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ITER-like Tokamak Exhaust Gases in JET Active Gas Handling System: Process Optioneering.

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ITER-like Tokamak Exhaust Gases in JET Active Gas Handling System: Process Optioneering.

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Abstract

The AGHS collects Tokamak exhaust gases from the JET machine, recovers the hydrogenic components and recycles the deuterium and tritium for fuelling the plasma. With the increasing fusion power and all-metal first wall and divertor, the forthcoming DTE2 experiment will see a change in the Tokamak exhaust composition compared to the DTE1 first series of experiments. A range of gases additional to those for fuelling the plasma will be added for critical applications such as plasma detachment and disruption mitigation.

One of these candidate gases is neon, which is anticipated to have a negative influence on storing the recovered hydrogen at an early stage of AGHS reprocessing. This paper will outline the trials and plant modifications which are in hand to provide a solution and enable downstream processes to operate as during DTE1. This will comprise a scrubbing circuit to mitigate the blanketing action of the neon in sorbing the hydrogen isotopes onto the existing depleted-uranium metal-hydride storage beds.

A second approach is also under study that has the potential to bring the tritium process circuit into closer alignment to that intended by ITER, thus providing process data for supporting the ITER fuel cycle design and increasing further the value of the JET experiments to the ITER project. JET's torus gases recovered onto AGHS's ITER Prototype Cryosorption Pump (PCP) will, on regeneration, be representative of the gas compositions received into ITER's Tokamak Exhaust Processing (TEP) system front end. The following adaptions of AGHS are being considered to make processing more representative of ITER:

- Helium, neon and hydrogen isotopes from 80K regenerations of the PCP could be routed directly to a Pd-Ag permeator that will replicate the first stage of TEP hydrogen processing.
- Other gases liberated from regenerating the PCP at 130K (so-called "warm" regenerations) could be cycled around a nickel bed and permeator train that will approximate to the operation of a palladium membrane reactor which is a second processing route within the TEP system.

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Keywords: Tritium, JET, ITER, Fuel cycle.

a. Background.

The JET DTE1 campaign of 1997 saw a broad-based series of D-T experiments producing a total of 675 MJ of fusion energy and setting records for fusion power (16 MW), ratio of fusion power to plasma input power (0.62, and 0.95 if a similar plasma could be obtained in steady-state) and fusion power duration (4 MW for 4 s). The JET Active Gas Handling System (AGHS) allowed the repeated use of the 20 g tritium on site, supplying a total of 99.3 g of tritium to the machine and routinely separating tritium to 99.5% purity[1].

Preparations are currently in hand for DTE2 that will provide data in support of ITER. Advances made in plasma research since 1997 give promise of greater powers and performance being achieved in this next D-T experiment. Torus fuelling will be in the order of 1000 gram over the campaign.

The carbon plasma-facing internals of the JET torus have been replaced by a fully representative ITER-like beryllium wall and tungsten divertor and the machine has been operating with this arrangement since 2011. Thermal radiation of carbon particles picked up in the plasma from the original carbon walls of the JET machine was beneficial in reducing the heat fluxes into the divertor. However, tritium retention in these carbon dusts is too high to be acceptable for a commercial sized fusion machine. Plasma operation with the all-metal plasma facing components will reduce tritium retention, but will require the use of additional gases, herein called “Plasma Enhancement Gases” (PEG), deliberately introduced into the plasma to provide thermal radiation and reduce divertor heat fluxes. Noble gases, along with nitrogen, hold the most promise for this duty. Higher atomic number (Z) gases, such as Xe, are best suited to the higher-temperature core region of the plasma, and lower Z gases in the relatively cooler regions of the divertor[2].

Gases will also be injected into the machine when needed for disruption mitigation[3]. A mixture of gases is expected for this mitigation process.

All of these developments will bring changes to the gas compositions and quantities that will need to be accommodated by the JET AGHS. The gases recovered from the JET machine during DTE2 will be representative of those from ITER. Options are outlined in this study to also make gas processing in the JET AGHS more ITER relevant to provide supporting performance information and operating experience.

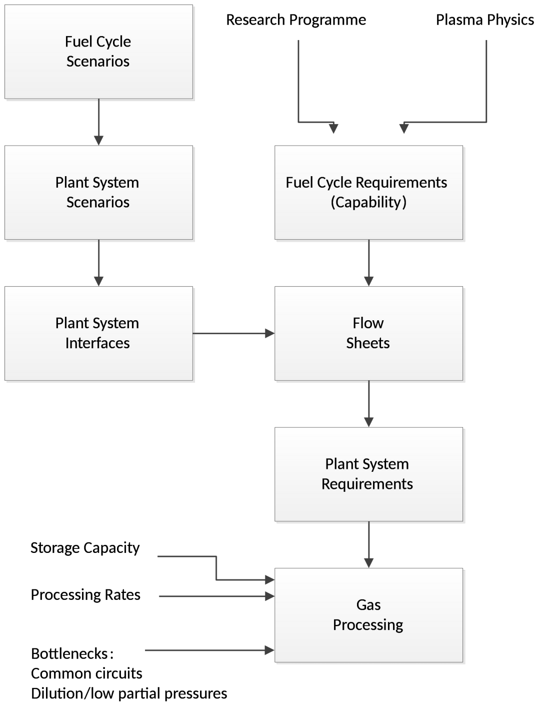


Figure 1. DTE2 preparedness study of JET AGHS.

