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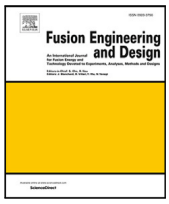
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Modeling fuel cycle dynamics beyond 50:50 deuterium–tritium operation

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ABSTRACT

Fusion Power Plant operation requires tight coupling between plasma and fuel cycle: the plasma sets exhaust flows and injection requirements, while the fuel cycle determines the availability of the fuel necessary to sustain operation. Dynamic fuel cycle models have largely been adopted to address startup inventory, tritium self-sufficiency, and safety, often under the assumption of 50:50 DT operation. For operation with a generic mixture, these assumptions no longer suffice because multiple atomic species evolve simultaneously and can drive transients both in the plasma and fuel cycle inventories. A lumped parameters, dynamic model is presented, coupling 0D multispecies plasma particle balances to a Residence Time method fuel cycle representation. The coupled state evolves deuterium, tritium, helium-3 and helium-4 in the plasma and in inner fuel cycle, outer fuel cycle and storage inventories, with interconnecting flows characterized by finite residence times. The model is then applied across different scenarios: 50:50 DT, tritium-lean and D^3He operation quantifying the resulting plasma composition evolution and fuel cycle inventory transients.

1. Introduction

Fusion Power Plants (FPPs) operation requires a careful balance between plasma physics requirements and engineering constraints. While the plasma sets the required fueling and exhaust conditions to sustain density and fusion power, enforcing the overall fuel mixture in the core, the fuel cycle determines the achievable throughput, recirculation delays, and inventories through pumping, processing, isotope separation, and storage. When operating with a standard deuterium–tritium (DT) mixture, tritium must be recovered and accounted for with tight inventory limits, driven by both economics and safety. Dynamic fuel cycle models have been extensively used to estimate startup inventory, required tritium breeding ratio, doubling time (t_d) and inventory limits in deuterium–tritium FPP. In particular, system level models based on residence time methods, such as those developed by Abdou et al. [1] and Coleman et al. [2] for EU-DEMO, by Meschini et al. [3] for the analysis of the ARC and STEP FPPs, and by Chen et al. for CFETR [4] describe a connected network of fuel cycle subsystems, each defined using lumped parameters and driven by prescribed tritium injection rate and burn fraction. In these studies, the plasma is typically treated as an interface to the fuel cycle, providing a constant or pulsed value of tritium injection and exhaust rates. Consequently, the plasma composition is assumed to be fixed during the lifetime of the FPP, helium species are not considered as dynamic inventories and fusion reactions beyond DT are not explicitly modeled, limiting operating scenarios to standard 50:50 DT fusion. A notable exception is the recent work by Hattab et al. [5] who developed a code in Julia that considers multiple species in the plasma to account for impurity accumulation when implementing a bypass or a direct internal recycling into the fuel cycle. Nonetheless, their analysis focuses on perturbations around a 50:50 DT mixture. Other models instead focus on the dynamic evolution of deuterium and tritium fractions in the plasma, to model a deuterium–deuterium (DD) startup scenario [6,7], but they either neglect deuterium–helium-3 (D^3He) reactions or avoid multispecies particle balance in favor of coupling via burnup fractions.

This study introduces a 0D plasma particle balance model coupled with a lumped parameter model of the fuel cycle, implemented in Python and open source, available at [8]. The model is based on the use of residence times [9] for each fuel cycle subsystem and particle confinement times in the plasma, simultaneously evolving deuterium, tritium, helium-3 and helium-4 inventories throughout both the plasma and the fuel cycle. While fuel cycle analyses have historically focused primarily on the evolution of tritium inventories, plasma modeling requires information on all the other species as well, in order to compute fusion power and burn rates consistently with the given mixture. Furthermore, considering the various species inside the plasma becomes essential to estimate imbalances at the exhaust that could be incompatible with direct internal recycling operation [10].

This approach also enables the study of regimes beyond nominal 50:50 DT operation (Section 3.1), including tritium-lean operation (Sections 3.2 and 3.3), which can reduce circulating tritium inventories

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in the fuel cycle, and operation with advanced fuels such as D^3He (Section 3.4) and tritium-assisted D^3He (Section 3.5). These peculiarities of the model are relevant given that tritium availability is expected to be a constraint for future FPPs [11,12], and because not all reactor concepts consider DT operation [13]. Moreover, even in scenarios considering D^3He, tritium can still be produced by side reactions and require careful handling in the fuel cycle. Some of these scenarios require a careful discussion on their feasibility, due to the necessary simplifications of the model and of the assumed plasma operating point. It has to be stressed that the aim of this study is therefore not to demonstrate the physical feasibility of the analyzed scenarios, but rather to describe the coupling of plasma and fuel cycle when a mixture different from 50:50 DT is considered and to describe the potential applications of the model.

