System Level Consequences of Nuclear Fusion Side Reactions in Working Gas Drives

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Thermal propulsion based on Thermonuclear Fusion appears to be one of the most attractive advanced options for space transportation. It offers high mass specific power for propulsion and thus relatively high exhaust velocities and accelerations enabling novel interplanetary trajectories and mass margins. Prior results hint that this may lead to a paradigm change. The present contribution offers an overview on current parametrical studies focusing on the effects of fusion fuels.

The present contribution relies on preceding studies identifying the most realistic device from a top down perspective. Assuming thermonuclear fusion in a magnetic confinement to be one of the most interesting approaches, respective propulsion alternatives were modelled and assessed. The so called Working Gas Drive using the fusion plasma to heat a working medium, hydrogen, has been identified to be the most interesting one. Common fusion reactor fuels were scrutinised with respect to the containment of ash on the base of an extended analytic criterion. The effect of side reactions in fusion plasmas were then modelled and enable approximate predictions on the neutron yield.

In the present contribution, the effects of side-reactions in D-T-^{3}He mixtures are evaluated. First, the models and a fusion ignition criterion are introduced, then the expectable side reactions are summarised, and finally, their effects at plasma level are assessed, also with respect to the release of neutron radiation. The results for D-T-^{3}He plasmas will be used to conduct a minor comparative system study with respect to the top level consequences of mixture ratios and ash confinement time scaling related to operation points, and confinement requirements. The data yielded consists in thrust, exhaust velocity, plasma temperature and the systems' mass setup. Estimations of missions to representative destinations in the solar system assuming a two continuous burn transfer ensue before concluding the contribution.

Key Words: Advanced Propulsion, Nuclear Propulsion, Fusion Propulsion, Concepts

Nomenclature

a	:	acceleration
α_{ava}	:	available mass specific power
α_j	:	mass specific jet power
B	:	magnetic field
β	:	stability index
c_0	:	speed of light
c_e	:	exhaust velocity
Δv	:	velocity increment
δ	:	Kronecker operator
E	:	atomic energy yield
η	:	efficiency
ξ	:	fraction of energy in charged products
ζ	:	product multiple
F	:	thrust
f	:	reflected fraction
g	:	absorbed fraction
h	:	mass specific enthalpy of medium
k_B	:	Boltzmann's constant
k_{back}	:	fraction fed back into plasma
k_T	:	fraction to thrust generation
k_{Rad}	:	fraction to radiators
m_0	:	initial mass of space craft (with fuel)
m_b	:	mass of space craft after burn
m_c	:	a characteristic mass (of reference)
$\dot{m}$	:	mass flow
μ_0	:	vacuum permeability
n	:	particle density
P_G	:	power gains
P_j	:	jet power
P_L	:	power losses
P_T	:	thrust power
p_{maq}	:	magnetic pressure
p_{th}	:	thermal pressure
φ	:	hot ion mode
Ψ_e	:	electron multiple
Ψ_Z	:	square weighted electron multiple
Ψ_{tot}	:	total particle multiple
ψ	:	fuel mixture ratio
Q	:	power multiplication factor
q_e	:	elementary charge (of an electron)
S	:	radiation constant
s	:	replenishment rate
$\langle\sigma v\rangle$	:	reaction rate coefficient
T	:	temperature

t_p	:	propelled period
t	:	time
τ_E	:	energy confinement time
$\tilde{\tau}_{Ea}$	:	ash confinement time factor
$\tilde{\tau}_{Ei}$	:	ion confinement time factor
Ξ	:	abbreviation for fusion power
Ω	:	abbreviation relevant to criterion

Further Sub- and superscripts

BrS	:	Bremsstrahlung
F	:	Fusion
g,h,j,k	:	distinguishing species in fusion plasmas
Syn	:	Synchrotron radiation

1. Introduction

In a space mission, the function of propulsion consists in general in the displacement of the spacecraft from one point or orbit to another which typically demands energy, classically represented as a velocity increment Δv.[1,2] Restricting to propulsion concepts of variable masses and basing on the conservation of momentum,

$$\Delta v = \int_{t_p} a \, dt \tag{1}$$

is built up by the system's acceleration a over the propelled period of time t_p which is the lower limitation of the entire transfer period, possibly also containing unpropelled periods.[1,2] The acceleration

$$a = \frac{F}{m_c} = \frac{\dot{m}\, c_e}{m_c} \tag{2}$$

is the force F provided by a mass flow $\dot{m}$ leaving the thruster at an exhaust velocity of c_e related to a characteristic mass m_c of the space craft. This can be a subsystem's mass, e.g. the mass m_w of the propulsion system among others, or the space craft's initial mass m_0 or its dry mass m_b after the propulsion burn. If c_e and m_c are invariant in time, the latter quantities can be identified in the result of the integration of eq. (2) yielding the Tsiolkovsky's classic rocket equation[1,2]

$$\Delta v = -c_e \ln\left(\frac{m_b}{m_0}\right) \tag{3}$$

which enables to understand that raising exhaust velocities enables fair fuel economy augmenting the ratio m_b/m_0.

However, many of present day's high c_e propulsion systems like ion thrusters entail relatively low accelerations and thus lengthy propulsion periods, being limited in jet power[2)]

$$\alpha_j < \alpha_{ava} \tag{4}$$

that is less than the available power α_{ava} and is defined

$$\alpha_j = \frac{P_j}{m_c} = \frac{\frac{1}{2}\dot{m}\, c_e^{\,2}}{m_c} \tag{5}$$

The last equation shows that at limited α_{ava} one can either enhance c_e or a at the cost of the reciprocal quantity. To raise both, α_{ava} must be augmented, calling for highly yielding power sources among which nuclear fusion can be found.

Nuclear fusion also ranks among the most attractive terrestrial power generation processes[3,4] and has been investigated for space propulsion since the 1950s.[5-13] Many proposed concepts propose a thermal approach powered by magnetically confined thermo nuclear fusion plasmas. In Europe, recent studies aim at identifying the most promising setup of a nuclear fusion thruster considering both the physics – beginning with the ignitability of the fusion fuels[10,11,12] and extending over plasma properties and potential neutron background radiation – and engineering key technologies applicable to subsystems.[8,9,13]

The present conference paper summarises some of the recent research conducted at the authors' institution. First, the system concept and architecture[12,13] is recapitulated in the next sections. This also encompasses a brief discussion of the possible fusion fuels[10] an implicit criterion for their ignitability with respect to fusion products or ashes[11] and side reactions[12] in section 3 and 4. The fifth and sixth sections summarise the findings in recent analyses, discussing the influence of varying fuel mixtures on ignition and propulsion characteristics before investigating the influence on the system masses in section 7 which also offers an estimation of the propulsion capabilities of the propulsion systems as they appear from the prior considerations.[9,13] The paper concludes with an outlook.

