Review of the ITER Fuel Cycle

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Abstract. ITER is a fusion tokamak, being fully designed for deuterium/tritium operation. The ITER Fuel Cycle consists of three major sections which are Vacuum, the Tritium Plant and Fuelling and Wall Conditioning. In general the Fuel Cycle supplies the fuel particles and impurities into the tokamak for stable plasma operation and processes all the exhaust gases from the Torus. The ITER Fuel Cycle must be capable of delivering, exhausting and purifying fuel particles (H_2, D_2 and DT) at rates that are orders of magnitude higher than have been done previously in industrial applications with fluids containing tritium. The plasma will be fuelled in the forms of hydrogenic ice pellet injection and gas puffing. The Fuelling system also provides hydrogen and deuterium to the diagnostics and heating Neutral Beam injectors respectively. The ITER vacuum pumping systems are used for initial evacuation, continuous maintenance of the required conditions in the torus, plasma density control and neutral particle exhaust. The Tritium Plant supplies deuterium and tritium from external sources and treats all tritiated fluids from ITER operation through Tokamak Exhaust Processing, Isotope Separation and Storage and Delivery Systems to remove and recover deuterium and tritium for refuelling. The Fuel Cycle also provides tritium confinement systems for the Tokamak Complex and the Hot Cell Facility. Confinement of tritium is achieved through multiple passive barriers and the use of active systems such as the Detritiation systems. Another challenging aspect for the Fuel Cycle is tritium accountancy and tracking. To satisfy safety criteria it will be necessary to track and trend the inventory within the vacuum vessel and other major Fuel Cycle systems. In order to perform this inventory measurement, tritium must be moved to hydride storage beds and measured. The ITER research plan encompasses four operational phases: hydrogen (protium), hydrogen / helium, deuterium / trace tritium and full deuterium/tritium operations. The Fuel Cycle systems are not all required to be available at the beginning; however each of the operational phases requires an increasing number of the systems to be available with increasing duties as time progresses in each phase. An initial coherent strategy to commission each of these systems as they are needed has been developed.

1. Introduction

The ITER Fuel Cycle consists of three major systems; Vacuum, Tritium Plant and Fuelling. . It can be further divided into 19 sub-systems as outlined in Figure 1. The Fuel Cycle supplies the fuel particles and into the tokamak for stable plasma operation and processes all the exhaust gases from the Torus. It must be capable of delivering, exhausting and purifying fuel particles (H_2, D_2 and DT) at an average rate of $200\ Pa{\cdot}m^3s^{-1}$ and peak of $400\ Pa{\cdot}m^3s^{-1}$, as well as supply inert gas s such Ne, Ar and N_2 with rates up to $100\ Pa{\cdot}m^3s^{-1}$ for radiating heat from the plasma. Such flows are orders of magnitude higher than have been done previously with tritium processes. This paper describes the major interfaces between these systems, the overall design status, schedule strategy and challenges associated with design of the ITER Fuel Cycle systems.

