THEA ENERGY

Outlining Tritium Fuel Cycle Design and Modeling for Thea Energy's Fusion Power Plant

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Abstract

Thea Energy, Inc. will build a quasi-axisymmetric planar coil stellarator, called "Helios", as its first fusion power plant (FPP). The fuel cycle will consist of lithium and hydrogen isotopes (including deuterium and tritium). Due to the pressing need to manage the safety and biological hazards of tritium, the pre-conceptual modelling quantifies tritium flow and inventory, ensuring that the system achieves tritium self-sufficiency and minimal inventories. TMAP8 tracks tritium flow rates through the fuel cycle components. Tritium behavior depends on component design, as well as plasma parameters such as the tritium burn rate and fraction, which are influenced by particle confinement time and fusion power. FPP parameters, such as tritium doubling time and plant availability (fuel-cycle operation time vs down-time), as well as potential fuel cycle technology improvements (such as direct internal recycling and faster tritium processing capability) also play a key role. Overall, the startup and reserve inventories and required tritium breeding ratio (TBR_{req}) values are viable for a Helios plant. For the baseline case, the inventories are <2 kg and TBR_{req} is 1.13. However, the inventories and TBR_{req} improve to <1 kg and 1.06 respectively assuming ambitious improvement goals, including high plant availability, high tritium burn efficiency, and a direct internal recycling loop. The feasibility cost-benefit analysis associated with each technology improvement will prove vital to complement further optimization and design advancements.

Introduction

The Helios fuel cycle will consist of:[1]

- Inner fuel cycle: processes unburned T fuel from the plasma collected by the vacuum pumps then refuels back to plasma
- Outer fuel cycle: processes fusion products that go to the blanket and divertor, particularly T bred in the blanket and diffused to flowing coolant

