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Alternative analysis for fuel storage and delivery in the ITER Tritium Plant

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ABSTRACT

The Storage and Delivery System (SDS) of the ITER Tritium Plant has to safely handle the fuel gases including tritium and deliver those gases to the Fuelling System (FS). Recently the ITER fuelling scenarios have been developed in more detail considering ramp-up, flat-top, and ramp-down. With this as input, an alternative analysis was performed for how SDS will support ITER inductive, hybrid, and non-inductive plasma operations. The fuelling rates from SDS to FS were evaluated. To supply gas to FS, SDS must draw gases from one or more sources. These sources could be SDS tanks, SDS hydride storage beds or the Isotope Separation System. Case studies were performed to evaluate the relative merits on various configurations. For inductive operations, it was found that tritium could be supplied with either 27 hydride beds and one tank or with 12 beds and four tanks. For deuterium supply the results were either 43 beds and one tank or 31 beds and four tanks. Also studied were options for distributing supporting gas inventories elsewhere in the Fuel Cycle or on larger hydride beds. Evaluation criteria included operability and safety.

1. Introduction

The Tritium Plant is a key facility for the overall Fuel Cycle. This is true for ITER as well as for future fusion power plant. The Tritium Plant delivers fuelling gases, such as tritium and deuterium, processes tritium-contaminated gases to remove impurities from hydrogen isotopes, separates the hydrogen isotopes, stores tritium and tritium-contaminated deuterium gases, and prevents the release of radioactive gases to the environment.

The Storage and Delivery System (SDS) of the ITER Tritium Plant has to safely handle fuel gases including large quantities of tritium-contaminated gases. One of the main objectives of the SDS is to deliver tritium and deuterium to the Fuelling System (FS) for subsequent delivery to the fusion reactor via gas puffing and pellet injection. Gas must also be delivered to neutral beam injection systems.

This study performed an alternative analysis for the ITER fuel storage and delivery fuelling process within safety constraints. Considering daily plasma operations, various process concepts were developed and analyzed with respect to the numbers of main processing components, such as tritium storage beds, buffer vessels, and fuel delivery pumps.

2. Fuelling scenarios of ITER

2.1. Fuelling requirement of ITER

ITER will operate with a 25% duty factor and the following scenarios: (1) inductive-450 s burn and 1350 s dwell, (2) hybrid-1000 s burn and 3000 s dwell, and (3) non-inductive-3000 s burn and 9000 s dwell [1–3]. Recently, these scenarios have been developed in more detail including fuelling requirements during the ramp-up, flat-top, and ramp-down portions of a plasma burn. These values for DT plasma operations are summarized in Table 1. The DT atomic ratios during fuelling are 3:1 to 2:1 for ramp-up; 2:1 to 1:1 for flat-top; and 6:1 for ramp-down. The fuelling times are 100 s for ramp-up, 400/1000/3000 s for flat-top for inductive/hybrid/non-inductive, respectively, and 300 s for ramp-down.

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Table 1
Fuelling rates for DT plasma operation in ITER.

Scenarios	Average fuelling rate (Pa m^3/s)			Min. period (s)
	Ramp-up	Flat-top	Ramp-down	
Inductive	130	220	70	1,800
Hybrid	110	176	55	4,000
Non-inductive	80	132	40	12,000

2.2. Fuelling rates required from SDS

The delivered fuel gases to the fusion reactor are recovered by a Vacuum Pumping System (VP). The hydrogen isotopes are purified in the Tokamak Exhaust Processing System (TEP) and the hydrogen isotopes (T2, DT, HT, D2, HD, and H2) are separated by the Isotope Separation System (ISS) [3].

ITER plasma operations campaigns are planned to occur over periods of one to two years followed by long term maintenance. Each campaign is planned for two weeks followed by a short term maintenance period. Daily operations are round-the-clock with approximately 4 h of maintenance. This study is focused on satisfying the fuelling requirements for the daily plasma operation in SDS.

