Technology gaps for the fuel cycle of a fusion power plant

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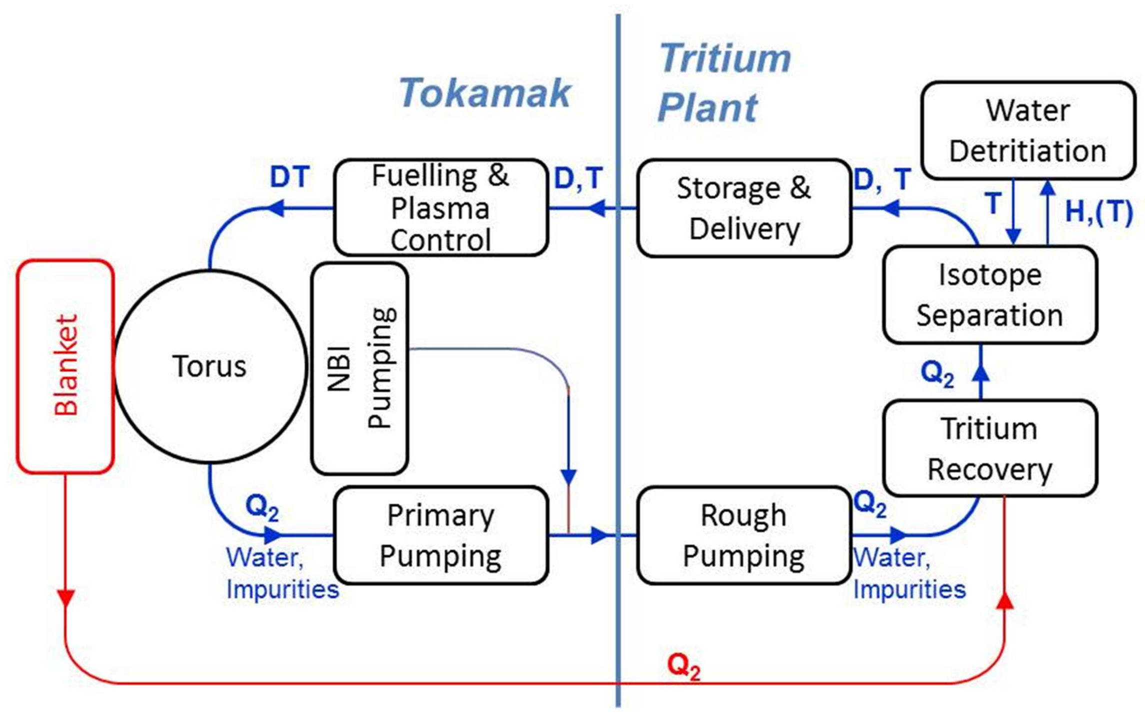
Background

Control and management of the fuel and fusion product streams is one of the most difficult issues for fusion power plant development. This function is provided by the fusion fuel cycle which comprises an inner part (the fuelling systems, the main pumping systems, the tritium plant systems) and an outer part (the blanket and tritium extraction systems). The technology to be employed at a demonstration fusion power plant (DEMO) should start wherever possible from the choices taken for ITER and reflect their maturity, RAMI aspects (reliability, availability, maintainability, inspectability) and consequences of the longer pulse length in view of a good balance of plant. In all areas where ITER does not serve as a convincing basis for scale-up, new technologies have to be developed. This paper is going through the current state of technology, addressing the technical readiness, identifying the areas which are considered to require essential supporting R&D towards a functional system for a reactor, and proposing potential solutions and R&D paths for their development.

Generic Fuel Cycle functions:

(a) provision of the fuel to the plasma;
(b) provision of fuel-type gases to the neutral beam injection systems (NBI);
(c) provision of additional plasma control (ELM pacing, divertor de-/attachment conditions);
(d) tritium accountancy and gas analysis measurement for tritium inventory determination;
(e) fusion ash exhaust via divertor and vacuum pumping of exhaust gas from torus and NBI;
(f) exhaust gas cleaning/ processing and fuel recovery;
(g) removal and recovery of tritium from the breeding blanket extraction system to achieve self-sufficiency.
(h) provide the fuel to be spent but also compensate for decay and losses, and produce additional tritium to be used as start-up inventories for other fusion plants.