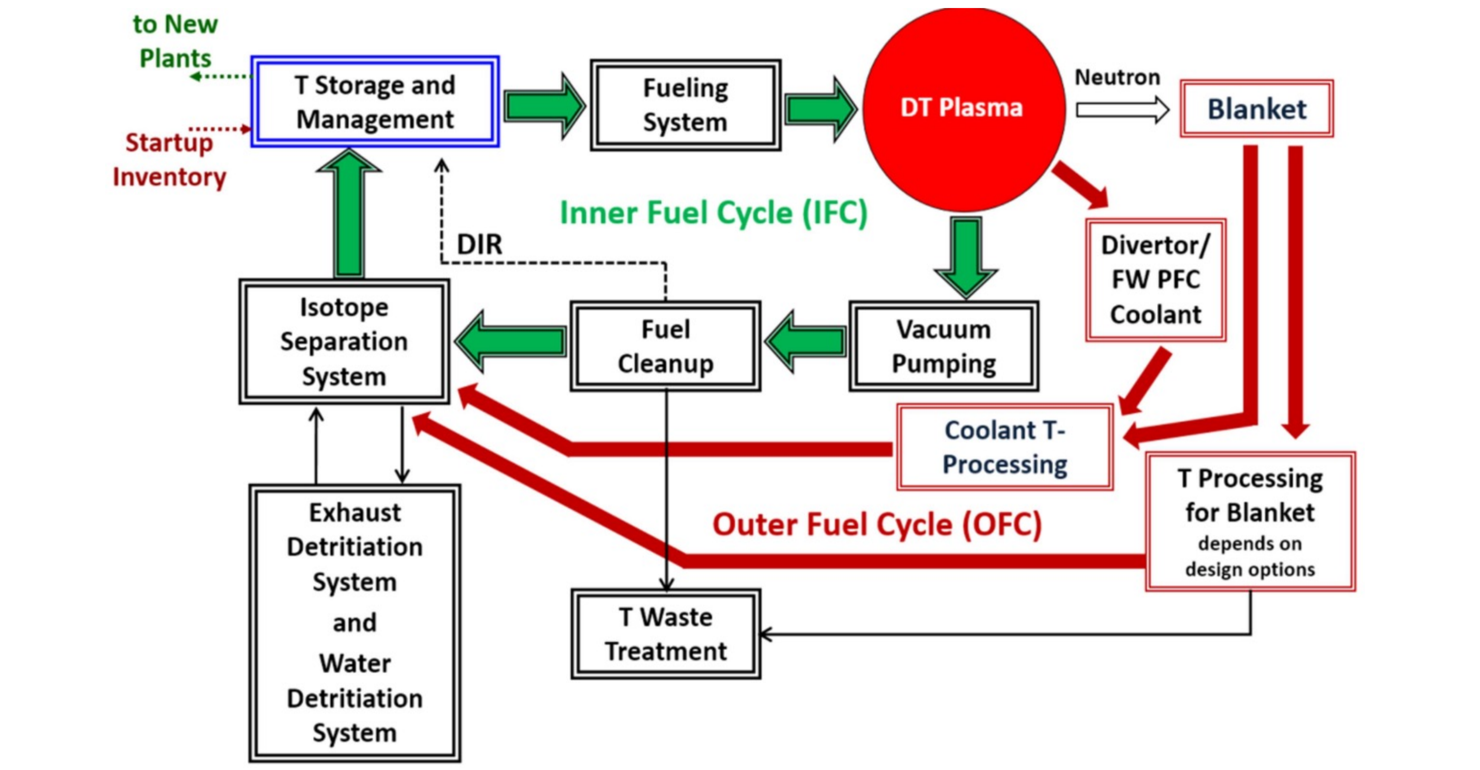


Figure 1: block diagram of ITER's fuel cycle components and T fuel flow between them.[1] Helios will have the same fuel cycle components and processing times, while allowing for a different blanket / divertor / first wall architecture

Methods

TMAP8 (Tritium migration analysis program from MOOSE code suite) implements a dynamic system model to calculate time-dependent T flow rates.[3] The model describes T balance and change in inventory over time for each component using the ordinary differential equation:

$$\frac{dI_i}{dt} = \sum_{j \neq i} \left(\frac{I_j}{\tau_j}\right)_i - (1+\varepsilon_i)\frac{I_i}{\tau_i} - \lambda I_i + S_i$$

Reserve inventory is calculated from T burn rate and TBF: $I_{res} = \dot{N}^- * t_{res} * q / (\eta_f * f_b)$.[1] For reference case, 25% of the system fails for a reserve time of 24 hours.

Table 1 – Equation Parameters and Values

Parameter	Symbol	Units	Reference Value	Parameter Type
Fusion power	P_f	MW	1270	Fixed
Tritium burn rate	$\dot{N}^-$	kg / s	2.255e-6	Fixed
Fueling efficiency	η_f	%	25	Fixed
Tritium burn fraction	f_b	%	11.6	Sweep: 2 – 22
Direct internal recycling fraction	DIR	%	0	Sweep: 0 – 90
Availability factor	AF	%	75	Sweep: 10 – 90
Doubling time	t_d	years	5	Sweep: 1 – 7
Tritium breeding ratio	TBR_{req}		1.15	Goal: smaller is better
Initial tritium inventory	I_0	kg	5	Goal: smaller is better
Reserve time	t_{res}	hours	24, q=0.25	Goal: smaller is better
Reserve inventory	I_{res}	kg	1.694	Goal: smaller is better

We use TMAP8 to:
- understand T flows in the system,
- observe which factors minimize inventory and TBR_{req},
- identify key technological improvements.

From the reference configuration, we sweep through individual parameters to understand the sensitivity of TBR_{req} and I_0.