2. Concept overview

Reference 13 introduces two principles to enable thermal propulsion relying on magnetically confined fusion plasmas. The first one uses the hypothetical ejection of fusion products which can reach a rather high exhaust velocity of up to several percents of the speed of light, yet entail relatively small thrust levels and efficiencies at a prohibitive mass principally driven by the radiators of the waste heat sink. The respective exemplary data[13] is collected in table 1 for an optimised magnetic field. In contrast to that, the working gas drive[9,13] employing an additional coolant/propellant yields however limited exhaust velocities yield limited exhaust velocities. However, they can provide for better thrust levels, more reasonable masses, and good efficiencies, as the waste heat is recovered by the additional medium and utilised for propulsion. Respective data is also collected in table 1. Hence, for the present consideration, ash drives have been discarded in favour of working gas drives.

Table 1. Parameter of fusion drives[13]

		$\tilde{\tau}_{Ea}$	m_w / t	T_B / keV	B / T	c_e / m/s	F/V_P / N/m³$_P$	η_T / -
Ash drives	**D-T**	1	4.83e2	21.2	3.4	1.5e6	0.4	0.9%
		5	4.97e2	16.8	4.1	3.0e6	1.3	3.6%
	D-³He	1	1.64e2	89.9	13.8	3.6e6	2.2	2.0%
		5	1.99e2	76.6	16.2	7.4e6	6.2	8.6%
Working gas d.	**D-T**	1	4.65e2	21.2	3.4	6.0e3	1.9e4	94.3%
		5	4.70e2	16.8	4.1	6.0e3	2.9e4	94.3%
	D-³He	1	1.04e2	89.9	13.8	1.8e5	2.0e3	90.6%
		5	1.21e2	76.6	16.2	1.4e5	3.7e3	90.6%

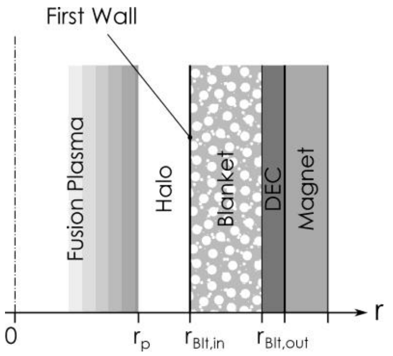

Fig. 1. Arrangement of the assumed one-dimensional reactor's components. Radiators and heat transport to them are not shown.[11)]

The working gas drive presumes a layered design of the reactor as depicted in figure 1 above. The core is the fusion plasma. The next layer is the so called halo in which a so called scrap of layer can be found, sweeping away particles escaped from the plasma and sputtered of the first wall. The latter confines the plasma vessel and is ensheathed with a blanket. Around the blanket, magnetic coils and direct thermal converters can be found. In working gas drives, blanket and first wall fulfil important functions exceeding the terrestrial ones of optional fuel breeding, heat harvesting and radiation damping, namely the space borne blanket is hypothesised to be porous and passed through with the coolant.[13)] The latter is assumed to be eventually injected into the scrap off layer and expanded as a propellant through a magnetic nozzle. Hydrogen appears as a particularly advantageous medium due to its small molar mass. The mass flow of a medium with the mass specific enthalpy h through a working gas drive

$$\dot{m} = \frac{P_{T,rad}}{h(T_{Blt,in}) - h(T_{Blt,out})} \tag{6}$$

is driven by the need to provide a cooling of the radiative power for thrust $P_{T,rad}$ sufficient to maintain the temperature requirements $T_{Blt,in}$ at the inner limitation of the blanket and at the $T_{Blt,out}$ outer. This mass flow can provide for an exhaust velocity of

$$c_e = c_0 \left[1 - \left(\frac{P_T}{{c_0}^2 \dot{m}} + 1 \right)^{-2} \right]^{\frac{1}{2}} \tag{7}$$

with c_0 the speed of light and

$$P_T = P_{T,rad} + P_{T,SOL} \tag{8}$$

the total thrust power composed of $P_{T,rad}$ and $P_{T,SOL}$ the thrust power tapped from the scrap off layer (SOL). Equation (7) has been derived to respect possible relativistic effects. Propulsive properties of working gas drives arising from eqs. (7) and (8) are discussed in reference 13. As in this reference, first, volume specific values are analysed, assuming a one-dimensional reactor of homogenous and isotropic plasma. Later, a generic spherical shape is hypothesised for the sake of a simplified subsystem estimation.

3. Fusion criterion overview

The setup of working gas drives also affects the ignitability of the fusion plasma.[11,12)] The fusion plasma is ignited, once the power losses are equilibrated by the fusion power yielded by the nuclear reactions. Restricting to the case of a steady state reactor this is modelled as a power balance

$$P_G = P_L \tag{9}$$

in which P_G summarises the net gains, and P_L the net losses. The threshold at which this occurs can be lowered by recycling a part of the losses.[11)] Note however, that the losses are also the actual power output of the reactor and full recycling would be as well infeasible as futile. Figure 2[11)] summarises the setup of the considered power flux: The power losses are emitted by the plasma. At the first wall, a fraction f depending on the phenomenon is reflected back into the plasma. Of the remainder, a part g is absorbed by the medium and used for propulsion:

$$k_T = (1-f)g \tag{10}$$

The final losses are recovered to a portion η by the thermo electrical converter (TEC) and the fraction

$$k_{back} = (1-f)(1-g)\eta \tag{11}$$

is used for the heating of the plasma. The rest

$$k_{Rad} = (1-f)(1-g)(1-\eta) \tag{12}$$

is the net waste and radiated into space. Note that in the case of ash drives (AD) also k_T is contributing to this fraction.

