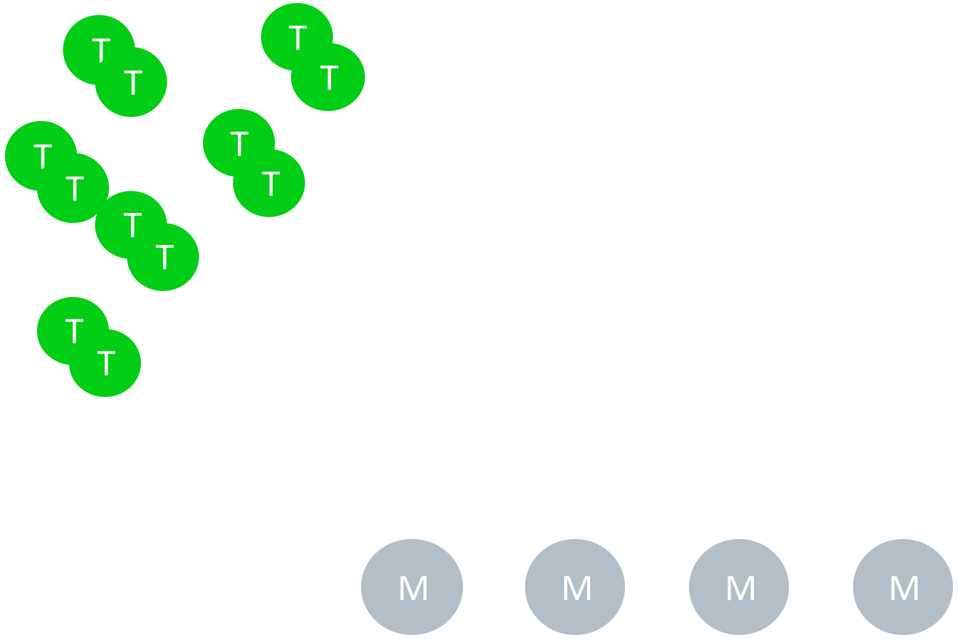
© 2024 Tokamak Energy Private and Confidential

Storage

Material	Hydride
Uranium	UH_3
$LaNi_5$	$LaNi_5Hx$
ZrCo	ZrCoHx
Ti, FeTi, Pd	various

Metal Hydrides

- Beds that absorb and release hydrogen isotopes (T_2, D_2, H_2) by forming solid metal hydrides.
- Act like chemical sponges for tritium.
- Reversible storage: heat to release, cool to store.
- High volumetric density compared to gas cylinders.
- Passive safety: tritium is chemically bound in solid phase.



© 2024 Tokamak Energy Private and Confidential

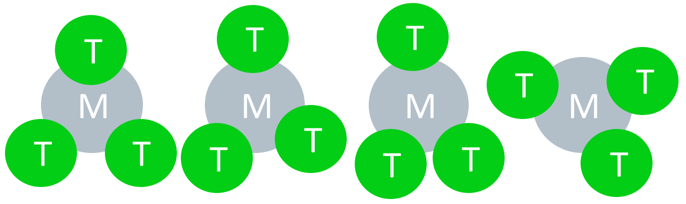
Storage

Material	Hydride
Uranium	UH_3
$LaNi_5$	$LaNi_5Hx$
ZrCo	ZrCoHx
Ti, FeTi, Pd	various

Metal Hydrides

- Beds that absorb and release hydrogen isotopes (T_2, D_2, H_2) by forming solid metal hydrides.
- Act like chemical sponges for tritium.
- Reversible storage: heat to release, cool to store.
- High volumetric density compared to gas cylinders.
- Passive safety: tritium is chemically bound in solid phase.

Cool



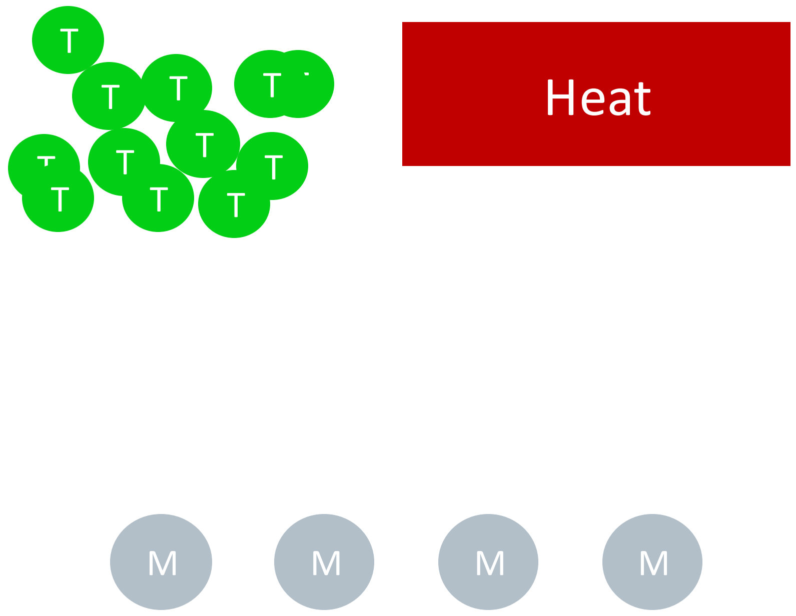
© 2024 Tokamak Energy Private and Confidential

Storage

Material	Hydride
Uranium	UH_3
$LaNi_5$	$LaNi_5Hx$
ZrCo	ZrCoHx
Ti, FeTi, Pd	various

Metal Hydrides

- Beds that absorb and release hydrogen isotopes (T_2, D_2, H_2) by forming solid metal hydrides.
- Act like chemical sponges for tritium.
- Reversible storage: heat to release, cool to store.
- High volumetric density compared to gas cylinders.
- Passive safety: tritium is chemically bound in solid phase.



© 2024 Tokamak Energy Private and Confidential

Storage

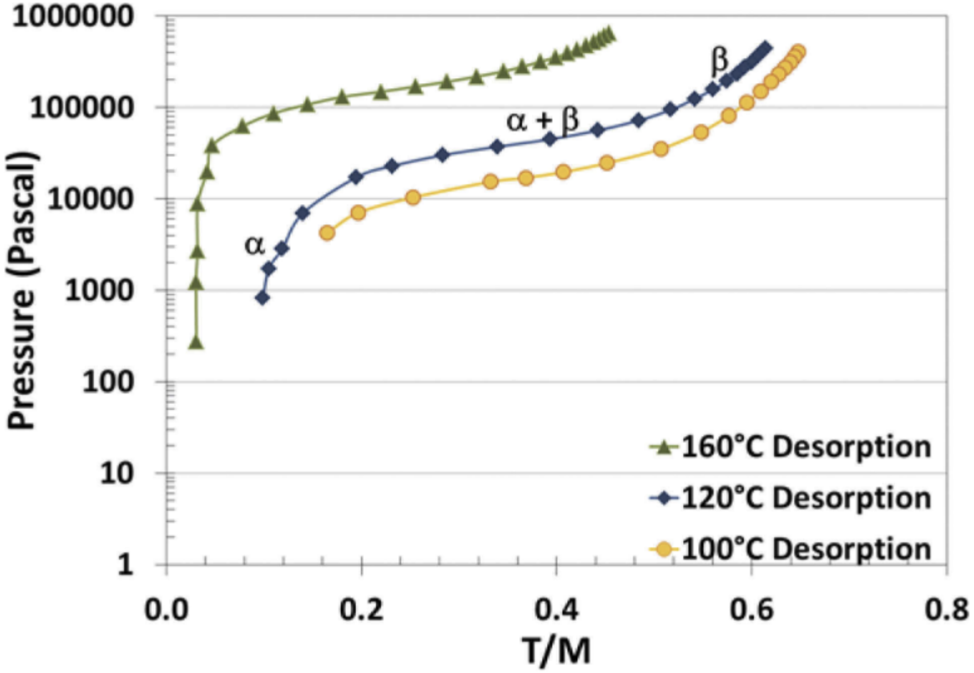
ITER Website – Uranium Beds

Metal Hydrides

- **α-phase (left side)**
  Hydrogen is dissolved in the metal — easy in, easy out. Pressure rises quickly.

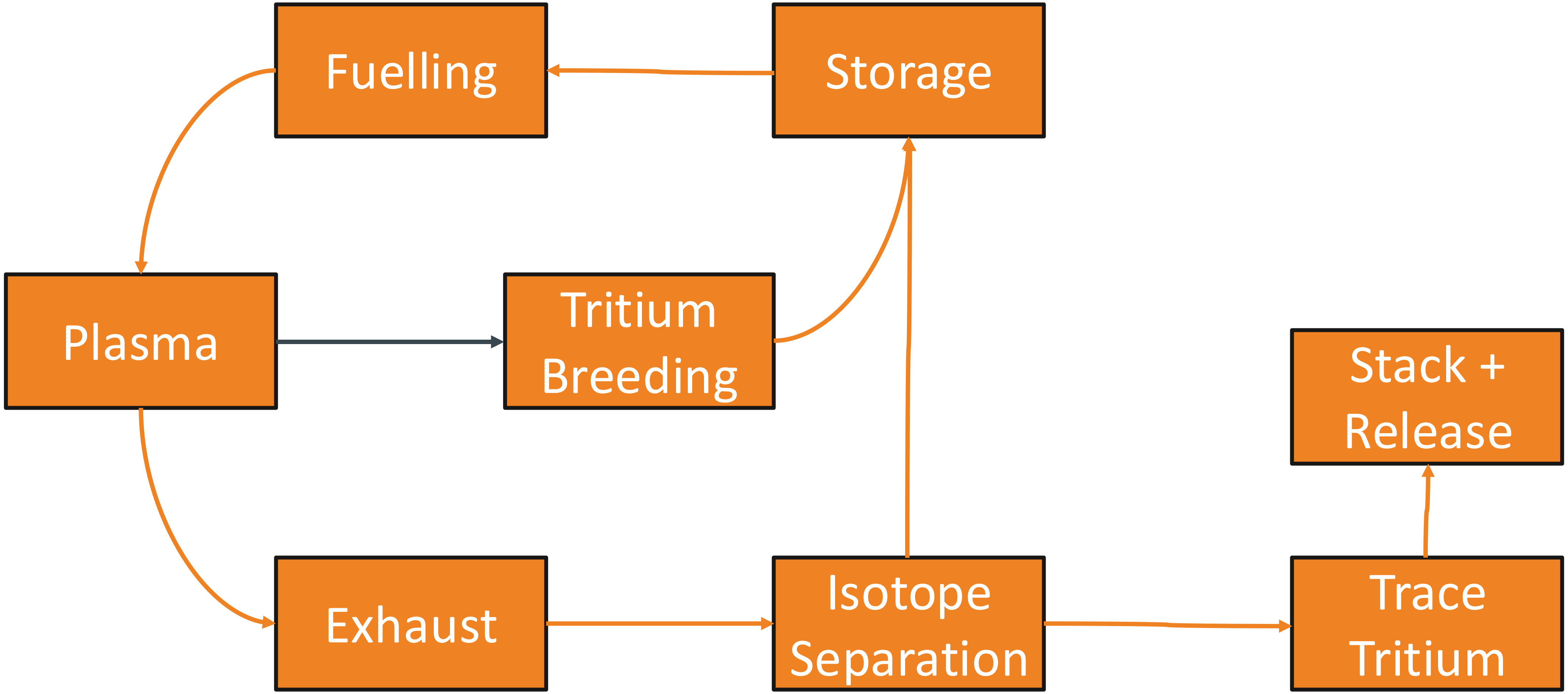
- **α + β Plateau (middle)**
  Metal and hydride coexist. Large amounts of hydrogen are absorbed or released at nearly constant pressure — ideal for storage and delivery.

- **β-phase (right side)**
  The hydride is full. Further hydrogen uptake requires much higher pressure — less efficient for operation.



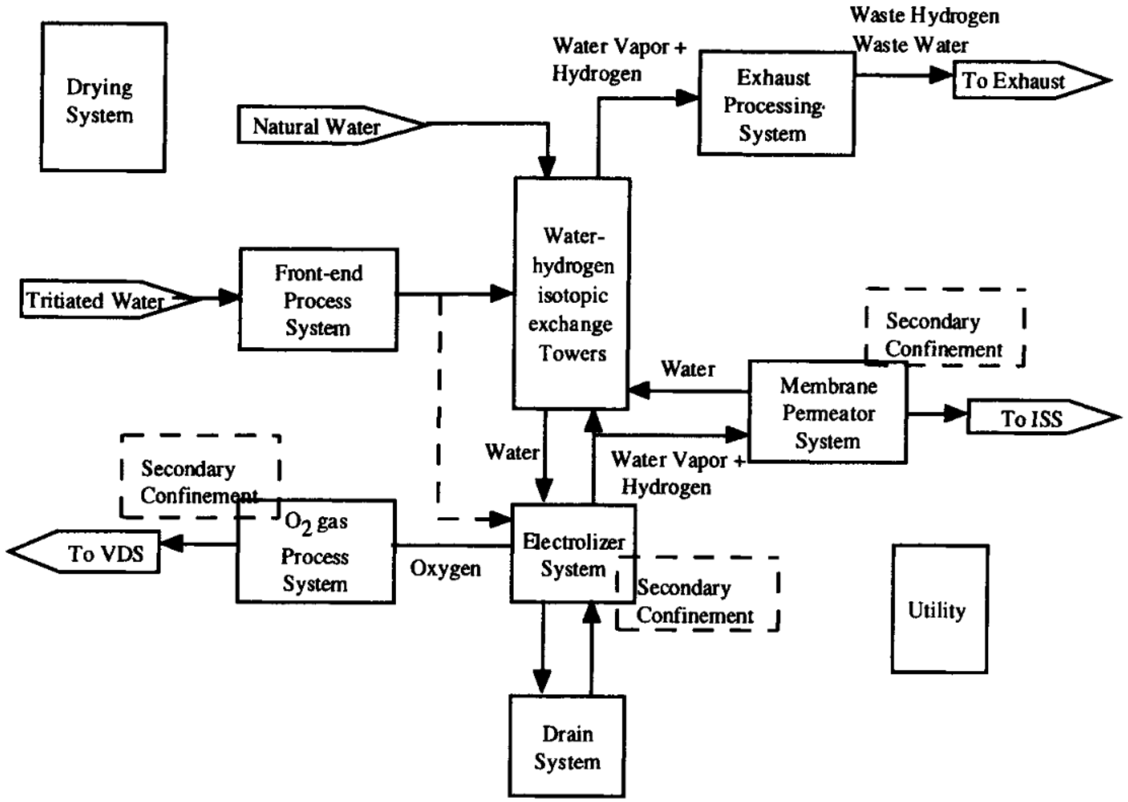
James et al. (2017), *Tritium Aging of $LaNi_{4.15}Al_{0.85}$ (LANA.85), Fusion Science and Technology*, 71(3), 565–569

© 2024 Tokamak Energy Private and Confidential


Fuelling
Storage
Plasma
Tritium Breeding
Stack + Release
Exhaust
Isotope Separation
Trace Tritium