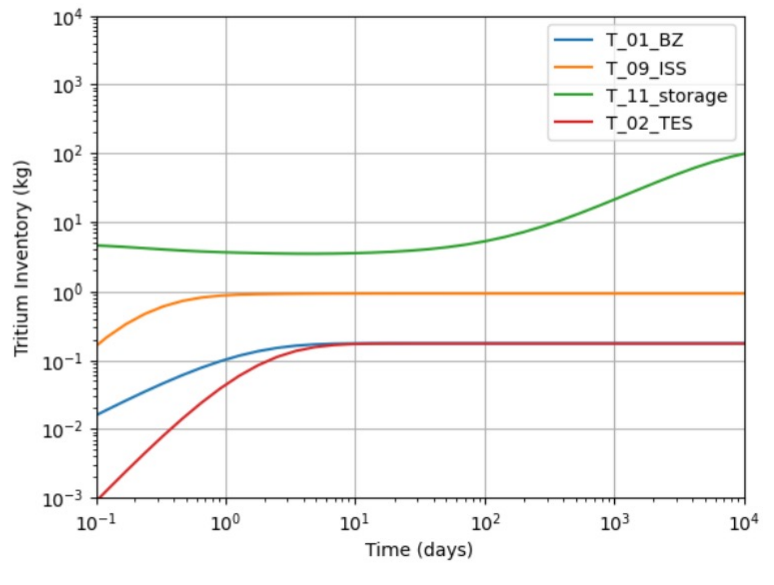


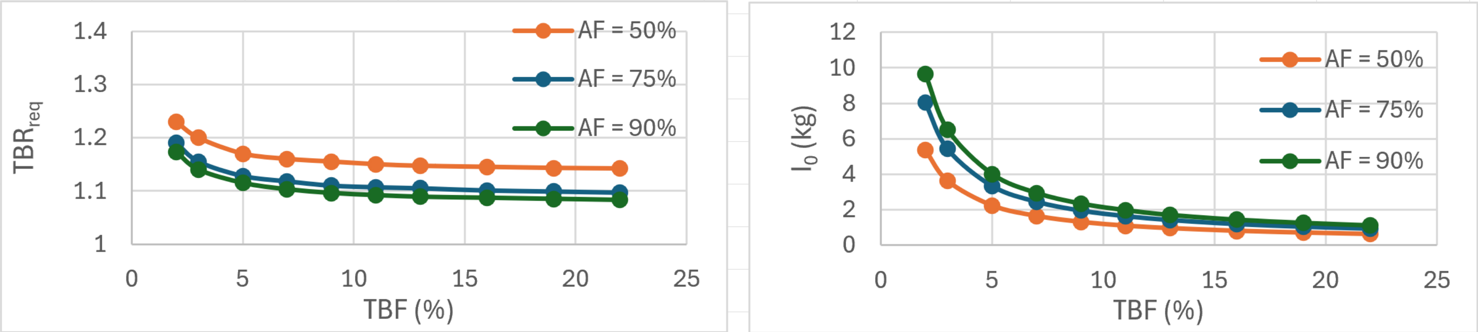
Figure 2: log plot showing the time evolution of tritium inventories in various components of the reference Helios fuel cycle

- Storage inventory goes down as T is pulled into the cycle
- As T is bred from the blanket, storage inventory rises and other component inventories stabilize
- The longest T residence times are in the breeding zone and T extraction system (1 day in each)[1]

Results

Increasing tritium burn fraction decreases required TBR and initial inventory:

The tritium burn fraction calculation is defined by uncertainty in the particle confinement time, for which estimates ranged from 1 – 17 s.



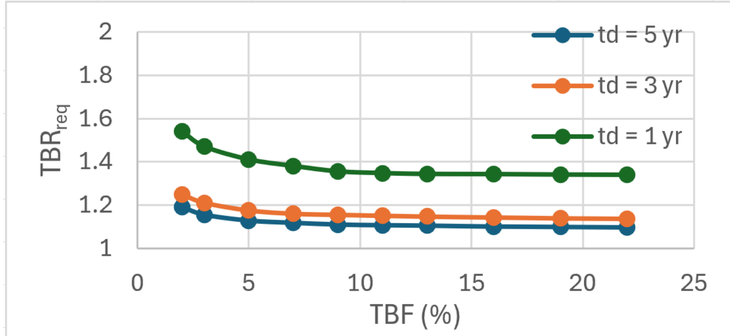


Figure 3: plots showing how I_0 and TBR_{req} change with tritium burn fraction, at different values of AF and t_d