The structure of an ongoing study of the JET AGHS for the DTE2 experiment campaign is shown in Figure 1. Demands from the experimental campaign are matched against the process capabilities and operational constraints of the AGHS. The study is expected to deliver optimized process routes and scheduling to maximise utilisation of the plant and limited tritium inventory to meet the high demands of the JET DTE2 campaign.

Plasma fuelling of the JET machine must satisfy a number of constraints. Amongst these are Limiting Conditions of Operation (LCOs) of the maximum permissible mobilisable quantities of tritium and total hydrogen within the torus and adjoining volumes (most notable of which are the two Neutral Beam Injectors (NBI)).

Plasma operations are halted when these LCOs are approached. The torus & NIB gases are then transferred to the AGHS to recover the tritium (and optionally the deuterium) for recycling and accountancy.

A DTE2 Fuelling Working Group established a series of reference plasma scenarios for each phase of the DTE2 campaign. This took into account tritium and total hydrogen limits and the PEGs mentioned previously. These reference scenarios are written into a spreadsheet which sets out the total quantity of gases expected to be put into the machine over each day of plasma operations. It provides the basis for planning AGHS operations over the campaign.

The campaign will constrained by the throughput capacity of AGHS to recycle tritium (also optionally deuterium) and reject detritiated waste gases from the fuel cycle. The T-T and D-T experiments will run on monthly campaign basis, with three weeks experimental time and one week for recovery and accountancy tasks. Figure 2 illustrates the activities over each week of experiments having a cycle of four days plasma operations and three days processing[4].

Each day of plasma operations will provide two shifts of experiment time and one shift to regenerate gases accumulated on the torus (pumped divertor) and neutral beam cryopumps.

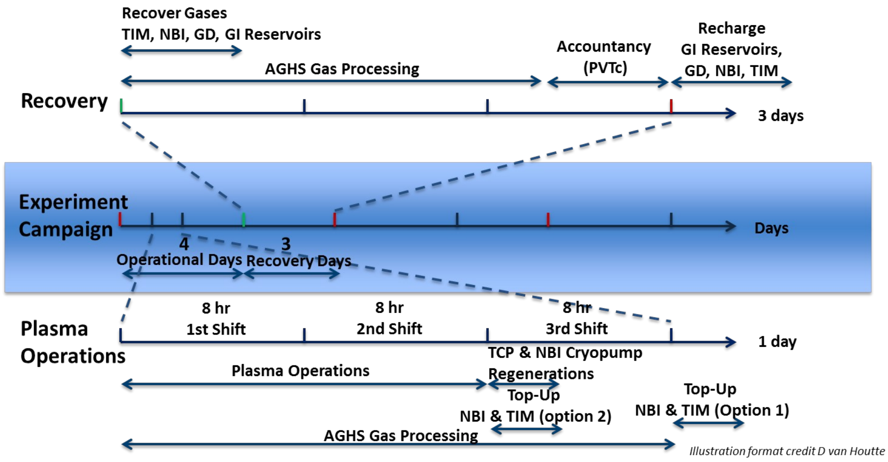


Figure 2. Experiment programme and scheduling of tritium plant operations.

b. Tokamak Fuelling.

The tritium fuelling per pulse for DTE2 (14.8 bar.l for 4.5 MA plasma current, 5s pulse) will be substantially higher than for DTE1 (9 bar.l for 3.5 MA plasma current, 5s pulse). The single gas injection module used for injecting tritium into the plasma for DTE1 will be replaced by 5 Tritium Introduction Modules (TIM), Figure 3.