The gains

$$P_G = \xi P_F + k_{Back,n0}(1-\xi)P_F + P_{Ext} \tag{13}$$

are composed of the fraction ξ of the fusion power P_F contained in charged fusion products P_F, the retrievable part (1- $k_{back,n0}$)(1 - ξ) of fusion power distributed to neutrons, and an external heating P_{Ext} = P_F/Q with Q the power multiplication factor. Note that in veritable ignition, P_{Ext} would be zero and thus $Q \rightarrow \infty$. Considering these gains on one hand, and on the other thermal losses P_{th} and losses by bremsstrahlung P_{BrS} and synchrotron radiation P_{Syn}, the power balance can hence be developed into

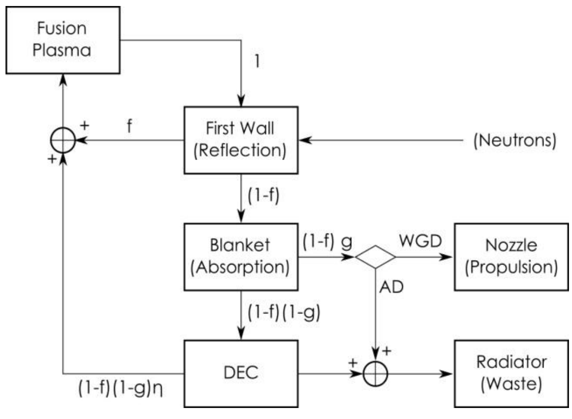

Fig. 2. Simplified power flux model.[11)]

$$1 = \frac{(1\text{-}k_{back,th})P_{th}}{\Xi P_F - (1\text{-}k_{back,BrS})P_{BrS} - (1\text{-}k_{back,Syn})P_{Syn}} \tag{14}$$

with $\Xi = (1/Q + \xi) + k_{back,n0}\,(1 - \xi)$. Detailed models for the involved phenomena are documented in references 11 and 12.

Other than the power balance, a particle balance[11,12] needs to be respected, for which steady state population is assumed. In general, each species in the plasma can appear as a reactant, but also as a product.[12] The consumption rate for the volumetric particle density n_j^{ir} of an ion species j among k species as a reactant (superscript ir) is

$$\frac{dn_j^{ir}}{dt} = -\sum_k \left(\frac{n_j^{ir} n_k^{ir}}{1+\delta_{jk}} \langle \sigma v \rangle_{jk} \right). \tag{15}$$

In this equation, the right hand is the consumption in all of the fusion reactions with particles of species k, involving a reaction rate coefficient $\langle\sigma v\rangle_{jk}$ describing the reaction probability for a given temperature. The Kronecker operator δ_{jk} is used to avoid double counting. The production rate (superscript ip), is analogously

$$\frac{dn_j^{ip}}{dt} = \sum_{g,h\geq g} \left(\frac{n_g^{ir} n_h^{ir}}{1+\delta_{gh}} \langle \sigma v \rangle_{gh} \zeta_{gh,j} \right) \tag{16}$$

with $\zeta_{gh,j}$ the product multiple. This number can be – for example – 2 in the case of proton production from a ^{3}He-^{3}He-reaction. Note, that eq. (16) also is the model for the potential generation of neutrons. The full particle dynamics sums up to

$$\frac{dn_j^{i}}{dt} = s_j + \frac{dn_j^{ir}}{dt} + \frac{dn_j^{ip}}{dt} - \frac{n_j^i}{\tau_j^i} \tag{17}$$

introducing the replenishment rate s_j of particles per volume and per period, and a general leaking rate in which the ion confinement time τ_j^{ir} is the time necessary to fully replace the the ions of species j as a reactant confined in the plasma. The derivation of the implicit criterion finally yields the triple product of particle density n_i, energy confinement time τ_E, and ion temperature T_i

$$n_i \tau_E T_i = \frac{\frac{3}{2} k_B T_i^2 \Omega_{Th}}{\Xi \Omega_F - \Omega_{Syn} - \Omega_{BrS}} \tag{18}$$

with k_B the Boltzmann constant, and using the following four abbreviations:[12]

First:

$$\Omega_F = \sum_k \left(\frac{\psi_{jk}}{1+\delta_{jk}} \langle \sigma v \rangle_{jk} E_{jk} \right) \tag{19}$$

in which E_{jk} is the energy yield per individual fusion reaction in MeV and ψ_{jk} a fuel mixture ratio relating the particle densities of species j and k.

Second:

$$\Omega_{Th} = (1 - k_{back,th})\Psi_{tot} \tag{20}$$

introducing the effective particle multiple Ψ_{tot} indicating the number of charged particles (ions and electrons) per ion.

Third:

$$\Omega_{BrS} = (1 - k_{back,BrS}) S_{BrS} \sqrt{\frac{k_B T_i}{q_e \varphi}} \Psi_e \Psi_Z \tag{21}$$

with the q_e the elementary charge in C, the bremsstrahlung constant S_{BrS} = 1.628 10^{-38} $m^4(Ckg)^{0.5}s^{-2}$, the number Ψ_e of electrons per ions, and Ψ_Z a square weighted electron multiple. The parameter φ is the hot ion mode, a factor relating the ion temperature T_i to the temperature T_e of electrons. However, prior investigations[11,12] substantiated that the influence of this parameter is negligible and it hence is not considered in the present contribution.

Fourth:

$$\Omega_{Syn} = (1 - k_{back,Syn}) S_{Syn} \frac{2\mu_0 k_B T_i}{\beta q_e \varphi} \Psi_e \Psi_{tot} \left(1 + \frac{5 T_i k_B}{2 m_e c_0^2 \varphi} \right) \tag{22}$$

using the radiation constant S_{Syn} = 6.212 10^{-23} $Cs^{-1}T^{-2}$ and the vacuum permeability μ_0. The latter allows together with the magnetic confinement stability parameter

$$\beta = \frac{p_{th}}{p_{mag}} = 2 k_B \frac{\mu_0}{B} \Psi_{tot} n_i \tag{23}$$

comparing thermal pressure p_{th} and magnetic pressure p_{mag} to estimate the magnetic field B.[11,12]

As the derivation isolates the energy confinement time τ_E to the left hand side, relative confinement times

$$\tilde{\tau}_{Ea} = \frac{\tau_a}{\tau_E} \tag{24}$$

of products and

$$\tilde{\tau}_{Ei} = \frac{\tau_i}{\tau_E} \tag{25}$$

of reactant ions appear on the right hand side, generically assumed the same for heavy particles, i.e. Helium isotopes, and assumed to be 62.5 % of this for light ions like Protium.