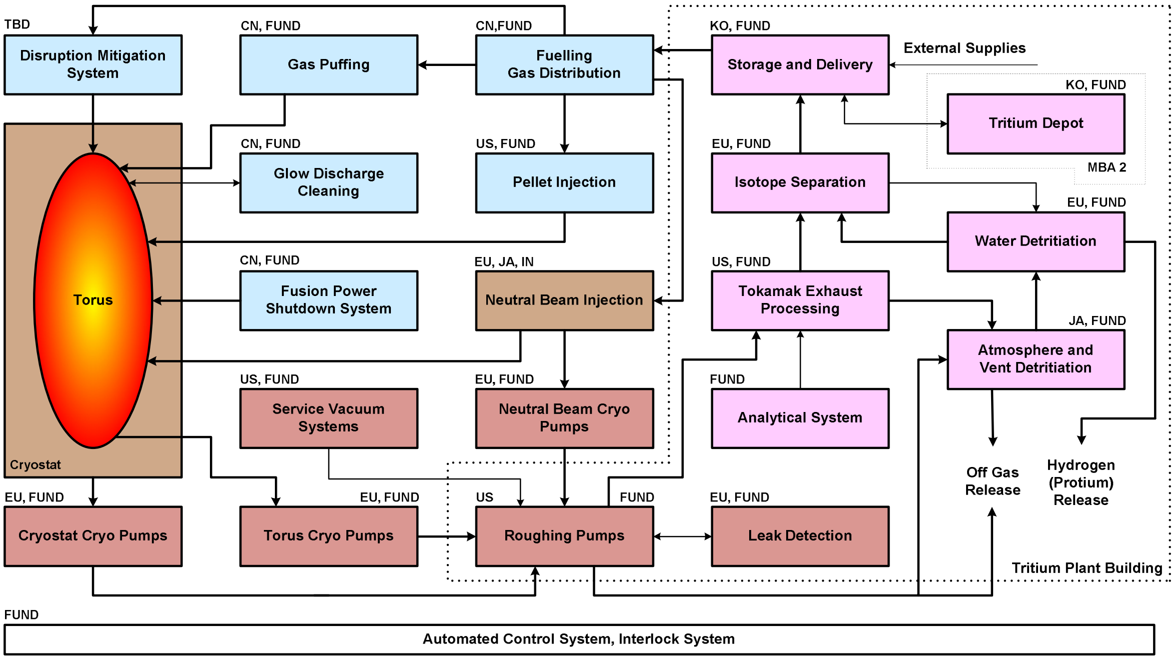

Figure 1. ITER Fuel Cycle Block Diagram

2. Fuelling and Wall Conditioning [1]

The ITER fuelling system forms a part of Fuel Cycle system and mainly consists of Pellet Injection System (PIS), Gas Injection System (GIS) and Disruption Mitigation System (DMS) as shown in Figure 1. The GIS and PIS are currently in the conceptual phase of design and the DMS is current in the pre-conceptual phase as it has not yet been baselined.
Each fuelling subsystem must fulfill the following functionalities for machine operation:

(1) Gas Injection System

- Injection of fuel gases for plasma density control and fuel replenishment for helium removal.
- Injection of impurity gases for radiative cooling enhancement, plasma detachment control and controlled discharge termination.
- Injection of minority species to improve RF H&CD coupling with plasma.
- Supply of H_2 or D_2 gases to the heating and diagnostics Neutral Beam (NB) injectors.
- Provision of wall conditioning gases.

(2) Pellet Injection System

- Injection of hydrogen isotope pellets for plasma density control.
- Provision of pellet injection into the edge plasma for control of Edge Localized Modes (ELMs).
- Injection of impurity ice pellet(s) into the plasma for studies of impurity transport and possible radiative cooling enhancement at the edge.

(3) Disruption Mitigation System

- Massive and rapid injection of particles into the Vacuum Vessel for disruption mitigation and suppression of runaway electrons.

2.1. Fuelling Parameters and System Configuration [1]

Tables I and II below compile the typical plasma fuelling and impurity injection parameters which the ITER fuelling system is designed to achieve. The DMS is described separately in Section 2.

TABLE I - PLASMA FUELLING PARAMETERS

Parameters	Unit		
Fuelling gas		^{3}He, ^{4}He	H_2, D_2, DT, T_2
Average/Peak fuelling rate for H_2, D_2, DT for gas puffing	Pa·m^3/s		200/400
Average/Peak fuelling rate for Tritium[1)] for pellet injection	Pa·m^3/s		111/111
Average/Peak fuelling rate for other hydrogen species for pellet injection	Pa·m^3/s		100/100
Average/Peak fuelling rate for ^{3}He or ^{4}He	Pa·m^3/s	60/ 120	
Duration at peak fuelling rate	s		< 10
GIS response time to 63% at 20 Pa m^3/s	s		< 1

1) 90% tritium + 10% deuterium.