2. Methods

2.1. Physical description of the system

The nuclear fusion reactions for light nuclei [14] considered in this work are:

(A) $D + D \longrightarrow T(1.01\,MeV) + p(3.02\,MeV)$
(hereafter denoted as DDp).
(B) $D + D \longrightarrow {}^3He(0.82\,MeV) + n(2.45\,MeV)$)
(hereafter denoted as DDn).
(C) $D + T \longrightarrow {}^4He(3.5\,MeV) + n(14.1\,MeV)$
(hereafter denoted as DT).
(D) $D + {}^3He \longrightarrow {}^4He(3.6\,MeV) + p(14.7\,MeV)$
(hereafter denoted as D^3He).
(E) $T + T \longrightarrow {}^4He + 2\,n + 11.3\,MeV$
(hereafter denoted as TT).
(F) $T + {}^3He \longrightarrow {}^4He + p + n + 12.1\,MeV$
(hereafter denoted as T^3He ch1).
(G) $T + {}^3He \longrightarrow {}^4He(4.8\,MeV) + D(9.5\,MeV)$
(hereafter denoted as T^3He ch2).
(H) ${}^3He + {}^3He \longrightarrow {}^4He + 2\,p + 12.86\,MeV$
(hereafter denoted as ${}^3He^3He$).

The neutrons generated by reactions (B), (C), (E) and (F) can then be used to breed tritium inside a breeding blanket, whenever present in the FPP design.[1] Losses due to particle confinement are accounted for, using an effective particle confinement time for each atomic species X, $\tau_{p,X}$.

For simplicity, the current implementation of the model considers only the presence of atomic deuterium, tritium, helium-3 and helium-4, but could easily be extended to include additional species. These species are assumed fully ionized in the plasma and neutral in the fuel cycle. Within the fuel cycle, molecular formation (e.g. T_2, D_2, H_2, ...) as well as the isotopic separation are not modeled. Instead ideal isotope separation is assumed, so that each atomic species is treated as an independent stream throughout the fuel cycle. Non radioactive losses are also neglected. In principle the code could be extended to include impurities, but this would require a more careful consideration of radiation losses in the plasma.

The volumetric reaction rate of a generic reaction r (any of Eqs. (A)–(H)), between two species a and b, is:

$$R_r = \frac{n_{a_r} n_{b_r}}{1 + \delta_{a_r,b_r}} \langle \sigma v \rangle_r \qquad [m^{-3}\,s^{-1}] \tag{1}$$

where n_{X_r} is the ion number density of species X involved in relation r, δ_{a_r,b_r} is the Kronecker delta (equal to 1 if $a_r = b_r$ and 0 otherwise),

[1] D^3He FPP usually do not foresee the use of a breeder, as their aim is to decrease the amount of tritium and neutron production, in order to reduce activation and the overall amount of radioactive material in the system.

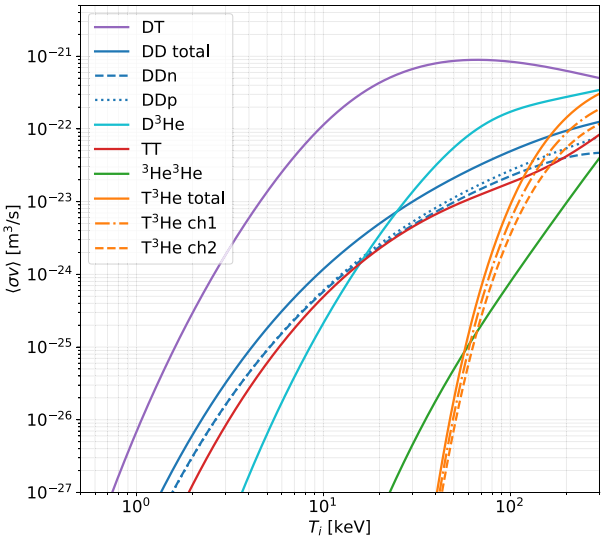


Fig. 1. Nuclear fusion reactivities for the reactions (A)–(H), obtained with analytical formulas [15,17] and used throughout the study.

and $\langle \sigma v \rangle_r$ is the Maxwellian-averaged fusion reactivity evaluated at the ion temperature T_i (assumed equal for all ions). Reactivities associated with reactions (A)–(D) have been calculated using the correlations defined by Bosch and Hale [15] as implemented in the `cfspopcon` Python package [16], while reactions (E)–(H) use the scaling defined by Caughlan and Fowler [17]. Fig. 1 reports the values of the reactivities used throughout this study in the range 10–100 keV.