4. Discussion of fusion fuels and respective side reactions

The implicit criterion (18) can be verified[12] by comparing it with predating fusion criteria such as Lawson's criterion[3] or recent work such as present in references 11. The advantage of the new criterion is consisting in enabling not only the study of the effects of ashes[11] and offering a better precision for advanced and aneutronic fuels operating at temperatures at which synchrotron radiation becomes relevant,[9,10] but also of side reactions, and complex fuelings involving more than two reactants. A Matlab™ based tool has been developed to analyse this implicit fusion criterion. Various reactant couples have been studied,[9,10] namely the nominal reactions of Deuterium and Tritium (D-T), of Deuterium and 3-Helium (D-^{3}He), of Protium with 11-Boron (p-^{11}B) and of 3-Helium with 3-Helium. The D-T reaction appears at the current state as the reaction of choice for terrestrial fusion reactors as it may ignite at the lowest conditions of all known reactions.[3,4] However, most of the fusion power, about 80%, released is so as neutrons which may entail radiologic issues such as activation and which requires some shielding.[3] Both activation and heavy shielding are not beneficial to space borne and especially manned space borne systems,[1,2] making a cause for more advanced fuels yielding less neutrons, like D-^{3}He. This reaction yields neutrons in its nominal D-D side reactions,[3] but considerably less than D-T. However, the criterion demands higher temperatures and particle densities than for D-T.[3,10 - 12] Even less neutrons are yielded in p-^{11}B fuellings and no neutrons are produced if one 3-Helium was used.[10]

However, already the application of the criterion published in reference 11 substantiated that the particularly attractive ^{3}He-^{3}He reaction will not ignite for reasonable helium confinement times and that the p-^{11}B will ignite only if a very rapid ash removal was available. Consequently, this contribution focuses only on nominal fuelling relying on Deuterium, Tritium and 3-Helium. In nominal D-T plasma, the main reaction is the D-T reaction, however, there would also be occasional D-D and T-T reactions, called in the frame of this investigation nominal side reactions.[12] Other than that, there are non-nominal side reactions also involving reactants which are products of the nominal main and side reactions. In fact, the summary in table 2 and 3[12] reveals that the nominal reactions of D-T and D-^{3}He plasma yield products like Tritium or 3-Helium, that are among the reactants of the other fuelling.

Table 2. Nominal reactions of D-T

	D	T
D	^{3}He + n / T + p	^{4}He + n
T	~	^{4}He + 2 n
Species: n, p, D, T, ^{3}He, ^{4}He		

Table 3. Nominal reactions of D-^{3}He

	D	^{3}He
D	^{3}He + n / T + p	^{4}He + p
T	~	^{4}He + 2 p
Species: n, p, D, T, ^{3}He, ^{4}He		

Thus, one can state that in both mixtures the same reactions are present as concentrated in table 4. Each reaction runs with a respective reaction rate coefficient which is a Maxwell convolution of the respective reaction cross section as retrieved from IAEA's databases.[3,12,14] Note however, that the p-p reaction has negligible cross section.[15] The breeding reactions with neutrons *n* and fusion reactions involving 4-Helium ashes are neglected conservatively, i.e. it is assumed that 4-Helium is a final ash and does not contribute to the power generation. For two reactions, p-T and p-^{3}He no cross sections have been found excluding them from the consideration for the time being. The reactant pairings not considered are marked grey in table 4, the remaining seven have been used.

Table 4. Nominal and non nominal reactions of D-T-^{3}He systems

	n	p	D	T	^{3}He	^{4}He
n	NA	D	T / p + 2 n	D + 2 n / p + 3 n	T + p / 2 D	^{3}He + 2 n
p	~	D	^{3}He / n + 2 p	^{3}He + n	2 p + D	N.A.
D	~	~	^{3}He + n / T + p	^{4}He + n	^{4}He + p	p + ^{5}He
T	~	~	~	^{4}He + 2 n	^{4}He + p + n / ^{4}He + D / ^{3}He + p	N.A.
^{3}He	~	~	~	~	^{4}He + 2 p	^{7}Be
^{4}He	~	~	~	~	~	^{7}Be + n / ^{6}Li n + p

5. Analysis of ignitability

In this section, the ignitability of Deuterium-Tritium-3-Helium plasmas is analysed. The parameters of the reactor setup are contained in table 5.[11-13]

Table 5. Reactor parameters[11-13]

Parameter	Value	Comment
$k_{back,Syn}$	0.95	Highly reflectable
$k_{back,BrS}$	0.103	Barely reflectable
$k_{back,th}$	0.006	Only DEC recuperation
$k_{back,n0}$	0.003	Barely recuperable
Q	$\rightarrow \infty$	(Ignition)
τ_E	0.5 s	Conservative assumption [20]
β	0.9	High stability

Five different mixtures are considered by ratio of replenishment rates s_j; the first is a classical D-T fuelling at a ratio of Deuterium to Tritium of 1:1; the second is another D-T mixture, lean in Tritium at a ratio of 4:1. The third and fourth are Deuterium-3-Helium mixtures of ratios of 1:1 and 4:1. Finally, the fifth fuelling is a mixture of all of the three fuels, i.e. D-T-^{3}He at a mixture of 4:1:3. For each of these five mixtures, a variation of the confinement time factor $\tilde{\tau}_{Ea} = \tilde{\tau}_{Ei}$ = 1; 5; 10 is studied. An evaluation of the ignitability arises from a comparison of the triple product of the classical D-T of 1:1 mixture. The triple product indicates a product of necessary Temperature, energy confinement time and particle density to realise the criterion (18). The triple product appears as a function of the temperature T_i which is in an order of magnitude of several millions up to billions of Kelvins, and is more aptly indicated in Kilo-Electron-Volts, with 1 keV = 1.1604 10^7 K. Figure 3 reveals that there is a temperature for which the triple product is in its minimum, and thus the minimum requirements to the system. In practice, a fusion reactor would be run at temperatures not exceeding that of the minimum to ensure that a cool down terminates the fusion burning. Figure 3 depicts the classical finding, that a D-T fed fusion plasma ignites at less temperature than a D-^{3}He fed one. It also confirms the expectation,[3, 11, 12] that longer ash confinement as represented by higher $\tilde{\tau}_{Ea}$ also tightens the situation as