TABLE II - IMPURITY GAS INJECTION FOR RADIATIVE COOLING

Parameters	Unit	Value
Impurity gases		N_2, Ar, Ne
Maximum number of impurity gases to be injected simultaneously		2
Average/Peak injection rate for each gas	Pa·m^3/s	10/100
Average/Peak simultaneous injection rate all gases	Pa·m^3/s	10/100
Duration at peak fuelling rate	s	< 10
Response time to 63% at 5 Pa m^3/s	s	< 1

The ITER fuelling system has the following configuration and is distributed around tokamak (Figure 2).

(1) Gas Injection System

- Upper port level: 4 gas valve boxes (GVB) to provide uniform toroidal distribution.
- Divertor port level: 6 GVBs at every 60° in toroidal direction.
- Dedicated manifold for fuel supply to the heating and diagnostic NB injectors.

(2) Pellet Injection System

- Three divertor ports, same as those for GIS, are allocated. (Each port is equipped with one PIS cask which can accommodate 2 injectors.)
- Two injectors will be installed for the beginning of machine operations.
- Six injectors will be available at the start of DT plasma operation.

(3) Disruption Mitigation System

- Two locations at upper port level are presently allocated.

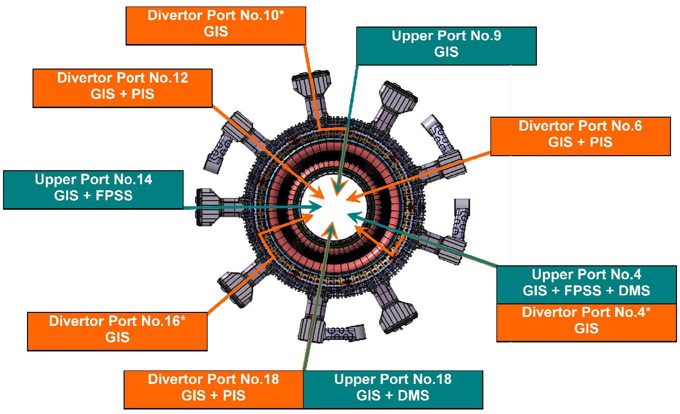

Figure 2. Toroidal distribution of tokamak fuelling

2.2. Disruption Mitigation System [1,5]

Mitigation of thermal and electromagnetic (EM) loads due to major disruptions, vertical displacement events (VDE) and runaway electrons (RE) is indispensable for machine protection in ITER. During the machine lifetime, these events are expected to occur roughly 3000, 3000 and 300 times respectively for disruptions, RE generation and VDEs. With each having the potential to cause serious damage to plasma-facing components, water cooling circuits, etc, it is critical that ITER be equipped with a sufficiently reliable mitigation system. This system must also ensure that its use does not lead to long periods of machine down time (to evacuate the particles which must be injected to mitigate the disruption). A reasonable recovery time of ~3 hours is currently specified. Physics studies are currently underway to define the DMS requirements and are being conducted in parallel with an engineering assessment of candidate systems. Table III compares 3 possible candidate systems – Massive Pellet Injection (MPI), Massive Gas Injection (MGI) and Massive Beryllium Injection (MBI) – from the engineering standpoint. Important elements to judge the feasibility of the system are: (1) environmental condition of the possible location of DMS installation, (2) gas load to vacuum system and tritium plant, (3) heat load to cryoplant, (4) repeatability and reproducibility of mitigation operation, and (5) safety concerns. Requirements on DMS, specifically impurity species and their quantities, have significant impacts on the Vacuum and Tokamak Exhaust Systems. Considering uncertainties in roughing pump design, and avoiding any impact on TEP design and operation, it is advised to avoid a prompt regeneration of torus cryopumps. This allows regulating the off-gas flow to the TEP. The following gas species and quantities seem not to require prompt cryopump regeneration: Ne - 40 kPa m^3; He - 40 ~ 50 kPa m^3 ; D_2 - 30 kPa m^3 (additional 20~30 kPa m^3 of Ne as mixture)