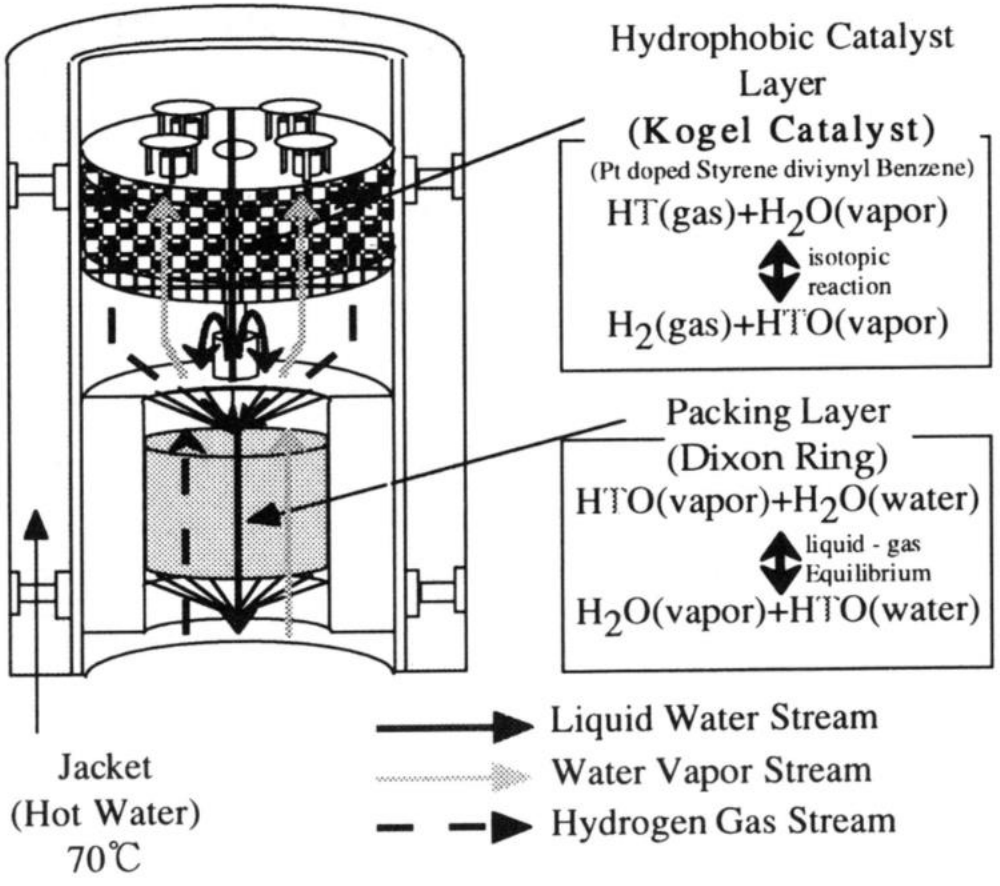
Trace Tritium

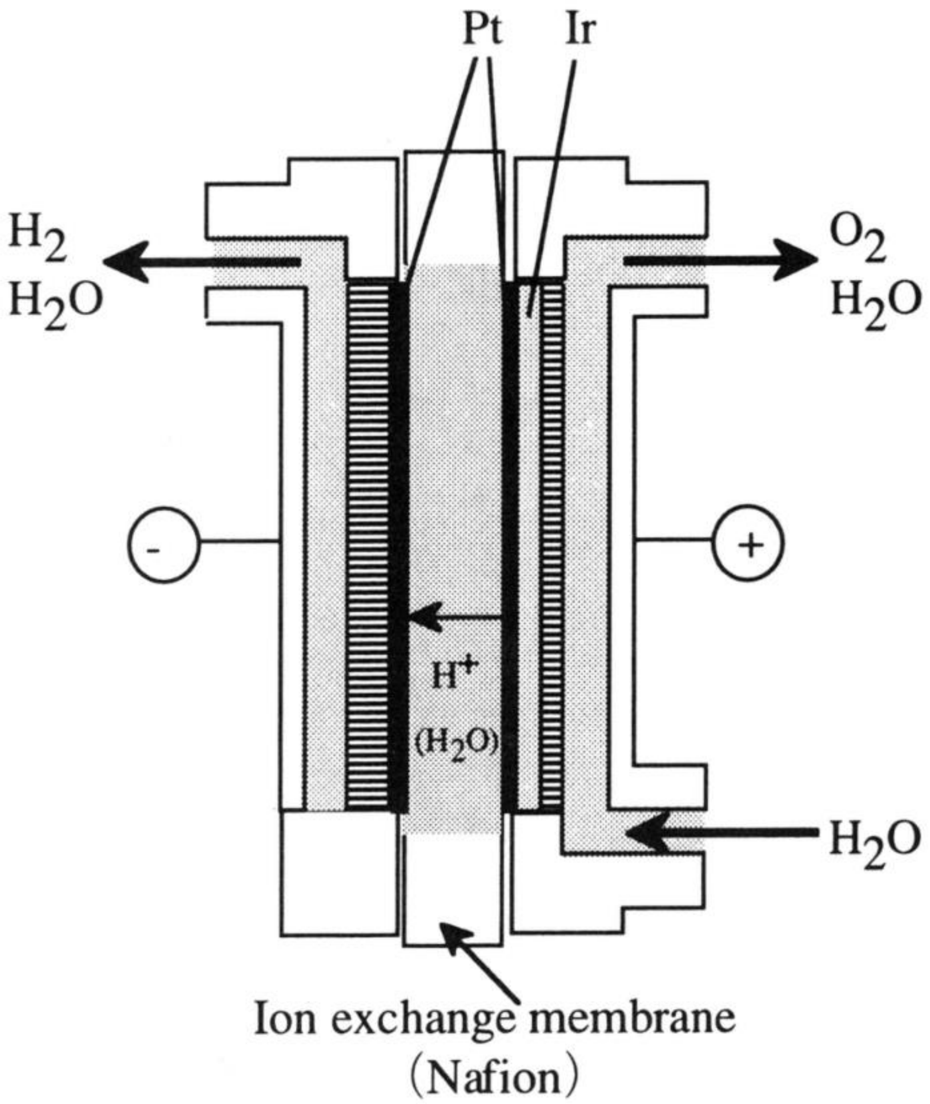
- Trace tritium recovery systems deal with trace tritium in systems:
  - Trace tritium in waste streams from isotope separation systems (tritium recovery is not 100 %)
  - Reactor coolant streams
  - Air from gloveboxes (especially due to tritium release during maintenance periods)
  - Process gases and liquids
- Example systems are electrolysis-based systems for water detritiation or getter beds to capture hydrogen or HTO from gas steams for gas detritiation



Iwai et al., 2002 *"The Water Detritiation System of the ITER Tritium Plant"* Fusion Science and Technology, 41(3P2), 1126–1130

Trace Tritium





Iwai et al., 2002 *"The Water Detritiation System of the ITER Tritium Plant"* Fusion Science and Technology, 41(3P2), 1126–1130

© 2024 Tokamak Energy Private and Confidential

Fuel Cycle Technologies

- Several technologies have been presented [we have gone in to varying detail on these!]
- It is important to consider the way we use tritium properties, rather than the technologies themselves!
  - There are many technologies that could be used for the different blocks you have seen
  - They utilize different things e.g.:
    - The permeation properties of hydrogen allow for hydrogen isotope separation from other gases
    - The boiling point differences alloy hydrogen isotope separation from each other
    - Chemical reactions between hydrogen isotopes and other molecules
- The fuel cycle is a purification process, where we attempt to get as much deuterium and tritium back to the fueling systems as fast as possible

© 2025 Tokamak Energy Private and Confidential

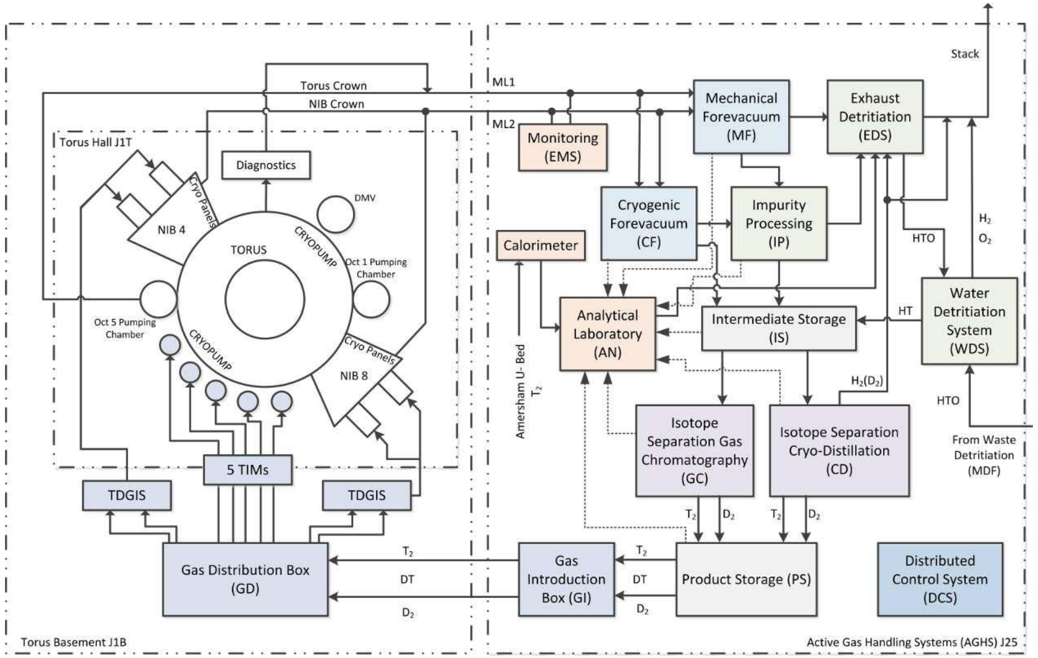
Tokamak Energy

Challenges in the fuel cycle

© 2025 Tokamak Energy Private and Confidential

Current Fuel Cycles

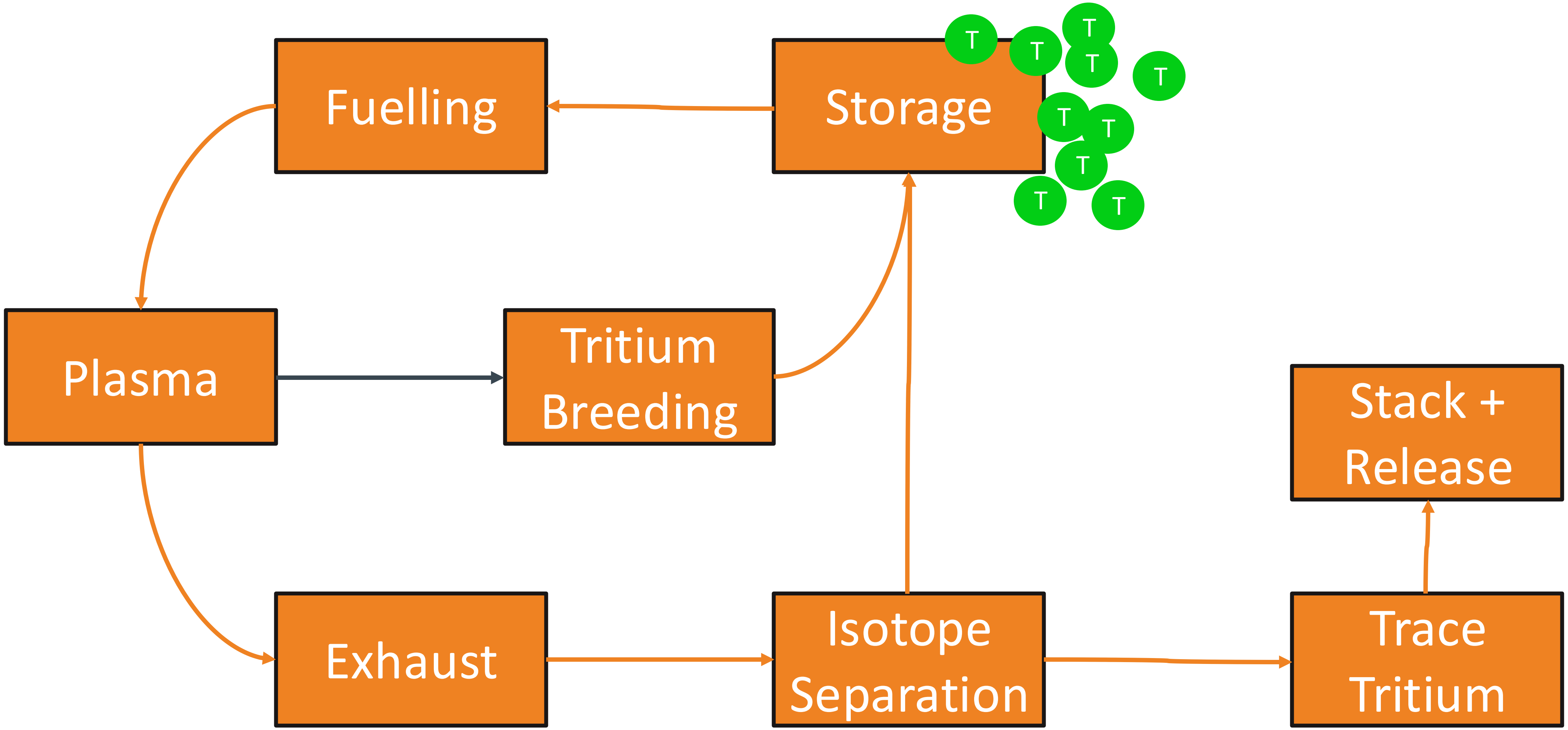
- There are not any continuous fuel cycles in operation today
- Historically, fuel cycles have been *batch* operated
- While the learning from these is critical – these systems will not be suitable for commercial fusion devices
- The only currently operating DT fuel cycle is at JET AGHS (Joint European Torus – Active Gas Handling System)



The key challenges

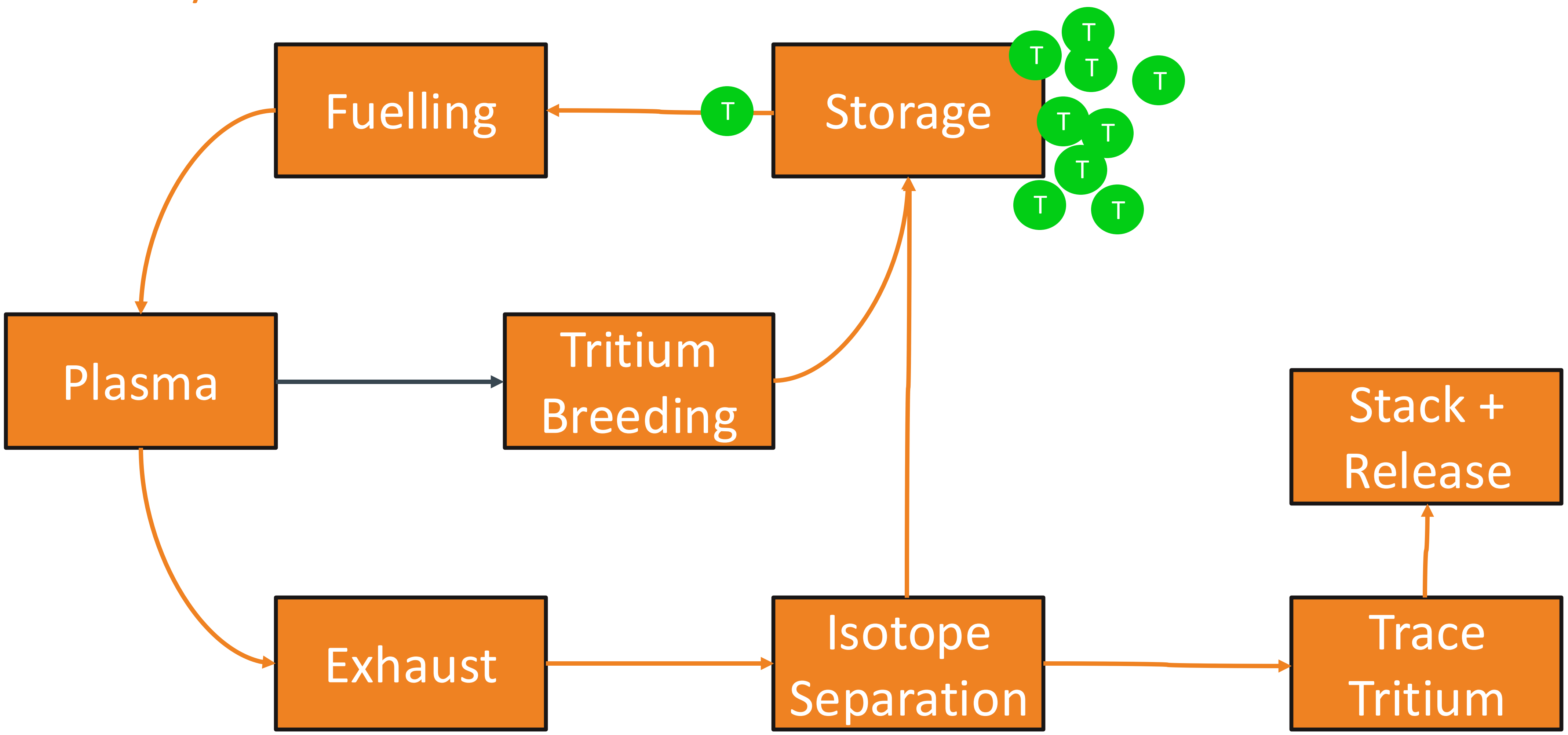
- Tritium Breeding Ratio – the ratio of tritium produced in the blanket to the tritium used must be >1 [more in Lane's talk after me!]
- Big startup inventories
  - It takes time to recycle unburnt and breed more tritium – in the meantime the plasma must be fuelled externally
  - As tritium is scarce, this initial *startup inventory* must be minimized
- Building an inventory for future plants – *doubling time*
- Tritium accountancy – how do we keep track of all the tritium
  - We need continuous methods of tracking tracking, and the concentrations in each of our Fuel Cycle systems
- Understanding losses in the system
  - We don't have a working continuous fuel cycle yet – how can we understand where those losses will be