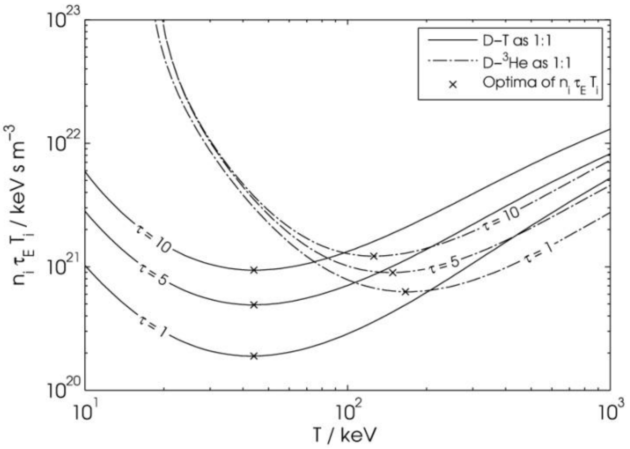

Fig. 3. Triple product of 1:1 D-T and D-^{3}He fuels as a function of T_i. Note that τ is actually $\tilde{\tau}_{Ea}$.

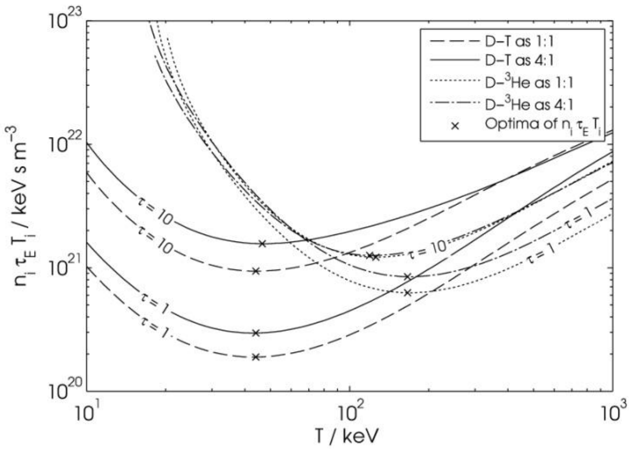

Fig. 4. Triple product of 4:1 D-T and D-^{3}He fuels as a function of T_i. Note that τ is actually $\tilde{\tau}_{Ea}$.

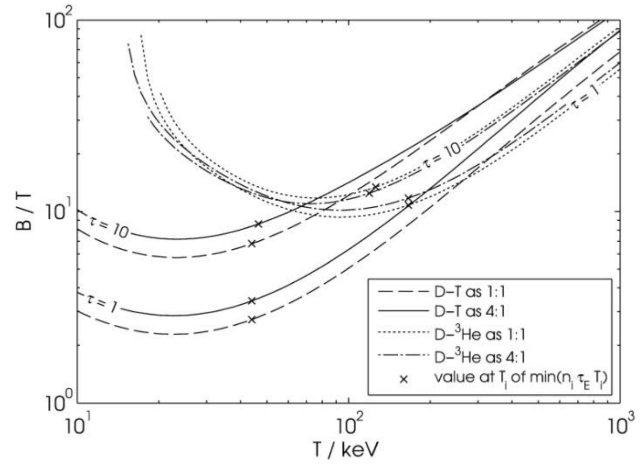

Fig. 6. Magnetic field B of 1:1 and 4: 1 D-T and D-^{3}He fuels as a function of T_i. Note that τ is actually $\tilde{\tau}_{Ea}$.

in general higher values need to be achieved. On the other hand, longer ash confinement also appears to reduce the temperature of the minimum in D-^{3}He plasmas. At $\tilde{\tau}_{Ea}$ = 10, the minimum of the triple products of D-T and D-^{3}He are similarly elevated. Figure 4 above documents how a relative leanness in Tritium is detrimental for the ignition of D-T fed reactors, independent of the ash and ion confinement. This is not valid for D-^{3}He systems. For $\tilde{\tau}_{Ea}$ = 10, the similar values are achieved for 4:1 as for 1:1 mixtures. Using a D-T-^{3}He replenishment, similar values are achieved as for a pure D-^{3}He one. However, the situation is eased for temperature lower than those at the optima, as can be seen in figure 5. In summary, the observation yields that only little benefit to the ignitability can be obtained from altering the fuel composition.

Also, a lean D-T mixture requires stronger magnetic fields, as insinuated by figure 6 plotting B against T_i. However, the same graph hints, that for lean D-^{3}He mixtures, a small reduction may be expected. Note that the crosses in this graph mark the value for the temperature of the optimum of the triple product and that the magnetic field reaches a minimum at even lower temperature albeit at the cost of higher triple products. Fig. 7 plots $B(T_i)$ for the advanced mixture of D-T-^{3}He at 4:1:3 and reflects the finding fro figure 5. While older publications state,

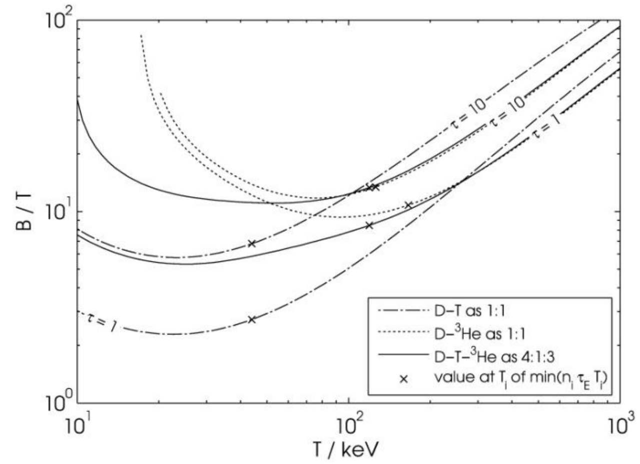

Fig. 7. Magnetic field B of simple and advanced D-T-^{3}He fuels as a function of T_i. Note that τ is actually $\tilde{\tau}_{Ea}$.

that a D-T plasma lean in Tritium may ease the neutron loads, the neutron generation density $n_{n0}(T_i)$ shown in figure 8 does not indicate any benefit. An evaluation of the mean energy distributed to these neutrons has yet to be conducted. On the other hand, for lean D-3He mixtures, more neutrons are generated reaching levels attained in D-T plasmas, reducing the radiologic advantage of the low neutronic reaction.