TABLE III - Comparison of advantage (+) and Disadvantage (–) of candidate DMS

Priority	DMS	Species & Quantity	Comments
1	Massive pellet injection (MPI)	Neon (40 kPa·m^3)	+ Less gas load to VS and TP due to high assimilation ⇨ Short recovery time and less heat load to cryoplant + Moderate environment in port cell for dedicated pellet injector + Easy to refill the gas + Easy to maintain (hands-on maintenance in port cell) – Not applicable for He
2	Massive gas injection (MGI)	Helium (500 kPa·m^3) or Neon (100 kPa·m^3)	+ Easy to refill the gas – Severe environmental condition in port plug (neutron and gamma irradiation, high magnetic field and high temperature) for dedicated MGI valves – Remote handling maintenance together with port plug – Higher gas load to VS and TP ⇨ Long recovery time and higher heat load to cryoplant
3	Massive beryllium injection	Beryllium (400 g)	+ No impact on VS and TP + Moderate environment in port cell dedicated for Be injector + Easy to maintain (hands on maintenance in port cell) – Beryllium dust issue – Tritium inventory and recovery issue – Refill of beryllium for repetitive injection

3. Vacuum System [2,3]

The ITER Vacuum System consists of a number of large or distributed vacuums including the torus vacuum, neutral injection vacuums, cryostat vacuum, cryogenic guard vacuum system, transmission line vacuums, and diagnostic vacuums. These are served by custom cryopumps (Torus (TCP), Neutral Beam (NCP), Cryostat (CCP)), and a mixture of standard and custom pumps in the Roughing Pump System (RPS), diagnostic, transmission line and Service Vacuum System (SVS). . In plasma operations the torus cryopumps operate in a fast regenerative mode cyclically pumping the tokamak and releasing the exhaust gas to the roughing system. In addition to the proven techniques for plasma density control it will be possible to control the neutral particle exhaust on ITER by varying the opening of the TCP's. All pumping systems apart from the cryogenic guard vacuum system discharge via the RPS to the Tritium Plant systems. Each of the vacuum systems fulfils the following functionalities to support machine operation:

(1) Torus Cryopumps

- Evacuation of the torus from the crossover pressure to the pre-bake base pressures.
- Pump-out of gases released from vacuum facing surfaces during baking and conditioning.
- Intra-pulse pumping to remove excess of fuelling gas, impurities and helium.

- Pumping between pulses to attain a low enough pressure for pre-fill and breakdown.
- Leak detection of Vacuum Vessel.

(2) Cryostat Cryopumps - Identical design to Torus Cryopumps.

- Evacuation of the cryostat to high vacuum prior to the cool-down of the magnet.
- Pumping of helium leaks
- Pumping of protium from outgassing metallic surfaces and gasses generated by irradiation of exposed epoxy (e.g. protium and alkanes).
- Leak detection of the Cryostat.

(3) Neutral Beam Cryopumps

- Evacuation of the Neutral Beams vessel from the crossover pressure to operation requirement base pressure.
- Pumping of excess gas and impurities during dwell time.
- Ensure the gas density distribution and the gas flow necessary for effective beamline operation.
- Pumping the gas that is fed into the ion source and the neutraliser for production of the ion beam.
- Controlling the pressure to minimise stripping losses.

(4) Roughing Pump System

- Roughing of the torus, Cryostat, NB, Service Vacuum System (SVS), diagnostics, transmission lines, from atmosphere,
- Evacuation of released gases from the torus, NB, and cryostat cryopumps during partial and total regeneration and from the Service Vacuum System (SVS) and Diagnostics.
- Sequential pumping/purging to dehydrate the cryostat internals prior to magnet cool-down
- Pumping of Torus, NB, Service Vacuum System or cryostat during leak testing
- Pumping of potentially wet volumes, to assist with drying following incident or air venting.