The set of equations describing the evolution of the inventories and the density in the plasma of a specific species X is then described by Eqs. (2a)–(2d), which are an extended version of the "basic fuel cycle model" described in [3], section 2.2.3 therein.

$$\begin{cases} \dfrac{dI_{OFC,X}}{dt} = +V_{plasma} \displaystyle\sum_r TBR_r \eta_{n_r} R_r - \dfrac{I_{OFC,X}}{\tau_{OFC,X}} - \lambda_X I_{OFC,X} & (2a) \\ \dfrac{dI_{IFC,X}}{dt} = \dfrac{I_{OFC,X}}{\tau_{OFC,X}} - \dfrac{I_{IFC,X}}{\tau_{IFC,X}} + \dfrac{n_X}{\tau_{p,X}} V_{plasma} - \lambda_X I_{IFC,X} & (2b) \\ \dfrac{dI_{STOR,X}}{dt} = \dfrac{I_{IFC,X}}{\tau_{IFC,X}} - \dot{N}_{inj,X} - \lambda_X I_{STOR,X} & (2c) \\ \dfrac{dn_X}{dt} = \dfrac{\dot{N}_{inj,X}}{V_{plasma}} + \displaystyle\sum_r \nu_{X_r} R_r - \dfrac{n_X}{\tau_{p,X}} & (2d) \end{cases}$$

The plasma is characterized by the burning volume V_{plasma}, the species number density n_X and particle confinement time, $\tau_{p,X}$. The fuel cycle has been collapsed to three main subsystems for simplicity: (1) the Inner Fuel Cycle (IFC), that includes the plasma exhaust, fuel cleanup system, isotope separation system and the detritiation system, (2) the Outer Fuel Cycle (OFC), that includes the first wall, divertor, breeding blanket, heat exchangers and tritium extraction system, and (3) the Storage (STOR), that includes the fueling system beside storage and management. $I_{IFC,X}$, $I_{OFC,X}$ and $I_{STOR,X}$ are the species inventories (in number of atoms) in each subsystem and the flow of each species is modeled considering the residence times $\tau_{IFC,X}$ and $\tau_{OFC,X}$. The injection term, $\dot{N}_{inj,X}$ may be defined as a function of time and system state. Radioactive decay of species X is represented by the constant λ_X, that is zero for stable isotopes. Tritium decay in helium-3 is also accounted

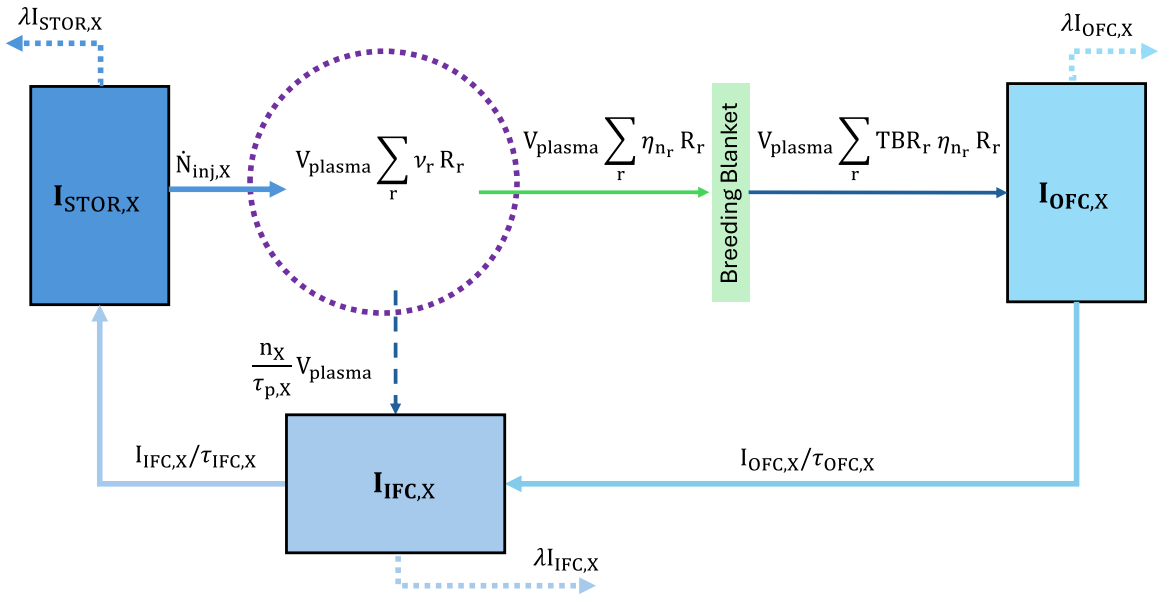


Fig. 2. Diagram of the inventories described by the System of Eqs. (2). Different shades of blue represent a generic species X, green has been used to represent the neutron flux and the breeding blanket (that are not explicitly present in system of equations), while the plasma is represented in purple. The equation representing the plasma have been written using a total number of particles rather than density of species X, to be consistent with the rest of the diagram.

towards helium-3 accumulation but has not been represented in system (2) for the sake of simplicity.

The net fusion source term in the plasma can be expressed using coefficients ν_{X_r}, where $\nu_{X_r} > 0$ for products, $\nu_{X_r} < 0$ for reactants, and $\nu_{X_r} = 0$ otherwise. Generation of species X in the blanket is regulated by a Tritium Breeding Rate TBR_r, depending on the neutron energy associated to the reaction (null if the reaction does not produce neutrons), and by the number of neutrons produced per reaction r, η_{n_r}. Since in this study multiple neutron energies stemming from different reactions are considered, TBR is used in the sense of "how many tritium atoms are bred per neutron produced by a specific reaction", and is therefore called *breeding rate* instead of *breeding ratio*.