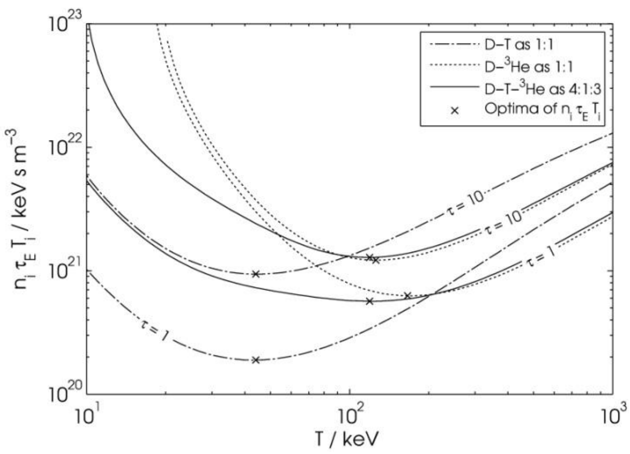

Fig. 5. Triple product of simple and advanced D-T-^{3}He fuels as a function of T_i. Note that τ is actually $\tilde{\tau}_{Ea}$.

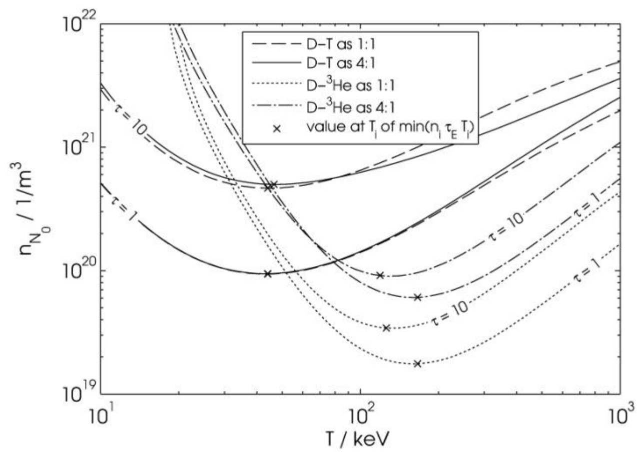

Fig. 8. Neutron population n_{n0} of 1:1 and 4: 1 D-T and D-^{3}He fuels as a function of T_i. Note that τ is actually $\tilde{\tau}_{Ea}$.

Figure 9 hints, that for D-T-^{3}He at 4:1:3, a neutron production less than in a D-T system can be expected. However, the relaxation is not as pronounced as for a pure D-^{3}He replenishment, except for high product confinement time factors, for which a relaxation in neutron production by a factor of about three was estimated. Thus, without a considerable relaxation of the criterion, of the magnetic field as compared to this pure mixture, even if lean in 3-Helium, and with neutron generation near to that in D-T plasmas, this mixture appears unattractive in terms of ignitability.

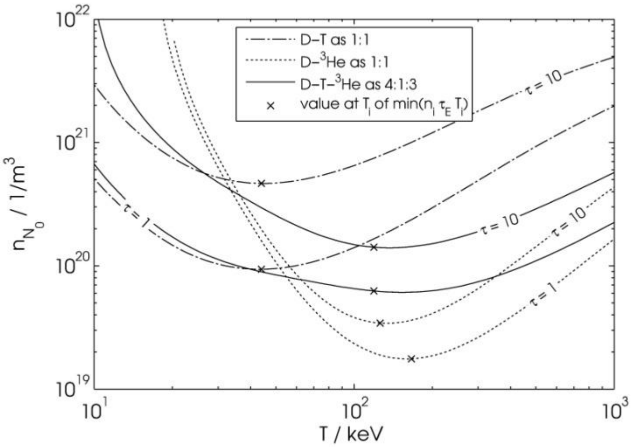

Fig. 9. Neutron population n_{n0} simple and advance D-T-^{3}He fuels as a function of T_i. Note that τ is actually $\tilde{\tau}_{Ea}$.

6. Analyses of propulsion parameters

In section 2, models for the mass flow (6) – hence the thrust force through

$$F = \dot{m} c_e \tag{26}$$

– and exhaust velocity (7) have been introduced. To estimate the mass flow, a typical terrestrial blanket material was assumed for the D-T mixtures. For the other mixtures, a more advance material composed of Tantalum-Hafnium-carbide (HfC to TaC at 4:1) has been assumed. In both cases, it was stipulated that at the inner limitation, the material's melting point may be reached by a minor margin, i.e. 2000 K for the D-T blanket, and 4000 K for the TaHfC-Blanket.[11,12] At the outer limitation, an operational temperature from the TEC is obtained, 1273 K for all of the mixtures.[16] The thickness of the blanket is 1.5 m for the D-T blanket and 0.3 m for the advanced one. Evaluating the eq. (7) for D-T at 1:1 and 4:1 yields an exhaust velocity comparable to that of chemical thrusters. This can be seen in figure 10. In its triple product optimum, it is about 6 kms^{-1} with little variation. The respective thrust as depicted in figure 11 ranges from 10^4 to 10^6 Nm^{-3}. The order of magnitude is the result of large portions of the fusion power being distributed to the neutrons penetrating the blanket. Due to them, as discussed in references 12 and 13, large coolant mass flows are necessary to respect the material's maximum temperature which is in turn detrimental to the exhaust velocity.

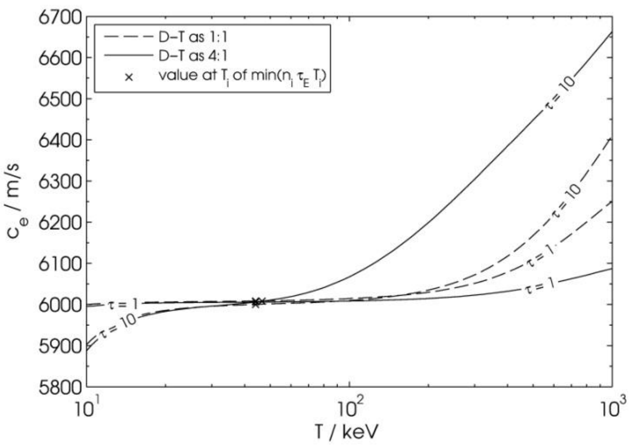

Fig. 10. Exhaust velocity of D-T fuels as a function of T_i. Note that τ is actually $\tilde{\tau}_{Ea}$.