To start plasma operations, fuelling gases will initially be supplied from storage hydride beds to buffer vessels. Then, the gases will be delivered from the buffer vessels to FS via tritium compatible pumps [4]. Unburned DT will be returned to the buffer vessels from ISS. When sufficient gases have been loaded into this recycle loop, supply from the storage hydride beds will be discontinued.

The tritium gas includes <20% D2(T) line, and the deuterium includes <20% T2 line.

Delivery rates for from SDS to support DT plasma operations are summarized in Table 2. To determine the conditions that require the most tritium, maximum flowrates are evaluated with 20%-D in T2 and 0%-T in D2(T), and only the highest tritium ratios are considered.

The required fuelling rates for D2(T) for DT plasma operations are summarized in Table 3. As for tritium flowrates, conditions resulting in the highest deuterium concentration are used: 0%-D in T2 and 20%-T in D2(T).

Table 2
Required fuelling rates in T2 line from SDS to FS.

Scenarios	Average fuelling rate (Pa m^3/s)			DT ratio for ramp-up/flat-top
	Ramp-up	Flat-top	Ramp-down	
Inductive	54.2	137.5	12.5	2:1/1:1
Hybrid	34.4	110.0	9.8	3:1/1:1
Non-inductive	25.0	82.5	7.1	3:1/1:1

Table 3
Required fuelling rates in D2(T) line from SDS to FS.

Scenarios	Average fuelling rate (Pa m^3/s)			DT ratio for ramp-up/flat-top
	Ramp-up	Flat-top	Ramp-down	
Inductive	121.9	183.3	70.0	3:1/2:1
Hybrid	103.1	146.7	55.0	3:1/2:1
Non-inductive	75.0	110.0	40.0	3:1/2:1

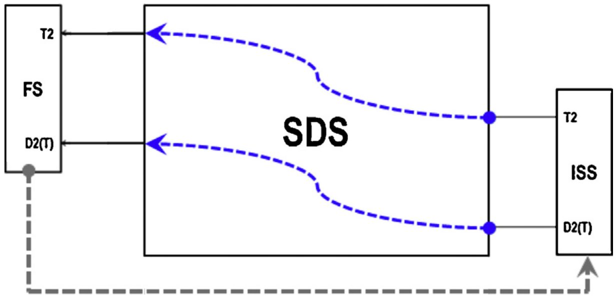
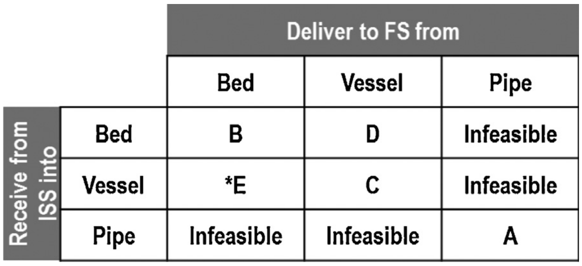


Fig. 1. Schematic diagram of SDS interfaces for DT plasma operation.



Receive from ISS into	Deliver to FS from		
	Bed	Vessel	Pipe
Bed	B	D	Infeasible
Vessel	*E	C	Infeasible
Pipe	Infeasible	Infeasible	A

Fig. 2. Feasible mapping of equipments to pass fuel gases through SDS for pulse-by-pulse plasma operation.

3. Alternative analysis of SDS process concept

3.1. SDS process concept

SDS receives gas from ISS and delivers it to FS as shown in Fig. 1. It is noted that there are various options for performing these two functions. SDS can receive gas from ISS into a hydride bed, a buffer vessel or simply into a pipe (i.e. into no component). In like manner, SDS can supply gas to FS via a hydride bed, a buffer vessel, or a simple pipe (no component). Thus, all receipt/delivery options are shown in Fig. 2. There are nine (three by three) theoretical cases, but four cases are irrelevant: i.e. pipe to bed, pipe to vessel, vessel to pipe, and bed to pipe. Also of no interest is case E consisting of gas receipt into a buffer vessel and gas delivery from a hydride bed. Buffer vessels are attractive because they supply gases very quickly. Thus, placing a hydride bed after a buffer vessel is not attractive. Rather, case B would always be more favorable than case E.

