The Fuel Cycle of Fusion Power Plants and Experimental Fusion Reactors

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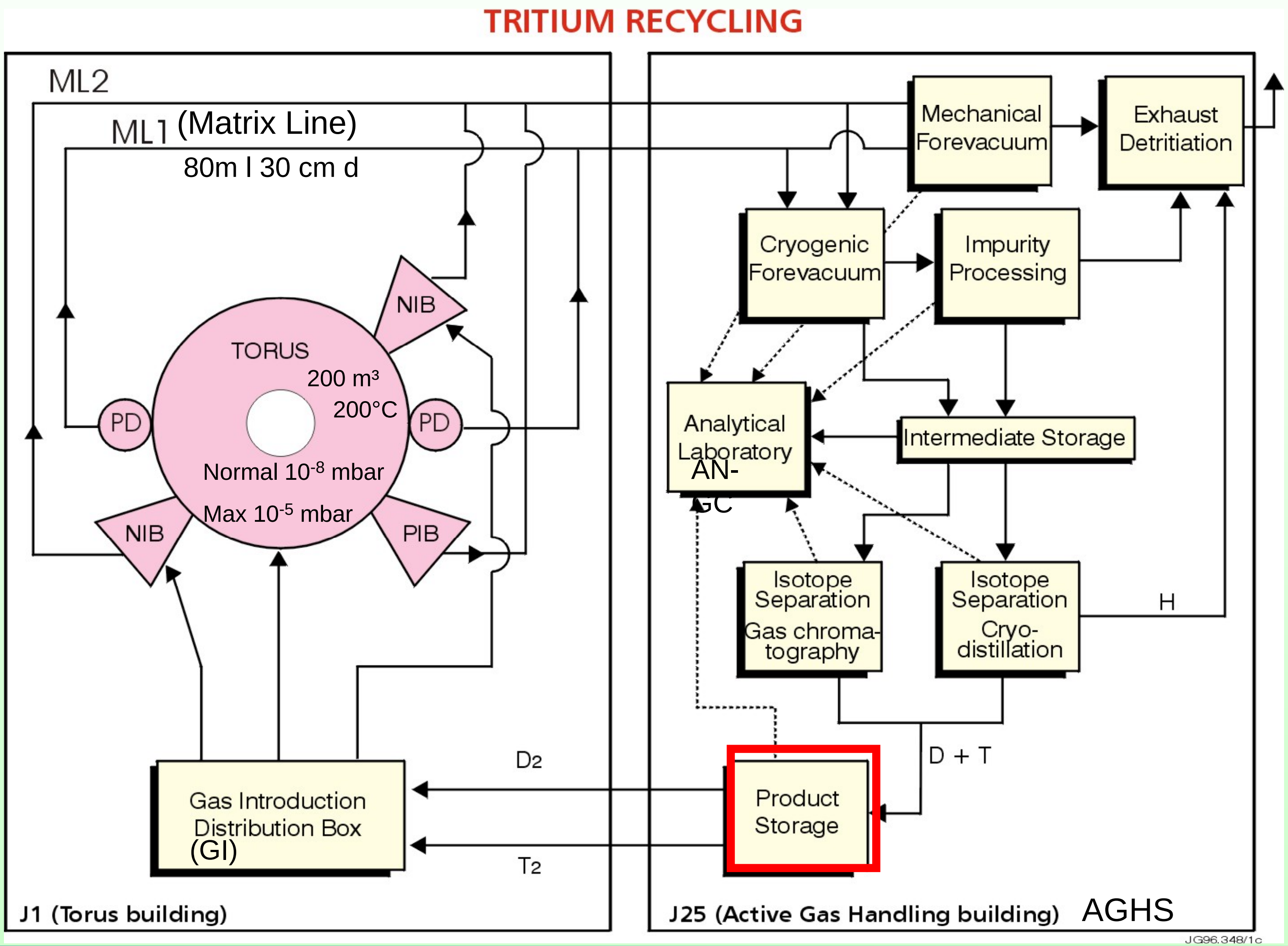
- **Fuel Cycle**
  - **Fuelling**
  - **Pumping**
  - **Tritium processing**
- **Safe handling of tritium**
- **Minimization of tritium inventories and of tritium effluents and releases**
  - **Water detritiation**
- **Recovery of tritium from breeding blanket**
- **Conclusions**

