2.7 Vacuum Pumping and Fuelling

2.7.1 Fuelling

2.7.1.1 Introduction

The fuelling system comprises a main gas supply system and a number of distribution systems i.e. the gas injection system (GIS), the pellet injection system (PIS), the local gas supply system for the neutral beam (NB) injectors and diagnostic neutral beam (DNB) injector, and the fusion power shutdown system (FPSS). The GIS is used for both plasma fuelling and the delivery of gases for wall conditioning. All gases are supplied to the various delivery systems from the tritium plant. Their system diagram is shown in Figure 2.7-1.

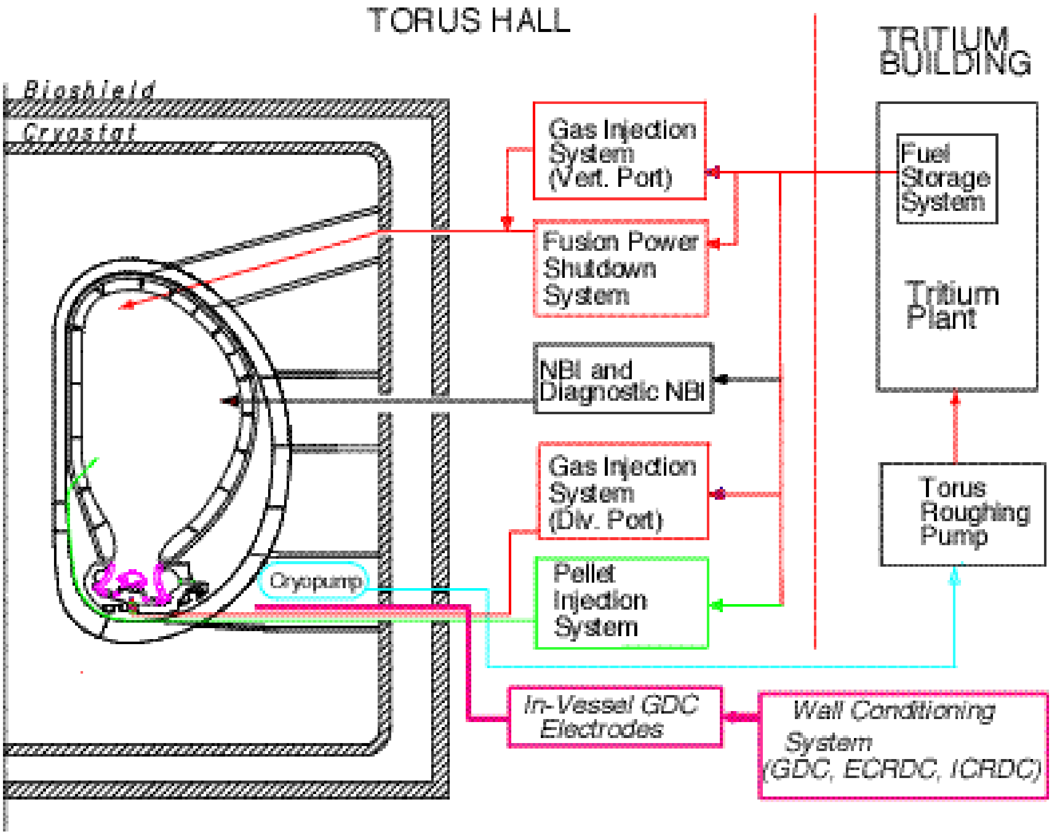

Figure 2.7-1 Fuelling system diagram

2.7.1.2 Main Gas Supply System

This system delivers all the required gases from the tritium plant. Six lines are used for the supply of plasma fuelling gases for the GIS and PIS, two of these lines also supply gas to the FPSS, and a further two lines supply the gases for the neutralisers and beam sources of the NB and DNB injectors. A common 50 mm evacuation line is provided to allow the recovery of gases from the various local gas supply systems by the tritium plant when not required, to pump and purge lines prior to the changeover to a different gas, and to allow the checkout of delivery systems during non-operational periods. The tritium plant provides this evacuation and purge function. The gases supplied to the various systems are from a common manifold that is routed from the tritium plant to the various distribution points around the bio-shield.

The plasma fuelling supply manifold comprises a single T_2 line and three impurity gas lines (typically Ar, Ne, and He) of 7 mm diameter and two lines of 16.5 mm (typically H_2, DT, and D_2). The lines are sized to provide a peak plasma fuelling rate of 400 Pam^3/s for D_2 and DT gas and 100 Pam^3/s for all other gases at a delivery pressure of 0.12 MPa. The total tritium inventory of the supply lines at this pressure with a 50/50 DT mixture in the 16.5 mm line and T_2 in the 7 mm line is ~ 10 g.
In addition to the above, two 7 mm diameter lines are used to deliver H_2 and D_2 gas to the NB and DNB injectors at a pressure of 0.6 MPa and to provide a minimum flow rate of 120 Pam^3/s.
All the above delivery lines are routed in a common secondary confinement line, nominally 150 mm diameter, rated at 0.6 MPa. The secondary confinement line is actively monitored for both internal and external leaks.

2.7.1.3 Gas Injection System

Plasma Fuelling

During plasma operations (H, D, DT and He) the GIS will be required to provide initial gas filling prior to plasma initiation, supply gas during plasma density ramp-up, control plasma density during steady-state burn, control the scrape-off layer (SOL), and to provide divertor heat flux control by radiative cooling (seed impurities). The system will allow the injection of up to six gases simultaneously, and will typically be used for three hydrogenic species and three impurity gases (e.g., D, T, DT, Ar, Ne, and He).

To provide flexibility for physics operations (e.g., between minimum neutral density in the main chamber and a strong plasma flow in the SOL), gas injection will be provided at two poloidal elevations, the top of the plasma chamber (upper port GIS) and in the divertor private region (divertor GIS). To minimise first wall erosion by charge exchange (CX) sputtering, the gas injected will be uniformly distributed toroidally at six discrete positions at the upper port elevation. The gas injection pipes at the top of the machine will end behind the blanket modules and gas will flow through poloidal slots (~ 1 to 2 m in length) to promote uniform flow and reduce local erosion due to CX sputtering.

The upper port GIS consists of six valve boxes evenly distributed around the outside of the biological shield. The valve box, nominally 0.51 m diameter x 0.66 m high, will be shielded against the magnetic field of ~ 0.1 T present in this location. The valve arrangement inside each valve box allows independent injection of up to six fuelling gases which flow into a common manifold before discharging into the plasma chamber through a single 10 mm discharge line. A 0.12 MPa rated isolation valve is used to isolate this manifold from the line connected to the torus, and a further isolation valve connects the manifold to the pumping and flushing line which allows each gas injection line to be pumped and flushed prior to changeover to a different gas. It also permits gas puffing tests for each gas species to be conducted during commissioning without using the plasma chamber (isolation valve to torus closed, isolation valve to evacuation line open). Incorporated into the upper port GIS valve boxes is the FPSS (2.7.1.4). The gas discharge manifold is routed from the valve box through the guard pipe to the upper port where it runs along the inside of the port and terminates behind the blanket module adjacent to the port. The length of the discharge line from the valve box to an area behind the blanket module is ~ 15 m allowing a fuelling response time of ~ 500 ms to be achieved.

At the divertor level, gas is injected into the divertor private flux region under the dome and into the divertor channels. Since the recycling fluxes are much lower in this region, local erosion due to CX sputtering is not an issue, allowing the selection of only three injection (toroidal) points at this location.

With the exception of the FPSS and the routing of the injection lines, the divertor GIS is identical to that of the main chamber GIS.