Two goals for a favorable configuration are to minimize the tritium inventory in the buffer vessel and to keep the discharging pressure of pump lower than atmospheric.

Fig. 3 shows a simplified view of the Fuel Cycle. Once initially loaded form hydride beds, T2 and D2(T) fuel gases will circulate from ISS to SDS, FS, Torus, VP, and TEP. SDS performs the shown transfer function with one of the cases described here (e.g. pipes (case A) or buffer vessels (case C)). Fig. 3 shows integrated flow

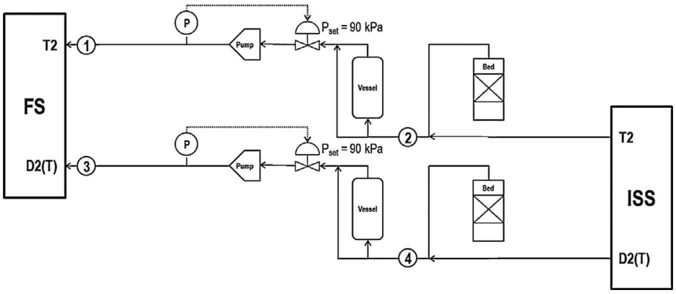


Fig. 3. Conceptual arrangement for flow not routed through hydride beds – without buffer vessels (case A) and with buffer vessels (case C).

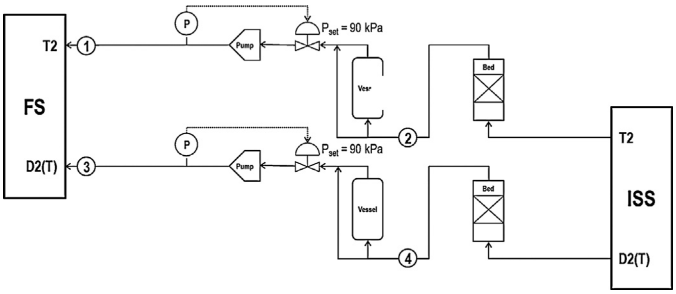


Fig. 4. Conceptual arrangement for flow through hydride beds – without buffer vessels (case B) and with buffer vessels (case D).

diagram scheme for both the cases A and C. The returned fuel gases from ISS shall be directly transferred to the pipes in the case A or to the buffer vessels in the case C. As needed, makeup gas may be added from storage hydride beds. ISS separation capabilities are key to evaluating the options in Tables 2 and 3.

Fig. 4 shows integrated flow diagram scheme for both the cases B and D. All gas from ISS is loaded on hydride beds. And beds are used to supply gases to FS either directly without a buffer vessel (case B) or through buffer vessels (case D). As in the previous paragraph, makeup gas can be added from hydride beds and ISS performance will influence how attractive an option is.

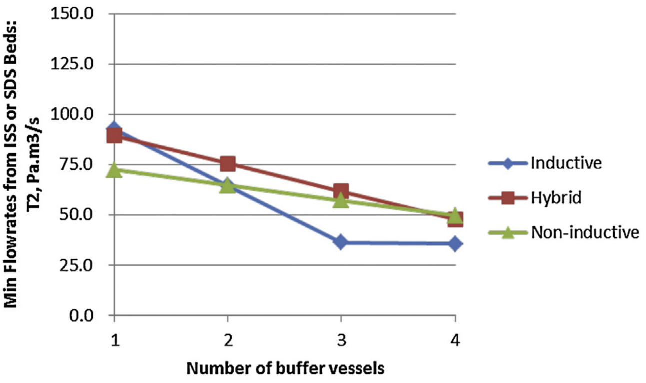
For cases B and D, fuel gases returned from ISS are stored in beds. To receive and store gas, the hydride beds must be cool (less than 150 °C) and to deliver gas they must be heated to approximately 400 °C. To support plasma operations there must be a sufficient number of cool beds for receiving gas, and time must be allowed for heating beds for gas delivery.