Startup Inventory

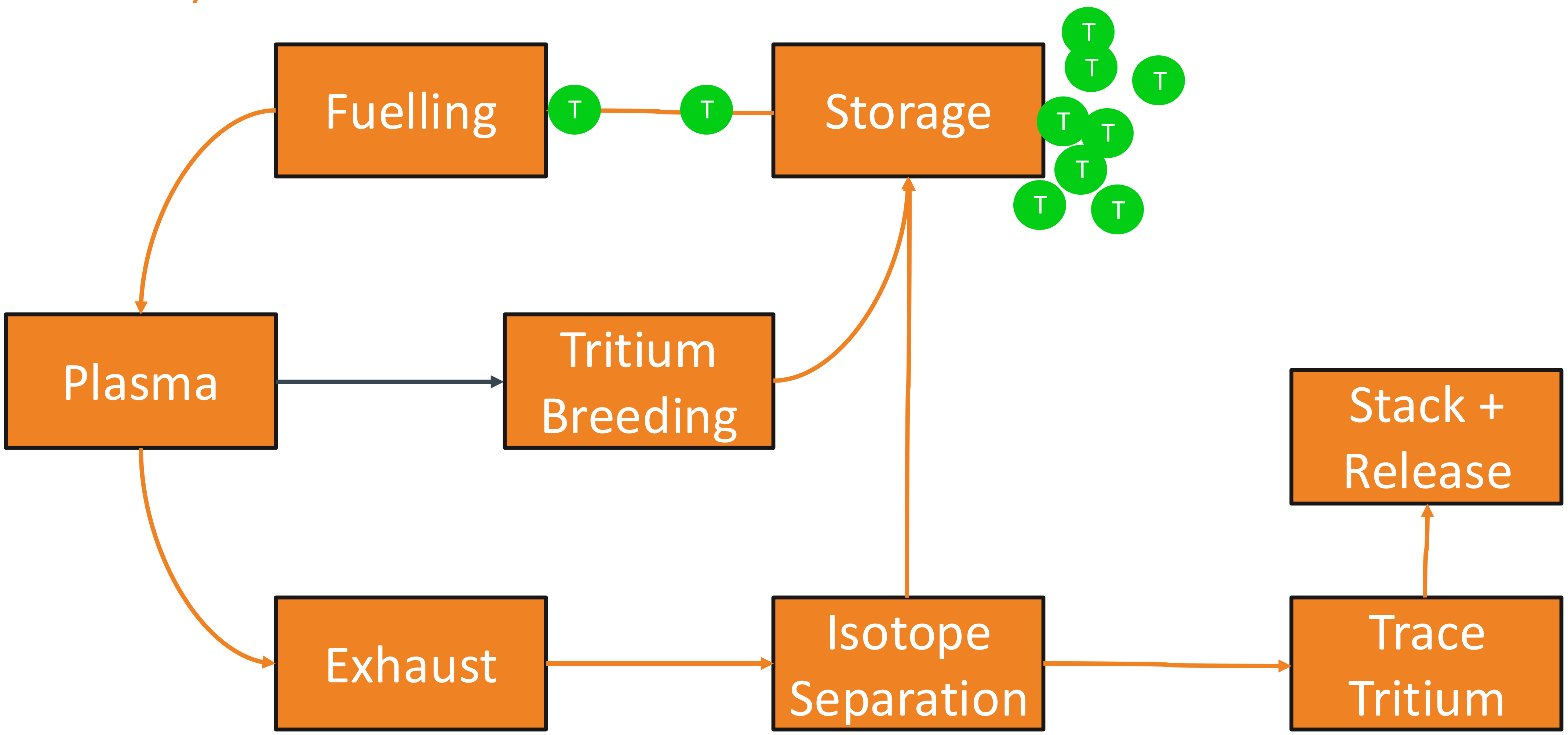


© 2025 Tokamak Energy Private and Confidential

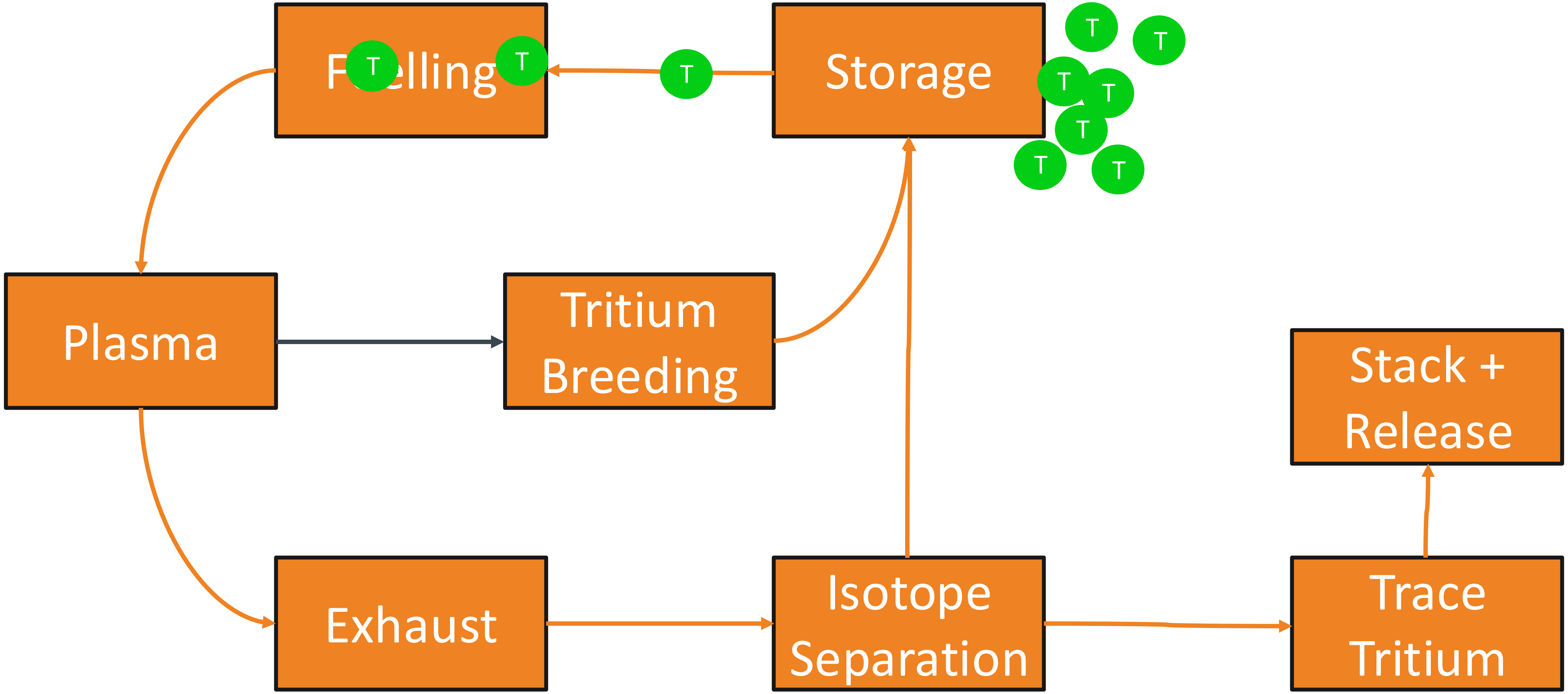
Startup Inventory



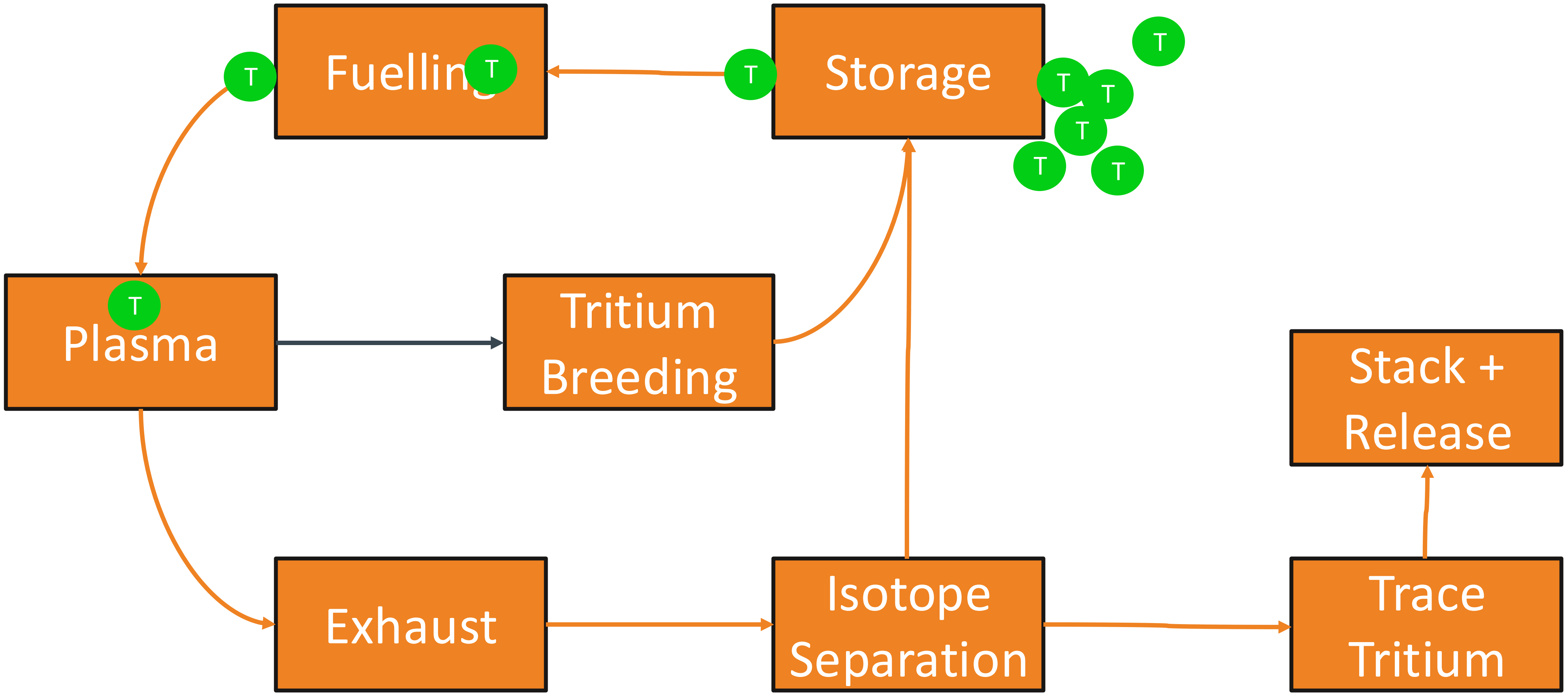
Startup Inventory



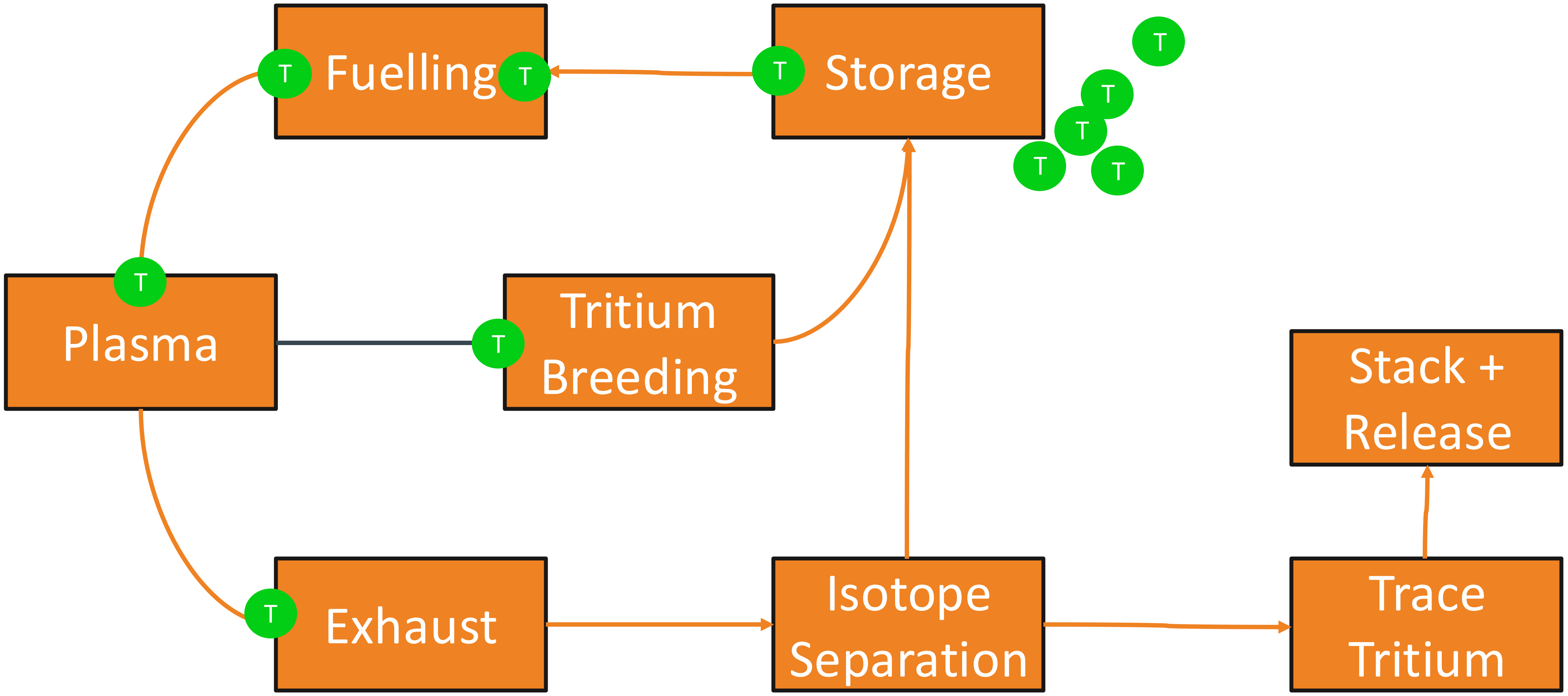
Startup Inventory



Startup Inventory

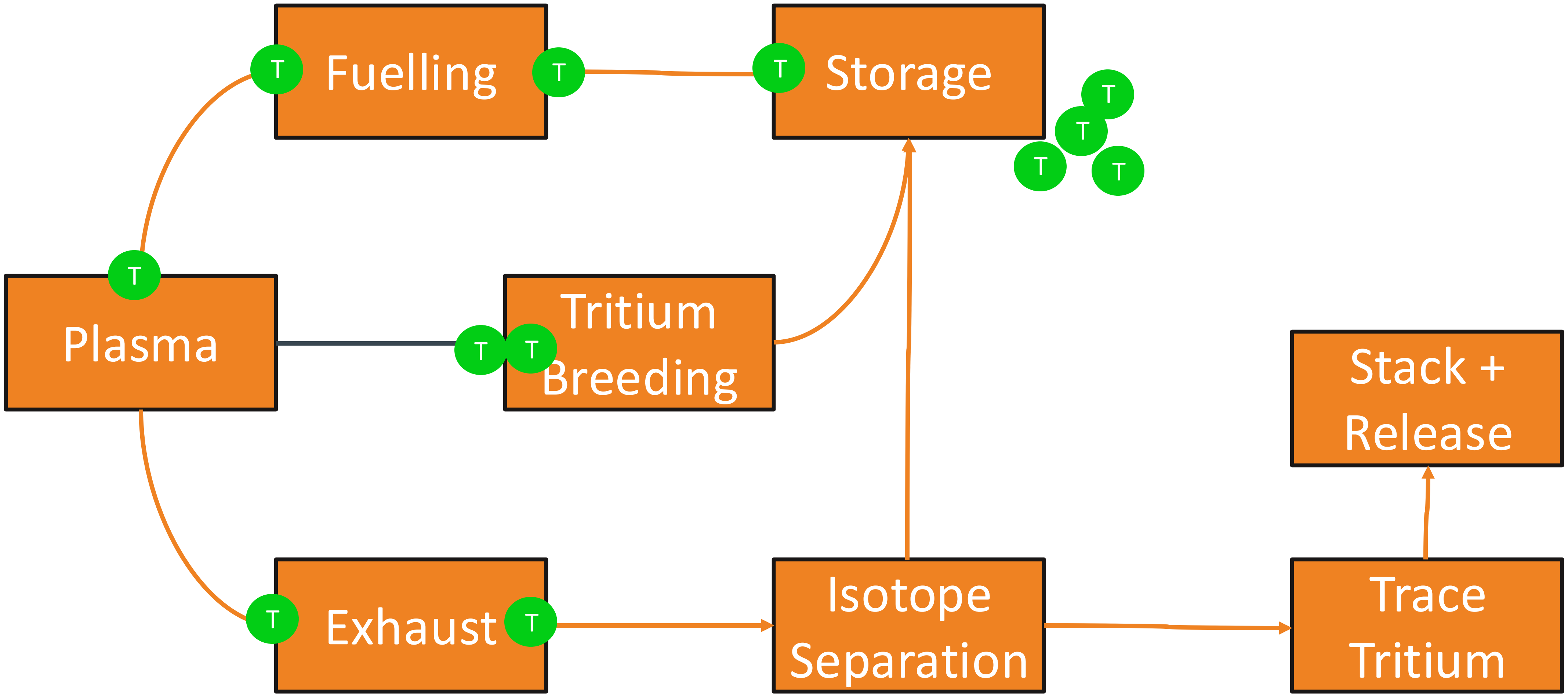


Startup Inventory