Wall Conditioning Gas Delivery

The GIS is also used for the injection of all gases required for wall conditioning. During discharge cleaning the GIS is operated in conjunction with the vacuum pumping system and provides a throughput of < 50 Pam^3/s for impurity removal. If wall conditioning with reactive gases is needed (for example, for the removal of co-deposited layers) then one of the impurity lines will be used for the delivery of this gas.

2.7.1.4 Fusion Power Shutdown System (FPSS)

The capability to inject impurity gases (e.g. Ne, Ar, etc.) into the torus is needed to provide an orderly shutdown of fusion power within ~ 3s so as to limit temperature excursions of the first wall and/or blanket following an ex-vessel coolant leak. Termination of fusion power within this time can be satisfied by the release of ~ 200 Pam^3 of impurity gas into the torus. This quantity of gas is provided by six gas cylinders, each charged with 1,000 cm^3 of the selected impurity gas at 0.12 MPa. The contents of each cylinder is isolated from the torus during normal operation by a 0.2 MPa positive shut-off valve which is opened on receiving a signal from the fusion power shut-down safety control system.

The gas cylinder, shut-off valve, a charging valve and a purge valve make up an individual FPSS mechanical assembly. Each one of these six assemblies is installed in one of the upper port GIS valve boxes. The isolation valve connects the gas cylinder to the common 10 mm discharge manifold of the GIS. Each gas cylinder is charged using the charging valve that is connected to the common supply manifold that also supplies the GIS. The purge valve connects the gas cylinder to the pumping and flushing line, also common to the GIS, allowing the cylinder to be pumped and flushed prior to filling.

2.7.1.5 Pellet Injection Fuelling

The pellet injection system will provide a fuelling rate of 50 Pam^3/s with 90%T/10%D pellets and 100 Pam^3/s for other hydrogenic species in the form of pellets of 3-6 mm diameter, sized to limit density and fusion power excursions to < 10%. The maximum repetition rate varies between 7 Hz for 6 mm pellets to 50 Hz for 3 mm pellets, and is available for pulse lengths up to 3,000s. Pellet speeds of up to 0.5 km/s, from the high field side, are considered necessary to achieve a penetration beyond the ELM-affected zone (~ 15% of minor radius).

Two injectors will be installed, providing not only operational redundancy but also the flexibility to use one of the injectors to deliver impurity pellets for physics studies. Each pellet injector will be capable of steady state operation and will consist of the following major hardware:

- a centrifuge pellet injector driver, for pellet delivery;
- a screw extruder, for pellet production;
- a gas feed manifold connected to the pellet injection gas supply system,
- a pellet injector cask housing the injector assembly (~ 6 m L x 4 m H x 3 m W);
- a single flight tube connected through a divertor port to the plasma chamber;
- a diagnostic, control and data acquisition system.

The pellet injector cask is similar to the remote handling casks, and will be moved by air cushions to allow transportation to and from the hot cell for maintenance. The cask will provide secondary containment for all the equipment located inside and be rated at 0.12 MPa. Divertor level ports 1, 7 or 13 are allocated for the pellet injectors, two for immediate use and the third fully equipped (excluding injector) for possible future use. The fuelling gas, cryogenic supplies, service vacuum, and electrical connections, are mounted on the rear of the cask allowing hands-on installation.

Each injector has a dedicated pumping system to keep the extruder, centrifuge and the flight tube under high vacuum. The guard vacuum of the injector is pumped by the guard vacuum system of the vacuum pumping system. The 5 cm diameter flight tube exits into the plasma chamber in the gap between two blanket modules on the high field side, after following the contour of the vacuum vessel below the divertor cassette. Outside the cryostat the flight tube is doubly contained, ending in a 0.12 MPa rated valve box which houses one 0.12 MPa rated isolation valve.

2.7.2 Wall Conditioning

2.7.2.1 Introduction

Wall conditioning will be used prior to plasma operation to remove water, oxygen and other impurities from the plasma-facing walls, to clean secondary surfaces not directly interacting with the plasma but potential sources of plasma impurities, to reduce hydrogenic gas recycling from the walls (desorption) during plasma start-up, and to minimise the in-vessel tritium inventory by the removal of co-deposited layers. The reference process for wall conditioning involves baking of all the in-vessel components to 240°C, glow discharge cleaning (GDC) without toroidal field using D_2 and He, and EC-DC or IC-DC (see below) with toroidal field using D_2 and He.

2.7.2.2 Baking

Baking will be undertaken following a vent of the machine to atmospheric pressure. The vacuum vessel will be heated to 200°C and the shield blanket, divertor, and other in-vessel components heated to 240°C by the primary heat transfer systems (PHTSs) of these components. Bakeout will be undertaken for a period of ~ 100 h until the total impurity pressure drops to < 10^{-3} Pa. At the completion of the bakeout cycle, the in-vessel components will be cooled to an operating temperature of ~ 100°C, at which time the total pressure for impurities will be < 10^{-7} Pa and < 10^{-5} Pa for hydrogen isotopes.

2.7.2.3 Glow Discharge Cleaning System

Based on the experience from present day tokamaks, a current density of > 0.1 A/m^2 will be needed for the effective removal of surface contamination. Adequate spatial distribution must be provided to achieve the toroidal uniformity of the GDC current needed and, in addition, sputtering of surfaces especially near to the electrode and of the electrode itself must be avoided. For ITER, with an accessible surface area of ~ 845 m^2, six electrodes extending ~ 1.25 m beyond the plasma-facing surface have been selected, with each electrode operating at up to 30 A.

The electrodes will be supplied from a constant current ~ 1 kV DC power supply located in the vacuum pump room. The working pressure during GDC is ~ 0.1-0.5 Pa and the discharge gases will be H_2 and D_2 for impurity removal, and He for degassing of hydrogenic gases absorbed in plasma-facing components.

2.7.2.4 Electron Cyclotron Resonance Discharge Cleaning System (EC-DC)

The required EC power for wall conditioning is estimated to be about 1 MW. Varying the toroidal field between 4 and 5.7 T between successive discharges allows the EC resonance to be swept across the plasma chamber. The working pressure during the EC-DC is in the range 0.01 Pa to 0.1 Pa and the working gases that will be used are D_2, He or O_2 similar to GDC. In ITER operation, EC-DC could be used between discharges as an option.

2.7.2.5 Ion Cyclotron Resonance Discharge Cleaning System (IC-DC)

The IC H&CD system can be used for discharge cleaning and will require a power of about 1 MW. The working pressure for IC-DC is about ~ 0.01 Pa to 0.1 Pa and the working gases are He or D_2. The use of IC-DC with helium gas is a potential candidate for wall conditioning between shots to remove weakly bonded hydrogen species on plasma-facing components.

IC-DC has also been proposed as a conditioning technique in high magnetic fields where high energy neutral helium atoms with 300 eV to 400 eV energies will be created. In this energy range, the desorption yield of implanted hydrogen species in plasma-facing components is large, and higher than that provided by GDC. However, this mechanism is probably insufficient for removing the co-deposited tritium.

2.7.3 Vacuum Pumping Systems

2.7.3.1 Introduction

The vacuum pumping system comprises the major systems listed below and the system configuration is shown in the Figure 2.7.3-1:

- roughing system;
- torus pumping system;
- cryostat vacuum pumping system;
- heating and current drive vacuum pumping systems;
- guard and service vacuum pumping system;
- diagnostic vacuum pumping system;
- leak detection systems.