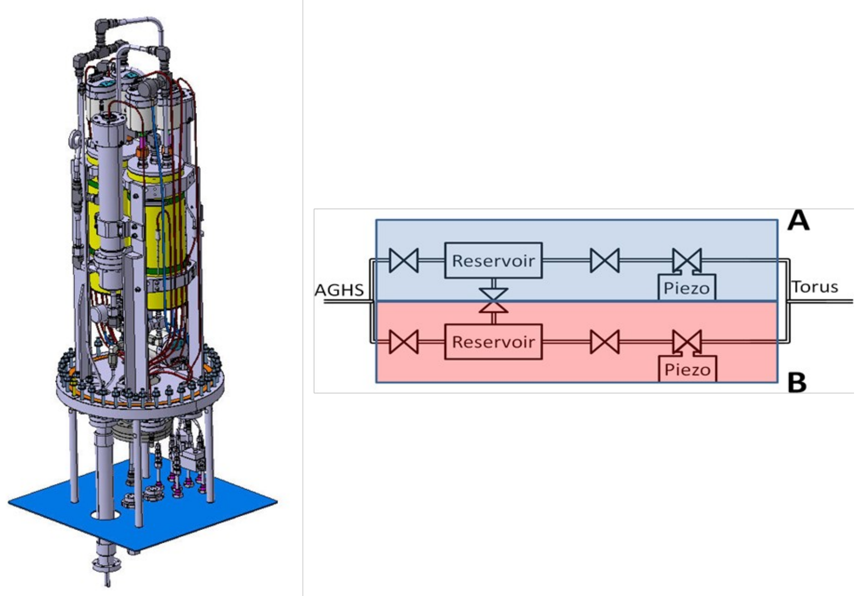


Figure 3. JET DTE2 Tritium Introduction Module (TIM).

The JET TIM is a new design of gas injection valve[5]. The device is divided into two streams which may be used singly or in pairs. Each stream has a 5-litre feed reservoir and an injection valve having a capacity of 1.6 bar.l/s when fully charged, 0.53 bar.l/s when averaged over 5 seconds. An injector can be configured to run coupled to a single reservoir or two in parallel. Control modes hand control of the reservoir valves between AGHS and Tokamak operations as appropriate for reservoir charging or gas injection[6].

Deuterium will be normally introduced into the torus by means of other injectors connected to a cylinder supply (Figure 4).

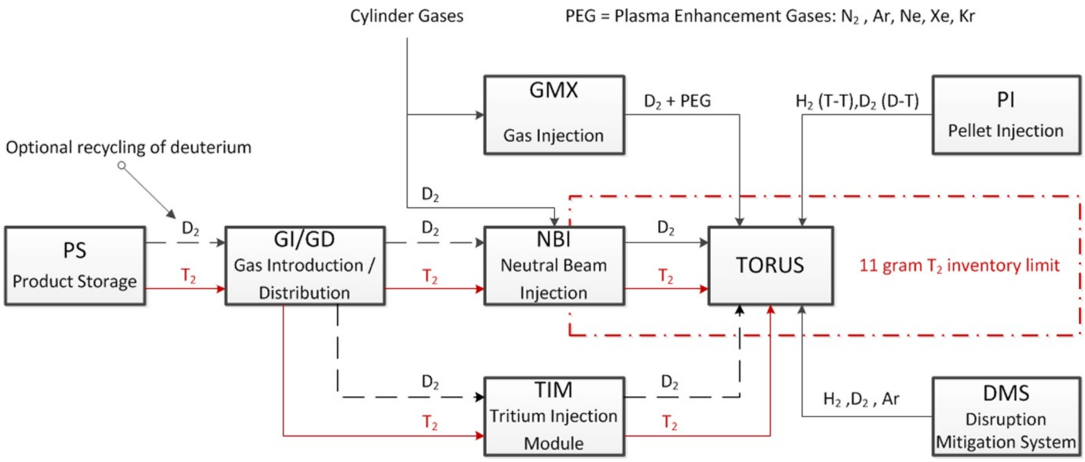


Figure 4. Tritium and other gas feeds to JET torus for DTE2.

Fuelling and neutral beam systems will be charged with tritium (and optionally deuterium) at the beginning of the four-day plasma operation period and thereafter top-ups will be made on demand. JET operating restrictions do not permit gas to be injected from a depleted-uranium metal-hydride bed (U-bed) directly to the torus, therefore each injector has been equipped with a 5-litre storage reservoir. These will be charged to a working pressure of 0.8 bar at the beginning of the four-day plasma operating session, topped-up as needed during the day and left filled during the third shift. The fuelling systems and AGHS gas introduction system will be emptied of tritium on completion of plasma operations on the fourth day and the gas returned to AGHS product storage.

The demands on the AGHS Gas Introduction and Gas Distribution (GI/GD) system to load the TIM reservoirs has also meant a review of the NIB gas supply; these will also be fitted with reservoirs so they can operate for longer durations between top-ups. These will be charged to operating pressure to permit NIB test pulses in advance of plasma runs whilst the TIMs are being supplied. The tritium used for these test pulses (0.65 g in 50% tritium DT experiments and 1.08 g in 100% tritium (TT) experiments) has to be included into the 11 g limit.