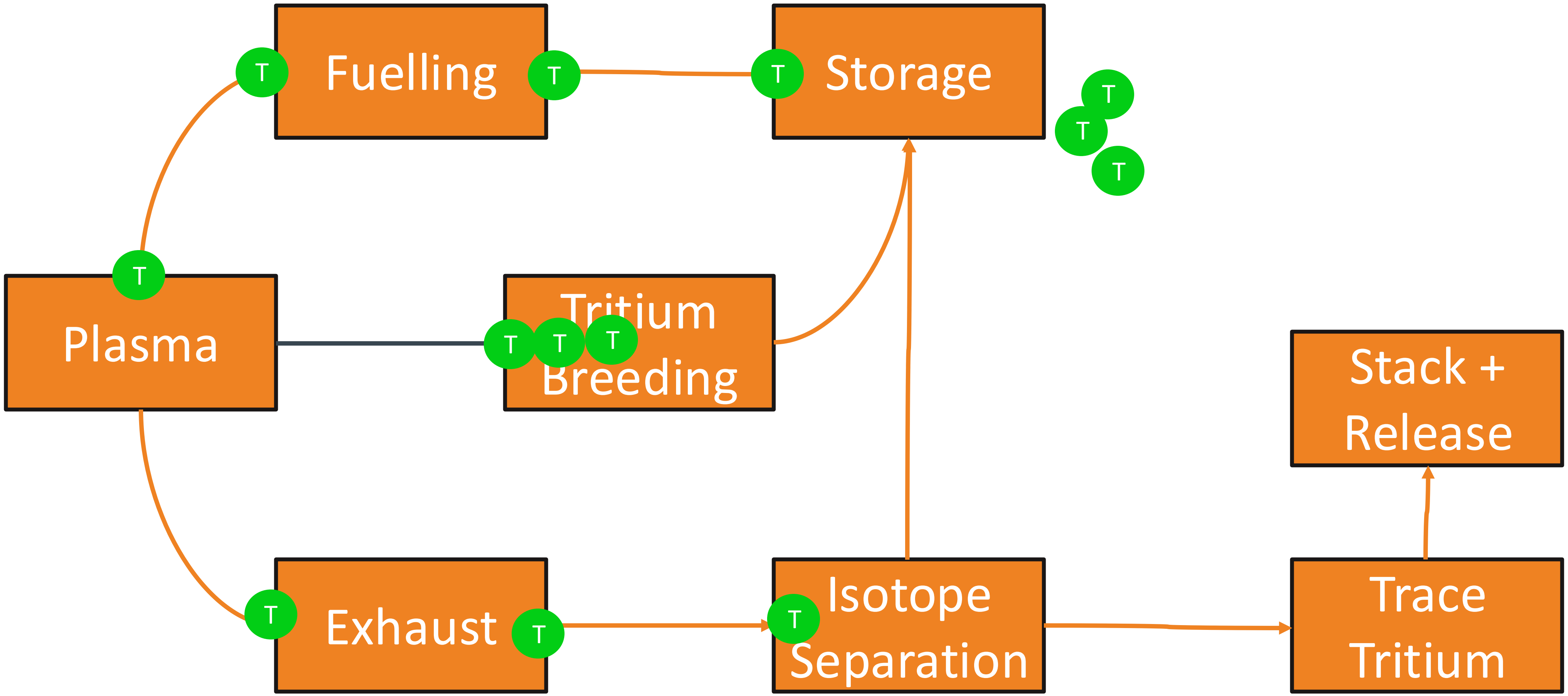


© 2025 Tokamak Energy Private and Confidential

Startup Inventory

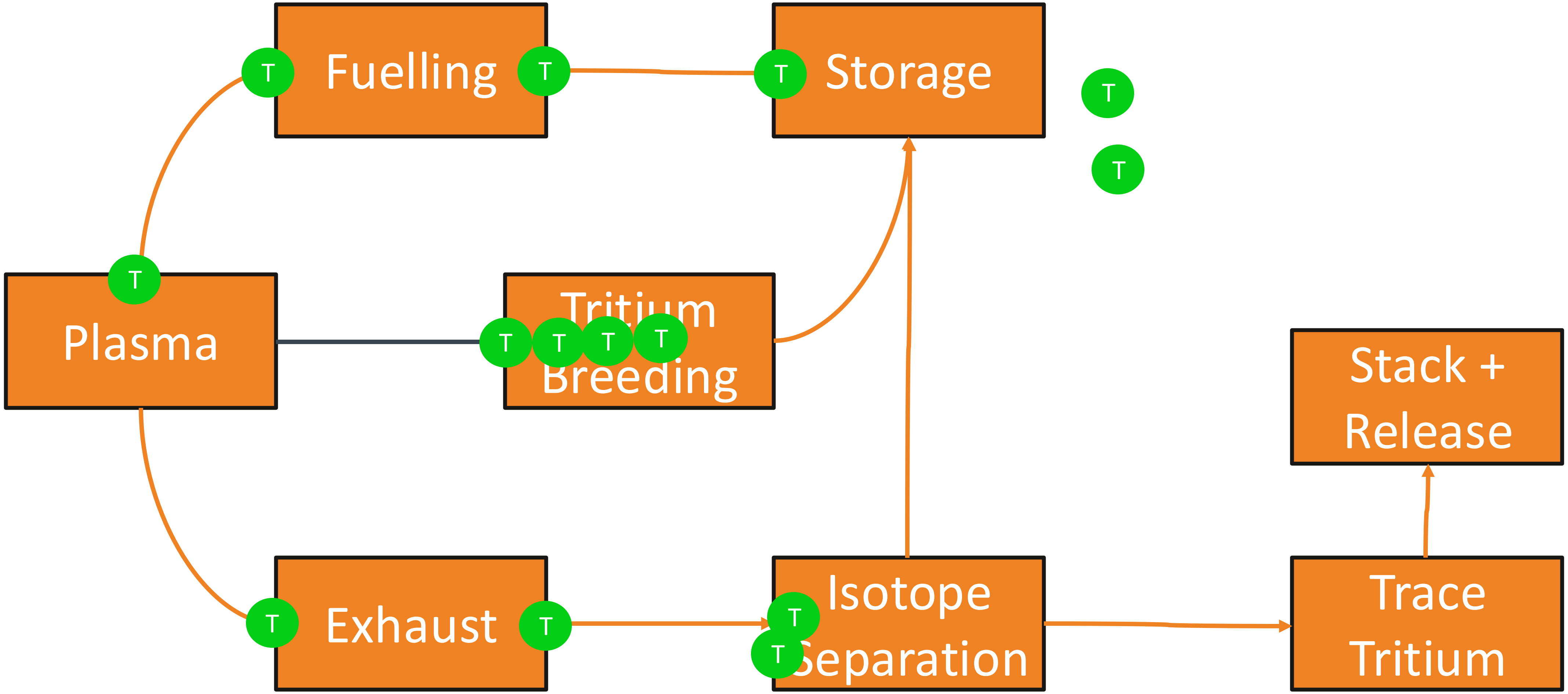


Startup Inventory

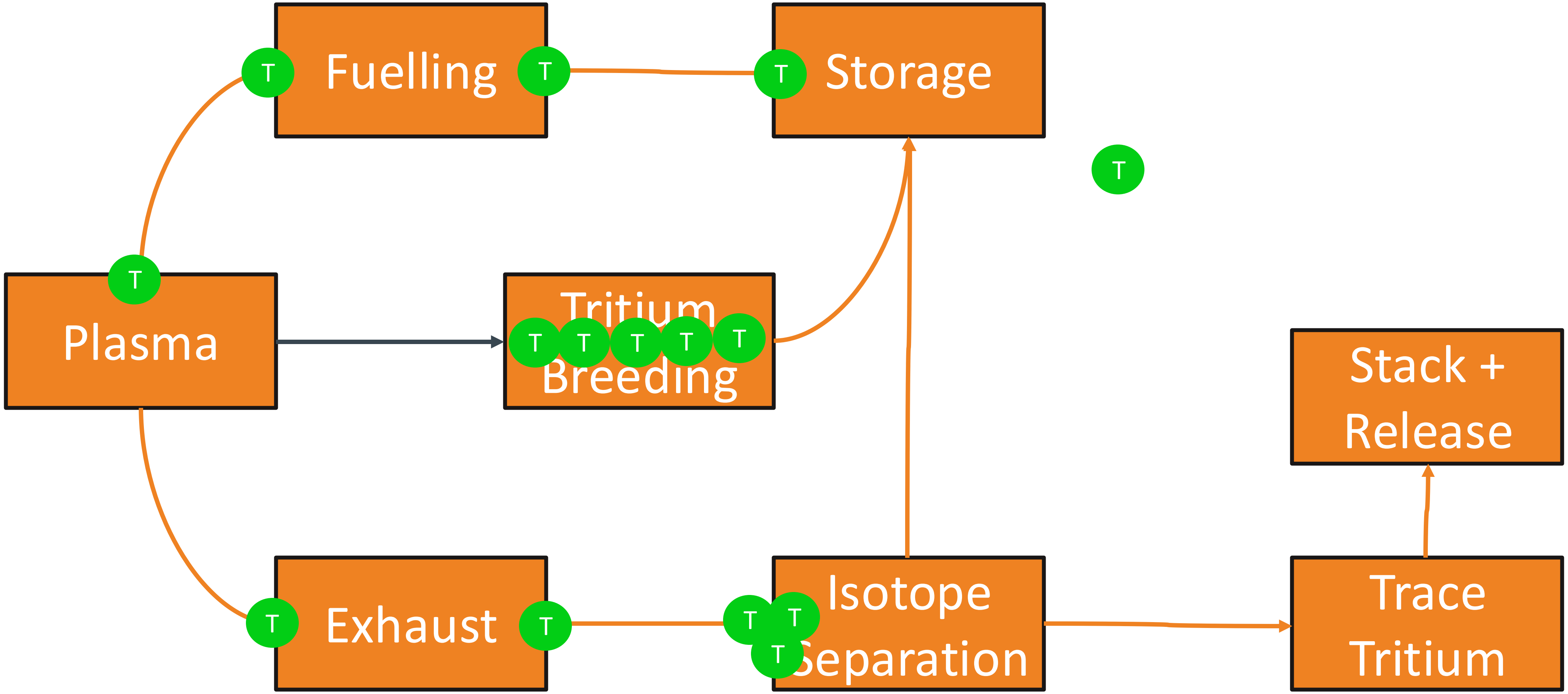


© 2025 Tokamak Energy Private and Confidential

Startup Inventory

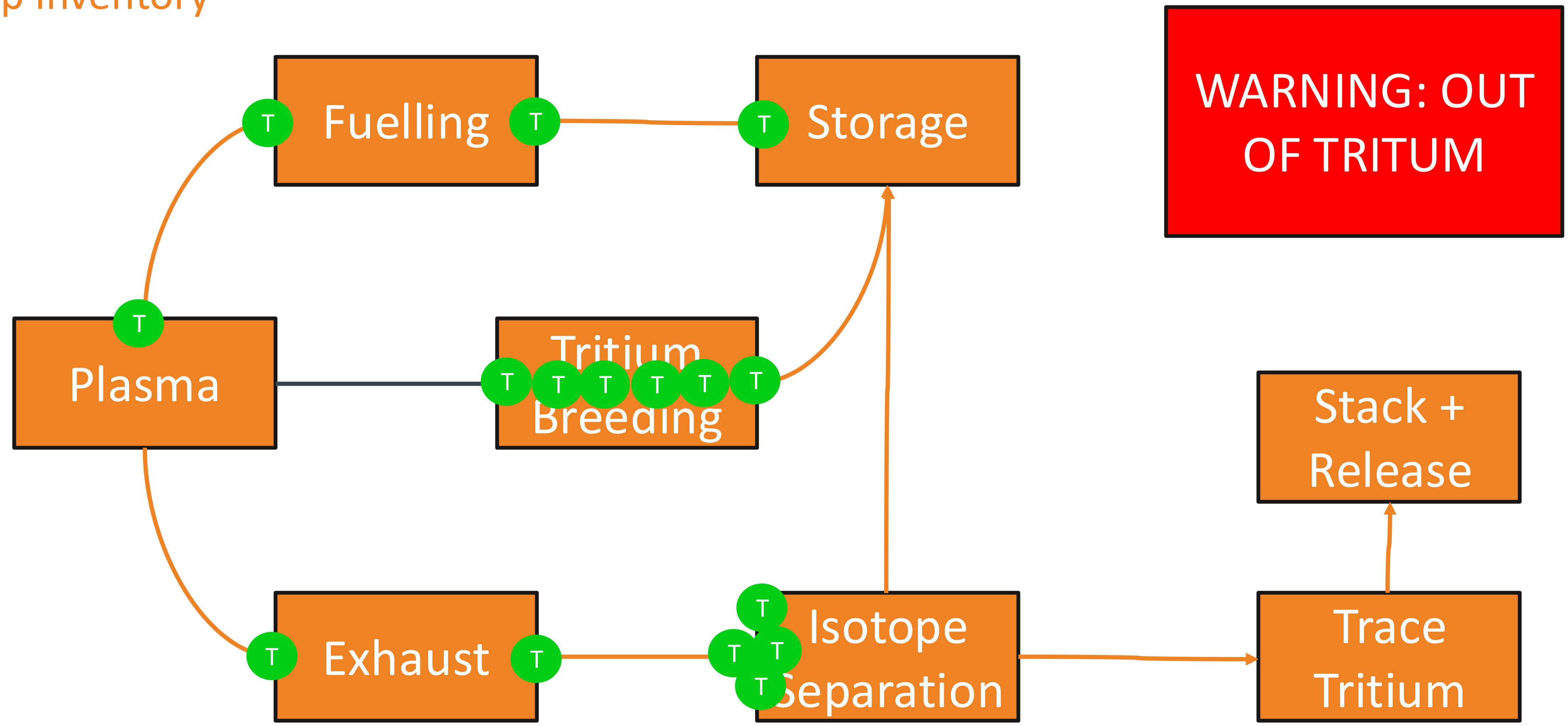


Startup Inventory