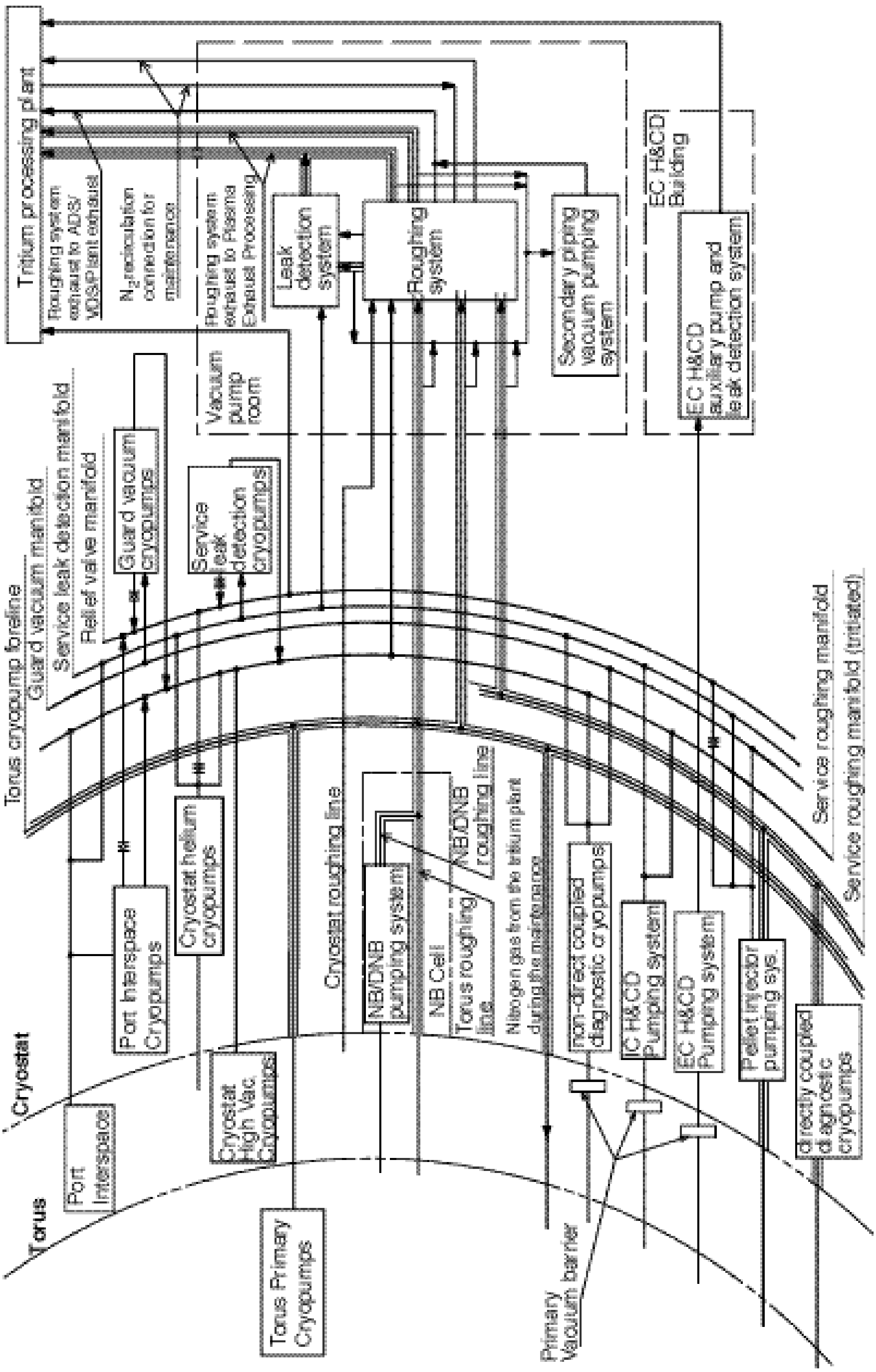

Figure 2.7.3-1 System Diagram of Vacuum Pumping System

2.7.3.2 Roughing System

The roughing system consists of a single integrated system which provides all major roughing functions. The roughing system comprises the following elements:

- four identical roughing pump sets;
- the roughing pump change-over valve box;
- the piping to the tritium plant.

The roughing system is used to evacuate equipment before crossing-over to a high vacuum pumping system, and for regeneration of cryopumps. The roughing system evacuates equipment from an initial pressure of 10^5 Pa to a base pressure of ~ 10 Pa. The primary functions of the roughing system are as follows:

- rough the torus prior to cross-over to the torus primary pumping system and evacuate each of the 10 (initially only 6 pumps may be fitted for short pulse operation) torus cryopumps during regeneration;
- rough the cryostat prior to cross-over to the cryostat high vacuum pumping system;
- evacuate the NB/DNB injectors during regeneration of their cryopanels;
- evacuate port interspaces and other miscellaneous volumes;
- regenerate guard vacuum and service leak detection cryopumps, and regenerate cryopumps for the cryostat high vacuum and cryostat helium pumping systems.

2.7.3.3 Torus Vacuum Pumping System

The torus vacuum pumping system comprises:

- the torus roughing line;
- the torus high vacuum pumping system;
- the torus venting system;
- gas re-circulation connections to the torus standby atmosphere detritiation system.

The torus high vacuum pumping system is used during plasma operations to pump the torus plasma exhaust consisting primarily of hydrogen isotopes together with helium and impurity gases. It also provides high vacuum pumping during all other phases of machine operation, including evacuation during dwell periods between plasma discharges, wall conditioning, bakeout and leak testing.

The design for the torus high vacuum pumping system is based on the use of up to ten batch-regenerating cryogenic pumps installed in the divertor level ports. These pumps are independently controlled to allow individual pumps to be regenerated, and to be shut down in the event of failure. A ring header, located at the lower magnet interface level, is used to connect the regeneration line of each cryopump to the roughing pumps. Mounted on the inlet of each pump is a valve that allows the regulation of pumping speed and also the regeneration of the pump when the inlet valve is closed. The inlet valve and its associated valve drive mechanism are an integral part of the vacuum vessel closure plug to facilitate remote maintenance.

The pumps are operated using supercritical helium at three nominal temperature levels: 4.5K for the cryopanel surfaces, 80K for the radiation shields and inlet baffle, and 300K to maintain the cryopump inlet valve below the vacuum vessel port temperature. The 80K radiation shield and inlet baffle provide an optically tight thermal radiation shield to limit heat transfer to the 4.5K panel. The 80K inlet baffle also serves to cool the incoming gas before it reaches the 4.5K cryopanel surfaces thereby reducing the heat load to the 4.5K surfaces.

The initial phase of tokamak operations will be limited to short pulses where six pumps are needed to meet pumping speed and throughput requirements. As operations progress, and the length of the pulse is extended, four additional pumps will be added to allow on-line regeneration during the pulse, and bring the total complement of pumps to ten. In either configuration the pumps will provide a throughput of 200 Pam^3/s, and a helium pumping speed of 60 m^3/s is needed to remove the fusion products produced under the various operating scenarios envisioned.

An operational limit is imposed by the hydrogen inventory that can be accumulated in a pump before regeneration is undertaken. This is to ensure that the pressure arising following a deflagration under any plausible combination of upset conditions is limited and can be contained within the pump. A deflagration could arise following the ingress of oxygen (water, steam or air etc) into the pump in the presence of an ignition source. The pump is designed to confine an internal deflagration pressure of up to 0.5 MPa without loss of confinement.

The six cryopumps initially installed will provide an accumulated pulse time of 400 s (short pulse) before regeneration is required, which will be undertaken during the dwell. To overcome the inventory constraint for longer pulses (steady-state) the complement of pumps is increased to ten, which allows on-line regeneration to be performed, while limiting inventories to acceptable levels. In this mode of operation six pumps continuously pump the plasma exhaust while four are in various stages of regeneration.