The foregoing places a much greater demand on the Gas Introduction/Gas Distribution (GI/GD) system than in the past. Modifications are in hand to increase or better utilize existing reservoir volumes so as to reduce the number of transfers needed to charge both the TIM and NIB reservoirs. The GI reservoirs are used to transfer gas to the fuelling systems in a series of expansions: with the reservoir supplied from a U-bed to a defined pressure before isolation and measurement by PVT. The PVT measurement is repeated on completion of the expansion. The PVT measurements are then compared to the pressure rise seen in the TIM on each transfer. Batch-wise transfers minimize the potential for over-charging the TIM or for discrepancies in tritium accountancy. Although integrating flow meters are installed in the PS tritium outlet manifold, it is not possible to know by direct measurement the quantity of tritium held in a U-bed when it is operating.

JET AGHS has four tritium U-beds, each of which Operating Limits & Conditions (OLCs) allow to be loaded to 30 g. This provides plenty of margin over the storage capacity needed for DTE2, although co-ordination of bed operations for feeding and receiving gas for plasma operations and PVT plus receiving product from the process gas chromatograph (GC) will need to be choreographed.

c. Tokamak Gas Recovery.

Tritiated gases from the torus and neutral beam cryopumps will be received into the AGHS Cryogenic Forevacuum (CF) system at the end of each day of plasma operation (Figure 5). This system comprises a series of liquid helium cooled cryo-condensation and cryosorption pumps. The controlled cooling and regeneration of these pumps in turn permits some separation of the recovered gas into a good quality hydrogen stream for sending onward to U-beds within Intermediate Storage (IS) and a low quality stream to a reservoir in Impurity Processing (IP).

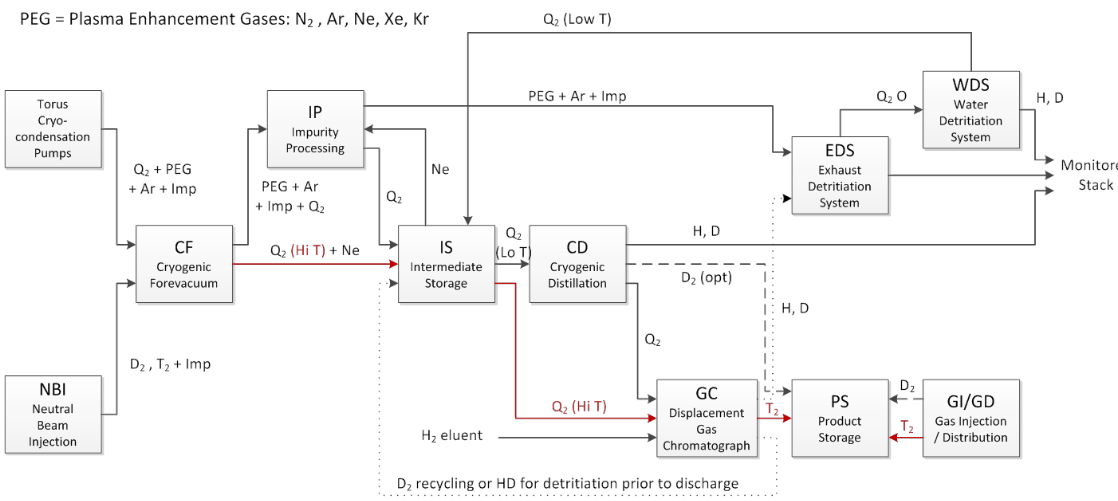


Figure 5. Recovery & processing of tritium and other gases.

As mentioned previously, with the increasing fusion power and all-metal first wall and divertor, the forthcoming DTE2 experiment will see a change in the Tokamak exhaust composition compared to the DTE1 first series of experiments.

Table 1. Summary of Tokamak gas loads into AGHS (excludes NBI).

Daily Torus Gas Pumped Divertor Inventories for Reference DTE2 Plasmas.									
Campaign	Scenario		Hydrogen				PEG		Total
			H_2	D_2	T_2	Total Q_2	Ar	Ne	
T-T	1	bar.l	109	0	21	129	10	2	141
		X	*0.77*	*0*	*0.15*	*0.92*	*0.07*	*0.01*	*1.00*
	2	bar.l	46	0	21	67	3	0	70
		X	*0.65*	*0*	*0.30*	*0.95*	*0.05*	*0.00*	*1.00*
	3	bar.l	57	0	27	84	3	1	89
		X	*0.65*	*0*	*0.31*	*0.95*	*0.04*	*0.01*	*1.00*
D-T	4	bar.l	4	110	22	136	7	0	143
		X	*0.03*	*0.77*	*0.16*	*0.95*	*0.05*	*0.00*	*1.00*
	5	bar.l	4	110	22	136	5	2	143
		X	*0.03*	*0.77*	*0.16*	*0.95*	*0.04*	*0.01*	*1.00*

The gas collected from the Pumped Divertor contains the greatest amount of PEGs (Table 1). This gas is collected onto a cryosorption pump having a charcoal panel. Hydrogen is collected from this panel by removing the cooling and allowing it to warm slowly to 77 K whilst having it connected to a cryo-condensation pump (which has no charcoal surface, therefore it cannot pump helium). Once the hydrogen has been collected on this pump, the donor pump is warmed further and evolved vapours pumped away to IP.