(5)Service Vacuum System is designed to provide vacuum service to more than 1500 clients:

- Interspaces of vulnerable components with double containment (double bellows, double seals interspaces)
- Systems requiring vacuum to operate (diagnostics, waveguides)

4. Tritium Plant Systems [4]

The Tritium Plant supplies deuterium and tritium from external sources and treats all tritiated fluids from ITER operation through Tokamak Exhaust Processing, Isotope Separation and Storage and Delivery Systems to remove and recover deuterium and tritium for refuelling. See Figure 3 for graphic depiction of Fuel Cycle and Tritium Plant systems interaction. Each of the Tritium Plant systems fulfils the following functionalities to support machine operation:

(1) Tokamak Exhaust Processing (TEP)

- Receive exhaust gases from Roughing Pump System
- Purify hydrogen isotopes through a combination of catalytic conversion of tritiated hydrocarbon compounds and permeation membranes
- Send detritiated ($< 7.4 \times 10^{-8}$ Bq/day) byproduct gases to Detritiation Systems for further processing
- Send purified hydrogen isotopes to Isotope Separation for further processing

(2) Isotope Separation (ISS)

- Receive purified hydrogen isotopes from TEP and Water Detritiation System (WDS)
- Separate hydrogen isotopes into three streams**,** 90% tritium/10% deuterium, deuterium/trace tritium, and protium
- Send separated streams to Storage and Delivery System and WDS

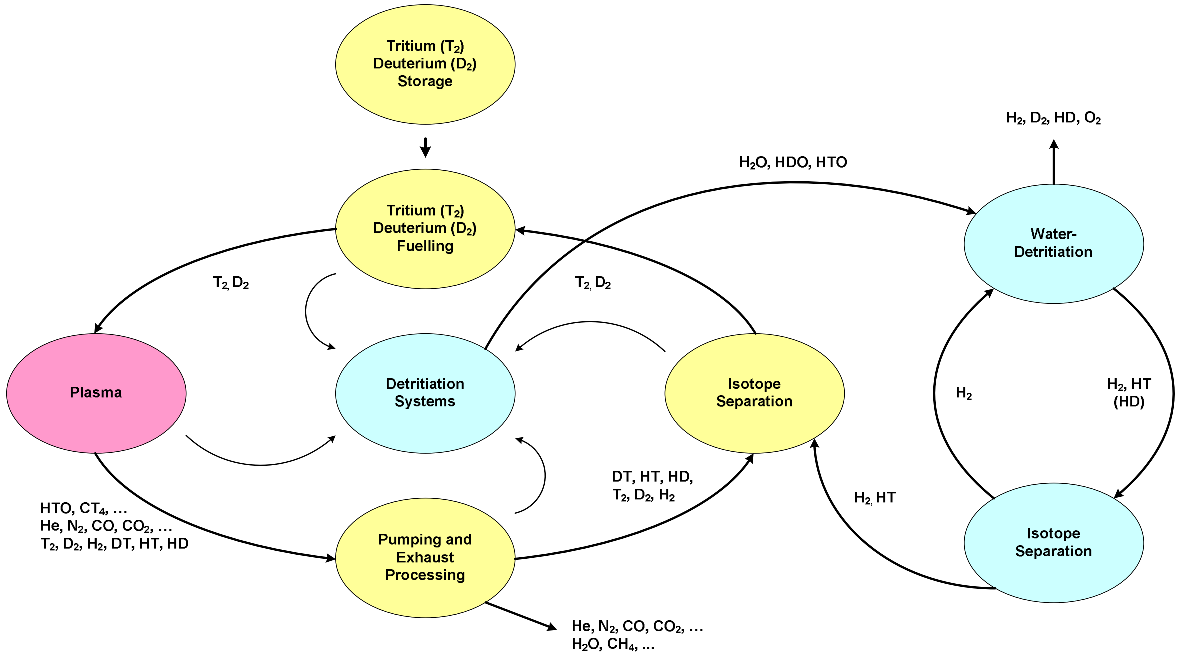

Figure 3. ITER Tritium Deuterium Loop

(3) Storage and Delivery (SDS)