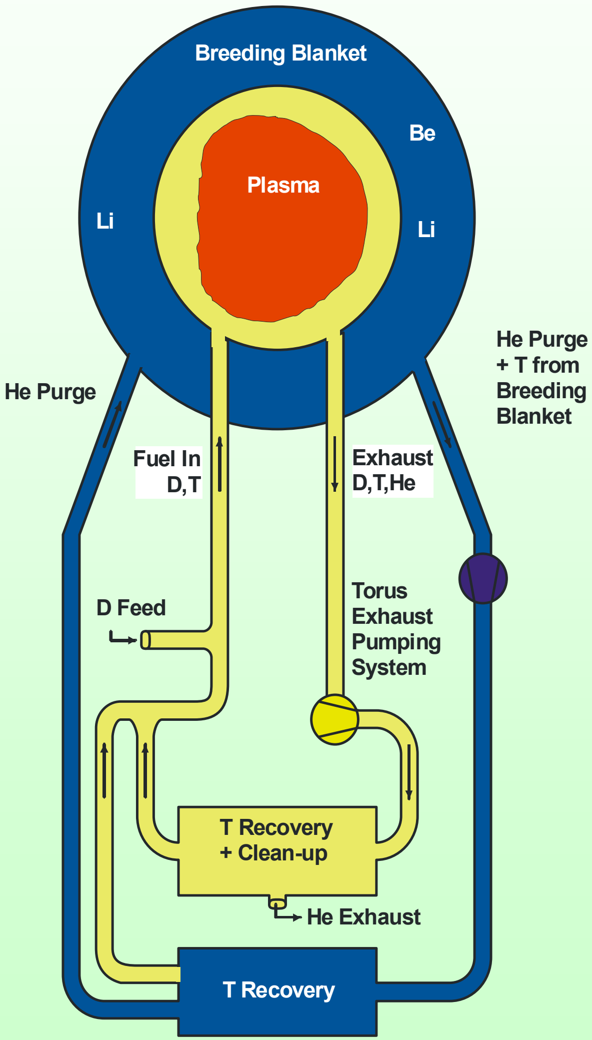
Active Gas Handling System at JET



Courtesy, D. Brennan, JET

Block Diagram of the DT Fuel Cycle for ITER

Developing the technology for fuel cycle of a fusion reactor



Facility	Location	Max. Inventory (g)	Throughput	Status	Function
TSTA	Los Alamos, USA	100	> 1kg	Decommissioned	Fuel Cycle tests
TFTR	Princeton, USA	5	~100g	Decommissioned	Tokamak
JET	Culham, UK	20	~100g	Operational	Tokamak
TPL	Tokai, Japan	60	-	Operational	Fuel Cycle tets
TLK	Karlsruhe, Germany	40	80g	Operational	Fuel Cycle tests

Comparison between ITER and DEMO

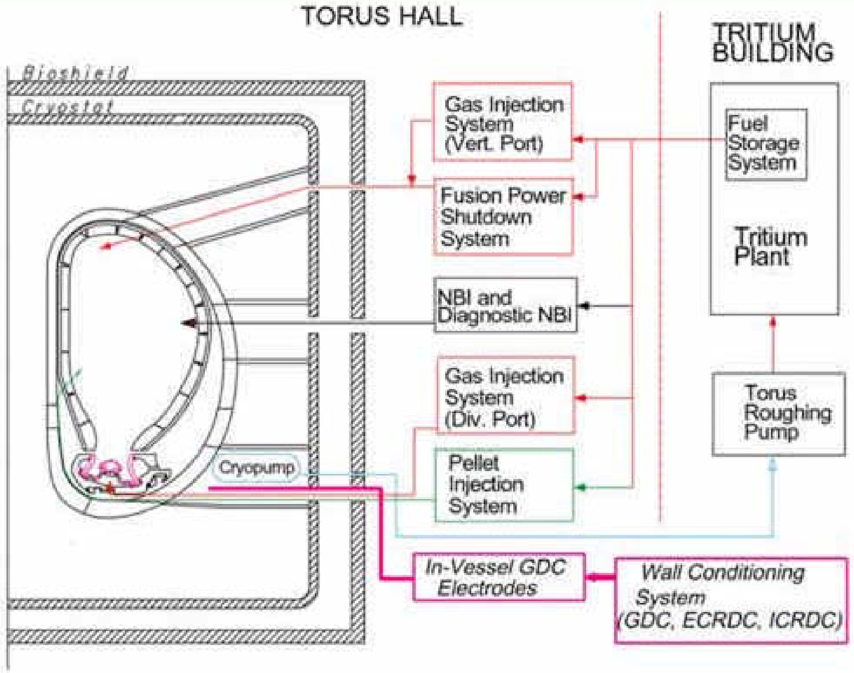
	ITER (0.5GW)	DEMO(3GW)
Tritium storage (kg/site)	~ 3	< 14[*4]
Tritium handling[*1] (kg/d)	~ 2	< 2
Total processing[*2] (kg/d)	~ 5.8	< 23
Consumption/Production[*3] (kg/d)	~ 0.017 / ---	~ 0.45 / ~ 0.5 TBR=1.1

*1: ITER: 1.2kg in VV + 800 g in T-Plant
*2: ITER:0.27g/s(100Pa.m³/s for T) x 450s/shot x 2shots/h x 24h/d, DEMO: 0.27g/s x 3600s x 24h
*3: ITER: 0.0008g/s(at 0.5GW) x 450s x 2shots x 24h、DEMO: 0.0008 x 6 x 3600 x 24 & TBR=1.1
*4: Tritium fuel for about one month operation (consumption)