Once this process is completed, the cryo-condensation pump is warmed and the hydrogen collected onto a U-bed.

d. Separating neon from Pumped Divertor gases.

Neon is one of the candidate plasma enhancement gases and may be used in low percent levels. Its vapour pressure curve is not dissimilar to that of tritium and results[7] from the ITER Prototype Cryopump show that neon is evolved at similar conditions to protium which is the most volatile of the hydrogen isotopes. Consequently, it is anticipated that the torus hydrogen transferred to the U-beds of the IS system from the cryo-forevacuum system will have significant levels of neon present, thereby leading to inhibiting hydrogen absorption owing to blanketing of the bed.

Serendipitously, a transfer pump set and reservoir are being added to the IS system for storage of product from the JET Water Detritiation System (JWDS). These same pumps will be used to circulate (scrub) the hydrogen-neon mixture through the IS U-beds, flowing conditions mitigate the blanketing effect of the neon which enables the hydrogen to be absorbed onto the U-bed (Figure 6).

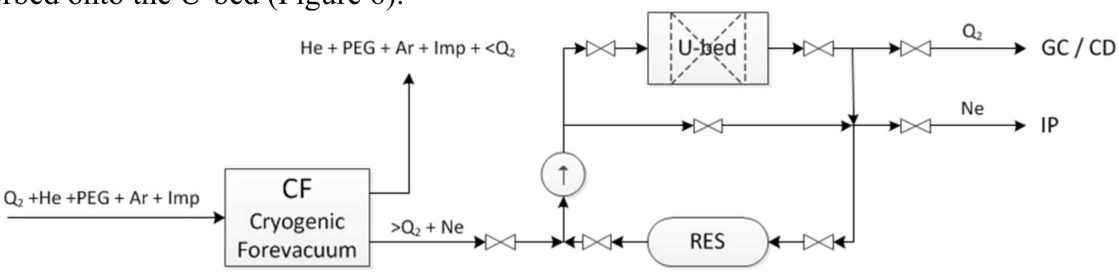
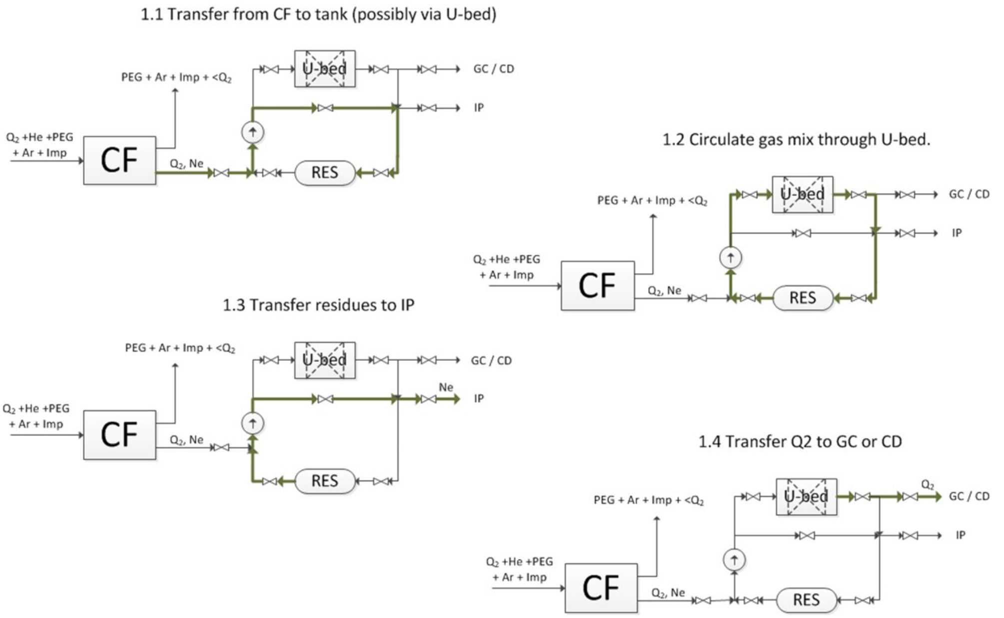


Figure 6. Scrubbing circuit for JET Intermediate Storage System.

The sequence of loading the U-bed and transferring out the neon stream to the IP system and hydrogen to isotopic separation is depicted in Figure 7.