Cases A and C required fewer beds compared to cases B and D. However, cases A and C are more closely dependent on ISS operability to meet fuelling requirements.

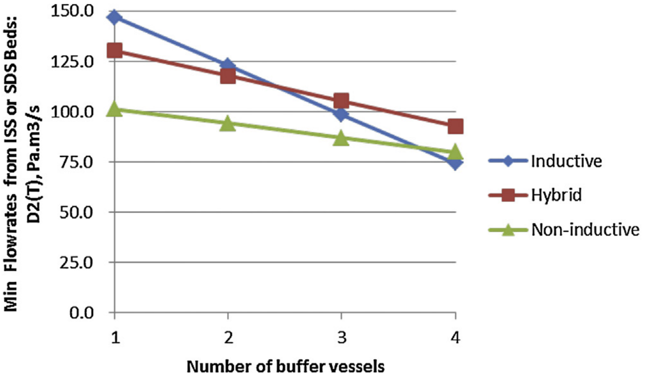
A mass balance model was developed to determine the numbers of hydride beds and buffer vessels for each of the four cases. The model included a limitation of 70 g of T for both hydride beds and buffer vessels.

3.2. Analysis

The model was run using some equipment parameters based on the analysis of Chang et al. [4–6]. The pumps were configured for parallel operation of four Metal Bellows MB601 pumps. Each pump two pumping stages were configured in series. The pump



(a) Minimum flowrate from ISS or SDS beds for T2



(b) Minimum flowrate from ISS or SDS beds for D2(T)

Fig. 6. Required minimum flowrates from ISS or SDS beds at points 2 and 4 in Fig. 5 during plasma burn.

configuration drives the minimum suction pressure necessary to maintain the flowrates in Tables 2 and 3. For inductive plasma operations, the required flowrates are 137.5 Pa m^3/s and 183.3 Pa m^3/s for T2 and D2(T), respectively. The associated minimum suction pressures are 43 kPa for T2 and 54 kPa for D2(T). The operating conditions for buffer vessels were set as follows: the maximum pressure was 120 kPa, the temperature was 25 °C, and the volume was 0.2 m^3. The desorption rate of beds was assumed constant at 20 Pa m^3/s. Fig. 5 shows the equipment configuration and operating conditions for the inductive plasma operation.