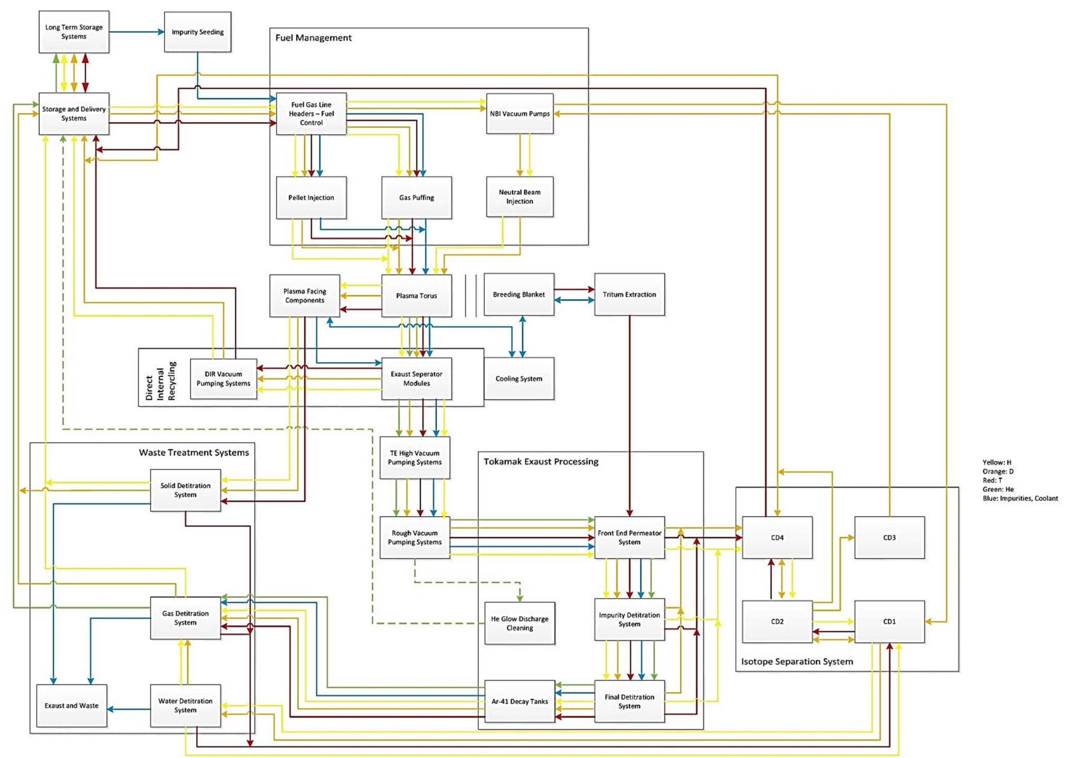


Starting point: ITER fuel cycle systems

For ITER, tritium will be supplied from external sources; hence, the outer part (red color) is only established at a minimum level via test blanket modules that allow for initial studies in a fusion environment, but with negligible tritium production. Whereas the ITER inner fuel cycle part (blue colour) is functionally very similar to the one expected for a fusion power plant. The tritium plant with its main elements of fuel clean-up, isotope separation, storage and delivery is a key system for both loops.

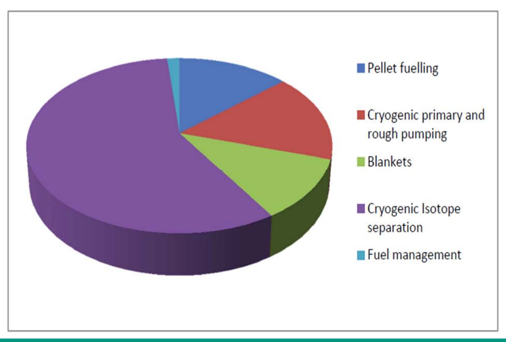
Steps from ITER to DEMO

DEMO will be a long-pulse/steady-state fusion machine that requires validated solutions in the following core areas, with significant factors above what is available from ITER:
1. The tritium self-sufficiency asks for a working breeding blanket concept with a multiplication factor (tritium breeding ratio) that makes up for the parts of the wall which are consumed by duct openings (around 10%).
2. The power output is related to a fuel throughput which is a factor two higher than at ITER (500 MW fusion power) (this does scale less than linearly as an increased burn-up fraction is expected).
3. The long pulse duration will result the fuel cycle to be operated in full steady-state.
Furthermore, in spite of the pulse duration and the large throughputs, the inventory is wished not to rise significantly beyond what is accepted for ITER. All technical solutions to be applied at DEMO must therefore be checked in terms of minimum processing time and minimum inventory build-up. The inventory issue is key for two reasons. First, there are safety and regulator requirements to comply with, second, if the inventory consumed by the steady-state process is significantly smaller than the limit, this leaves a lot more operational margin (e.g. for inventory build-up in walls etc.) and, thus, increased net electricity production to the grid.