Figure 12 depicts that this is eased for the low neutronic D-^{3}He systems. The part $P_{T,rad}$ is small compared to $P_{T,SOL}$ and thus the coolant once injected into the SOL is heated up to temperatures beyond the temperature limit of the blanket enabling exhaust velocities of up to 120 kms^{-1} at thrust levels between 10^3 to 10^5 Nm^{-3} comparable to those of D-T systems. Again, the D-T-^{3}He mixture does not provide a benefit. The thrust density is similar to the conventional D-T fuelling, as figure 13 on the next page hints. The exhaust velocity ranges up to 20 kms^{-1}. Recall that this is obtained at a tight triple product and with a limited relaxation in neutron production.

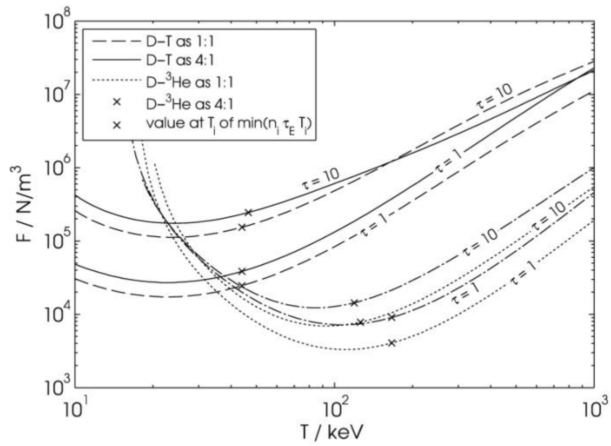

Fig. 11. Volumetric thrust densities of 1:1 and 4:1 D-T and D-^{3}He fuels as a function of T_i. Note that τ is actually $\tilde{\tau}_{Ea}$.

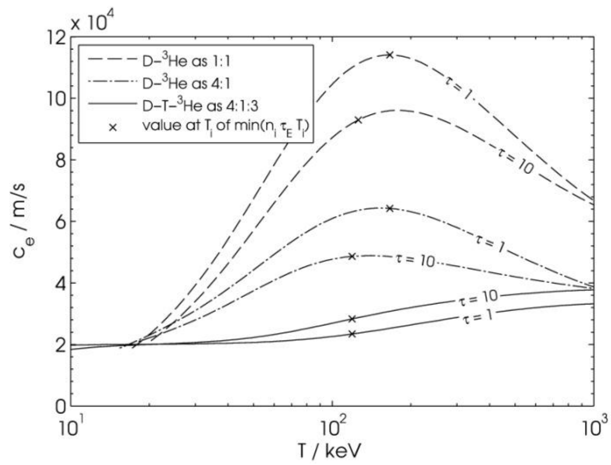

Fig. 12. Exhaust velocity of simple D-^{3}He and the advanced D-T-^{3}He fuels as a function of T_i. Note that τ is actually $\tilde{\tau}_{Ea}$.

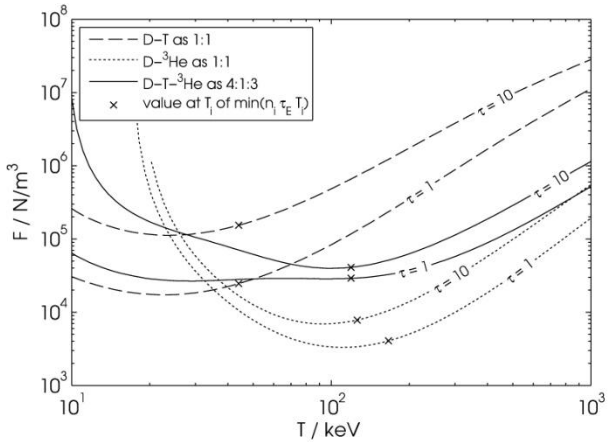

Fig. 13. Volumetric thrust densities of simple and advanced D-T -^{3}He fuels as a function of T_i. Note that τ is actually $\tilde{\tau}_{Ea}$.

7. Mass based subsystem studies and mission analyses

Applying the same mass models introduced in reference 11, the working gas drives summarised in table 6 are obtained for the temperature of optimum magnetic field, considering the respective masses m_{BLT}, m_{DEC}, m_{Mag}, m_{Cryo}, m_{Rad} of blanket, thermoelectrical conversion, supra conducting magnets, their cryo plant, and radiators. To consider the optimum magnetic field enables a comparison with the old data from reference 13 also included in table 6. The plasma volume was assumed to be V_P = 10 m^3. The most important finding at first sight is that for the same fuel and fuel ratio, masses are heavier if side reactions are considered. In fact, the driving contributors are the radiator and the thermo electrical converter. This is a consequence of neutronic side reactions. The neutronic heat loads cannot be recovered in the scrap off layer and are absorbed in the blanket instead, augmenting the need for cooling – hence the comparatively reduced exhaust velocity and higher thrust mentioned above – and thus related masses, such as m_{DEC} and m_{Rad}. The table also suggests that the masses of blankets are not affected by side reactions, but this is merely the result of the modelling of the blanket thickness which does not consider the presence of neutronic side reactions. This presents a flaw of the model. This is particularly inappropriate in the case of the D-T-^{3}He fuelling, since its neutron production compares to the one of a classic D-T fuelling, as substantiated above, and a respective working gas drive should hence be equipped with a suitable shield.

To conclude the present contribution, a mission analysis based on an analytic approximation as introduced in reference 17 has been conducted. The approximation supposes a field free transfer along a straight line between two planets, e.g. Earth and Mars, ideally for the shortest distance between both, here D = 7.85 10^{10} m. The transfer consists of two continuous burns, the first to accelerate the space craft, the second to decelerate. In contrast to classic Hohmann or spiral transfers, this enables relatively short voyage durations. Also note, that in this case, the voyage duration is identical to the propelled period t_p which is modelled

$$t_p = \frac{c_e}{F} m_b \left(\frac{m_0}{m_b} - 1 \right) \tag{26}$$

while the voyage distance is obtained according to

$$D = \frac{c_e^{\,2}}{F} m_b \left(\sqrt{\frac{m_0}{m_b}} - 1 \right)^2 \tag{27}$$

using the quantities defined above. These equations can be solved to provide mass distributions and voyage durations, and the respective results are documented in table 6. It was also assumed, that the mass after burns contains the thruster and a payload of 200 tons. The analysis has also been repeated for D-T and D-^{3}He thrusters from ref. 13 using this condition.