For short pulse operation each pump is regenerated during the dwell time. With a duty cycle of 0.25 this limits the complete regeneration sequence for all six pumps to 1,200 s for a 400 s pulse. Regeneration is undertaken sequentially on each pump with ~160 s being available for the process in this case. The maximum tritium inventory of all six pumps during short pulse operation when fuelled with a 50/50 DT mixture at 200 Pam^3/s is 88 g.

During longer pulses (> 400 s) a new regeneration sequence is started every 75 s (the incremental cycle time, T_{ic}) throughout the burn. The value of T_{ic} is dependent on a number of parameters which include the time needed to heat up and desorb the plasma exhaust gases (hydrogen and helium), the time needed for evacuation of the desorbed gases (sizing of the roughing system), the time needed for cool down (places demands on the cryoplant), and the accumulation of hydrogen and tritium inventories. Based on the results of earlier studies, a T_{ic} of 75 s has been selected as being a reasonable compromise for these parameters while satisfying deflagration limits. The total maximum tritium inventory stored in the cryopumps when fuelled with a 50/50 DT mixture at a fuelling rate of 200 Pam^3/s is 109 g.

The torus venting system is available to vent the torus at a variable rate and to any pressure up to atmospheric pressure. The venting gas used will typically be nitrogen delivered to the torus through the torus roughing line.

During maintenance activities, nitrogen gas will be recirculated through the standby atmosphere detritiation system in order to remove mobile tritium desorbed from the walls of the torus. Three equally spaced lines connected from the cryopump regeneration ring header to the divertor ports are used to carry the recirculating gas from the tritium plant to the torus. The torus roughing line provides the gas return path.

2.7.3.4 Cryostat Pumping System

The cryostat is pumped from crossover pressure to high vacuum using the cryostat high vacuum pumping system. This system consists of two cryopumps located inside the cryostat suspended underneath the cryostat lid. The pumps are cooled with single phase helium supplied from the cryoplant. They incorporate plain cryopanels (no sorbent coating) to suppress helium pumping, while pumping other gases species. This allows adequate cryostat pressure to be maintained during leak testing and prior to cooldown of the magnets. The net pumping speed provided by both pumps is 500 m^3/s for water vapour and 100 m^3/s for nitrogen. Regeneration of the high vacuum cryopumps is accomplished using the service roughing manifolds. These cryopumps are required only prior to and during cool down of the magnets. The fully cooled magnets provide subsequent pumping of condensables.

For helium pumping during all phases of operation, a pumping system that provides a helium pumping speed of 5.5 m^3/s is installed external to the bioshield on a duct located at the lower magnet interface level. Prior to cooldown of the magnets, the pumps are available for pumping helium but can be valved out while helium leak testing is being conducted. However, after the magnets are cooled the helium pumping system is available to pump small helium leaks from the cryogen lines inside the cryostat. This is necessary to ensure that the total pressure within the cryostat is maintained < 10^{-3} Pa to limit convective heating of the magnets and thermal shields.

2.7.3.5 Heating and Current Drive Vacuum Pumping Systems

NB Injector and Diagnostic Neutral Beam (DNB) Pumping System

Each NB injector and DNB injector module is connected to the torus via a fast shutter valve which does not provide an absolute leak tight isolation from the torus. For initial evacuation, the shutter valves are opened and the injectors are roughed down, together with the torus, using the torus roughing system. Upon reaching crossover pressure of the torus high vacuum system, the shutter valves are closed and the NB cryopanels are cooled down. During their regeneration, the shutter valve is closed and the beamline cryopanel warmed up while being pumped by the roughing system. With the shutter valve closed during regeneration, the leakage into the torus is ~ 10^{-2} Pam^3/s.

IC H&CD Pumping System

The IC H&CD system includes coaxial vacuum transmission lines (VTLs) which are open at one end to the torus vacuum and closed ~ 5 m away by double sets of 0.1 MPa vacuum windows. The annular space in the VTL on the vacuum side of the windows and the annular space between the windows must be maintained below 10^{-2} Pa to avoid arcing.

A pair of vacuum pumps will pump each VTL annular vacuum space. The pumps are non-evaporable getters, which will reside in the secondary volume between the vacuum vessel closure flange and the cryostat secondary closure plate. Each VTL has two pumps, but only one pump is active at any one time, if failure of this pump occurs the second pump is energised to continue the pumping duty.

EC H&CD Pumping System

The EC H&CD system consists of corrugated waveguides that are routed from the gyrotrons up to the torus equatorial and up to the upper ports. The waveguides are open to the torus vacuum at one end. A vacuum window is located at a position corresponding to the VV closure plate and an isolation valve is located at the cryostat secondary closure plate. On the torus side of the vacuum window the waveguides are pumped by the torus. The space between the window and the isolation valve is pumped together with the waveguide run.

LH H&CD Pumping System

A dedicated pumping system is not foreseen for the LH H&CD system. The neutral gas pressure in the waveguides of the LH launcher has to be < 10^{-4} Pa in order to maintain a good high RF power handling capability. The plasma provides adequate pumping at the mouth of the launcher to satisfy this requirement

2.7.3.6 Guard and Service Vacuum Pumping

Overall Configuration

The guard and service vacuum pumping systems are designed to provide common vacuum facilities for numerous users. These common services are provided by a series of vacuum manifolds that completely encircle the bioshield at the various levels of the machine with local connections provided for each individual user.

Service Roughing System

The service roughing system is used for roughdown of various volumes prior to cross-over to their respective high vacuum pumping systems and for cryopump regeneration. The vacuum system pressure varies as various pumps are regenerated and volumes evacuated.

Of the four toroidal ring manifolds installed, one of these, which is located at the equatorial level, will be dedicated to tritium service and used primarily for regenerating the cryopumps of direct coupled diagnostics (i.e. tritiated). The three remaining manifolds will be used for non-tritium service. All the ring headers are pumped by the main roughing system located in the vacuum pump room.

Guard Vacuum System

The guard vacuum system is used to provide pumping at locations where a semi-permanent vacuum is required and is designed to provide a pressure of < 10^{-2} Pa. Examples of guard vacuum applications include pumping cryostat double seal interspaces and pumping of diagnostics that require vacuum but are not connected directly to the torus. The guard vacuum is also used to allow continued tokamak or cryostat operations by differential pumping of the double seal interspaces of otherwise detrimental leaks. The guard vacuum pumping systems consists of three manifolds from which piping and valves branch off to the volumes requiring guard vacuum pumping.

Port Interspace Vacuum System

The port interspaces (i.e., the port volume between the vacuum vessel flange and the cryostat flange) are maintained at ≤ 10^{-2} Pa by a dedicated cryopump for each port. The use of a dedicated cryopump on each port is dictated by the prevention of cross-contamination. Cross-contamination could occur if a leak developed in the primary vacuum boundary or a divertor cooling line. With the selected configuration, each port interspace is completely separated from the others during operations since the cryopump foreline valves remain closed.

A manifold assembly located outside the bioshield and behind each vacuum vessel port is used to connect the port interspaces to the service roughing and service leak detection ring headers. A closed-cycle cryopump is mounted on the manifold to provide medium vacuum after the port interspaces have been roughed out

Service Leak Detection System

The service leak detection system is used to provide a permanent leak detection at locations requiring routine leak checking. Examples are the cryostat double seals, port interspace volumes, the guard and service vacuum manifolds, and the cryogenic valve boxes. Almost every volume requiring hook-up to the guard and service vacuum systems will also include a connection to the service leak detection system.