The solution of Eq. (2d) gives the possibility of computing additional metrics to evaluate the performance of the analyzed scenarios. This study considers the fusion power (both total and per-reaction channel) and the Tritium Burn Efficiency (TBE), measuring tritium burning rate compared to tritium injection rate. TBE is more appropriate than the tritium burn fraction when considering coupling between plasma and fueling system, because it captures the global balance between tritium injection, recycling, pumping, and burning, rather than the single burning events inside the core [18].

Overall, this model considers the plasma as a 0D, fully ionized mixture of hydrogen and helium isotopes, where their production and consumption due to fusion reactions are computed from reactivity fits, while particle transport is modeled by effective particle confinement terms. The presence of neutrals, impurities, as well as radiation is not considered. The fuel cycle is represented as three connected inventories (IFC, OFC and STOR), where flows between them are modeled with residence times, and are coupled with the plasma through injection (from STOR to plasma), exhaust (from plasma to IFC) and breeding (in the OFC). The architecture of the fuel cycle is assumed to be the same for each operational condition considered. This study will focus on the effects of operating with various fuel mixtures (namely 50:50 DT, T-lean and D-^{3}He) on the fuel cycle. A schematic diagram of the system is presented in Fig. 2.

2.2. Computational model

The 0D, dynamic model reproducing plasma-fuel cycle coupling has been implemented in Python (v3.13.7) and is openly available on GitHub [8]. This section briefly describes the overall structure of the code, its capabilities and possible future implementations.

Simulations are defined by two separate YAML files: a configuration file defining solver configuration and a parameters file, used to describe a single or a set of operating scenarios. These files can then be passed to the main entry point to run an analysis with the chosen set of parameters.

Internally, the code generates a single state vector containing both plasma densities and fuel cycle inventories and evolves it in time using SciPy `solve_ivp` function. Since the system involves vastly different characteristic timescales (from a few seconds for the particle confinement times to hours or days for the fuel cycle residence times), the system is treated as stiff and integrated with the implicit BDF method.

The code allows to perform a parallelized parametric analyses (implemented using `concurrent.futures` class `ProcessPoolExecutor`), considering all possible combinations of the input parameters.

In order to keep the model lightweight, all input parameters are considered constant, except for the injection rate, that can be defined as a function of time and of the state vector. Future improvements may include the option to define temperature and density profiles, so that reaction rates are computed from volume integrals rather than from volume-averaged quantities, enabling more realistic power estimates.

3. Results

This section describes five scenarios of interest for FPPs, which are designed to illustrate the main capabilities of the model, namely, the possibility of operating with a multispecies fuel mixture where the specific composition can evolve across operations and the advantages of having a direct coupling between plasma and fuel cycle.

To enable a consistent comparison, all cases are evaluated considering a generic magnetic confinement FPP, where the total average ion density is kept the same in every scenario and particle confinement times are assumed identical for all species. In the fuel cycle, τ_{IFC} is assumed longer for helium isotopes than for hydrogen isotopes to reflect slower processing of helium streams due to the more complex separation of helium isotopes. The parameters used in the analyses are summarized in Table 1. The plasma volume, average ion temperature

Table 1
Main parameters used in the analyses.

Parameter name	Symbol	DT	D^3He	Unit
Plasma volume	V_{plasma}	150	354	m^3
Average ion temperature	T_i	15	70	keV
Tritium breeding rate of DT neutrons	TBR_{DT}	1.15	0.0	–
Tritium breeding rate of DD neutrons	TBR_{DD}	0.9	0.0	–
Total average ion density	$n_{tot,avg}$	1.5×10^{20}		m^{-3}
Particle confinement time (for all species)	τ_p	1		s
IFC residence time for hydrogen isotopes	$\tau_{IFC,(D,T)}$	8		h
IFC residence time for helium isotopes	$\tau_{IFC,(^3He,^4He)}$	12		h
OFC residence time (for all species)	τ_{OFC}	4		h

and density are taken for a typical compact, high-field tokamak using ARC-like parameters [19]. The TBR for DT neutrons is set above one in order to represent a breeding blanket under realistic operating assumptions, while the TBR associated with DD neutrons is taken to be lower because 2.45 MeV neutrons are less effective for tritium breeding than 14.1 MeV DT neutrons [20]. The particle confinement time is fixed at $\tau_p = 1$ s for all ion species. The residence times for the inner and outer fuel cycle loops are treated as lumped processing times for a group of components, rather than the residence time in a single component. For the outer fuel cycle, a residence time of $\tau_{OFC} = 4$ h is adopted for all species, consistently with previous studies [1]. For the inner fuel cycle, longer residence times are assumed because this loop includes exhaust pumping, exhaust processing, and isotope separation processes. Hydrogen isotopes are assigned $\tau_{IFC,(D,T)} = 8$ h, while helium isotopes are assigned $\tau_{IFC,(^3He,^4He)} = 12$ h. The larger value for helium reflects the additional delay associated with helium extraction and separation from the exhaust gases and it is used as a conservative assumption for the comparatively lower throughput helium processing line. In the absence of a detailed design of the reactor and its fuel cycle system, these values are therefore used as representative assumptions to show the capabilities of the model.