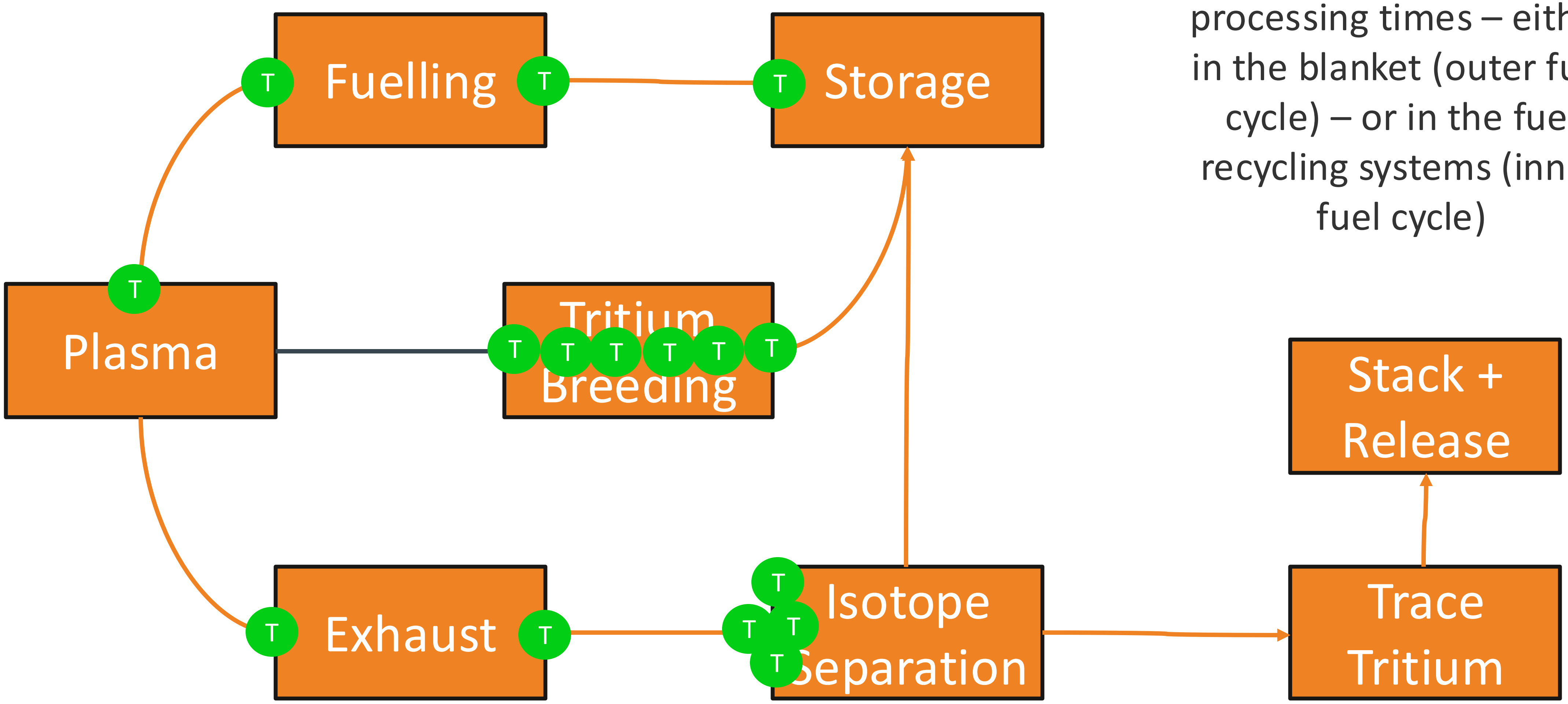
© 2025 Tokamak Energy Private and Confidential

Startup Inventory



© 2025 Tokamak Energy Private and Confidential

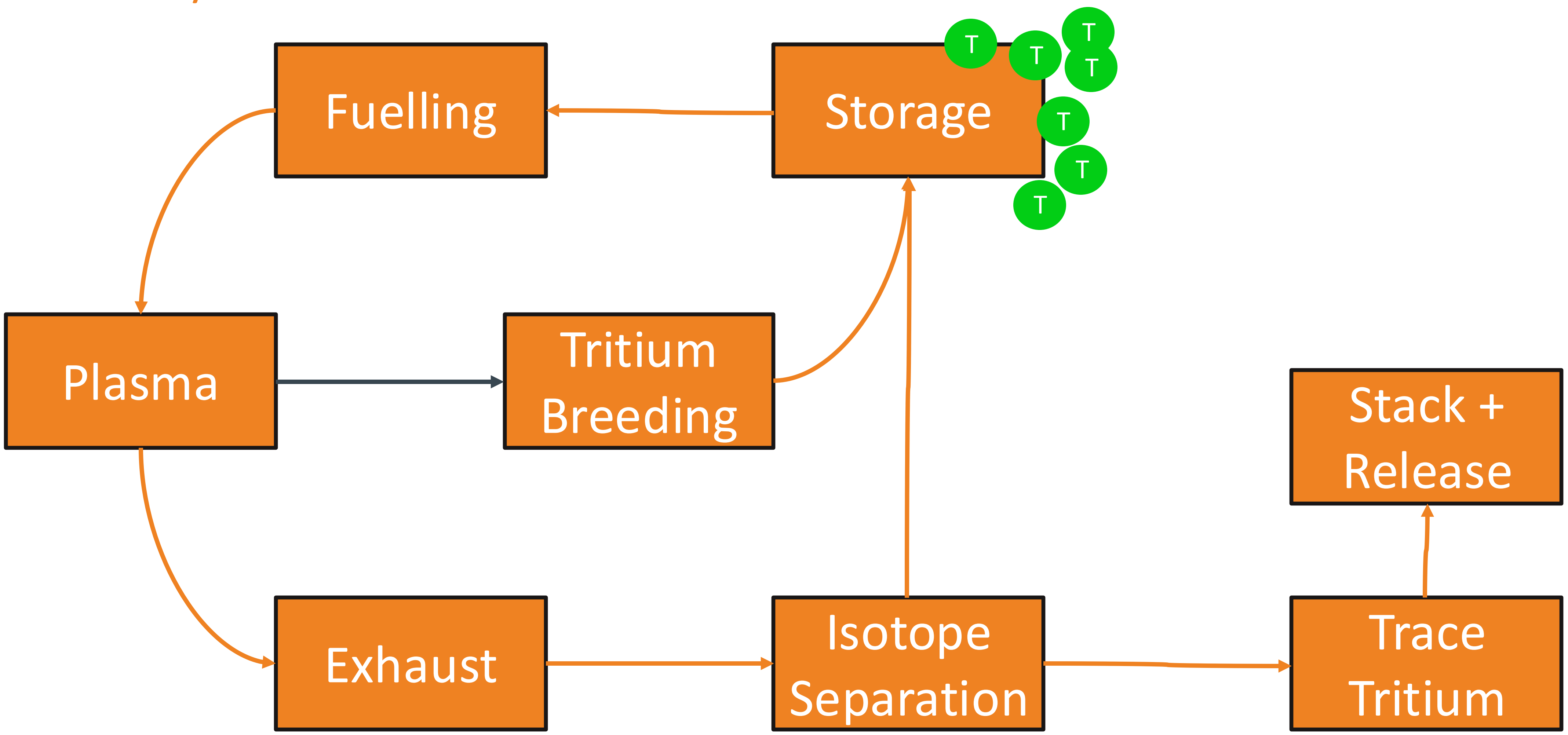
Startup Inventory



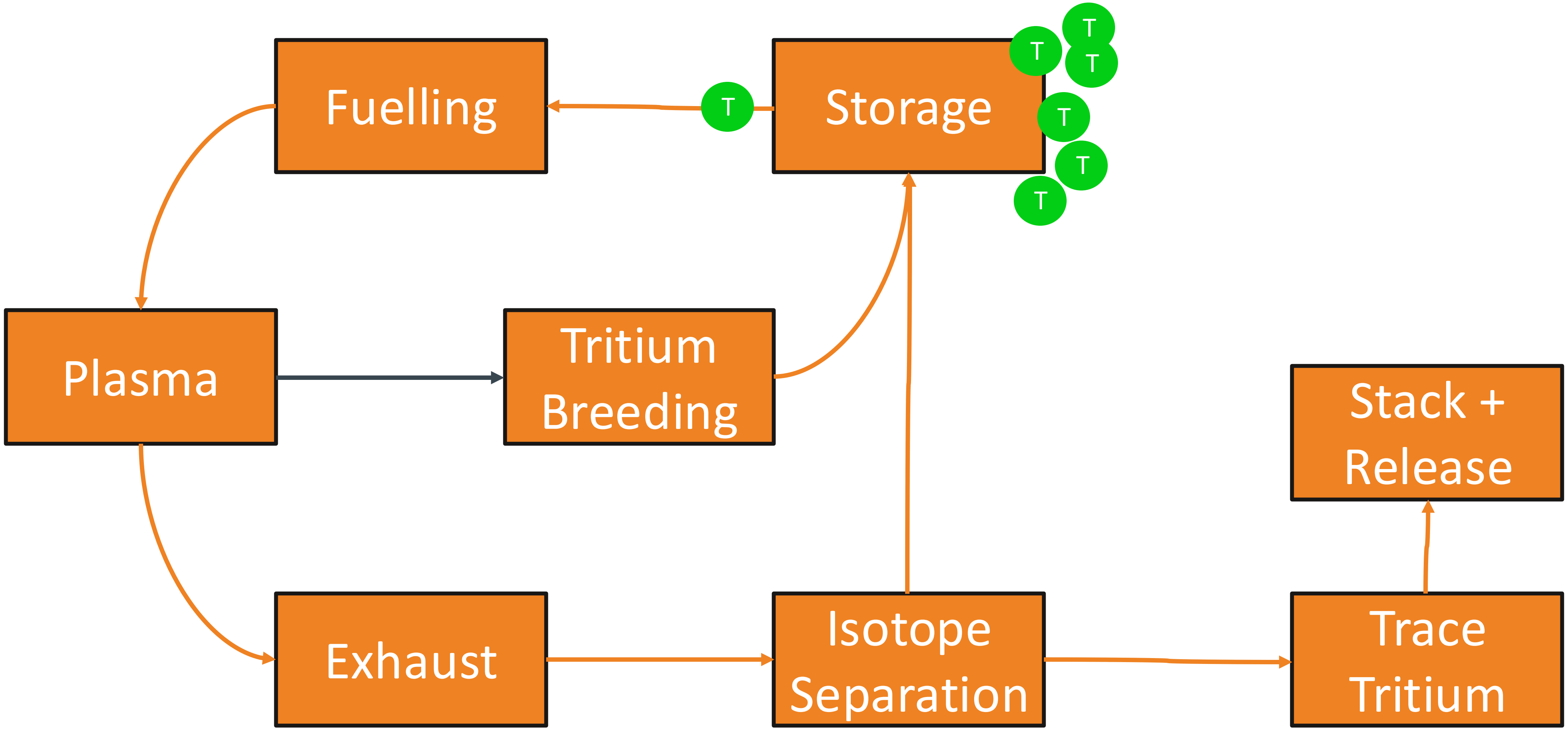
Need to improve processing times – either in the blanket (outer fuel cycle) – or in the fuel recycling systems (inner fuel cycle)