Nishi, Hayahi & all, ISFNT -7, May 22-27 Tokyo, Japan

ITER Fuelling

- **Fuelling rate: 120 Pam^{3}s^{-1} of D_2, DT, T_2**
- **Short burn pulse of 450 s (repetition time 1800 s)**
- **Long burn pulse of 3000 s (repetition time 12,000 s)**



1. Gas fuelling system
2. Pellet injector system
- High density in the hot central plasma gives higher rate of fusion reaction and reduce the interaction with the surrounding materials

- Solution : to fire high speed pellets of solid frozen hydrogen or deuterium

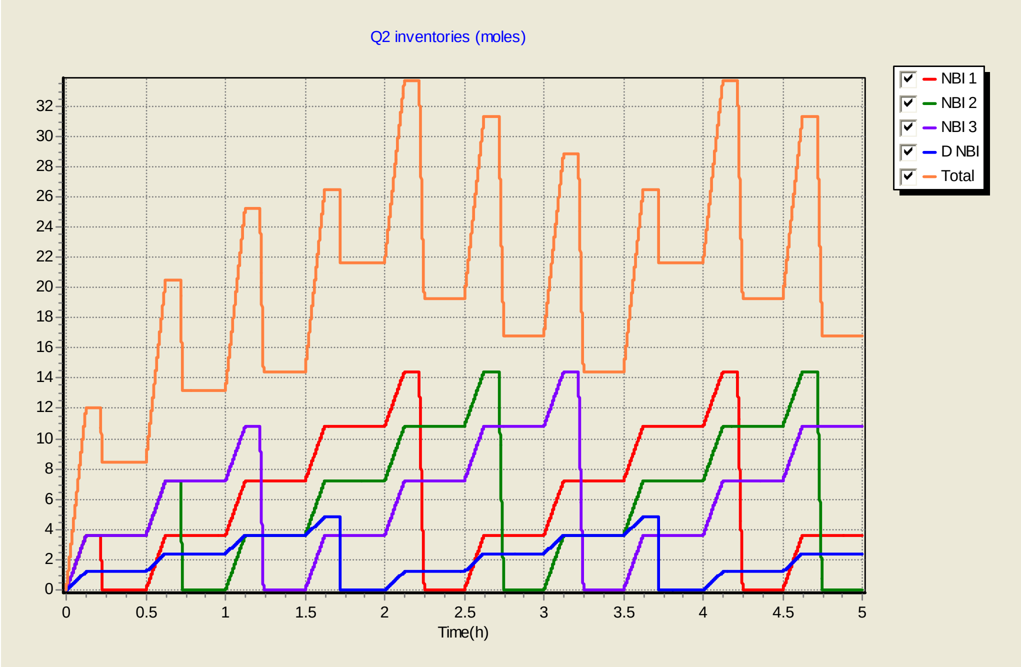
Extrusion cryostat – solid hydrogenic rod is pushed out from screw extruder continuously
Chopping unit cuts a piece and directs the pellet into centrifuge
Pellet is accelerated to the barrel periphery and ejected to the flight tube

Neutral Beam system

- **In combination with other heating systems (ion cyclotron, electron cyclotron, lower hybrid) the Neutral Beam system supports the plasma heating**

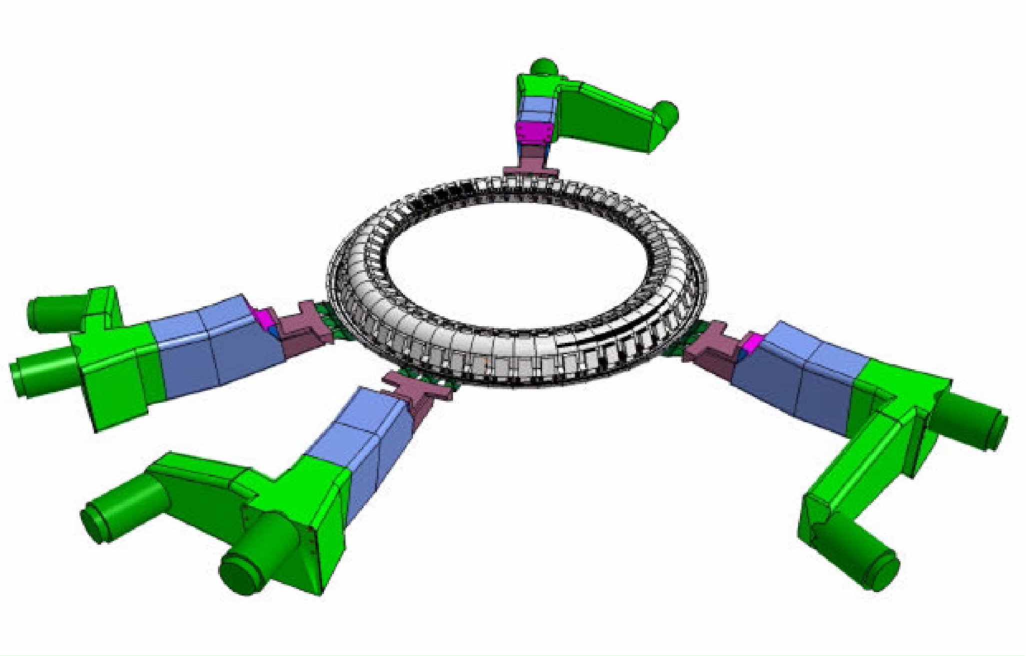
• The Neutral Beam Injectors system for ITER consists of three heating and current drive (H&CD) NB injectors and a diagnostic neutral beam (DNB) injector. The H&CD NB injectors are operated with deuterium. The injector incorporates a large cryopump in order to pump the gas that is fed into both the ion source and neutralizer .