Due to the significantly lower reactivity of D^3He with respect to DT (see Fig. 1), the D^3He cases adopt a higher ion temperature and a larger plasma volume, to achieve a fusion power comparable to the reference DT scenario defined in Section 3.1.

3.1. Standard 50:50 DT operation

The first analysis is performed on standard 50:50 DT operation, with an initial tritium inventory in the storage. The simulation was set up by imposing initial density fractions for both deuterium and tritium to 50% ($f_D = f_T = 0.5$), an initial tritium inventory in the storage $I_{STOR,T} = 1.63$ kg (startup inventory for the analyzed case, considering no reserve inventory) and the target was to double the initial inventory, while keeping the total density constant by enforcing the same injection rate for the two main species, deuterium and tritium.

This scenario results in a 640 MW FPP, with more than 99.7 % of the power coming from DT reactions. After a short transient (less than 5 s) from the initial 50:50 DT condition, the plasma reaches a steady-state composition of $f_D \sim f_T \sim 0.495$, $f_{^4He} \sim 0.01$ and traces of helium-3 ($f_{^3He} \sim 2.6\times10^{-5}$). The injection rate of deuterium and tritium remains constant at about 1.14×10^{22} atoms/s. Fig. 3 reports the evolution of $I_{STOR,T}$ for a $f_T = 50$ % case, obtaining a doubling time, defined as the time needed to double the startup inventory, of 231 days. This scenario considers no reserve inventory.

These results are in agreement with the fuel cycle model presented by Meschini et al. [3]. To verify the implementation, the same simplified scenario considered in this work was reproduced using their open-source code [21], available on GitHub and hereafter referred to as the single-species FC model, that gives a startup inventory of 1.63 kg and a doubling time of 229 days, in close agreement with the presented model. The difference in doubling time is likely due to differences in the numerical solver. Further verification should compare the present framework against both plasma and fuel cycle models.

Table 2
Results for different tritium fractions f_T.

f_T [%]	P_{fus} [MW]	$I_{IFC,T}$ (t = t_d) [g]	$I_{OFC,T}$ (t = t_d) [g]	$I_{STOR,T}$ (t = 0) [g]	t_d [days]	TBE [%]
10	230	328	7	330	99	3.57
20	409	657	12	650	128	3.18
30	537	986	16	980	155	2.78
40	614	1315	18	1310	187	2.39
50	640	1644	19	1630	232	1.99

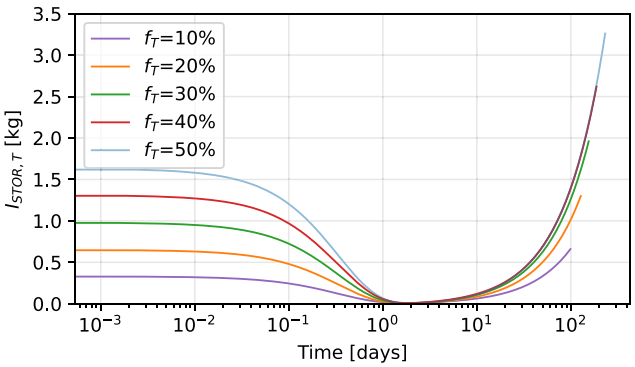


Fig. 3. Evolution of the tritium inventory in the storage for different initial tritium density fractions. The entire transient, up until the doubling time of each scenario, is shown. No reserve inventory is considered.

3.2. Tritium-lean operation

FPP designs typically assume operation at approximately 50:50 DT mixture, which maximizes the fusion reaction rate. Reducing the tritium fraction in the plasma, i.e. tritium-lean operation, effectively raises the probability of tritium particles in the plasma to react with the deuterium population, increasing in turn the TBE [22], but also decreases the amount of tritium throughout the inner fuel cycle, reducing the circulating inventory. The tradeoff is that deviating from 50:50 DT operation also decreases the fusion power density at fixed n_{tot} and T_i, so a tradeoff is needed between minimization of the tritium inventories and power production.

A similar setup to that described in Section 3.1 is used to study four different tritium-lean scenarios, having an initial tritium fraction ranging from 10% to 40% and comparing the resulting scenarios to a standard 50:50 DT scenario.

The main results are summarized in Table 2. As the initial tritium fraction is reduced, the amount of tritium decreases across the systems, particularly in the IFC, and the doubling time is reduced. This reflects the combined effect of a lower overall amount of recirculating tritium and an increase of TBE. Fig. 3 shows the evolution of $I_{STOR,T}$ for the analyzed tritium-lean scenarios.

Comparing directly the nominal 50:50 DT scenario with the f_T = 40 % case, it can be seen that 4 % reduction in fusion power corresponds to a reduction of both doubling time and total tritium inventory in the FPP of about 19 %.