© 2025 Tokamak Energy Private and Confidential

Startup Inventory

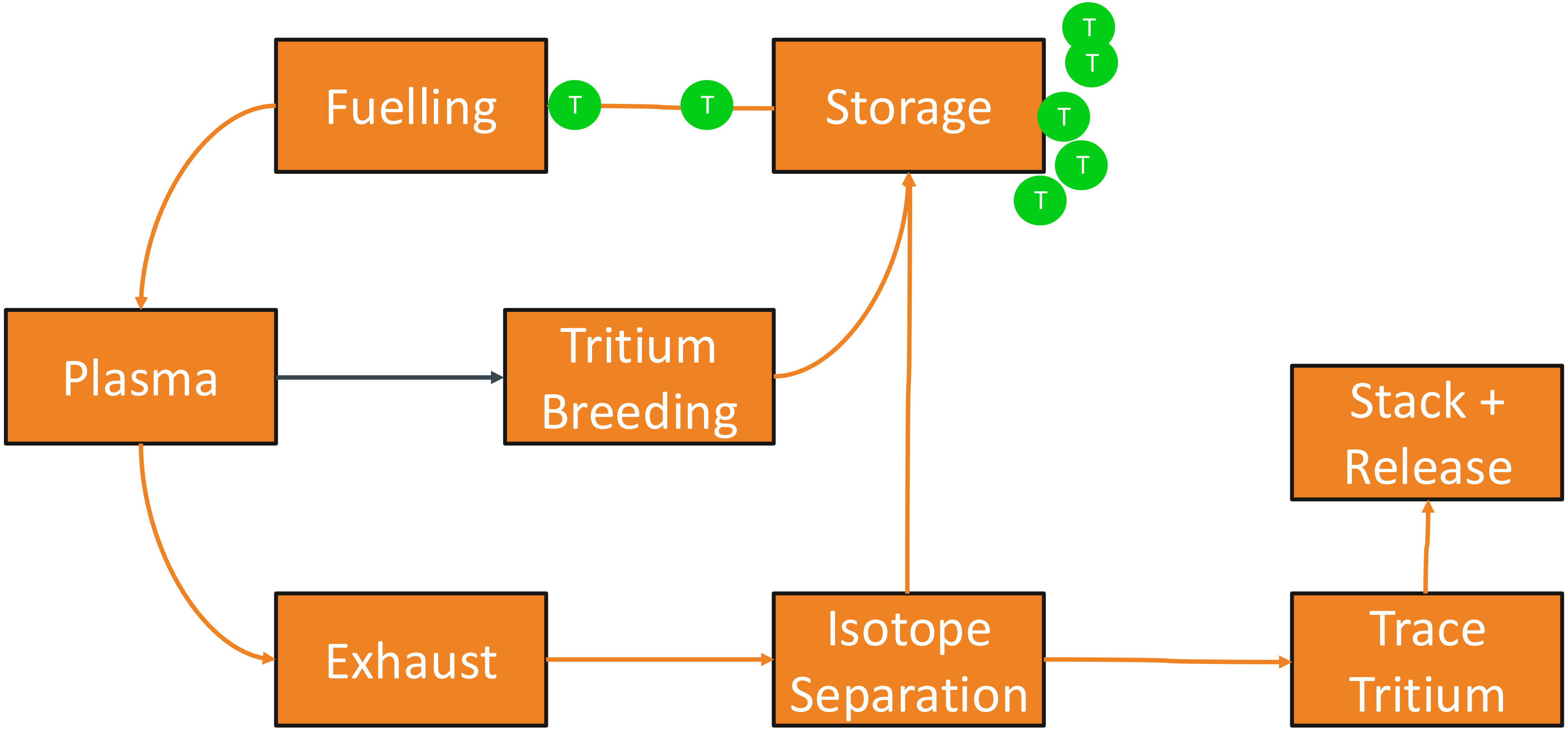


Startup Inventory



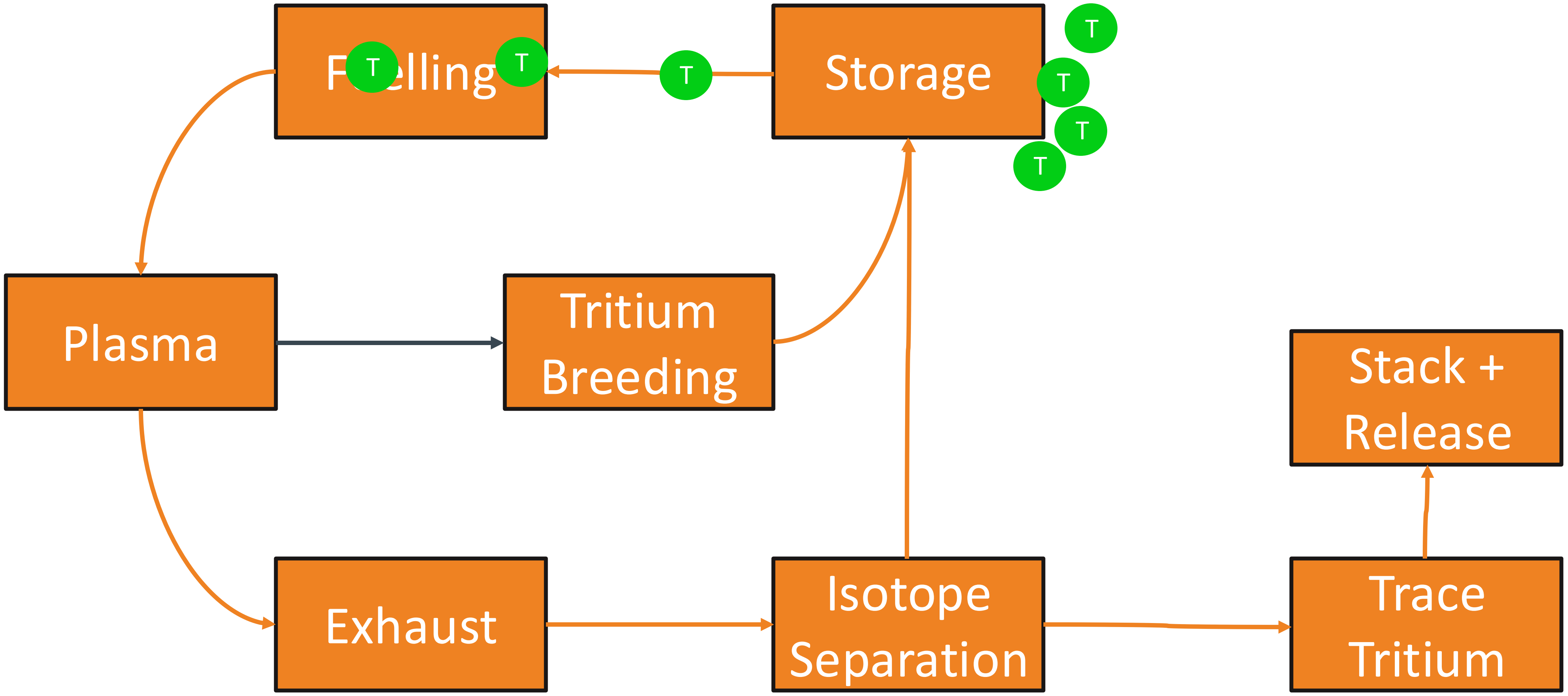
© 2025 Tokamak Energy Private and Confidential

Startup Inventory



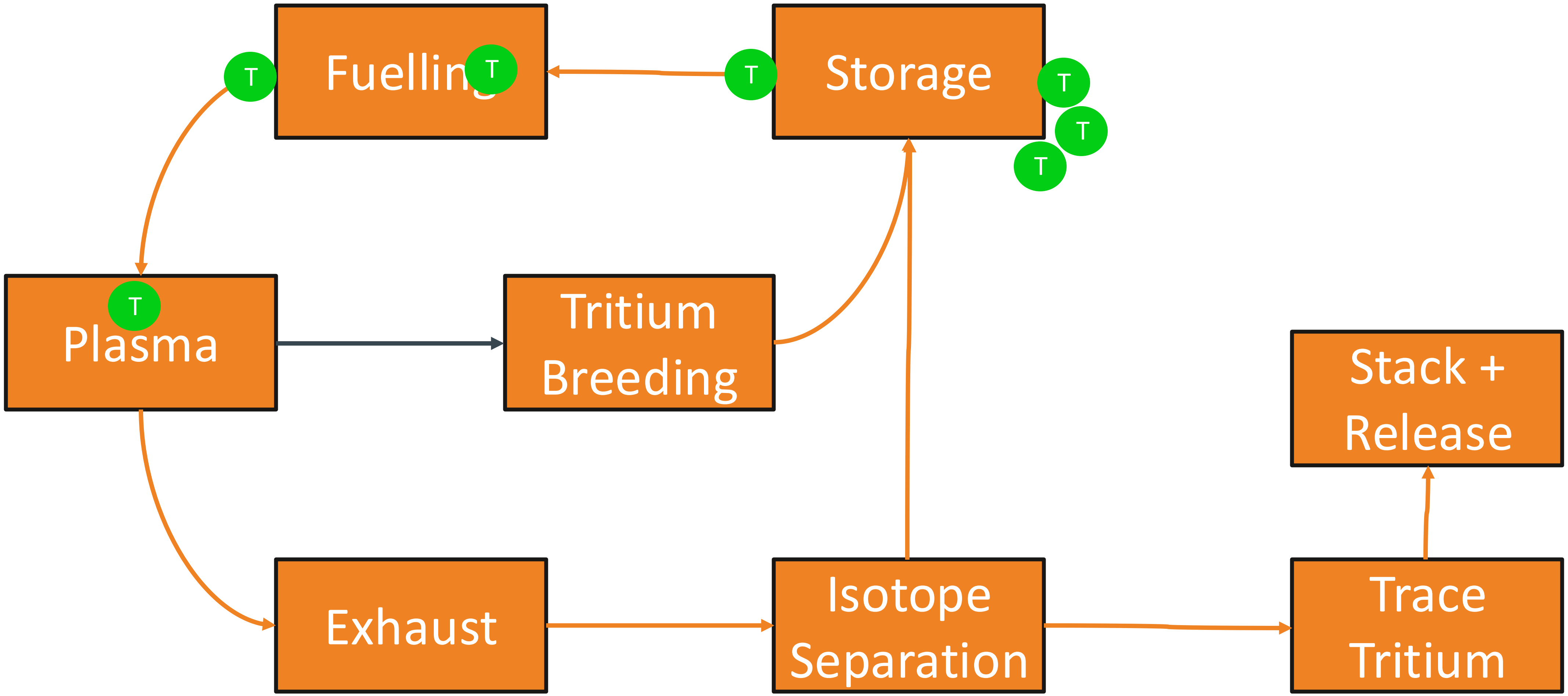
© 2025 Tokamak Energy Private and Confidential

Startup Inventory



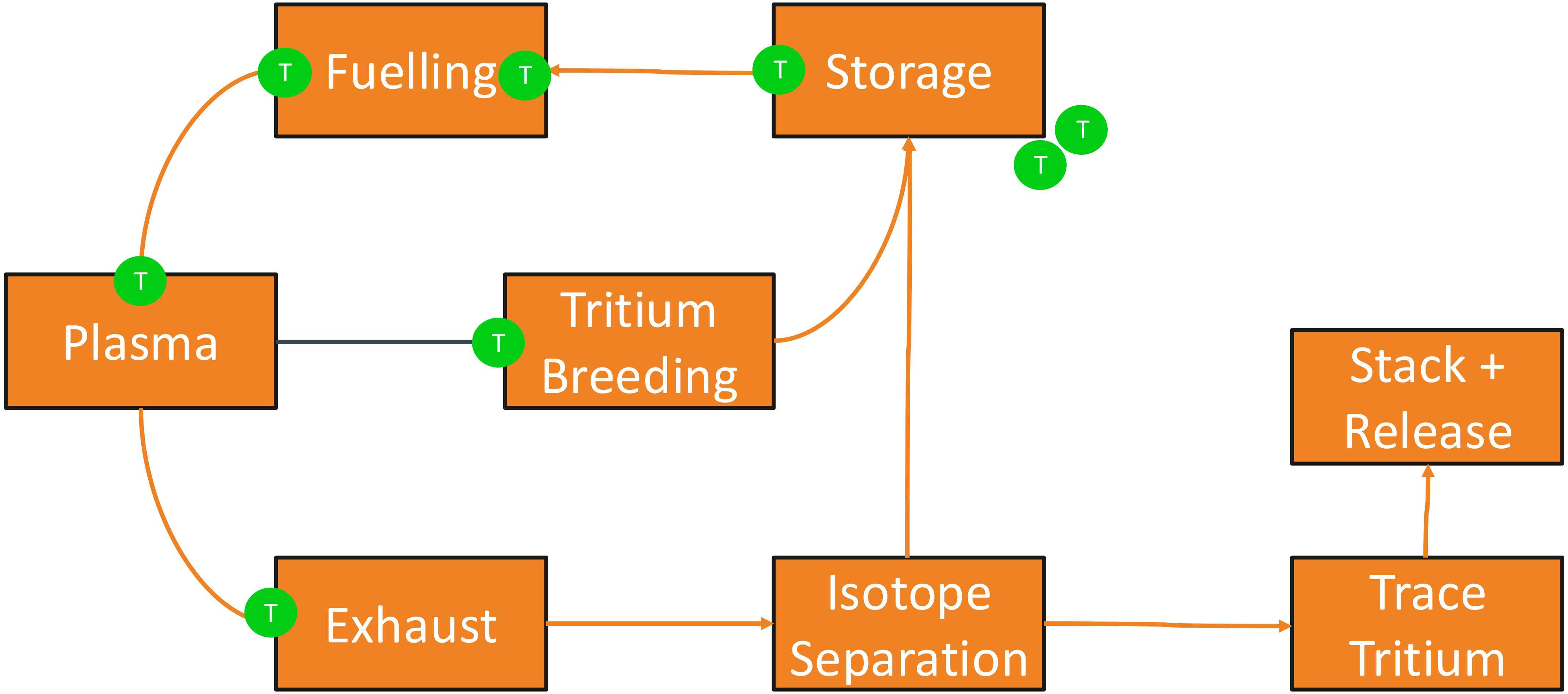
© 2025 Tokamak Energy Private and Confidential