• To minimize the hydrogenic inventories in the cryopumps of the NB injectors, a staggered regeneration pattern is envisaged to be used during plasma dwell time.



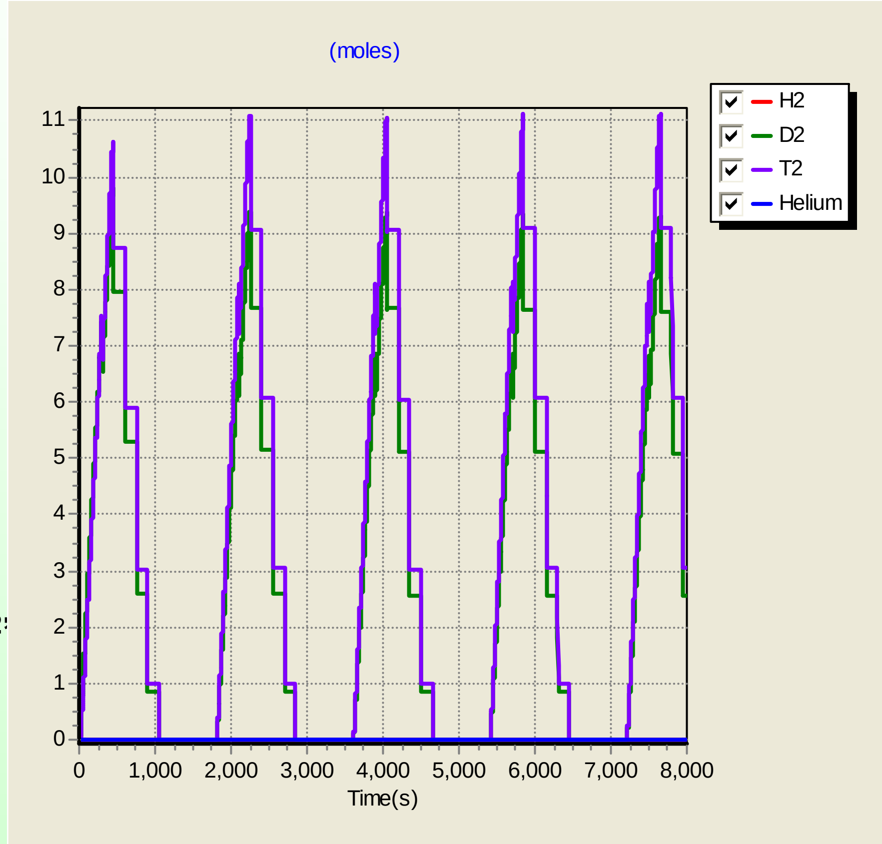
Vacuum pumping system for ITER

- **High pumping speed and throughput at low pressure ⏩ pump location should be close to the Torus**
- **High magnetic fields and highly mobile dust particles ⏩ pumps without moving parts**
- **Cryopumps backed by roughing pumps**
- **Currently 8 cryopumps are envisaged to be used in ITER**