However, the reduction in doubling time is generally smaller than the reduction in startup inventory, and this is more evident as the tritium fraction decreases. For instance, at $f_T = 10$ %, the reduction in startup inventory is about 80 %, whereas the doubling time decreases by only about 57 %.

The $f_T = 30$ % case was benchmarked against the previously cited model used in [3]. The two models predict the same startup inventory and final IFC and OFC inventories, while the single-species FC model gives a slightly longer doubling time, $t_d = 163$ days, about one week more than the results reported in Table 2. When DD neutron breeding is

excluded, the present model predicts $t_d = 160$ days, closer to the result obtained with the single-species FC model that accounts only for DT neutrons breeding. It is interesting to notice how this configuration, which uses a $TBR_{DD} = 0.9$, results in an additional production of about 70 g of tritium over the doubling time.

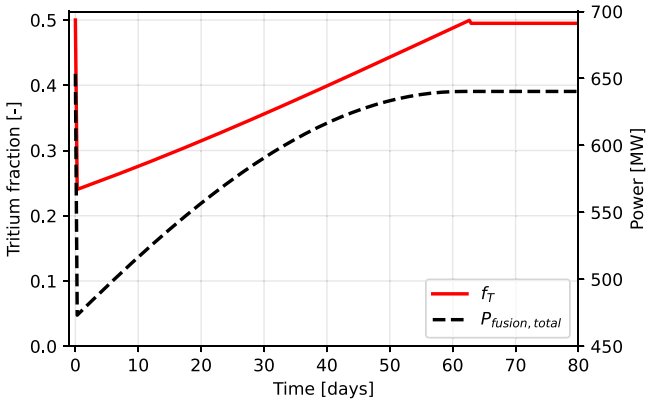
3.3. Tritium-lean operation as a mitigation for startup inventory loss

An additional case is considered in which the plant runs out of tritium, representative of a loss of tritium in the storage during early plant operations. A common assumption in fuel cycle simulations is that, if the storage inventory is completely depleted, then the reactor must be shut down [1,3]. Given the engineering complexity and the cost of a FPP startup, it might be more economical to keep operating instead, using the tritium produced by breeding while operating at a lower tritium fraction. Since the amount of tritium bred is proportional to the neutron source (first term on the right hand side of Eq. (2a)), while the tritium injected is a factor 1/TBE higher (by the definition of TBE $\equiv \dot{N}_{\text{burned,T}} \,/\, \dot{N}_{\text{inj,T}}$), the tritium injection rate in this scenario temporarily drops significantly when it starts relying on the tritium bred only. We assume for simplicity that some tritium is lost instantly at the beginning of the operations, as more detailed tritium loss functions would not add any insight on the transient. Fig. 4 shows the transient for an initial 50:50 DT mixture with an initial storage inventory equal to half of the nominal startup inventory required (815 g). The target is still to reach twice the nominal startup inventory, i.e. $I_{\text{STOR,T}}(t_d) = 3.26$ kg.

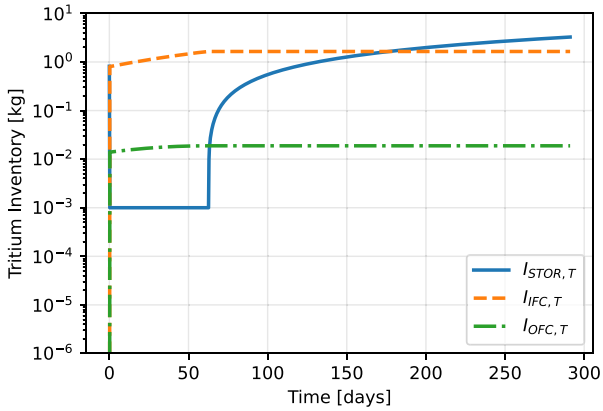
To model this scenario, the deuterium and tritium injection functions keep the total density constant, while maintaining the same proportion in the plasma. This continues until the tritium storage inventory reaches the minimum tritium inventory allowed in the storage, of 1 g. Since the initial inventory is not sufficient to sustain the necessary tritium density in the plasma $I_{\text{STOR,T}}$ is depleted (Fig. 4(b)) while the other inventories grow as tritium circulates in the fuel cycle. The tritium fraction in the plasma, f_T, drops to about 25% during the first hours of operation reducing the fusion power along with it (Fig. 4(a)).

At this point the system switches to a different injection method: all the tritium reaching the storage and delivery system is directly routed to the fueling system and to the plasma (no accumulation of tritium in the inventory), while deuterium injection is adjusted to keep the total density constant. This phase continues until a 50:50 DT mixture is restored in the plasma. During this phase the tritium fraction and the power steadily grow, while the tritium $I_{\text{STOR,T}}$ remains constant at 1 g, as all the tritium coming from the IFC is immediately reinjected into the plasma. Once a 50% tritium fraction is reached, the FPP restores nominal operations at 50:50 DT mixture.