Startup Inventory

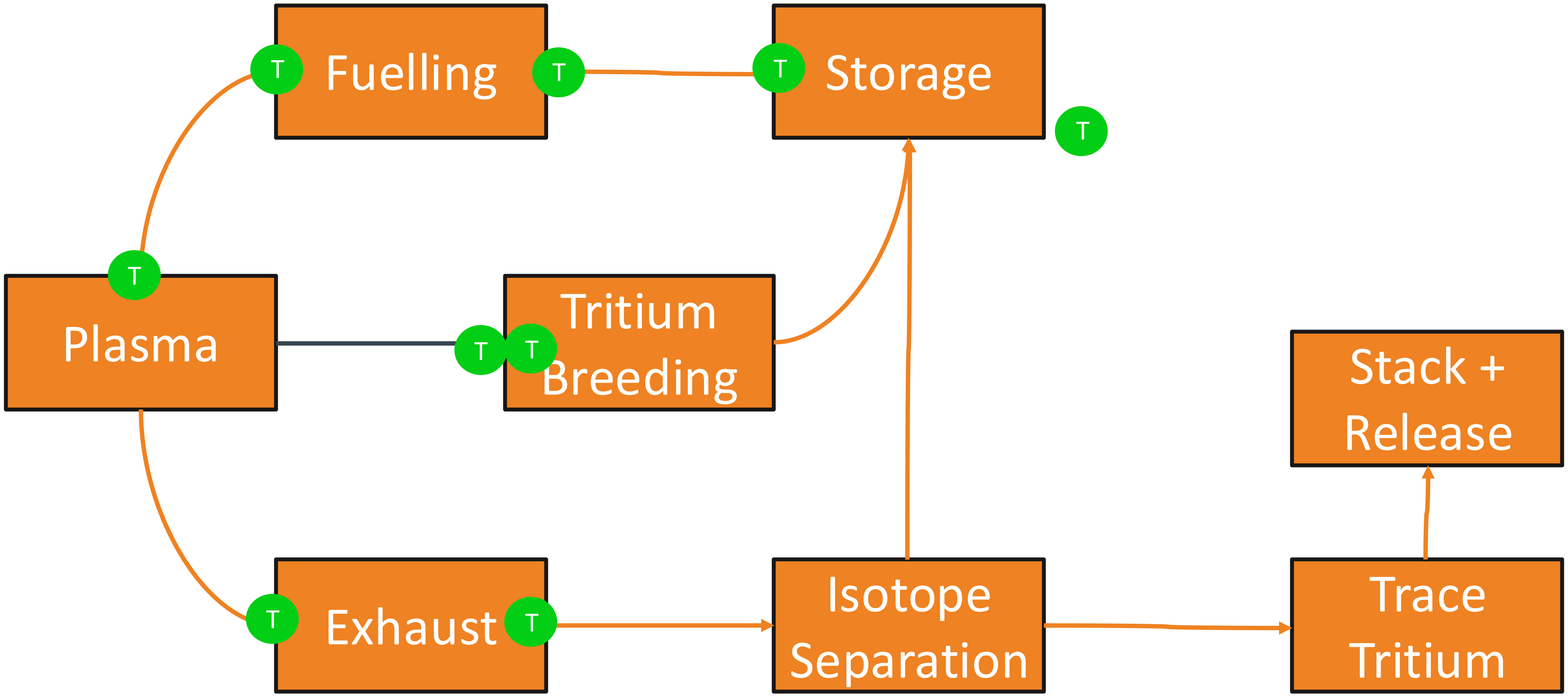


© 2025 Tokamak Energy Private and Confidential

Startup Inventory

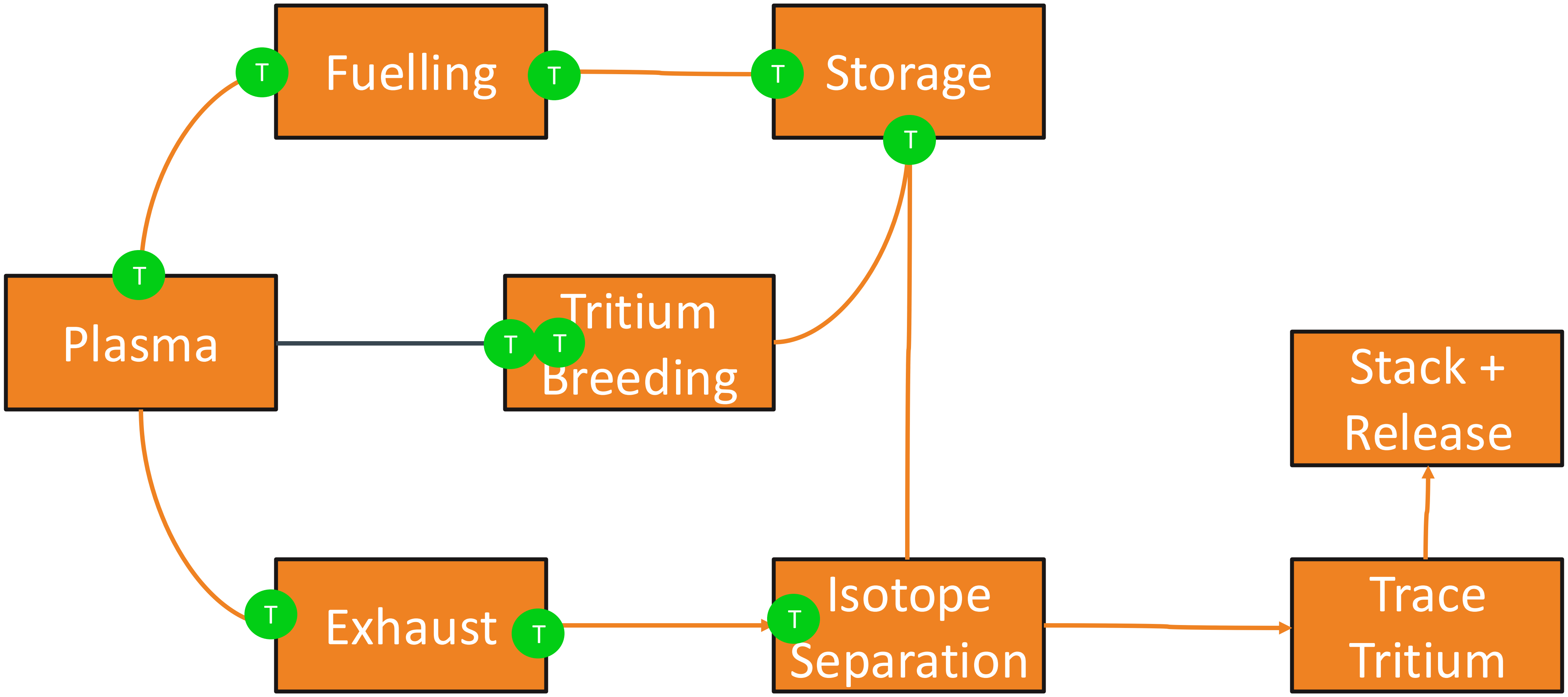


Startup Inventory

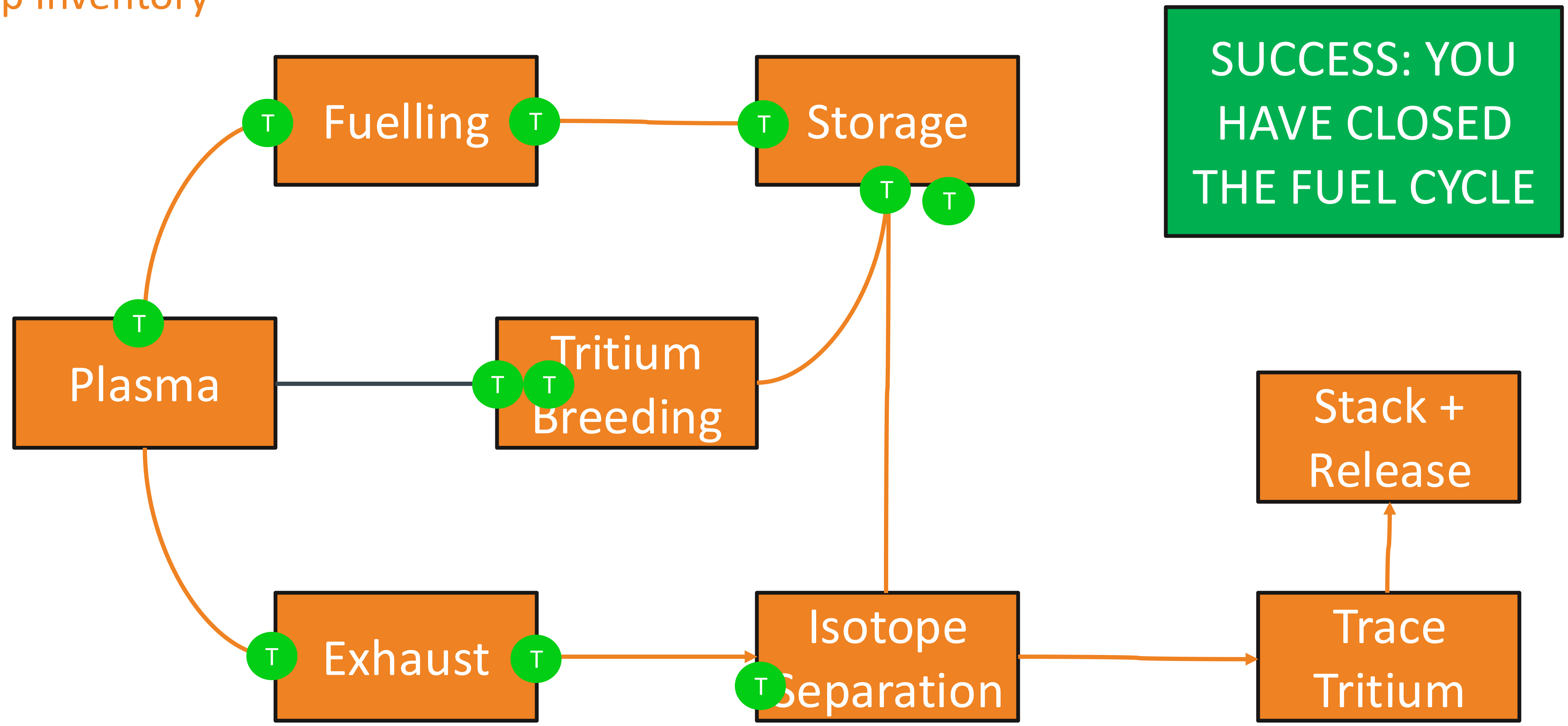


© 2025 Tokamak Energy Private and Confidential

Startup Inventory

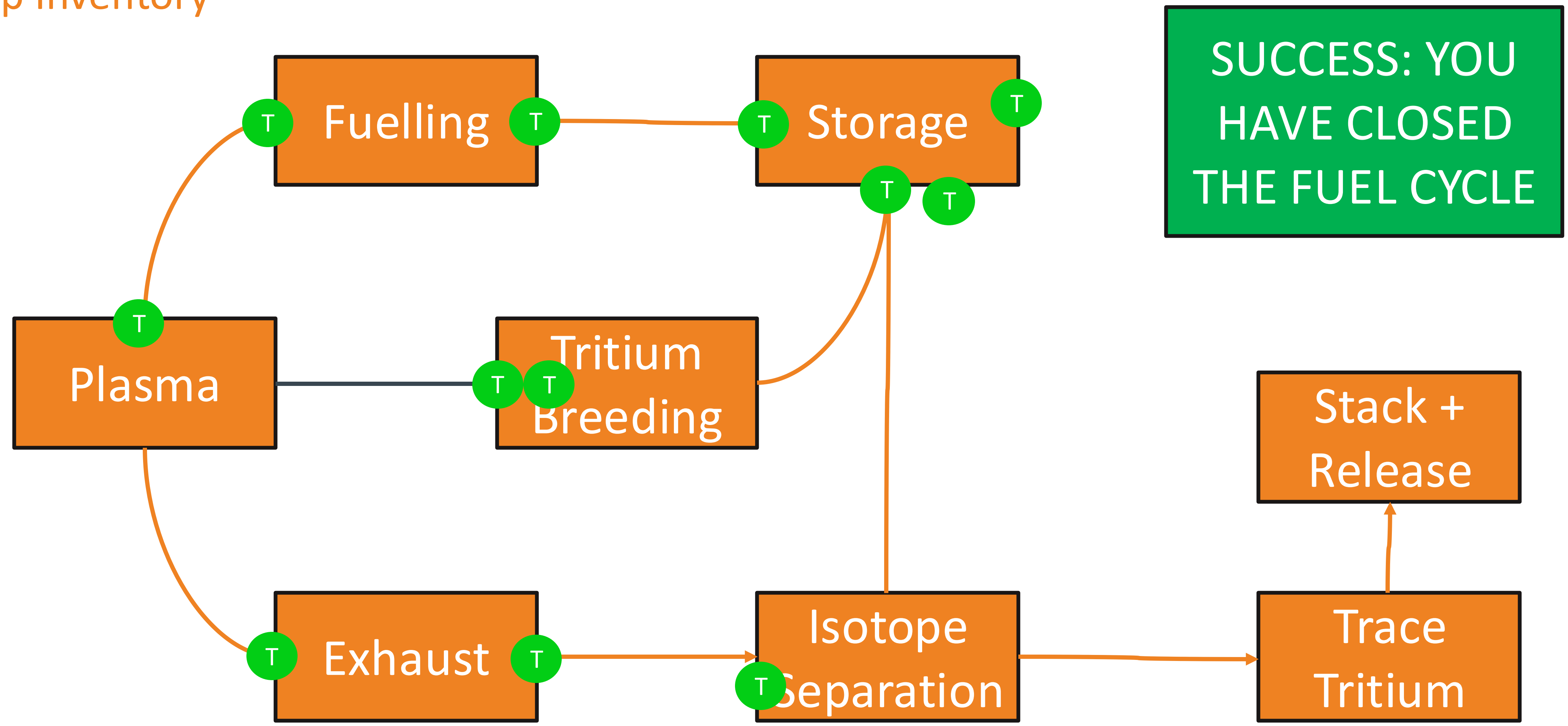


Startup Inventory



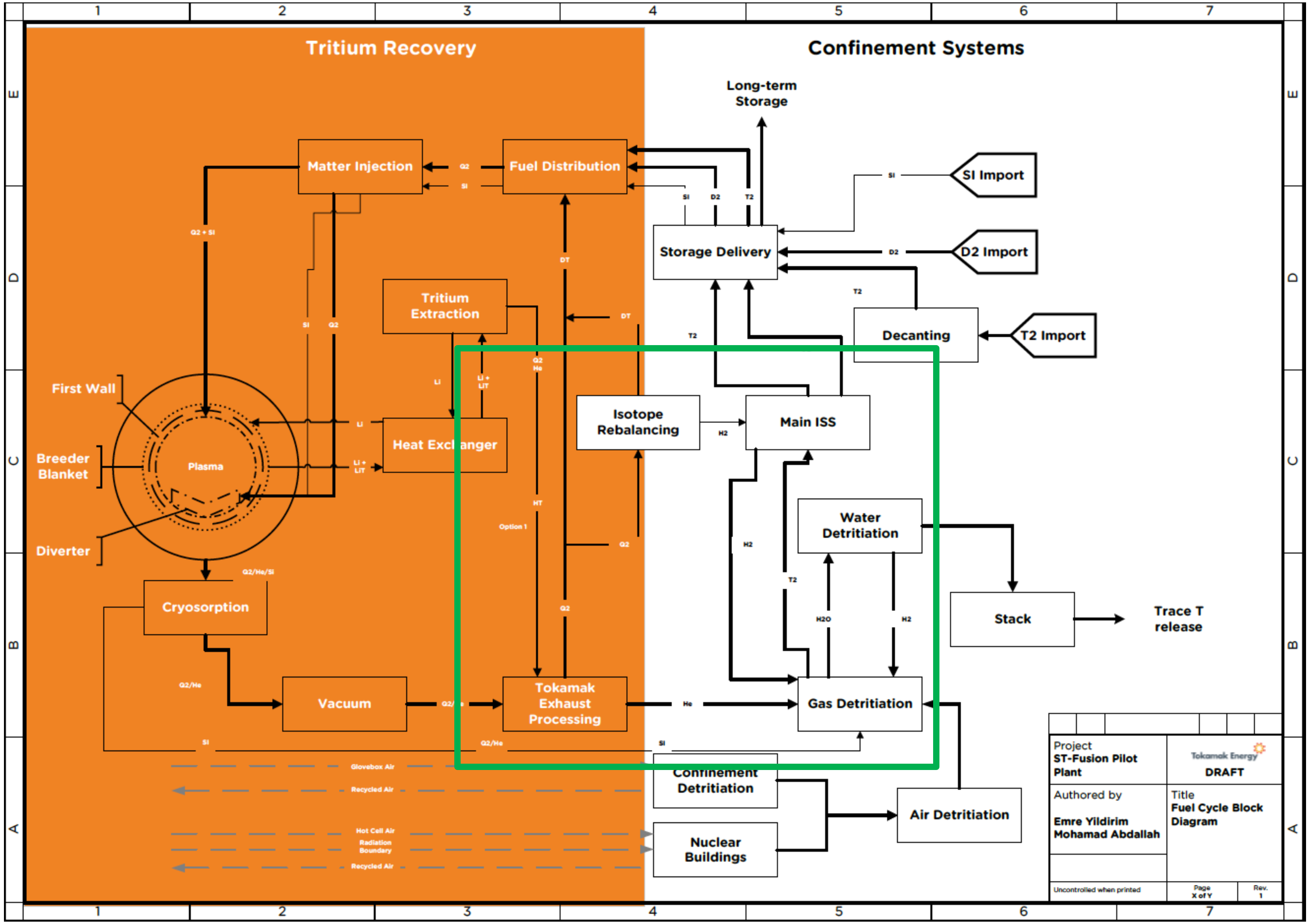
© 2025 Tokamak Energy Private and Confidential