- TBF ~2%: a particle confinement time of ~1 second, ~ first-gen FPP
- TBF < 2%: T self-sufficiency is not for reasonable TBR or I_0
- TBF > 2% and t_d increases: TBR_{req} and I_0 values relax

Direct internal recycling makes the system more performant:

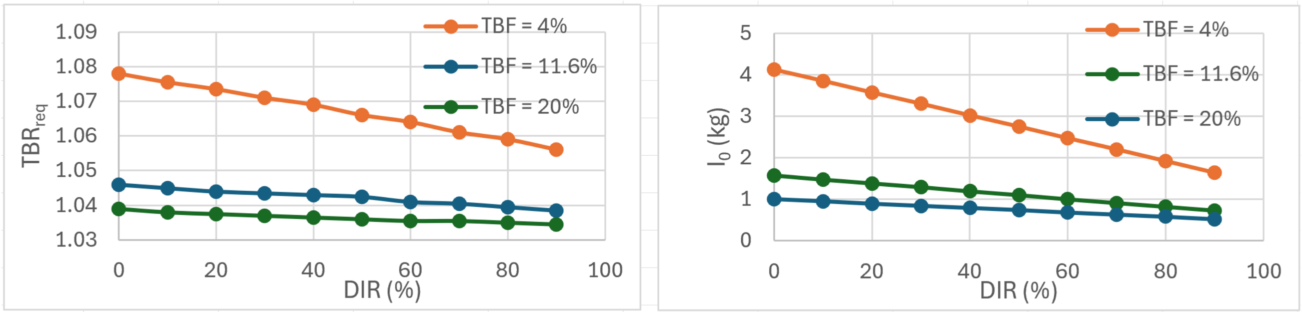


Figure 4: plot showing how I_0 and TBR_{req} change with direct internal recycling fraction and tritium burn fraction

- Including a DIR line from FCU to storage and increasing the DIR fraction of fuel which skips the ISS and EDS / WDS stages helps to reduce TBR_{req} and I_0[1,2]
- However, DIR also leads to a more complex IFC design

Shorter doubling time imposes stringent constraints on the system:

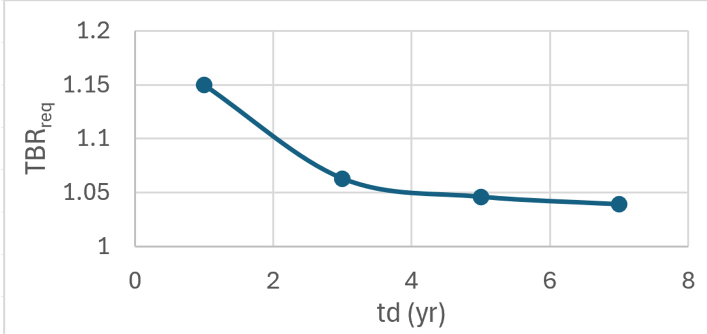


Figure 5: plot showing how TBR_{req} changes with doubling time

- Increasing doubling time relaxes how fast T needs to be bred in the blanket, so the TBR_{req} comes down
- As FPPs ramp up energy production, reducing doubling time to meet rising demand becomes key

Reserve inventory becomes smaller as TBF increases:

- A larger reserve amount allows longer reserve times and larger failures, but requires a larger inventory of tritium to be kept on site

Low availability factor decreases required inventory but increases required TBR:

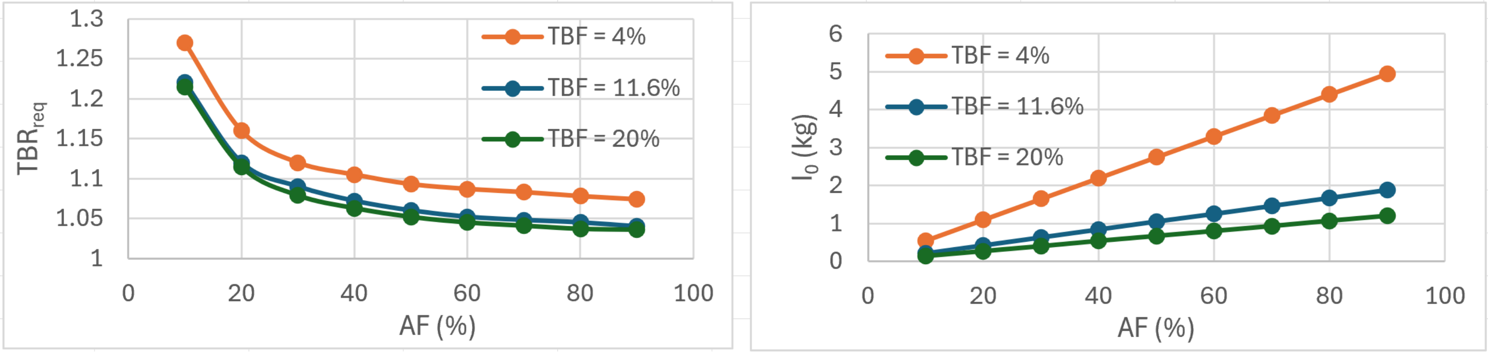


Figure 6: plot showing how I_0 and TBR_{req} change with availability factor and tritium burn fraction

- Increasing AF gets closer to steady-state operation, so increases I_0 as fuel cycle will be operating for more time, and needing larger inventory supply
- Decreasing AF while holding t_d increases TBR_{req}, particularly dramatically when AF < 50%; more tritons must be produced for every neutron because the breeding window is shorter

Conclusion

Overall, the I_0 and TBR_{req} values are reasonably achievable for the Helios FPP likely operating cases shown in the table below. Additionally, from single parameter sweeps, the I_0 values range from 0.2 – 16 kg, reserve inventories from 0.9 – 15 kg, and TBR_{req} from 1.03 – 1.23. Since the upper values of the ranges are more challenging, we rely on technology improvement to make T self-sufficiency achievable, to improve AF, TBF, fueling efficiency, and implement the DIR loop.

Table 2 – Fuel cycle parameters for likely operating cases

Parameters	Conservative Case	Baseline	Fuel Cycle Advances	Plasma Ops Advances	Both FC + PO Advances
AF (%)	50	75	90	75	90
TBF (%)	2	11.6	11.6	22.3	22.3
f_{DIR} (kg)	0	0	70	0	70
t_d (yr)	5	0.5	0.4	0.4	0.4
TBR_{req}	1.145	1.13	1.1	1.1	1.06
I_0 (kg)	5.36	1.57	1.12	1.0	0.75
I_{res} (kg)	14.99	1.68	1.68	0.874	0.874

Future development of the FC cycle model includes high fidelity component modelling and optimization, whole device modelling, and technology selection.

References

1. M. Abdou et al., "Physics and technology considerations for the deuterium–tritium fuel cycle and conditions for tritium fuel self sufficiency," *Nucl. Fusion*, vol. 61, p. 013001, (Nov. 2020).
2. S. Meschini et al., "Modeling and analysis of the tritium fuel cycle for ARC- and STEP-class D-T fusion power plants," Nucl. Fusion, vol. 63, p. 126005, (Sep. 2023).
3. P. A. Simon et al., "MOOSE-based Tritium Migration Analysis Program, Version 8 (TMAP8) for Advanced Open-Source Tritium Transport and Fuel Cycle Modeling," *Fusion Eng. and Design*, vol. 214, p. 114874, (May 2025).

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