The piping and pumping configuration is similar to the guard vacuum system and consists of three independent toroidal ring manifolds. The ring manifolds are initially roughed down by the service roughing system prior to entering high vacuum operation.

The pumping system is identical to that of the guard vacuum services system except that the cryopumps do not contain charcoal-coated cryo-pumping arrays so that helium will not be pumped during leak detection.

2.7.3.7 Diagnostic Pumping Systems

The diagnostic pumping systems will be designed on a case-by-case basis as the diagnostic designs are further developed. However, a common design strategy has been developed.

The diagnostics can generally be divided into two types from a vacuum system design standpoint. A window separates the non-direct coupled (non-throughput) diagnostics (type 1) from the torus, whereas the direct coupled (throughput type) diagnostics (type 2) are connected directly to the torus vacuum. The type 1 diagnostics that require vacuum will be pumped, in general, by the guard vacuum system. Closed cycle cryopumps regenerating into the tritiated service roughing system manifold will be used to pump the type 2 diagnostics.

2.7.4 Leak Detection Strategy and Methods

2.7.4.1 Introduction

Plasma performance depends to a large extent on the impurity concentration within the plasma. Water molecules entering the SOL are decomposed and ionised causing a rise in the impurity level within the plasma with oxygen being of particular concern. The formation of < 0.1 monolayers of oxygen in a 24 hour period is one method that has been successively employed to establish an acceptable leak rate in a fusion experiment. In the case of ITER, formation of 0.1 monolayers in 24 hours equates to a leak rate of ~ 10^{-4} Pam^3/ s, which compares with 10^{-6} to 10^{-5} Pam^3/s for current machines due to the size difference[1].

Data from present tokamak operation shows that normal plasma performance can be maintained with leak rates in the 10^{-7} to 10^{-5} Pam^3/s range. Within this range, some machines have also reported a gradual deterioration in leak tightness with time (age) with no noticeable deterioration in plasma performance. From the above, and the relative volume, it can be concluded that a leak rate in the 10^{-6} to 10^{-4} Pam^3/s range would not result in a deterioration of plasma performance in ITER.

Another important quantity influencing plasma operation is the impurity base pressure after baking and conditioning resulting from outgassing and possibly leaks. Given the installed pumping speed (160 m^3/s) the total impurity gas load (outgassing plus leaks) must not exceed 10^{-5} Pam^3/s. This would require both the outgassing rate and the leak rate to be in the 10^{-6} Pam^3/ s range. Adding some safety margin leads to an integrated global leak rate of 10^{-7} Pam^3/s, which is therefore the one specified for ITER.

The goal of the leak detection strategy is therefore to guarantee that the leak rate inside the primary vacuum boundary, in operating conditions, shall not exceed 10^{-7} Pa m^3/s.

2.7.4.2 General Strategy

Due to the fact that ~1,000 individual components reside within the primary vacuum boundary, the sensitivity of leak checking on the component level prior to installation in the machine (e.g. in the factory or, if subassembly takes place at the ITER site, at the sub assembly level) should be ~ 3 orders of magnitude better than the global leak rate requirement, i.e. < 10^{-10} Pam^3/s. This leak rate should, however, not be interpreted as the acceptable leak rate for each component. The policy for acceptance must be "if there is a detectable leak fix it". The acceptance of "unfixable" leaks in components must be controlled on a global basis to ensure the global vacuum integrity is not jeopardised. At installation (e.g. installation welds on water cooling pipes inside the machine), a similar detection sensitivity of < 10^{-10} Pam^3/s should be achieved if possible and the same controls applied as with the acceptance of individual components. A special case in this respect is the VV, where leak checking will be performed after subassembly of 2 sectors (in the assembly hall) but the above sensitivity may not be achievable at that time. A global leak check with the fully assembled vessel prior to, as well as after, baking with all in vessel components installed will have to be done, most likely with reduced sensitivity.

[1] All leak rates reported in this section are to be intended as equivalent He at 25 C.

To check the above strategy and the required sensitivities one can also use the experience on present day machines. The most complete source of information available on component leaks during operations has been prepared by JET, and of particular interest are the leaks that developed in welds during operations. In this category, leaks were recorded in 0.7% of 1772 installed items over a six year operational period with leaks in the 10^{-9} to 1 Pam^3/s range. This compares with 1.2% that occurred during the assembly phase. Unfortunately the concurrence of individual leaks is not reported.

Using the 1.2 % and the 0.7% failure rate exhibited by JET during assembly and operations, respectively, as a guidance this would indicated that a decrease in the commissioning test sensitivity from 10^{-10} to 10^{-8} Pam^3/s, after assembly is complete, would be reasonable. This relaxation would allow a more flexible selection of leak detection tools, the potential for wet leak testing, and provides shorter times for localising leaks. A similar sensitivity should be the goal for leak checking during operations or during re-commissioning after large maintenance shut downs.

In contrast to existing machines, the ITER VV is embedded in a cryostat vacuum vessel which also needs to be leak checked. In principle the same strategy and also the same tools (see below) will be applied but some special features exist. There are three phases of leak checking in the cryostat: the pump down phase, the coil cool down phase, and the operation phase with cold coils. While, during the pump down phase, air leak checking problems are similar to those inside the VV and limited hands on access may exist under certain circumstances at least for initial commissioning, the other two operation phases are somewhat different. Due to the cool down of the coils, the air leak checking system is increasingly competing with a large pump, and helium leaks may just occur due to the cool down. Therefore the leak checking system will have to use accumulation methods (charcoal coated cryo-pumps) as well as He leak checking. This is in particular true for the operation phase where the coils are at 4.5 K.

Port interspaces (i.e. the space between VV flange and the cryostat flange in each port) have their own pumping systems and are also connected to the central leak checking station. Again He spray facilities (most likely to a large extend hands on) will be used to find leaks there.

Following the above general strategy, it is clear that leak testing must be a part of the initial commissioning procedure for all vacuum components, and have the following objectives:

- locate and fix all detectable leaks to the greatest extent practical, with all leak testing conducted dry, and at the highest achievable sensitivity;
- test and catalogue the global leak rates of all components at their lowest testable (sub system) level i.e. water-cooled components at the sub-circuit level (this will use a similar He leak checking strategy to that described below);
- commission, check out, and calibrate specially installed leak test equipment to confirm performance by using simulated leaks (all equipment will have to be tested and from time to time re-calibrated by using calibrated leaks - dependent on the equipment this will have to be done for the global leak checking system as well as e.g. RGAs, etc.);
- commission and check out of leak test scenarios applicable to all phases of operation by using simulated leaks (although this may not be practical in all cases it should be done for some components by introducing a calibrated leak (possibly a reservoir filled with air) and then seeing if the methods work in the machine environment);

During initial commissioning, hands-on access will be available (at least on the subcomponent level prior to installation) allowing the highest possible levels of sensitivity to be achieved. However, also a full shake-down of equipment and procedures that will be needed for all remote leak testing has to be performed at this stage. In particular, after assembly is complete, leak checking inside the VV and for the cryostat will need to be done partly by remote tools anyway due to the size and complexity of the machine.

During this initial commissioning phase, the detection sensitivity and the allowable leak limit for individual components at < 10^{-8} Pam^3/s to < 10^{-10} Pam^3/s, depending on the component, is considered both reasonable and achievable.

Further commissioning and possible improvement of the remote leak checking tools will be possible during the hydrogen operation phase. In this phase, while hands-on access will still be available, remote leak detection techniques and leak test scenarios should be applied to the maximum extent possible in preparation for later DD and DT operations.