Figure 7. Sequence for receiving Q_2 + Ne mixture into JET IS, separating & storing the Q_2, rejecting the Ne and transferring the Q_2 to isotope separation stage.



We expect to place a time limit on the duration of gas scrubbing before the Ne is transferred to IP for further processing and the IS U-beds are heated to transfer the hydrogen for isotopic separation.

The principal method employed for isotopic separation is by means of a displacement gas chromatograph (GC) system, unless the tritium fraction is less than 1%, in which case pre-enrichment runs will be performed by the JET Cryogenic Distillation (CD) system. The JET process GC system has four separation columns operated in sequence, each of which can process 30 bar.l of Q_2. The operation of the GC system has been reported elsewhere[8].

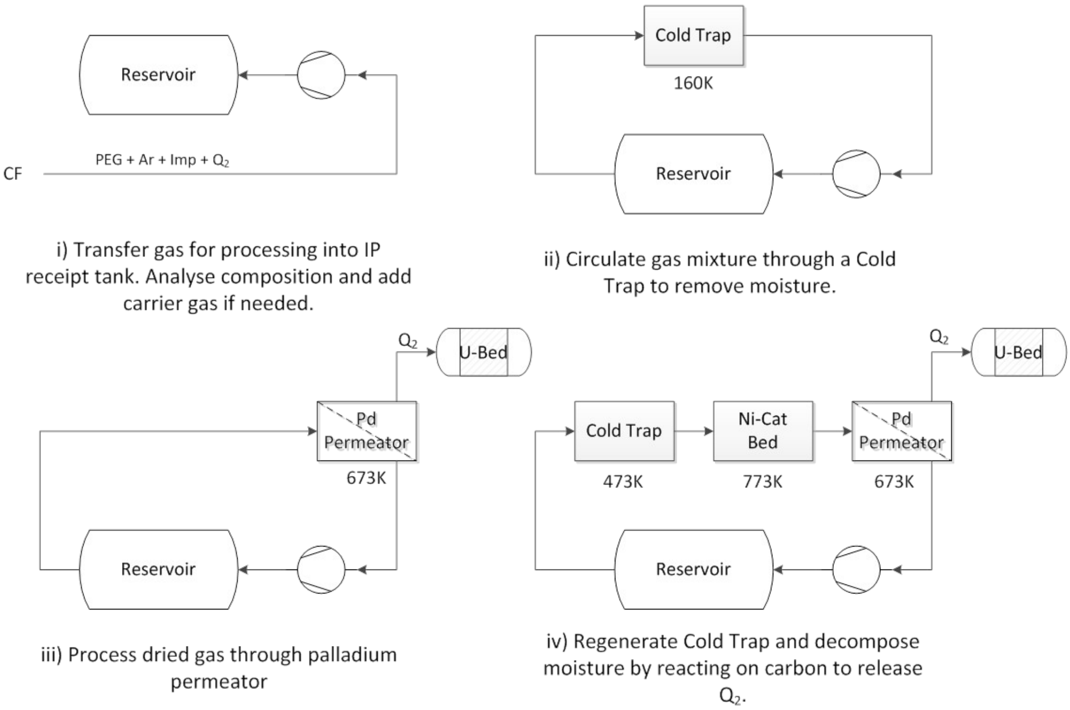
e. Impurity Processing.

The lower quality gas stream from CF is pumped into a reservoir in the Impurity Processing (IP) system where it is analysed[9] (Figure 8(i)). Helium or argon may also be added as a carrier gas. The next step is to remove any moisture present by circulating the gas mixture through a Cold Trap (Figure 8(ii)). This operates at 160 K from a LN_2 supply.

The dried gas is now passed across a palladium-silver membrane operating at 400°C and the hydrogen permeate is sorbed onto a separate U-bed (Figure 8(iii)).

On completion of this step, the Cold Trap is heated to 200°C and the regenerated vapour pumped through a nickel catalyst bed operating at 500°C which has been preloaded with carbon. This promotes water cracking and the hydrogen product is taken out at the downstream permeator module (Figure 8(iv)).

Figure 8. Stages in JET Impurity Processing System.