- Storage of fuel gases (hydrogen isotopes) in metal hydride beds
- Delivery of fuel gases to the fuelling system (GIS, PIS)
- Delivery of other gases(Ar, He-3, He-4, Ne, N_2, H_2, CO and Ar/O_2) to the ITER systems
- Measurement of the tritium inventory in SDS
- Collection of the He-3 produced by the decay of tritium

(4) Water Detritiation System (WDS)

- Collection and Temporary storage of tritiated water produced by the Detritiation Systems (DS) and other sources during normal operation and maintenance of the machine and from other sources.
- Processing of tritiated water for tritium removal
- Enriching tritium from tritiated water into the gas stream to be fed to the Isotope Separation System (ISS)
- Discharge of decontaminated hydrogen and oxygen

5. Detritiation and Confinement Systems [4]

The Fuel Cycle also provides tritium confinement systems for the Tokamak Complex and the Hot Cell. Tritium diffuses and permeates through materials, the rate at which is temperature and material dependent. To address this, confinement of tritium is achieved through multiple passive barriers and the use of active systems (See figure 4). The passive barriers consist of process piping, jacketed vessels, guard or second barrier piping, gloveboxes, and building confinement sectors. The active systems consist of measures such as ventilation pressure cascades and detritiation systems. The DS is set up to maintain the cascade. Room detritiation is only utilized as needed and if it is called upon the HVAC to the affected room is isolated and the DS is brought online. The glovebox detritiation is continuous and the gloveboxes are also maintained in a negative pressure cascade with respect to the room. To address potential flammability issues, the gloveboxes are also maintained inert with a nitrogen atmosphere.

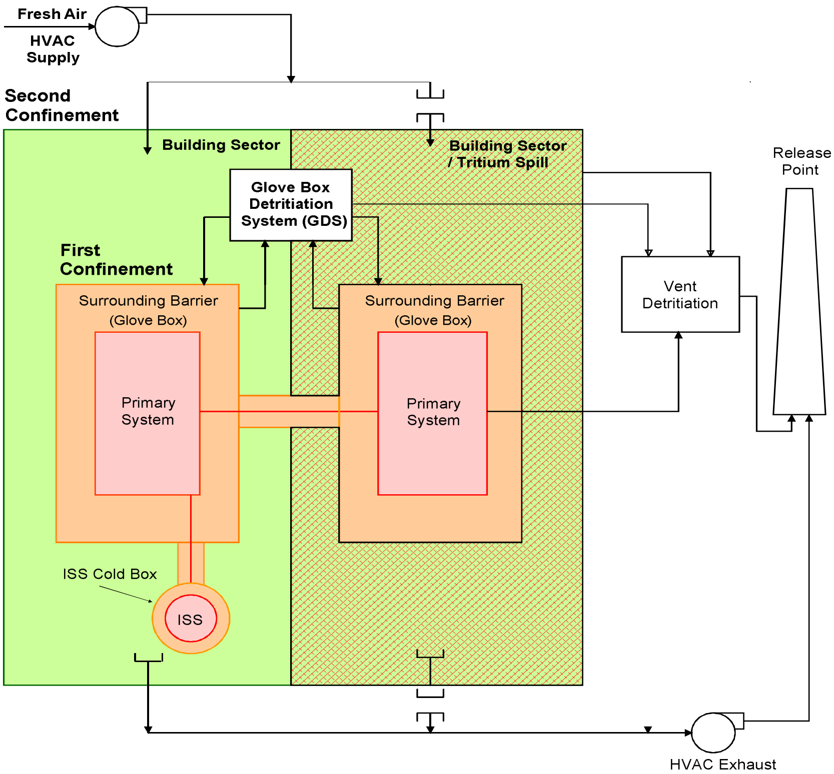

Figure 4. ITER Confinement Strategy

Detritiation Systems (DS) Functions:

- Detritiation of tritium process effluents, purge and vent gases, etc.
- Tritium confinement by maintaining a lower pressure inside the buildings and their parts than atmospheric pressure
- Together with the HVAC isolation and radiological trigger monitors, provide detection of tritium and mitigation of its impact on the plant, workers and general public

6. Tritium Accountancy and Tracking

Another aspect for the Fuel Cycle is tritium accountancy and tracking which is challenging due to the high tritium throughput. As stated earlier, the Fuel Cycle will be dealing with unprecedented flows of fluids containing tritium. To satisfy safety criteria it will be necessary to track and trend the inventory within the Vacuum Vessel and within other primary fueling components such as the Cryopumps, the Pellet Injection System, the Isotope Separation System and the Storage and Delivery System hydride storage beds. The components ofthe ISS, the PIS and the Cryopumps will have their tritium moved to the SDS. The residual inventory in the Vacuum Vessel will then be determined by difference. The hydride storage beds will utilize what is known as In-Bed Calorimetry. In order to perform this inventory measurement tritium must be moved to the hydride storage beds and measured.

Depending on the physical or chemical appearance of tritium, the following four categories can be classified: (1) tritium in process; (2) tritium retained; (3) tritium removed; and (4) tritium bred. The various categories of tritium require different measurement technologies or estimation methods. Tritium in process can be measured by In-Bed Calorimetry or *PVTc* measurements. It is a challenging to sample and measure tritium retained, which consists of tritium retained in the vacuum vessel, in retrieved divertor cassettes and dust, in processing pipes and components and in cooling water. Tritium removed includes tritium decayed, tritium burned by D-T fusion reaction (measured by neutron diagnosis), tritium released to the environments and tritium in solid waste and liquid waste. Tritium will be bred predominantly in the beryllium first wall and the amount will be estimated from neutron diagnosis and modeling; whereas tritium bred in the test blanket modules will be measured in its tritium recovery system.

7. Commissioning Strategy

The ITER research plan encompasses four operational phases: Hydrogen (Protium), Hydrogen / Helium, Deuterium / Trace Tritium and Full Deuterium/Tritium Operations. The Fuel Cycle systems are not all required to be available at the beginning; however each of the operational phases requires an increasing number of the systems to be available with increasing duties as time progresses in each phase. As the various systems come on line, the interfaces between these systems will change and so the challenges associated with the integration of these systems. An initial coherent strategy to commission each of these systems as they are needed has been developed, taking the changing requirements into account to support the ITER research plan. One of the challenges associated with this commissioning strategy is to address the appropriate time to introduce tritium into the fuel cycle and how quickly to ramp up the inventory. As certain systems are brought on line, there are cliff edge effects in terms of the amount of inventory required to operate them. For instance, prior to operation of the Isotope Separation System (ISS), tens of grams of tritium could be processed throughout the fuel cycle with great efficiency, but once the ISS is brought on line hundreds of grams will be required.

8. Summary of Design Progress

The Fuel Cycle of ITER is still in the early phases of design in most cases with some of the systems transitioning into preliminary and final design. The Gas and Pellet Injection systems are still in the conceptual design phase while the Disruption Mitigation System has yet to be accepted into the baseline and is still pre-conceptual. The Roughing Pump and Service Vacuum Systems are in conceptual design while the Neutral Beam Cryopumps and the Torus and Cryostat Cryopumps are in the final design phase. The Tritium Plant systems are all in the conceptual design phase with the exception of the Tokamak Exhaust Processing system which has just begun the preliminary design phase. The different phases of design presents challenges with interfaces and change control on the interfacing systems, however, ITER now has a well structured change control and design review process to track and maintain interfaces, especially with regard to changes.

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