During DD and DT operations only remote leak detection techniques and leak test scenarios can be used inside the VV and to a certain degree also inside the biological shield. It is almost certain that during commissioning the levels of sensitivity achieved hands-on (assisted), and with dry components will be higher than can be achieved using "remote" techniques and in particular with wetted components. Nevertheless, the sensitivity for leak detection for each individual component during operation should be < 10^{-8} Pam^3/s, which is most likely achievable for the majority of the components

2.7.4.3 Testing Methods and Installed Equipment

Available leak detection methods for the VV and the in-vessel components are divided into two groups: vacuum methods and methods that require venting of the machine. As already mentioned, the same or similar methods will be applied to the other vacuum systems. The main advantages of vacuum methods is that there is no need of the torus to be vented but application of these methods is restricted to identification of leaks up to ~ 10^{-1} to 1.0 Pam^3s^{-1}. The second group of methods are used at atmospheric pressure and can be applied both for small and large leaks. While, during commissioning, in some cases conventional hands-on He leak checking can be performed also for the in-vessel components, the issue for ITER operation is to find remote methods capable of detecting and localising leaking water cooling circuits inside the VV within an acceptable time frame. In the following paragraphs the main methods and the required tooling are briefly outlined.

A leak in a cooling circuit (the most likely type of leak) or generally inside the VV, will be detected by the global leak detection system. It consists of a leak checking station located in the vacuum pump room which is connected via the torus roughing line to the machine and which monitors the torus vacuum virtually constantly (checking the exhaust gas from the cryo pumps). Similarly the other vacuum systems are connected to a global leak checking station which checks the exhaust gas of all high vacuum pumps with the exception of the cryostat, which is connected via special accumulation cryopumps (long accumulation times) to its leak checking station.

Leak Localisation by Visible Spectroscopy

If a leak detected in the VV is sufficiently small to continue plasma operation or to engage a glow discharge then a spectroscopic method for leak localisation using the plasma wide angle viewing system may be used if the sensitivity of the system will be sufficient (R&D in progress).

In ITER a spectroscopic in-vessel viewing system which covers ~ 90% of the surface is foreseen, aimed at giving first hand visible observation for the machine operators during plasma operation as well as to monitor certain impurity lines by utilising band pass filters and surface temperatures by infrared spectroscopy. Employing further remotely changeable narrow band pass filters will allow the selection of a spectroscopic emission line of neutral oxygen on this system. This will possibly enable detection of a cloud of increased oxygen light around the leaking component. Pending further R&D, it is expected that a leak of < 10^{-6} Pam^3s^{-1} can be localised within a few m^2, which would thus provide a relatively fast way of pinpointing e.g. a few suspect blanket modules or divertor cassettes or port plugs, i.e the components most likely to develop leaks. This method could be used to localise leaks in a pressure range between 10^{-7} Pa and 1 Pa.

Spiking

Spiking describes a method where a chemical additive which can be easily identified by an RGA (residual gas analyser) is supplied to a sub-loop of the cooling water circuit (typically at the ppm level) in order to identify which system (e.g. divertor, blanket, VV, port plugs….) or which sub-loop of a system is leaking. This will be the reference method employed to pinpoint leaks at the system and subsystem and in some cases even at the component level. The advantage of this approach is that it does not need draining and drying of the water circuit and, depending on the number of components connected to a given sub-loop, is able to provide a rough localisation of the leak.

The major requirements for the spiking element to be added is:

- not to poison the cryopumps;
- not to cause corrosion in the water circuit;
- not to be one of the major outgassing species;
- sufficient vapour pressure at 100 C;
- sufficient solubility in water;
- sufficiently stable in a fusion environment (e.g. high level of γ radiation);
- readily removable from the vessel
- easily removed from the cooling loop after completion of the test;

Both inert gases and water-soluble compounds are potential candidates for these additives. Inert gases meet nearly all requirements for a spiking element, but their major drawback is their very low solubility in water which will significantly reduce the level of sensitivity that can be achieved. In the case of e.g. krypton, which has one of the highest solubility levels, this is 10^{-5} mole fractions at 50˚C. Whereas the soluble mole fraction for alcohol, one of the water soluble compounds that are being considered, varies from 10^{-4} to infinitely soluble. Outstanding R&D results will determine which of the many possible spiking additives can be used and also which will provide the required sensitivity. For the successful use of spiking, either a few (<4) different substances are needed, or a fast cleaning (reduction by > 1 order of magnitude) of the tested circuit from the spiking substance has to be possible.

Accumulation method

In the case when the concentration of the tracer element is low, accumulations of leakage gases over time will be required in order to obtain the threshold level of the leak detector and thus detectable readings. The cryopumps are used for this procedure and the regenerated gases are analyzed by the RGA, evaluating the gas content accumulated over the pumping time. The average leak rate can be calculated by dividing the gas content by the pumping time.

The accumulation method could also be used to roughly localise leak sources by using the geometrical features of the pumping system. This modified method compares the integral amount of water or spiking additive in each of the toroidally placed cryopumps during their regeneration, thus allowing the identification of the most likely toroidal quadrant where the leak is located. The sensitivity of this method is determined by the time of integration (pumping time). A model using a Monte Carlo approach was employed to evaluate the different particle fluxes into each cryopump (Fig. 2.7.4-1). The difference in particle flux ranges from 3 to 4 which allows at least the quadrant to be identified and thus reduces considerably the area required to be checked.

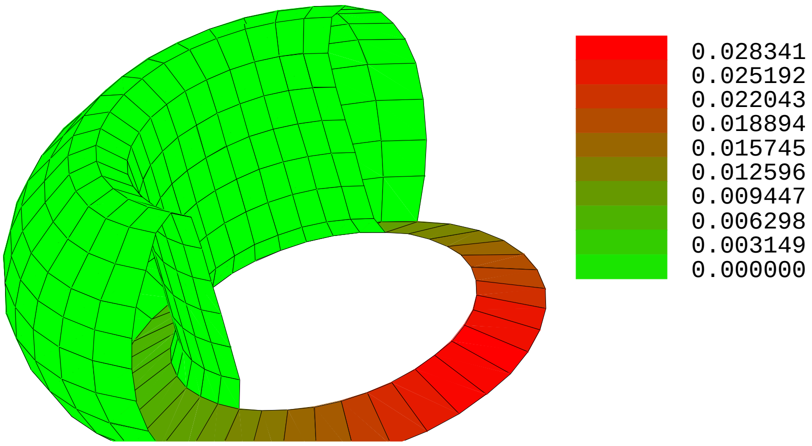

Figure 2.7.4-1 Difference in Particle Flux Ranges

Laser methods

The existence of a substance (e.g. water or tracers) can be detected through absorption of lines in the UV to IR spectral range since these lines are specific for each material. Both water and also some tracers can be detected by measuring the degree of absorption of the substance. A laser source is particularly convenient for this purpose due to the good controllability and its narrow oscillation lines.

Laser spectroscopic methods that can be applied for gas density measurements are differential absorption lidar (DIAL) and tuneable laser absorption (TLDAS). The DIAL method is based on the comparison of the absorption of two wavelengths: one has a high absorption coefficient and the other one a low absorption coefficient. The TLDAS method is based on the detection of the varying light intensity when the light is passing through the suspected area by sweeping the laser wavelength around the absorption line of the suspected substance.

For the DIAL method, CO_2 and H_2O are considered as probe materials, in the case without and with water, respectively. For CO_2, a leak > 20 μm diameter (10^{-5} Pam^3/s) is theoretically detectable, while a leak > 5 μm diameter can be theoretically detected for H_2O. For TLDAS, a leak >8 μm diameter (10^{-6} Pam^3/s) can be theoretically detected with water as the target substance. Both of these methods require a view through the cloud of e.g. water escaping a leak or being reflected back and then detected by the spectrometer. Therefore it may be difficult to use these absorption methods on ITER.