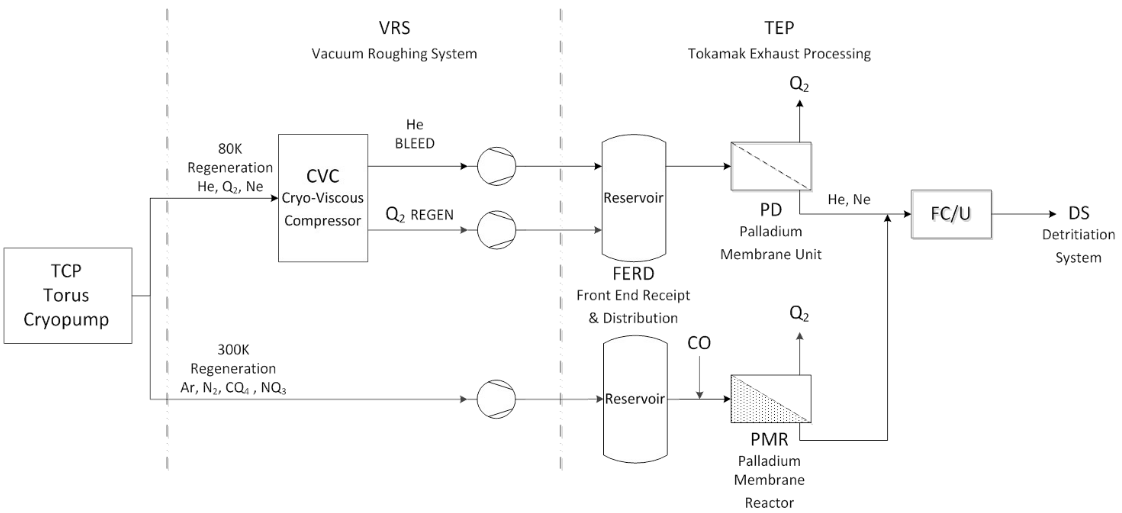


Hydrogen collected on the IP U-bed is subsequently transferred to Intermediate Storage before undergoing isotopic separation.

f. Options for ITER-relevant AGHS processing.

Unlike the JET Pumped Divertor cryopump, ITER Torus Cryopumps (TCP) have charcoal surfaces and are able to pump helium. Six TCPs will be sequentially regenerated to 80 K during plasma operations and the gas transferred via a cryogenic compression stage and mechanical pumps in the Vacuum Roughing System to the Tokamak Exhaust Processing (TEP) system within the Tritium Plant System for recovery of the hydrogen and detritiation of the waste stream (Figure 9).

Figure 9. Simplified diagram of ITER Tokamak Gases Handling.



The gases recovered from the 80 K regeneration will be Q_2, He and Ne. These will be processed through a cascade of palladium permeators and the retentate sent forward to a final oxidation-absorption clean-up stage.

The JET machine collects torus gases on a cryo-condensation pump with a contribution also from turbo-molecular pumps (TMP). The cryopump will be regenerated to 77 K at the end of each day of tritium operations and the gas inventory is expected to be in the region of 70 – 140 bar.l.

Whilst the gas composition from this pump will not be a close match to that from the ITER TCP (although "argon frosting" of the JET torus pump may bring the comparison closer), an improvement can be had through the use of a particular module in the AGHS CF system which houses an ITER prototype cryopump (PCP) (Figure 10)[10]. The 0.4m^2 charcoal-faced cryopanel pumping element of the PCP fully represents one of the 26 or so elements to be included into each ITER TCP. The gases evolved from regenerating the PCP at

77 K are thought to be representative of the gases received into TEP from an 80K regeneration of an ITER TCP via the VRS.

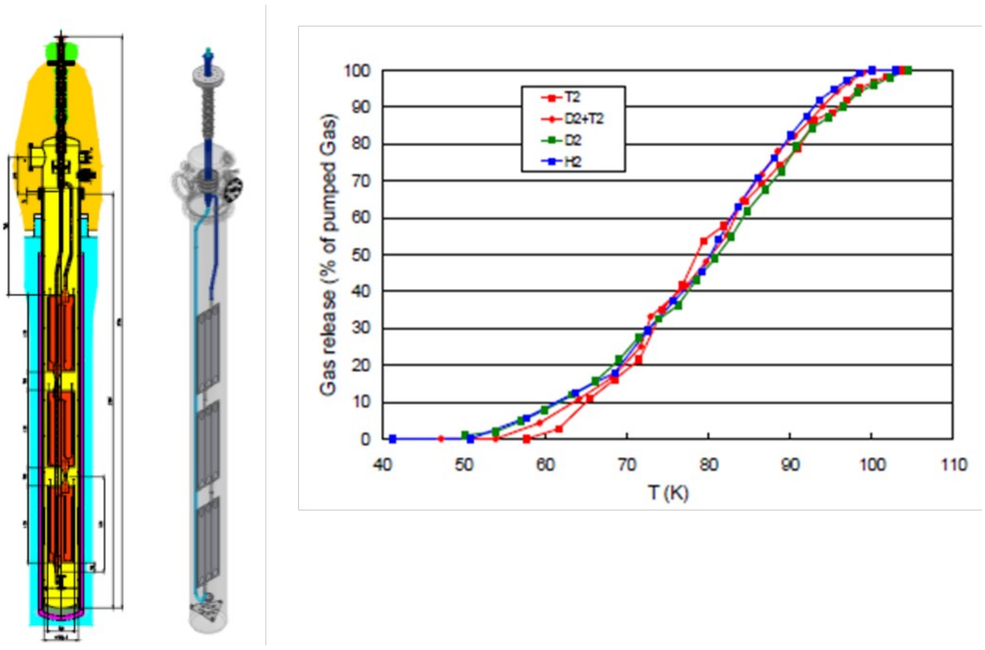


Figure 10. ITER Prototype Cryopump (PCP) with hydrogen release results.