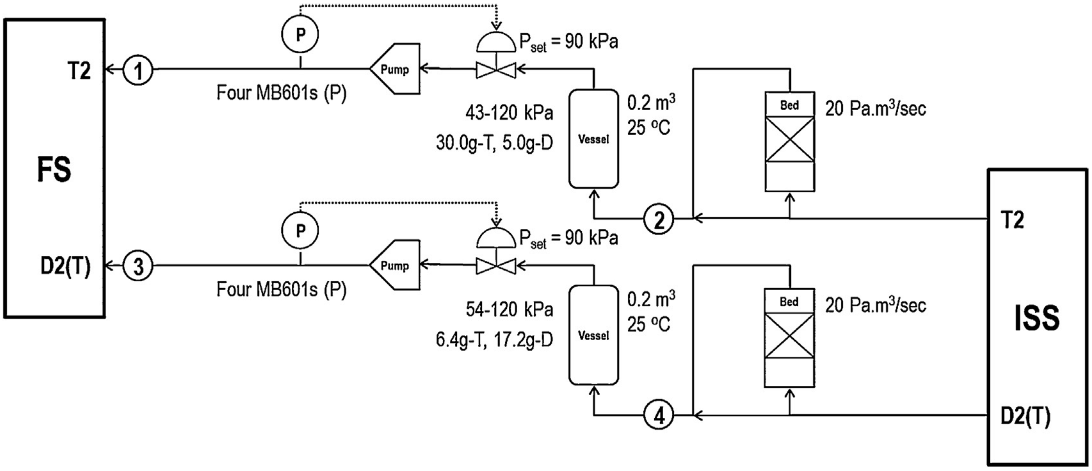
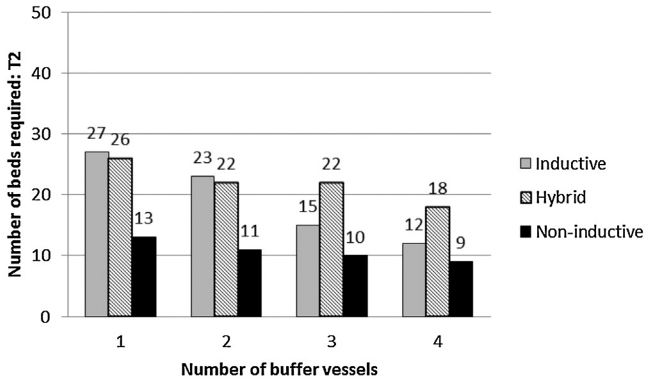
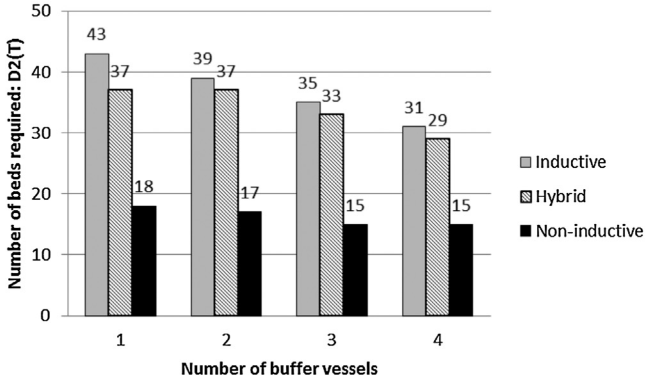


Fig. 5. Equipment configuration and operating conditions in the model for inductive plasma operation.

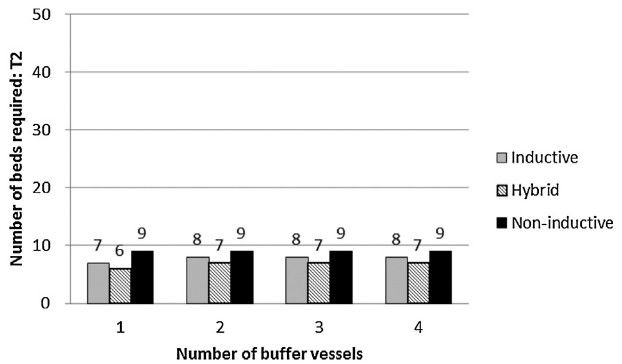


(a) Minimum number of beds in SDS for T2

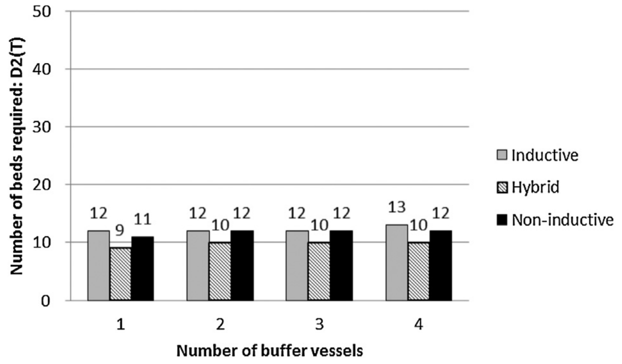


(b) Minimum number of beds in SDS for D2(T)

Fig. 7. Required minimum number of beds in SDS for daily plasma operation.



(a) Minimum number of beds in SDS for T2



(b) Minimum number of beds in SDS for D2(T)

Fig. 8. Required number of beds in SDS: fuel distributed case in the Fuel Cycle.

The time profile for the flowrate from SDS to FS is somewhat of a "square wave", i.e. it is on during burn and off during dwell. Considering just a single burn cycle, in one extreme, if there is sufficient buffer vessel capacity, no flowrate from beds or ISS is needed to sustain flow to FS. In the other extreme, if there is no buffer vessel capacity, beds and/or ISS must support all the flow to FS.