Unified Fuel Cycle Simulator

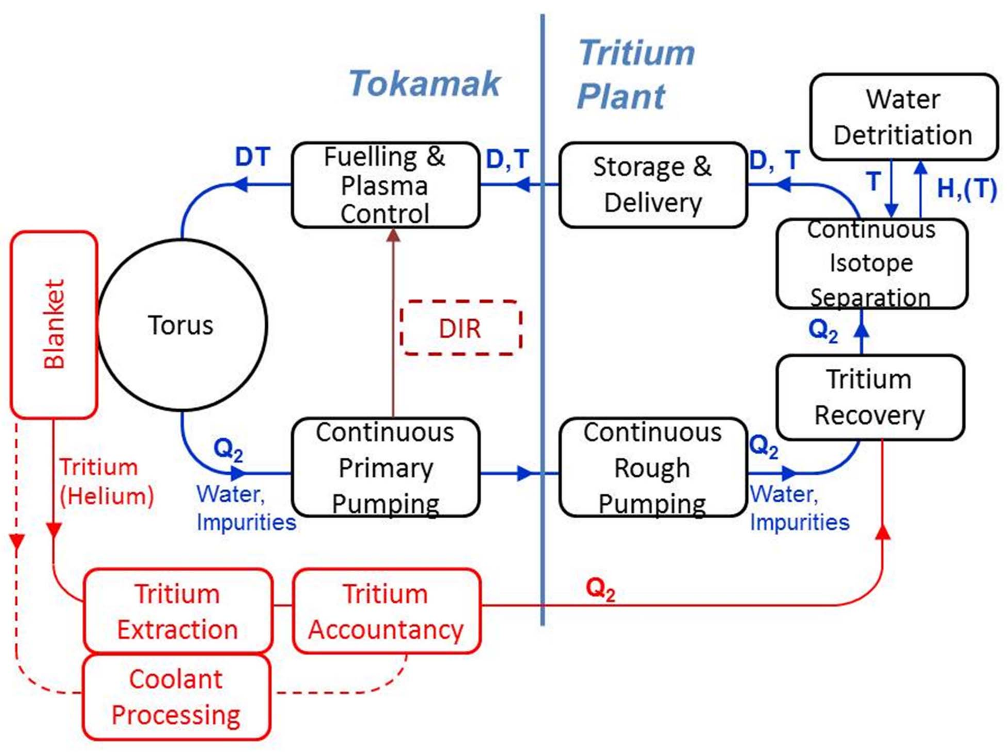
A simple software tool has been written, which handles the fuel cycle as a network of 26 functional blocks which are characterised by in- and outgoing species specific flowrates and residence times. The diagram on the right illustrates the typical inventory contributors for an ITER-style DEMO

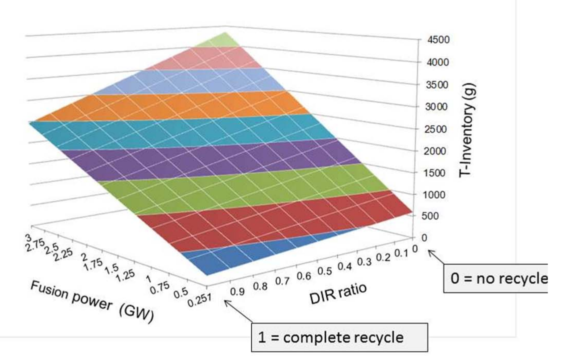


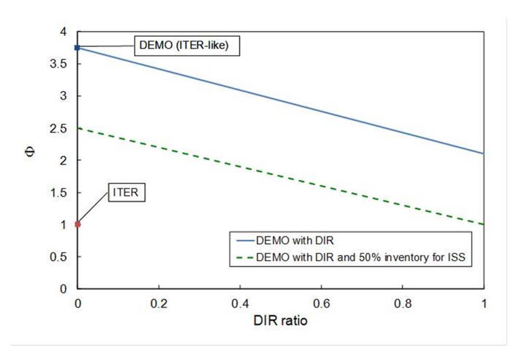
Reference case: 2 GW fusion power, 1500 m³ plasma volume, TBR 1.1, Burn-up fraction 1 %, no NBI inventories, optimistic (i.e. minimum) blanket inventories

DEMO Inner Fuel Cycle

The ITER gas exhaust and cleaning system is based on the philosophy to transfer the full amount of exhaust gas via primary and rough vacuum pumps to the tritium plant, and there to separate the gas species in a defined way so as to produce a given fuel mixture again for re-injection into the torus. It would have a large positive impact on the size of the tritium plant, if the separation would be partly or completely performed in the pumping system, and, thus, a considerably smaller flowrate to be processed towards and in the tritium plant. The separated hydrogen species could potentially be lead to the fuelling systems directly. Obviously, this is working only, if the sharpness of separation is sufficiently high and if there is a feedback controlled fuel gas management which is able to produce the correct composition from the various source flows. We call the new concept ´Direct Internal Recycling (DIR)´.







DEMO Outer Fuel Cycle

The DEMO outer fuel cycle represents a significant extrapolation from the ITER TBM programme and, hence, has to be addressed in a complementary work plan. In line with the strategy taken for the inner fuel cycle, the main driver shall be to develop a fully continuous tritium extraction system (membrane processes instead of adsorption cokumns) and to address the issue of tritium permeability into the breeder coolant (different for the different breeding blanket concepts).

Parameter	ITER	DEMO	Gap
Tritium production	~ 25 mg/day (1 TBM)	~ 500 g/day (machine)	2×10^4
He flow rate in TES	8 - 40 m^3/h	~ 10 000 m^3/h	~10^3
Tritium permeation	~ 10 mg/d	~ 10 g/d	~10^3
He flow rate in CPS	75 m^3/h	~ 50 000 m^3/h	~10^3

Conclusions

The ITER fuel cycle contains a series of discontinuous, cryogenic and batch-wise processes, which would end up in an inacceptably high inventory build-up when just being extrapolated to DEMO. A novel fuel cycle concept which is based on continuous non-cryogenic processes has been developed which promises a 2GW (fusion power) DEMO to be operated with the same inventory as the 500 MW ITER.

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