The JET study is assessing whether the palladium permeator within the AGHS IP system can provide relevant data to support the ITER design and provide operating experience. The IP process runs in batch mode (Figure 11) and recirculates the feed gas until the separation has completed, unlike the continuous, once-through scheme to be employed by ITER.

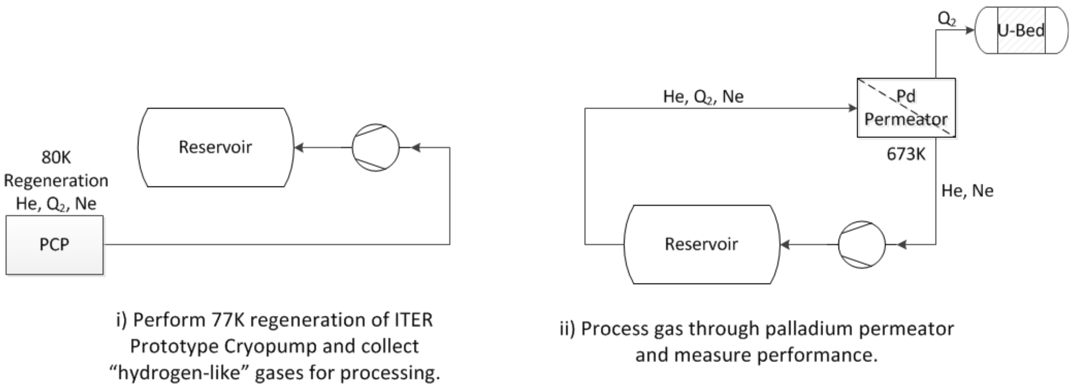


Figure 11. Option for processing "hydrogen-like" gases in AGHS.

The AGHS PCP is also equipped with heater controls and temperature measurements that can be used to reproduce a 300K regeneration of an ITER TCP. Whilst the gas composition will exclude those contributions pumped onto the torus 77 K baffles, there will be some components that will be relevant to ITER.

It is proposed to operate a Ni-catalyst bed in series with the permeator in a recirculation mode (Figure 12). The Ni-cat bed is normally pre-loaded with carbon to promote the heterogeneous water-gas reaction $Q_2O + C \leftrightarrow CO + Q_2$ and water cracking reaction $2Q_2O + C \rightarrow CO_2 + 2Q_2$ and the hydrogen product is taken out at the downstream permeator module. However, within the current study UKAEA are also assessing whether CO can be metered into the feed stream or, indeed, whether it is feasible to add a PMR module into the IP system.

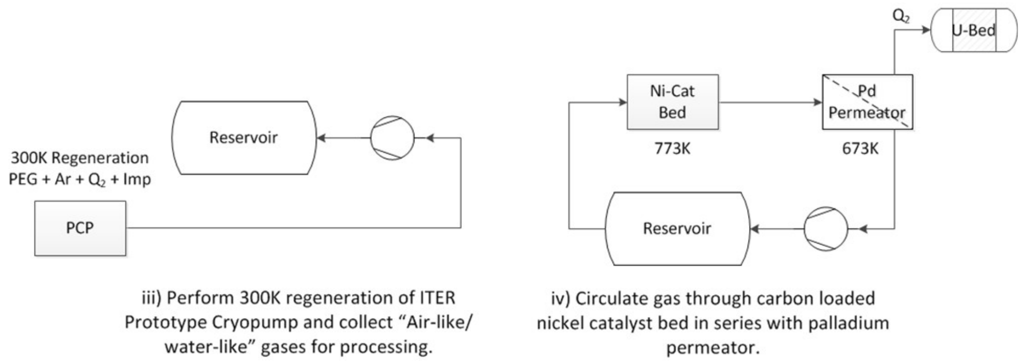


Figure 12. Option for processing "air-like" gases in AGHS.

g. Summary.

The JET AGHS is being readied for DTE2. Greater fuelling demands, higher capacity injection systems and use of plasma enhancement gases require optimisation of AGHS processes.

An early stage of AGHS processing must be adapted to permit recovered hydrogen to be stored from a mixture containing neon.

Options are under study for running the AGHS CF and Impurity Processing plants in a manner representative of that intended by ITER. This will provide relevant data to support the ITER design and provide operating experience.

h. References

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