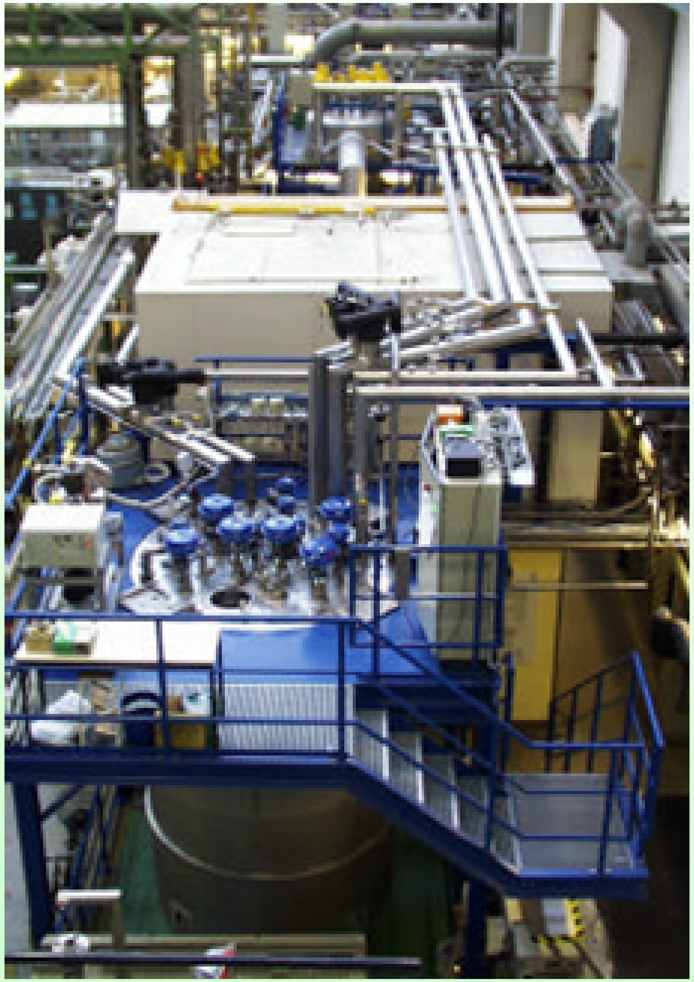
Cryopumps operation

- **pumping mode**
  - **cryopanels (activated charcoal coated panels) are cooled down to 5K, the cryosorbent is loaded with gas molecules**
- **regeneration mode (partial regeneration)**
  - **cryopanels are heated up to ~90 K, hydrogenic gas molecules are desorbed from the panels, pressure inside the pump increase, pump housing is evacuated by torus roughing pumps**
- **high temperature regeneration (total regeneration)**
  - **cryopanels are heated up at 300K, impurities (Ar, N_2, CH_4, CO, CO_2) are desorbed from the panels; water vapours and polytritiated carbons are desorbed at higher temperatures (>450K)**



•During plasma operation only pumping mode and partial regeneration mode takes place
•To minimise the hydrogenic inventories, a staggered pattern for cryopumps regeneration is envisaged to be used (4 pumps pumping and 4 pumps under regeneration)
•High temperature regeneration is envisaged to be performed every night

Test facility for ITER Model vacuum pump (TIMO)



The cryopump is a 1:2 scale model (pumping speed of 50 m^3/s for DT) of the ITER 1998

Pump performances have been tested:
- Pumping speed
- Ultimate pressure
- Regeneration mode (warm-up time (150s), evacuation time(300s), cooling time(150s) have been experimentally confirmed)

The Three Step Process for Tokamak Exhaust Processing

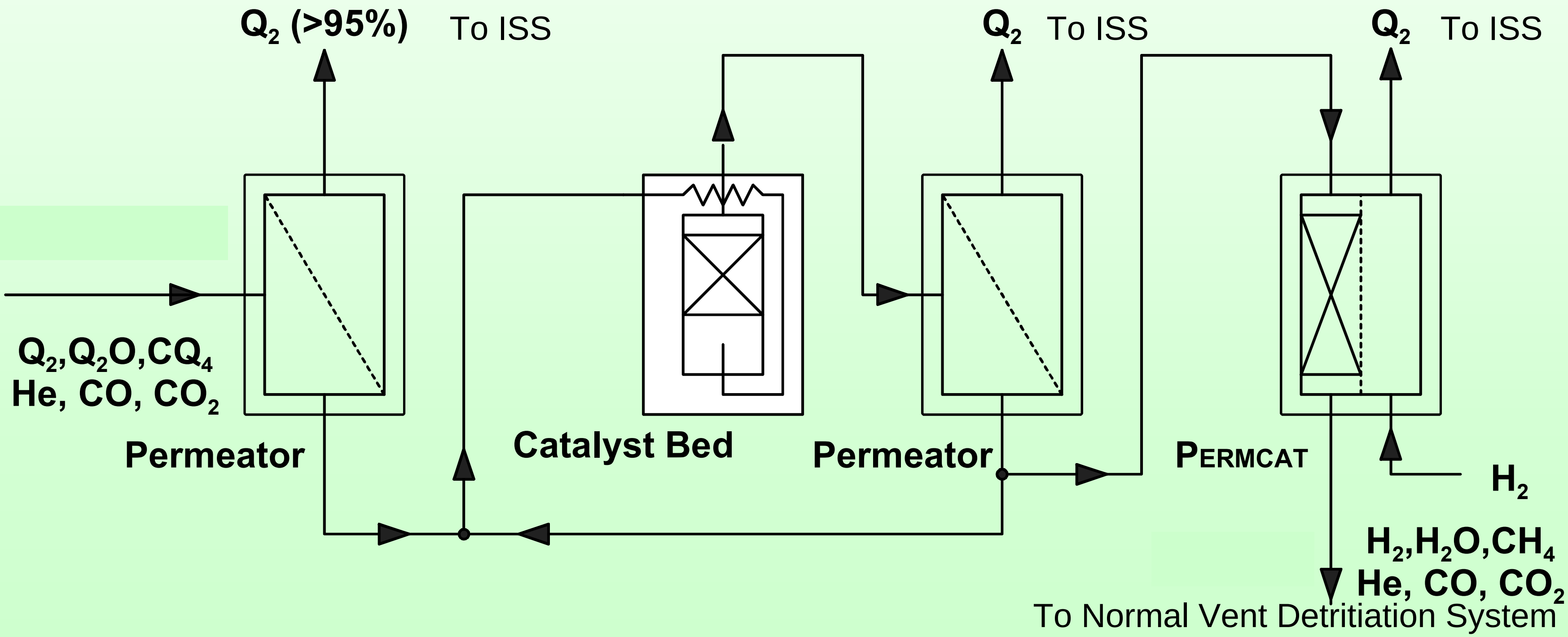
Chemistry of the 2nd step: (Q = H, D, T)