The evaluation substantiates that D-T thrusters are in general too feeble to provide for advantageous propulsion in the frame of the transfer proposed by Williams. First, the necessary propellant reaches prohibitive amounts while the dry mass

Table 6. Masses and thrust parameters of working gas drives at 10 m^3 of plasma.

Scope	Fuels	Ratio	$\tilde{\tau}_{Ea}$ / -	T / keV	B / T	F/V_P / Nm^{-3}	c_e / ms^{-1}	η / %	m_{Blt} / t	m_{Mag} / t	m_{Cryo} / t	m_{Rad} / t	m_{DEC} / t	m_{tot} / t	t_{voy} / d	m_0 / t	m_b / t	m_b/m_0 / %	m_p / t
Without side reactions	D-T	1:1	1	21.2	3.4	1.90e4	6.00e3	94	456	3	1	1	4	465	157	4.30e5	1.51e2	0.0	4.30e5
			5	16.8	4.1	2.90e4	6.00e3	94	456	5	2	2	6	470	161	6.72e5	6.20e2	0.1	6.72e5
	D-^{3}He	1:1	1	89.9	13.8	2.00e3	1.80e5	91	59	12	4	6	22	104	28	5.24e2	2.54e2	48.4	2.70e2
			5	76.6	16.2	3.70e3	1.40e5	91	59	17	6	9	30	121	24	8.20e2	2.71e2	33.1	5.49e2
With side reactions	D-T	1:1	1	22.7	2.3	1.72e4	6.01e3	94	456	1	0.3	2	8	469	164	4.05e5	6.19e2	0.2	4.05e5
			5	22.7	4.0	5.33e4	6.00e3	94	456	4	1	8	26	495	159	1.22e6	6.45e2	0.1	1.22e6
		4:1	1	22.7	2.9	2.70e4	6.00e3	94	456	2	1	4	13	476	161	6.27e5	6.26e2	0.1	6.26e5
			5	22.7	5.0	8.40e4	6.00e3	94	456	7	2	12	41	518	157	1.90e6	6.68e2	0.0	1.90e6
	D-^{3}He	1:1	1	95.5	9.3	3.39e3	1.03e5	91	59	7	2	13	45	127	29	1.16e3	3.29e2	28.4	8.28e2
			5	85.5	10.7	4.96e3	9.36e4	91	59	10	3	18	60	149	27	1.58e3	3.51e2	22.2	1.23e3
		4:1	1	90.4	10.2	7.43e3	5.91e4	91	59	9	3	16	55	142	29	3.53e3	3.44e2	9.8	3.18e3
			5	80.9	10.1	8.27e3	5.34e4	91	59	9	3	16	55	141	30	4.39e3	3.43e2	7.8	4.04e3
	D-T-^{3}He	4:1:3	1	25.3	7.5	2.67e4	2.01e4	94	59	2	1	13	44	119	52	6.03e4	3.21e2	0.5	6.00e4
			5	35.3	9.8	6.44e4	2.07e4	94	59	7	2	33	112	214	49	1.33e5	4.16e2	0.3	1.32e5

fraction is negligible. Second, the duration of more than 150 days or 5 months is rather lengthy. Note, that an average Hohmann transfer to Mars takes about 8 months providing better propellant economy. The influence of side reactions does not alter the outcome, nor does a variation of the mixture.

In contrast to that, the consideration of side reaction in D-^{3}He working gas fusion drives makes a difference. In preceding studies, this fuelling appeared very attractive for fusion propulsion. In the present case, the side reactions' neutron production alters the propulsion characteristics in a way which reduces the benefits identified in prior studies, namely the good propellant economy. While the voyage to Mars takes approximately a month which is excellent in both models, the dry mass fraction drops from about a half to one quarter, if side reactions are considered, and for a mixture lean in ^{3}He to nearly a tenth. This is however still an interesting option if manned space flight is intended.

8. Conclusion

Thermal propulsion based on nuclear fusion is one of the most interesting advanced concepts for space flight. It is likely that its mass specific power can reach magnitudes in which it will provide for the necessary exhaust velocity and acceleration to induce a paradigm change for interplanetary travel. The actual system setup is however not yet fully known. It has been the objective of the present and proceeding studies to identify features, challenges and key technologies through an increasing depth of modelling.

The study[11)] of the impact of fusion ashes to the plasmas' ignitability substantiated that the ash retention in systems with advanced fuel pairings like ^{11}B-p and ^{3}He-^{3}He entail considerable challenges, in contrast to more classic ones like D-T and D-^{3}He. Estimating propulsion systems relying on these fuels[13)] indicated that the neutron production of D-T reactions may be a significant detriment to this mixtures applicability, as the heat surge forces higher coolant/propellant mass flows. This effect is even more severe than the additional mass due to D-T blankets and shielding. In the frame of this consideration, only the aneutronic main reaction of the D-^{3}He fuel appeared to be able to tap the paramount fusion power and yield interesting exhaust velocity and acceleration, enabling short timed and mass economic missions in the solar system. This is also consistent with other recent research focussing on D-^{3}He fusion propulsion.[18)]

The results summarised in this contribution prove, however, that the neutron production of the D-^{3}He side reactions reduce the systemic benefits of this reaction. The emission of neutrons causes a heat surge in the blanket making larger coolant mass flows necessary, reducing the exhaust velocity, causing an increased initial propellant mass and therefore a reduced initial acceleration. The mission performance is therefore also reduced, as documented in table 6. But even despite this observation, D-^{3}He remains the most attractive fusion fuel, still enabling paradigm changing missions. Further, a variation of the 1:1 mixture ratio does not provide any benefits. The neutron production augmented and the propulsion performance reduced.

A first evaluation of a fusion fuelling involving three components (D-T-^{3}He) showed that no significant advantage in ignitability can be obtained while the detriment of the raised neutron production is taken. This finding is yet calling more research. It is intended to conduct a parameter study consisting in varying the mixture rate. Other imminent investigations focus on the confinement system and the injection of coolant into a fusion reactor's scrap of layer.

Acknowledgements

A part of the work leading to the present contribution was conducted in the frame of a doctoral thesis funded by the *Ministry of Science, Research and the Arts* of the State of Baden-Württemberg, Germany. Another part was carried out in the frame of a master thesis sponsored by the *Academic-Social Working Group* of Austria.

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