With this in mind, the first part of the analysis was to determine the required flowrates at points "2" and "4" in Fig. 5 for various numbers of buffer vessels. This was done for each ITER plasma operation scenarios, and the results are given in Fig. 6. This shows the flowrates during burn with respect to the number of buffer vessels for T2 and for D2(T). For inductive plasma operations, 93 Pa m^3/s of T2 is required for one buffer vessel. This number is reduced to 36 Pa m^3/s for four vessels. For D2(T) the corresponding numbers are 147 Pa m^3/s (one vessel) and 74 Pa m^3/s (four vessels).

As a basis for evaluating hydride bed performance the following assumptions were made: 0.5 h for desorption, 2 h for cooling, 0.5 h for absorption, 0.5 h for evacuation of outer jacket of bed, and 1 h for pre-heating. It was assumed that beds were filled to 90% of the full capacity (i.e. 90% of 70 g-T equivalent). Fuel cycle conditions assumed were as follows: fuel gases return from ISS after two pulses for inductive plasmas, after one pulse for hybrid plasmas, and during burn (after about 60% of burn) for non-inductive plasmas.

Using these assumptions, the required number of hydride beds configured according to case D was determined for each type of plasma operation and for various numbers of buffer vessels. The results are given in Fig. 7 for both T2 and D2(T). For inductive plasmas, 27 beds are required T2 with one buffer vessel. This number is reduced to 12 for four vessels. For D2(T) the corresponding numbers are 43 for one vessel and 31 for four vessels. It is also observed that, compared to inductive and hybrid operations, non-inductive plasmas operations require fewer beds.

4. Alternatives

4.1. Fuel gases distributed in the Fuel Cycle

Analysis in the previous section assumed that all available inventory was returned from the fuel system systems to SDS as soon as possible. This resulted in the need for larger SDS capacity. As an alternative, it is possible to leave some inventory distributed in Fuel Cycle systems other than SDS. This was analyzed by considering that inventory could be held not only in the SDS buffer vessels but also in the ISS cryogenic distillation columns, the buffer vessels in the Tokamak Exhaust Processing (TEP), the cryopumps in VP, etc.

This analysis was performed for the case A/case C configuration (recycle flow not through SDS hydride beds). The required number of hydride beds for this configuration is given in Fig. 8. The number of beds increases slightly as the number of buffer vessels increases. This is due to higher minimum inventory associated with larger numbers of vessels. Compared with Fig. 7, however, the numbers are markedly lower, i.e. 27 to 7 for T2 and 43 to 12 for D2(T) for inductive plasma operation with one buffer vessel.

As the number of buffer vessels increases, the required flowrate from ISS or/and SDS beds can be decreased, but the amounts of fuel gases in the buffer vessels increases. This is an engineering trade-off that must be assessed.

4.2. Other considerations

In the analysis above, only numbers of fixed capacity buffer vessel and hydride beds were considered. And only one pump configuration was considered. However, considering safety, operability and other factors, future work will assess whether or not there is value in examining a broader range of design options.

5. Conclusions

An alternative analysis for the plasma fuelling function of SDS was performed considering the most recent understanding of ITER inductive, hybrid, and non-inductive plasma operations. This study examined impacts of these various operations on SDS. A mass balance model was prepared and run to examine various configurations of buffer vessels and hydride beds to meet plasma requirements. Results were quantified in terms of numbers of buffer vessel and/or hydride beds required to support operations. Consideration was given to accumulating all inventory in SDS and to utilizing Fuel Cycle capacity elsewhere in the Fuel Cycle. These values will be useful in making engineering decisions as the SDS design progresses.

The results of this study will also need to be considered together with broader design issues such as the storage and delivery requirements for neutral beam gas supply, supporting hydrogen-only and deuterium-only plasmas during the ITER DT phase, and controllability and operability of multi-bed/multi-vessel system.

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