Another possible laser method is laser-induced fluorescence (LIF), which is based on the detection of light emitted by the target substance after exposure to laser light. A theoretical estimate shows that leaks of > 4-6 μm diameter (10^{-7} Pam^3/s) are detectable by the LIF method when using NO gas without cooling water in the circuits. In the case of using Rhodamine 6G (Rh6G), leaks of >1 μm diameter (10^{-9} Pam^3/s) are theoretically detectable.

Laser methods seems to be sensitive enough for a precise localization of leaks and can be theoretically applied at the last stage of the leak checking process. However, extensive R&D is needed before this technique can be applied to ITER.

Leak Localisation by Movable Water Sensors Under Vacuum

In cases where the number of possible sub-loops is small and so the identification of a sub loop by spiking is not sufficient to pinpoint the leak, additional tools can be employed, such as a movable RGA. This method requires the surface of the component to be scanned using a vacuum sensor such as a vacuum gauge or RGA head. Preliminary tests, using a uni-directional vacuum gauge, indicated that 10^{-6} Pam^3/s levels of leaks could be detected with about 1 m between the gauge head and the leak source. The sensitivity of the method depends strongly on the accessibility of the target components by the mounted sensor head. Reducing the distance between the head and the target is a key to improved sensitivity. Presently a "snake arm" which could carry such a sensor is under investigation. This snake arm will be deployed under vacuum from a cask which can be connected to the VV at the divertor level. Since the casks can be connected to the machine at 6 equidistant locations, such a snake arm can reach all in vessel surfaces with a lightweight tool such as an RGA or vacuum gauge.

The above methods conclude the available tools for leak checking under vacuum and without complete draining and drying of the water cooling circuits.

Leak Testing with He in Vacuum and at Atmospheric Pressure in the Vessel

This type of tool will be used to find leaks which are too large to be compatible with vacuum conditions needed for the above methods or will be used to further pinpoint the location of leaks after the above methods have been applied. In cases of large leaks, pressurising the different sub-lops and monitoring the pressure drop and the water leakage rate will allow the identification of the cooling loop responsible. Thus this approach is the equivalent to spiking for large leaks. In order to localise the leak more accurately than with any of the above methods, conventional He leak checking methods have to be applied albeit under rather severe boundary conditions (remote tools needed). To this end, the water containing loop, which has been identified by the above tools, needs to be completely drained and dried before He leak checking can commence.

There are two possible approaches for He leak checking. The first one is after draining and drying to evacuate the water pipes and to rout the exhaust gas to the leak checking station as well as to use a movable tool, e.g. the snake arm, to spray He at the suspected components inside the VV as one would do with hands-on leak checking. The second is to pressurise the water pipes with He gas and to use sniffers or hoods on each of the suspected components, again using the snake arm, and routing the exhaust gas to the leak checking station. The surplus He will be removed by the cryo-pumps (half of the pumps operate at 4.5K and mostly with closed inlet valves, and half of the pumps at > 20K, i.e. without He pumping) in the case of testing in vacuum. In the case of larger leaks, where testing has to be done in atmospheric pressure, the MDS system will remove the surplus He. As the sensitivity of the sniffer method is in most cases 1 to 2 orders of magnitude lower than one using the leak checking station for pumping the pipes and spraying He from the plasma side, special mechanical enclosures enriching the leaking He around the most sensitive areas, such as e.g. branch pipe welds or divertor cooling pipe welds, may have to be installed. The use of specially built hoods, e.g. for the blanket modules, is not practical due to the complex and different shapes of the in vessel components.

Because of the higher sensitivity and flexibility the most attractive approach from a leak checking point of view would be to evacuate the water pipes and to use a RH tool to move a He spraying gun along the suspected components. However, even if the components are dried, there might be sufficient dirt and water vapour left in the system and also the large gate valves used to close off the cooling manifold may not be sufficiently leak tight to use this method. Therefore sniffer-based methods may have to be employed and are foreseen.

In general, the equipment selected is commercially available although some adaptation and re-configuration will be needed to use it in ITER. The equipment identified above for the various leak detection tasks will, in combination, cover the wide pressure ranges that will be needed. These tools will thus permit gross leak testing, performed in the roughing regime at high pressures, and fine leak testing performed under high vacuum conditions. In the fine leak testing range the sensitivities specified will be achievable, i.e. for the torus, individual leaks of > $1x10^{-8}$ Pa m^3/s.

2.7.5 Procedure of Leak Localisation in ITER

In order to understand how the above described leak checking methods are applied practically in ITER, the available general leak checking methods have to be translated into a leak checking procedure for each component taking additional boundary conditions such as repair methods into account. Therefore, besides the choice of leak checking tools to find the leak, how long it will take to localise and repair is also important. The permissible localisation time must be seen in relation to the repair time, which in most cases will be several weeks or even month. Therefore the choice of leak checking tools and the adaptation of the component design to leak checking should be such that a leak can be localised within a small part of the repair time, i.e. in most cases within several days to a few weeks.

2.7.5.1 Design Features Required for Leak Checking

The design of components must take full account of the leak detection techniques that are to be implemented to ensure that a plausible overall leak test strategy is developed. For example in order to be able to perform spiking on sub-loops with only a few blanket modules connected to it, the appropriate valves and spike additive supply lines have to be implemented in the design. To this end the following provisions are foreseen in the design of the cooling manifolds. The blanket is anyway divided into 3 large cooling loops each serving ~1/3 of the blanket. In each of these loops at each machine sector 8 pairs of feed and return pipes are supplying 2 to 4 modules each. The divertor has only one cooling loop but can be divided into 3 large subsections (3 large feeder pipes). Each of these feeder pipes serves 18 cassettes from where sub-loops serving 3 cassettes each branch off. The port plugs are cooled by two separate loops, one connected to the same secondary heat exchanger as the VV (cooling the VV flange and the plug) and one connected to the blanket cooling system (cooling the blanket section of the port plug). Each port plug / flange and blanket section of the plug is a sub-loop and means to separate them are foreseen (see below).

To be able to perform spiking, as well as draining and drying, the following additional connections and closure valves are provided. The spiking additive is added by a small pipe and valve to each of the main cooling manifolds of each of the three blanket, one divertor, the two VV and the two port plug cooling systems. The draining and drying is also performed by a system connected by 2 pipes and valves to the main cooling manifold of each heat transfer system. As the draining plant can only blow out 4 blanket modules and 3 divertor cassettes and one port plug (blanket part or flange / plug part, see 3.3) and as the drying plant can only dry 1/3 of the divertor as well as the blanket modules of one machine sector or one port plug, additional means of separating each sub-loop are implemented.

Two principle possibilities for sub-loop isolation exist, namely to use ice plugs or valves. The ice plugs would be the preferred method because they are simple, relatively cheap and have no mechanical components. However, they are unsuitable for high pressure and thus unsuitable for separating the sub-loops during the blow-out required for draining. Due to this incompatibility, valves are foreseen on each sub-loop inlet pipe. Most likely the spiking additive will not diffuse down the return pipe when the feeder is valved off, therefore no valves need to be installed on the return pipes. However, ice plugging at the returns will be needed during blow-out and may be used during other times as long as the after-heat from the components can be removed.