This scenario demonstrates that, for what concerns tritium management, no reactor shutdown is needed even if a fraction of the startup inventory is lost during the startup transient. Instead, the reactor can keep operating at a lower tritium core fraction, and consequently lower fusion power, until the 50:50 DT mixture is restored. While this takes several weeks (about 62 days in Fig. 4(a)), it is likely more cost-effective than shutting down the machine. Furthermore, this scenario suggests that a reserve tritium inventory might not be needed, and relying on tritium-lean operations could be a better pathway. This could significantly reduce the startup inventory, as the reserve inventory (depending on assumptions on component reliability) contributes to a major fraction of the startup inventory [1,3]. An extreme case of this scenario is a startup with no tritium at all (i.e. a DD startup). However, such a scenario requires careful considerations about plasma operations, and technical and economical feasibility, and will be examined in detail in future work.



(a) Evolution of tritium density fraction and total fusion power in a tritium-lean scenario with tritium reinjection. Only the initial transient, up until 50:50 DT operation, is shown.



(b) Evolution of tritium inventories in the IFC, OFC and storage in a tritium-lean scenario with tritium reinjection. The entire transient, up until the doubling time, is shown.

Fig. 4. Evolution of the main metrics for tritium-lean operation with tritium reinjection: tritium fraction in the plasma, total fusion power, tritium inventories in the fuel cycle subsystems.

3.4. D^3He operation

The D^3He fuel mixture is classified as an "advanced" fusion fuel, for the attractive promises of reduced neutron production, at the cost of substantially more stringent requirements on plasma parameters and the scarcity of helium-3 [23].

With the aim of reducing the tritium present in the plant at a minimum, breeding and OFC have been turned off in the model. Nonetheless, some tritium is still being produced by DD reactions; part of it is burnt in the plasma, while part is lost, reaching the IFC. Fig. 5 shows how even the use of a fuel mixture without tritium can result in a significant amount of it in the fuel cycle. In particular, about 70 g of tritium are accumulated in the storage during 10 full power days of operation. This result shows that tritium management remains a relevant design and safety issue even for a D^3He FPP.

3.5. Tritium assisted D^3He operation: the "Coppi's match"

Achieving the temperatures required for efficient operation of a D^3He mixture in toroidal magnetic confinement reactors is beyond current capabilities. For this reason it has been proposed to start operation with a DT mixture, bringing it to ignition, and then gradually replace tritium with helium-3 (The "Coppi's match" [24]). This

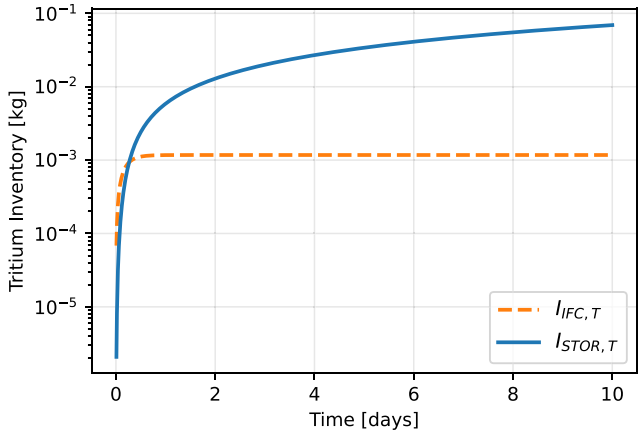
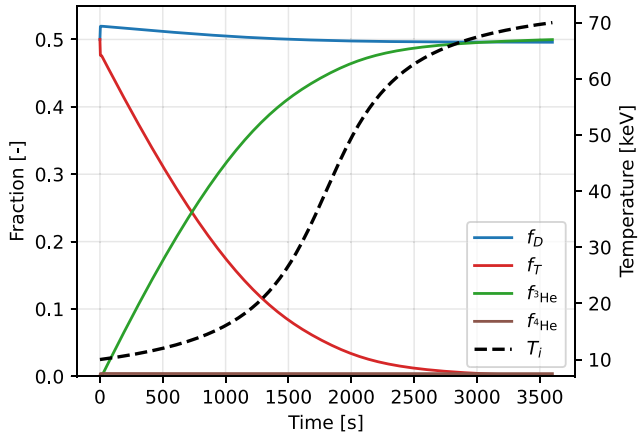
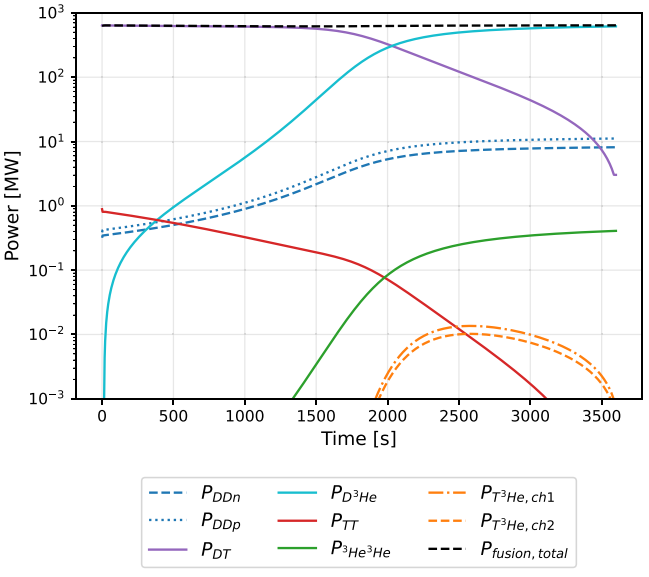


Fig. 5. Evolution of the tritium inventory (IFC and storage) for a 50:50 D^3He scenario.