$CQ_4 \leftrightarrow C + 2\,Q_2$

$C + CO_2 \leftrightarrow 2\,CO$

$CO + Q_2O \leftrightarrow CO_2 + Q_2$

$CO + 3\,Q_2 \leftrightarrow CQ_4 + Q_2O$

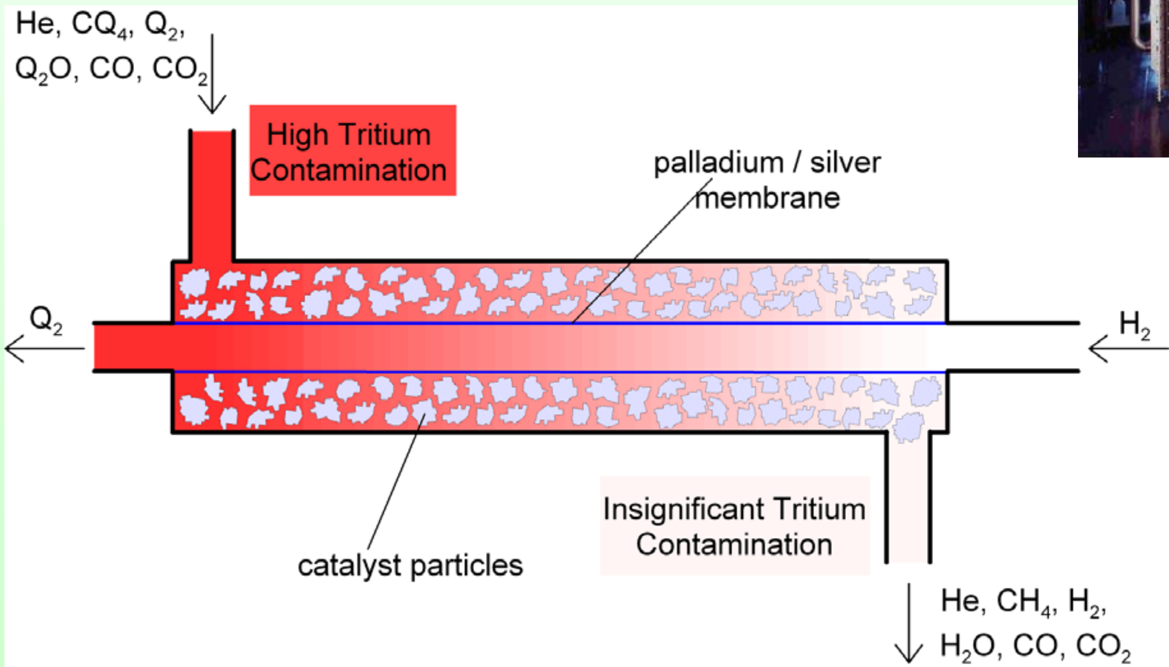


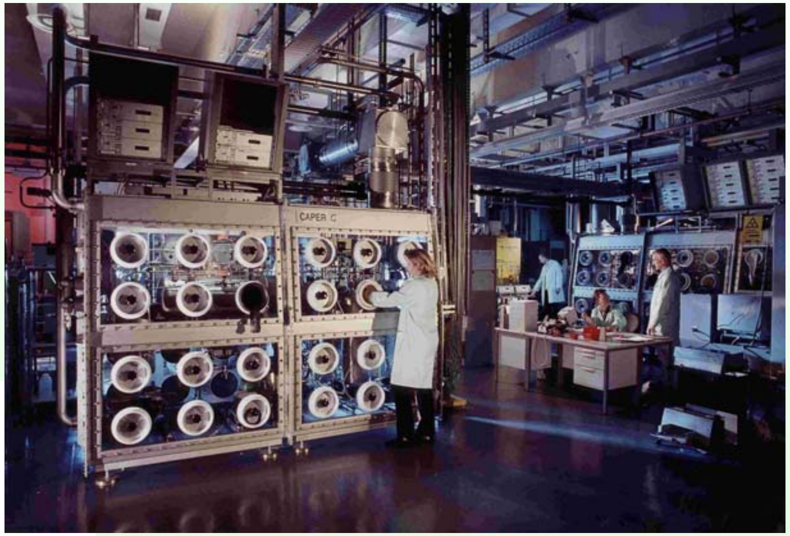
PERMCAT (Permeator/Catalyst) Principle for Final Clean-up