Startup Inventory

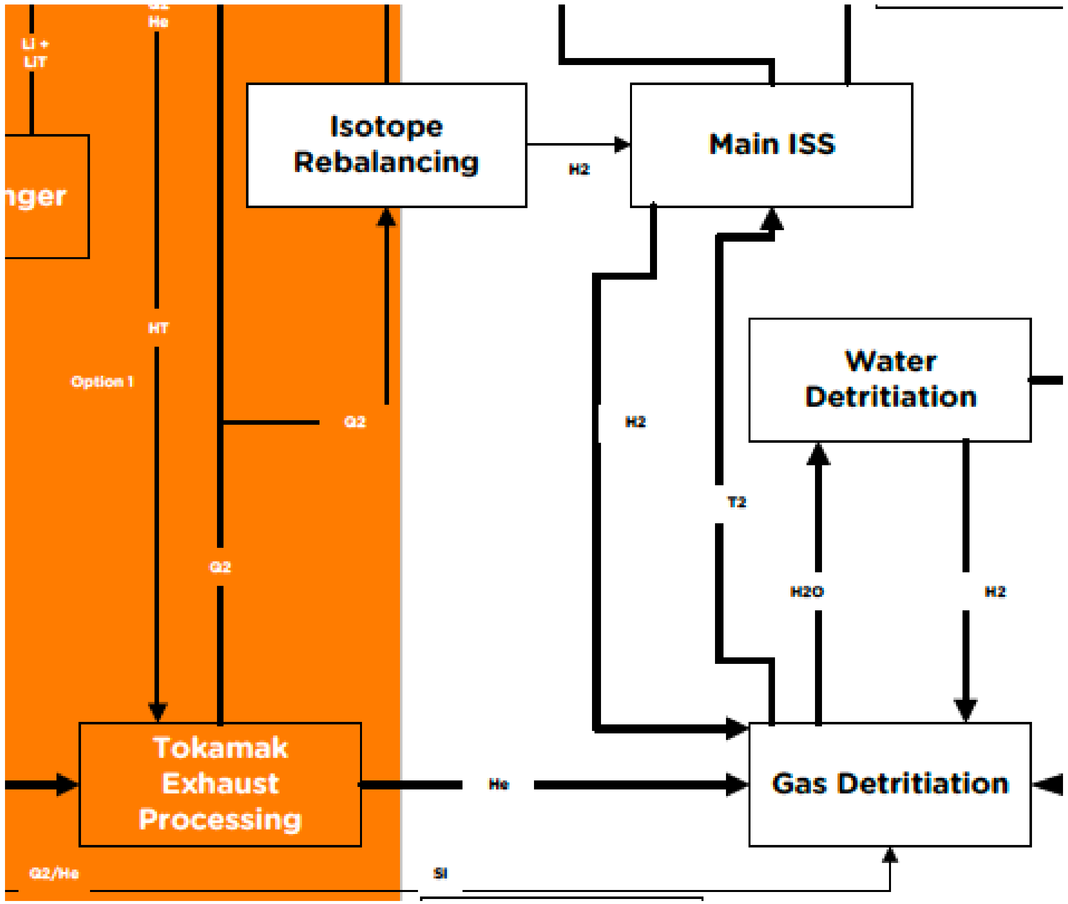


© 2025 Tokamak Energy Private and Confidential

Speeding up processing times - example

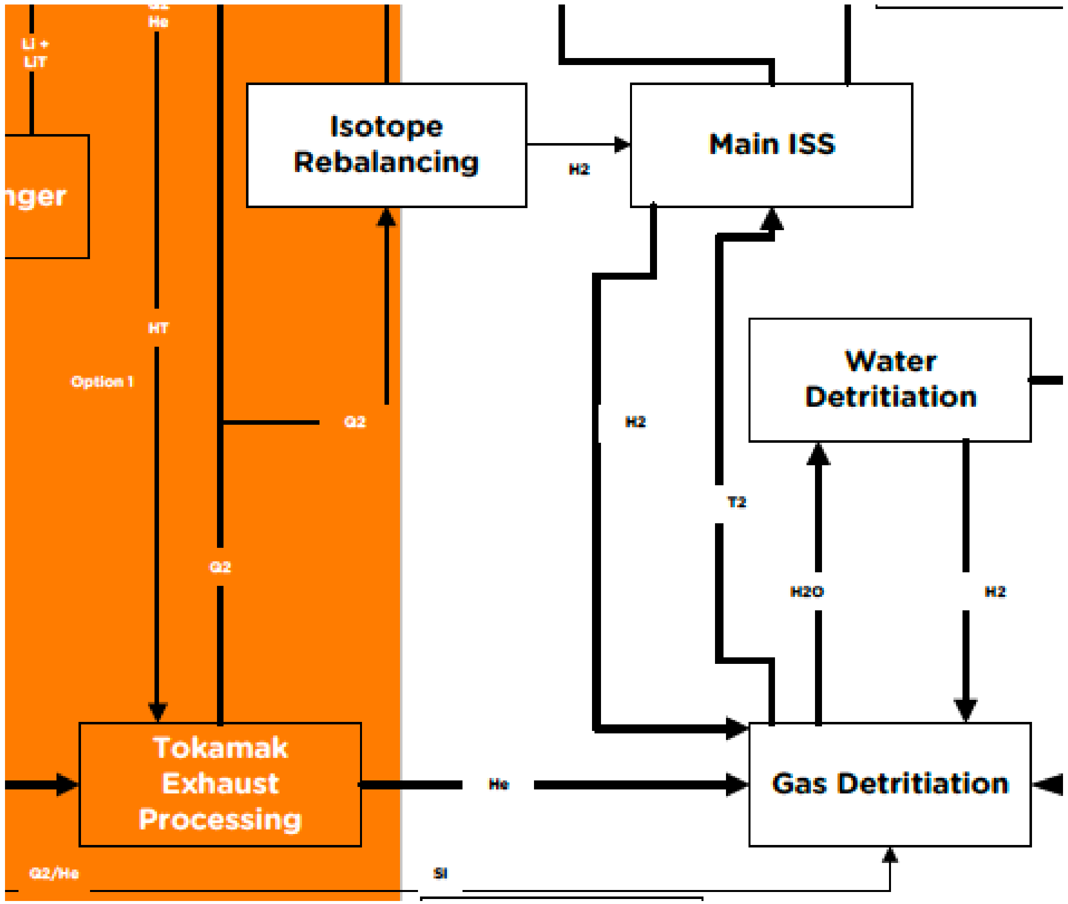


Speeding up processing times



- Instead of having a single isotope separation function have a fast-rebalancing loop and one for trace tritium recovery
- This is sometimes called *direct internal recycling*
    - Allow only hydrogen isotopes to permeate through the fast loop to directly inject them back into the plasma
    - Do minimal isotope balancing in this loop to maintain ~50:50 D:T
    - Protium build up is usually the limiting factor

Speeding up processing times



- Some of the technologies discussed earlier can be utilized here:
  - Palladium diffusers, metal foil pumps – remove hydrogen isotopes
  - Cryo distillation columns, or TCAP can be used to rebalance – the more of this you need to do the slower your processing time!

© 2025 Tokamak Energy

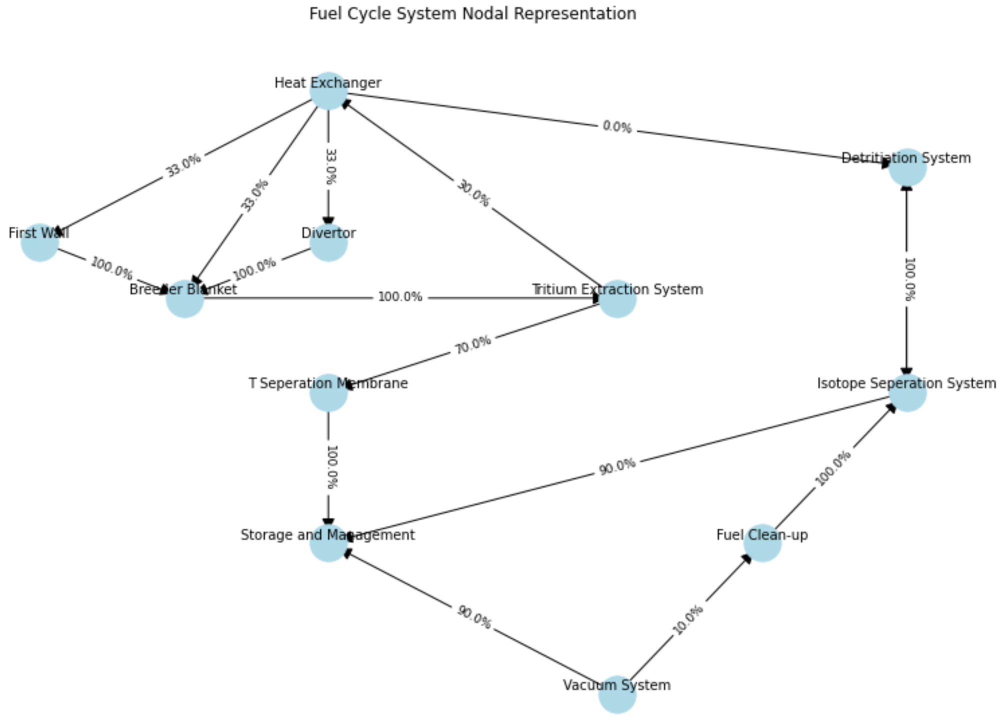
How we explore those

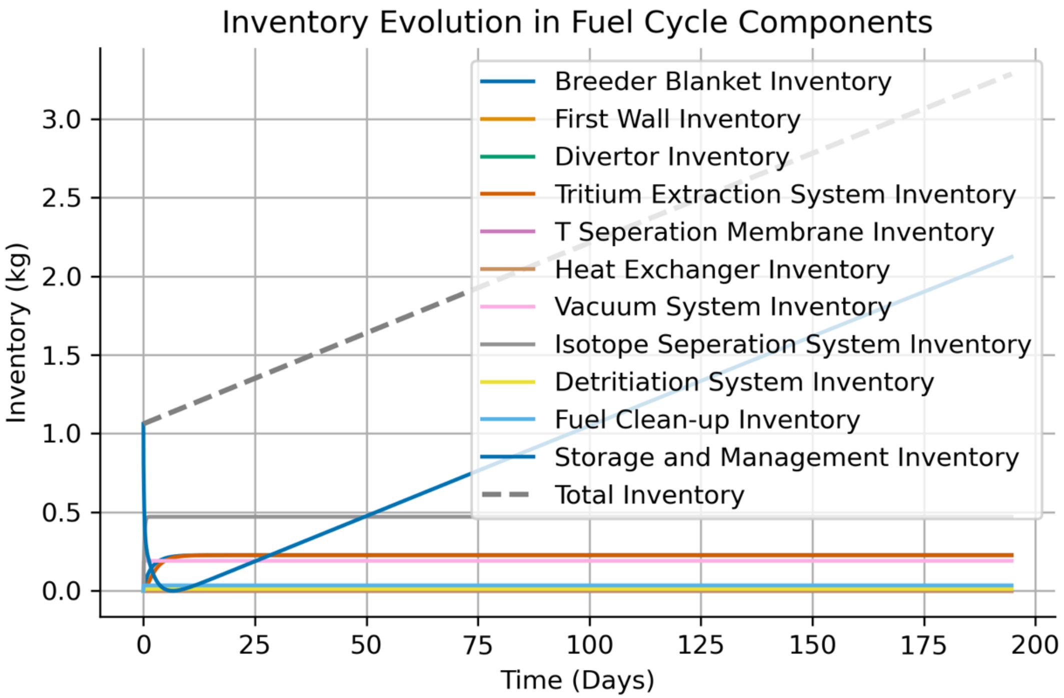
- We can explore these with *inventory models*
- These gives us an overview of the system to understand architecture, efficiency and processing time effects on key high level parameters
- They use the function $\frac{dI_i}{dt} = \sum_{j \neq i} \left(\frac{I_j}{\tau_j}\right)_i - (1 + \varepsilon_i)\frac{I_i}{\tau_i} - \lambda I_i + S_i$
  - I_i — Tritium inventory in component *i*
  - τ_i — Residence time in component *i*
  - ε_i — Non-radioactive loss fraction in component *i*
  - λ — Tritium decay constant
  - S_i — Source term (e.g., tritium produced in blanket)
  - $(I_j / \tau_j)_i$ — Flow of tritium from component *j* to component *i*

© 2025 Tokamak Energy

How we explore those

- We can use this model to explore parameters such as required startup inventory for different residence/processing times for different components or for higher level parameters like TBR requirements, or effect of fuelling efficiency
- We can see in this outputs based on an architecture similar to Meschini *et al. Modeling and analysis of the tritium fuel cycle for ARC- and STEP-class D-T fusion power plants.* Nuclear Fusion, Vol. 63, 126005 (2023).

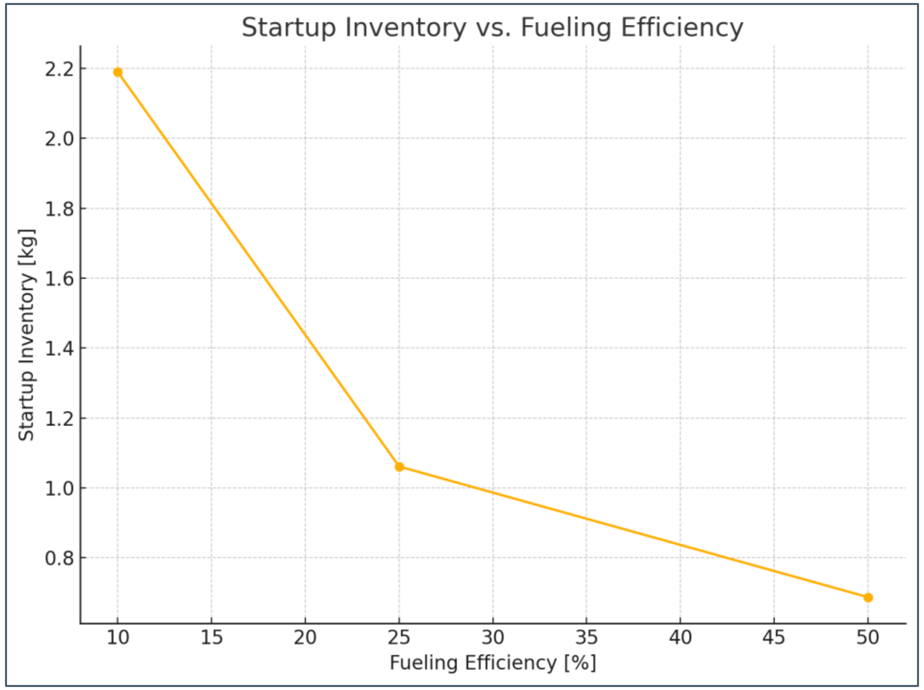


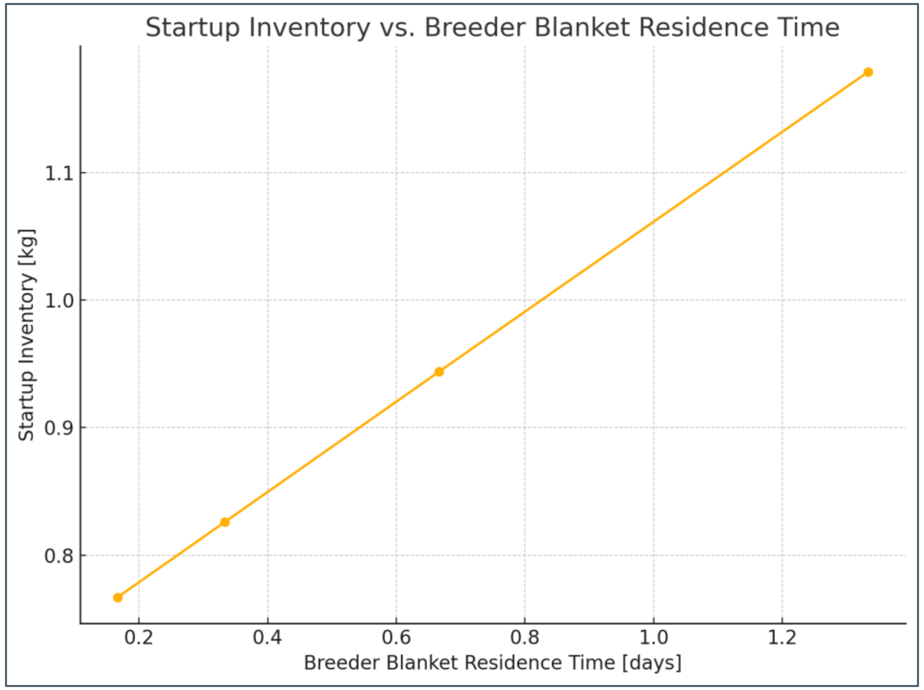


© 2025 Tokamak Energy

How we explore those

- We can use this model to explore parameters such as required startup inventory for different residence/processing times for different components or for higher level parameters like TBR requirements, or effect of fuelling efficiency
- We can see in this outputs based on an architecture similar to Meschini *et al. Modeling and analysis of the tritium fuel cycle for ARC- and STEP-class D-T fusion power plants.*
  Nuclear Fusion, Vol. 63, 126005 (2023).





© 2025 Tokamak Energy

Beyond inventory models

- Inventory models are just the start!
- Closer to realization -> process engineering
  - Models to understand the full flow in and out of all components
  - Greater detail to understand off normal events and scheduled and unscheduled downtime
- Models must better match real world values – building components to validate these models is the only way to do this
- We need to better understand unknowns, e.g.:
  - How much protium build-up will there be – directly affects how much we can recycle fast in DIR
  - In long pulse conditions – what will be retained in plasma-facing material

© 2025 Tokamak Energy

Tritium Accountancy Systems

- Tritium accountancy is key for two main reasons:
  - Operation – tritium accountancy allows us to understand where are fuel is, how efficiently our systems are working and that we are getting the fuel we need where we need it
  - Regulation – for licensing, safety and compliance as tritium is a controlled substance
- Current status:
  - Mass balance audits that are performed over days and are not real time
  - And usually requires modelling to correct for any decay
- Where we need to be
  - Real-time inventory tracking, with minimal uncertainty
  - Need localized accountancy and digital integration with plant monitoring and control

- **ONE SLIDE DOES NOT DO THE IMPORTANCE OF THIS JUSTICE!!**

© 2025 Tokamak Energy

Tokamak Energy

Who works on the fuel cycle?

© 2025 Tokamak Energy Private and Confidential

What disciplines make up the fuel cycle

- This is an area with a variety of backgrounds
- Chemical Engineers
  - Isotope separation (e.g., cryodistillation, TCAP), Purification systems, catalytic reactors, flow control
- Materials Scientists
  - Permeation barriers, hydrides, getter materials, Compatibility with liquid metals, irradiation effects
- Vacuum Engineers
  - Cryopumps, turbomolecular systems, conductance optimization, Divertor and exhaust system design
- Plasma Physicists
  - Burn fraction modeling, fuelling dynamics, Plasma-surface interaction and exhaust behavior

© 2025 Tokamak Energy

What disciplines make up the fuel cycle

- This is an area with a variety of backgrounds
- Control System Engineers,
  - Real-time tritium monitoring and automation
- Radiation Chemists
  - Polymer degradation, radiolysis, tritiated compound behavior, Organic contamination and mitigation strategies
- Health Physicists / Safety Specialists
  - Tritium containment and release modelling, Dose assessment, safety cases, environmental protection

© 2025 Tokamak Energy

Tokamak Energy

Finale!

Key Takeaways

- The fuel cycle looks to purify deuterium and tritium, and get rid of waste exhaust with minimal losses
- Tritium is scarce, so we must be constantly making more in the fusion device
- Hydrogen isotopes mainly behave similarly but the radioactive nature of tritium means it must be carefully controlled, and additional limits must be placed on it
- There are many technologies that make up fuel cycle system, and they use different properties of hydrogen isotopes to manipulate the compositions through different systems
- The challenges of tritium and the fuel cycle are plentiful but there is a variety of people working on it (hopefully including some of you!)

© 2025 Tokamak Energy Private and Confidential

THANK YOU AND ANY QUESTIONS?

CONTACT US:

EMRE YILDIRIM

emre.yildirim@tokamakenergy.com

www.tokamakenergy.com

This is what a 100 million ˚C fusion plasma looks like in ST40