(a) Evolution of each species density fraction and ion temperature in a tritium-assisted D^3He scenario.



(b) Evolution of each fusion power channel and total fusion power in a tritium-assisted D^3He scenario.

Fig. 6. Evolution of the main metrics for tritium-assisted D^3He scenario: species density fraction, fusion power channels and total fusion power.

approach brought to an advanced design of Ignitor [25] and to the Candor D-^{3}He tokamak [26].

In order to reproduce this scenario with the current code implementation, the temperature has been defined as a time-dependent function with an arctangent profile (Fig. 6(a)), increasing from 10 to 70 keV in 1 h, in line with fueling system timescales. The tritium and helium-3 injection rates are then adjusted to keep the fusion power nearly constant at 640 MW. Fig. 6(b) shows the contribution of each reaction channel to the total fusion power. It is interesting to notice that, due to the dominance of DT cross section in the entire temperature range, the plasma composition becomes richer in helium-3 before the D^3He channel overtakes DT in power contribution.

This scenario requires a limited tritium injection rate, decreasing in time, and no breeding is considered in the OFC, hence effectively removing it from the fuel cycle system, since the aim is to transition to D^3He operation. This translates to a reduction in the startup inventory and a reduced amount of tritium in the inner fuel cycle (about 115 g and 112 g respectively).

This scenario, even if subject to numerous assumptions concerning the physical and technical feasibility, suggests that a continuous transition from DT to D^3He operation can be achieved while maintaining an approximately constant fusion power.

4. Conclusions

This study presents a system-level lumped parameters model that allows to evolve a mixture of deuterium, tritium, helium-3 and helium-4 consistently across the plasma and the fuel cycle.

For a reference compact tokamak configuration, the 50:50 DT case produces ~640 MW with >99.7 % of fusion power from DT reactions and reaches a steady-state plasma composition after a short transient. Storage tritium inventory doubles in ~231 days (this case has been used as baseline for comparison with the other scenarios). This is consistent with prior models [3] using residence time method for the fuel cycle, with only small differences in startup inventory and doubling time.

Beyond verifying the baseline, the main contribution of the model is enabling the analysis of regimes where standard fuel cycle approaches are not applicable, or become inconsistent, particularly when the 50:50 DT assumption is relaxed, when tritium availability becomes a constraint for operation, or when alternative fuel mixtures are considered.

In tritium-lean operation, the model shows how reducing f_T can improve TBE and reduce tritium inventories in the fuel cycle, at the cost of fusion power. A second case considers how a nominal 50:50 DT FPP that loses part of its tritium startup inventory during early operation, can avoid shutdown by operating at a lower tritium fraction while breeding and recovering tritium and steadily increasing f_T to the initial state. This scenario is particularly relevant when tritium reserves for startup are limited.

The model was then used to quantify how much tritium a D^3He mixture would produce during operation, and how it would impact the fuel cycle. Results show that the tritium production from a 50:50 D^3He mixture is not negligible, and tritium processing components are required to purify the exhaust. Finally, we modeled a transition from DT to D^3He operation at increasing temperature, demonstrating that, from a fuel cycle perspective, the fusion power can be kept steady throughout the transition by adjusting tritium, deuterium and helium-3 injection.

Future work should focus on relaxing the most limiting assumptions of the model, especially from the plasma physics side. This may include a more detailed (but still simplified) particle transport model that can capture the evolution of each species inside the plasma while explicitly considering the impact of key physical phenomena, rather than reducing their net effect into a single particle confinement time. This would then open to the possibility to study more in details the coupling between fuel injection, plasma composition and exhaust with

fuel cycle constraints. A further step towards physical consistency would be evolving temperature and density in time as functions of the state of the system. This would ensure physical consistency. However, the introduction of these extensions should be carefully evaluated to remain device-agnostic across all magnetic confinement reactors, since assumptions on density profile and time evolution are often dependent on the design of the machine. Ultimately, only an integrated approach can capture the dynamics between evolving plasma composition and fuel cycle, which is of particular importance due to the limited tritium availability, to properly investigate scenarios deviating from a 50:50 DT operation.

CRediT authorship contribution statement

Alessandro Morandi: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Raffaella Testoni:** Writing – review & editing, Supervision, Conceptualization. **Massimo Zucchetti:** Writing – review & editing, Supervision. **Samuele Meschini:** Writing – review & editing, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data is available on an open access repo on GitHub.

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