2.7.5.2 Leak Checking Procedures

Due to the complexity of the in-vessel components, in situ repair for e.g. blanket modules, divertor cassettes, port plugs, port limiters etc is impractical, and repair must be achieved by component replacement. As a result, there is no need to pinpoint the leak on a particular component except for the cooling connections (e.g. branch pipes) and it is thus sufficient to identify the source of the leak to the component level. In some cases it might be even quicker to replace say in the order of 2 to 4 blanket modules instead of introducing more elaborate methods to localise the leak further. More studies are needed to understand the optimal approach. For other components, e.g. the vacuum vessel, the port extensions, etc., are permanently installed, and removal for repair is not an option. There, in-situ repairs must be made and thus the leak localisation has to be more accurate, i.e. the leak has to be localised down to the cm^2 level. With these two distinct types of components, therefore, somewhat different leak checking strategies are dictated. In situ repair will be only possible with draining and drying, and subsequent He leak checking.

To better understand how leaks can be found and repaired in ITER a small leak in a blanket module is taken as an example. A leak will be detected by the global leak checking system which monitors the in-vessel vacuum. It will not be clear which component is responsible for this leak. Therefore the first step is to distinguish in which major system the leak is, i.e. in the divertor, in the Blanket, in the port Plugs or in the VV. This can be done by supplying the same spiking additive successively to each of the major cooling loops (3 for the blanket, 1 for divertor and limiter, 2 for the VV and 2 for the Port Plugs) and to monitor the response of the RGA. In case of large leaks, pressure variations will be used instead which should also identify the main cooling loop.

Leak Checking Procedure for the Blanket

Supposing that a small leak is discovered in one of the 3 major blanket cooling loops, the next stage will be to concentrate the testing onto this loop. There are two possibilities: either to use the spectroscopic approach or to go further with spiking on the sub-loop level. Assuming that the spectroscopic approach is not sufficiently sensitive in this case, the next spiking step is to add a different additive (from the one used to identify the main system) to subsequent sub-loops of the leaking main cooling system and to check with the global leak checking system whether this particular additive can be detected, using direct as well as accumulation techniques (if higher sensitivity is needed). Initially all sub-loops will be valved off and opened one after the other, circulating the water containing the new spiking additive at low speed. The water circulation time will be in the order of 500 s and up to the same time may be needed for checking if the additive shows up in the global leak checking system in particular if the accumulation method needs to be used. So each sub-loop will require in the order of 1000 s to be checked, i.e. ~ 30000 s or ~ one working day to check 1/3 of the blanket.

This method should finally be able to identify the leaking sub-loop and its 2 to 4 blanket modules. Again several methods could then be applied to localise the leak further, namely to use a vacuum water sensor head (RGA), which is remotely operated (by the snake arm) or to drain and dry the sub-loop and commence with He leak checking. The sensor head method will be tried first and if the leak is localised at a particular blanket module or at its branch pipe weld, leak checking is finished and repair can start. Assuming that the sensitivity of the sensor head (10^{-6} Pa·m^3/s) is not sufficient and thus He leak checking will have to be applied, after draining and drying the sub-loop it will be pressurized with He and e.g. the snake arm will be used to move the sniffer over the suspect modules. Possibly only the weld connection should be checked by this method. It is not clear if the design and the sensitivity (in terms of time delays) will be sufficient to distinguish between a leak in the water connection and in the module in all cases. But if the leak is on the FW there should be a distinguishable time delay between sniffing the front of the module and inside the hole for pipe welding and cutting access. If the leak is identified at the pipe connection, re-welding could be tried without the need to remove the module. Otherwise the module will be removed and leak testing on it will commence in the hot cell to clearly identify the leak. The repair approach will depend on the outcome of this test.

Leak Checking Procedure for the Divertor and the Limiter Port Plugs

In cases where the leak is detected in the divertor or in the limiter port plugs (which are in the same cooling loop) again spiking will be used to identify which 3 divertor cassettes or which limiter port plug is responsible. After this, the leaking sector or the limiter plug (see below), which is the one accessed by a particular RH port, is drained and dried. Then the water pipes of the three leaking modules are successively opened outside the bio-shield, a tool is inserted which can isolate the weld connecting the pipe to the cassette by a balloon from the cassette body, and He is sprayed into this area. In the second step the balloon is deflated and the He can also reach the cassette body. This approach can distinguished between a leak in the divertor itself and in the water pipe connection. If the leak is found in the water pipe connection re-welding could be tried, and if the leak is in one of the three cassettes, all cassettes from the RH port up to the leaking ones are removed and further leak checking will be performed in the hot cell.

Leak Checking Procedure for the Port Plugs and VV Flanges

The leak checking for the port plugs (including the VV flange) in the equatorial and top level, as well as for VV flanges at the divertor level, is performed as follows. Presently all port plugs have two independent cooling loops, one serving the front blanket module which is mounted on the plug, and the other one serving the plug body and the VV flange. The latter one is routed through the same secondary heat exchanger as the VV cooling loop, while the blanket part is connected to the blanket cooling system except for the two limiters where it is connected to the divertor loop. Each port plug can be separated by valves from the rest of the cooling system and, in similar fashion to blanket or divertor, successive introduction of the spiking substance by opening the valves isolating each port plug successively will allow the leaking one to be identified (blanket part or plug-flange part). Once the leaking port plug is identified it will be removed and further leak checking will be performed in the hot cell.

Leak Checking Procedure for the Port Interspaces

Leaks into the interspace vacuum will again be identified by the global leak checking system and due to the possibility to valve each interspace connection to the leak checking station off it will be possible to find the leaking port interspace without He spraying or other methods. If the leak is a water leak piping routed through the interspace is to be suspected and a spiking procedure will follow to check which cooling pipe it is. If it is an air leak then the cryostat flange is to be suspected and He spray will be used to localise the leak. This can be performed hands on assisted.

Leak Checking Procedure for the Cryostat

Leaks in the cryostat can have two major origins, one is the He cooling circuit of the coils or thermal shields, and the other one is a possible air leak. An air leak will be very difficult to detect during operation because the cold coils will act as a large cryo-pump, and even with the accumulation method the sensitivity will be low. In case an air leak is detected by the leak checking system or by an increase in the cooling requirement (icing of thermal shields), He leak checking using automated tools (for He spraying) operating between bio-shield and cryostat will be employed. In particular the areas around flanges for the ports and other personnel access holes will be checked first using the accumulation method. If no leak is found but an air leak is suspected (to much heat loss from the coils) the coils have to be warmed up to increase sensitivity and the procedure repeated. If again no leak is found the cryostat body has to be suspected and spraying has to be extended to this large region (an unlikely event).

In case of a He leak from the cooling circuit, operation will be possible for some time but a warm up of the coils and leak checking will eventually be required in particular if leaks are large or increasing. The first step is to identify the leaking circuit by using the He distribution circuit and its numerous valves. Localisation will be done by a sniffer inside the cryostat after warm up of the coils to find the leak while the cooling circuits will be pressurized with room temperature He. In situ repair will be carried out as necessary.

General Remarks

The above descriptions are related to small leaks. In case of large leaks in a water circuit, where the leak checking station cannot be used any more, one has to use pressurization and possibly the in vessel viewing system to localize leaks. Pressurization will work similarly to the spiking approach, where all sub-loops will be closed, and the pressure will be increased in successive loops in order to find the one leaking by a pressure loss over time.

In conclusion, pending some R&D results which will confirm or define the various leak checking methods better, a leak in ITER will be detectable in a reasonable time and with the required sensitivity. Small design modifications on the in-vessel components, however, may be needed to support leak checking and / or to allow easier pinpointing of leaks. These will have to go hand-in-hand with the improved understanding of leak checking procedures and tools available in the environment envisaged for ITER.