Chemistry of the PERMCAT:

$$H_2 + CQ_4 \leftrightarrow CH_4 + Q_2$$

$$H_2 + Q_2O \leftrightarrow H_2O + Q_2$$

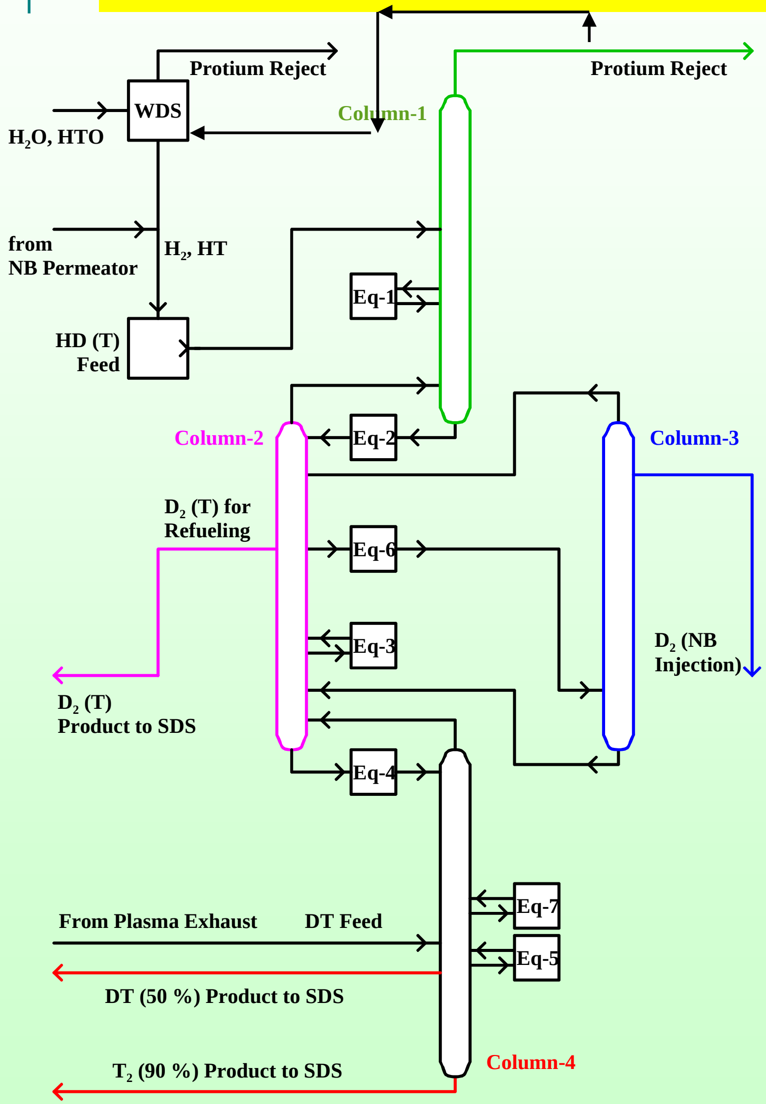




Integrated tests with a TEP like system have been carried out at TLK, also under conditions considerably beyond the design limits (tritium at higher concentrations and flow rates);

The tritium concentration at the outlet of the third step (PERMCAT) could be kept below the design target, i.e. 1 Cim^{-3} proving the decontamination of tritiated gases at levels required by ITER.

Isotope Separation System of ITER



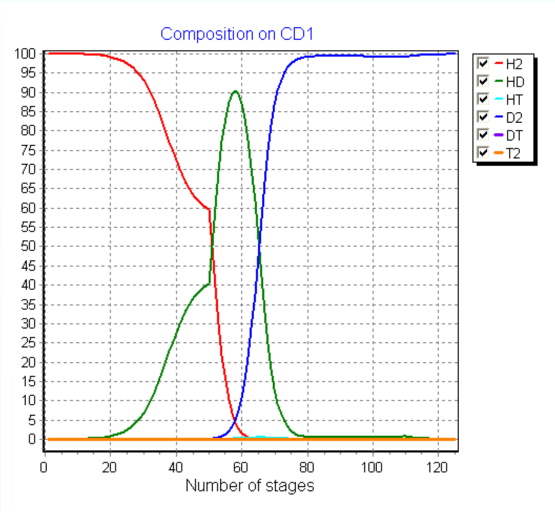
Large scale cryogenic distillation systen for tritium production is in operation in Darlington, Canada.
Investigations on ISS systems for fusion have been carried out at LANL, TFTR and JET.

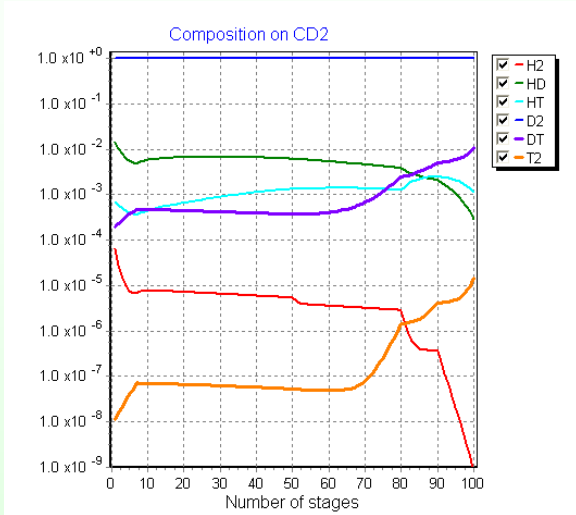
The requirements of ITER ISS are to produce :
T_2 (T> 90%)
D_2 for Neutral Beam Injectors (T<200 ppm, H<0.5%)
D_2 for fuelling (H<0.5%)
H_2 ($T<10^{-7}$)

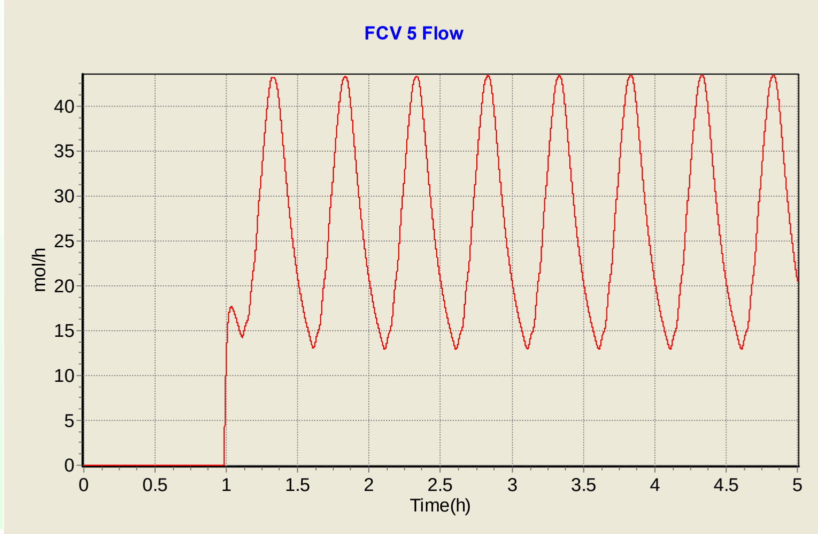
ISS will have to handle rapid fluctuations in feed compositions and flow rates
Accurate dynamic modeling is compulsory,
was developed and will be benchmarked at FzK

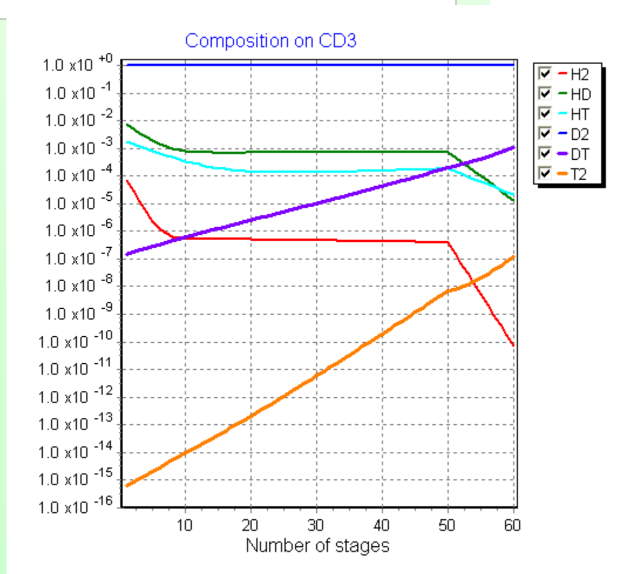
Pending R&D issues:
1. The constrol system of a multicolumn cascade system at rapid fluctuations in the feed flowrates and composition.
2. The ability of WDS to process the protium reject stream from ISS

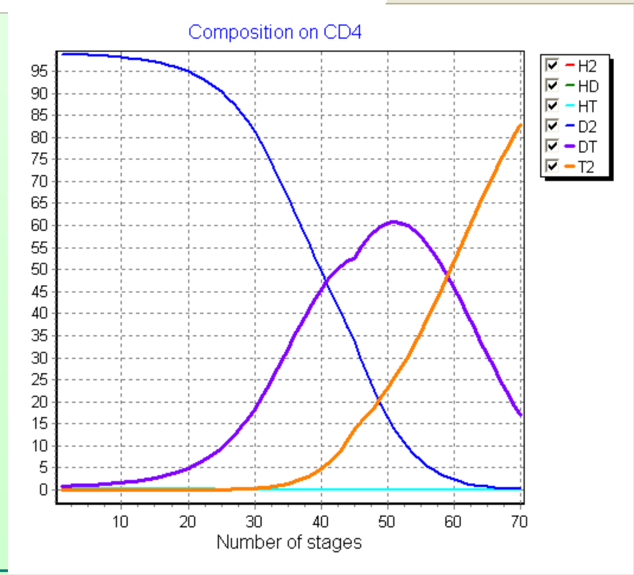
Concentration profiles in the ISS CD columns











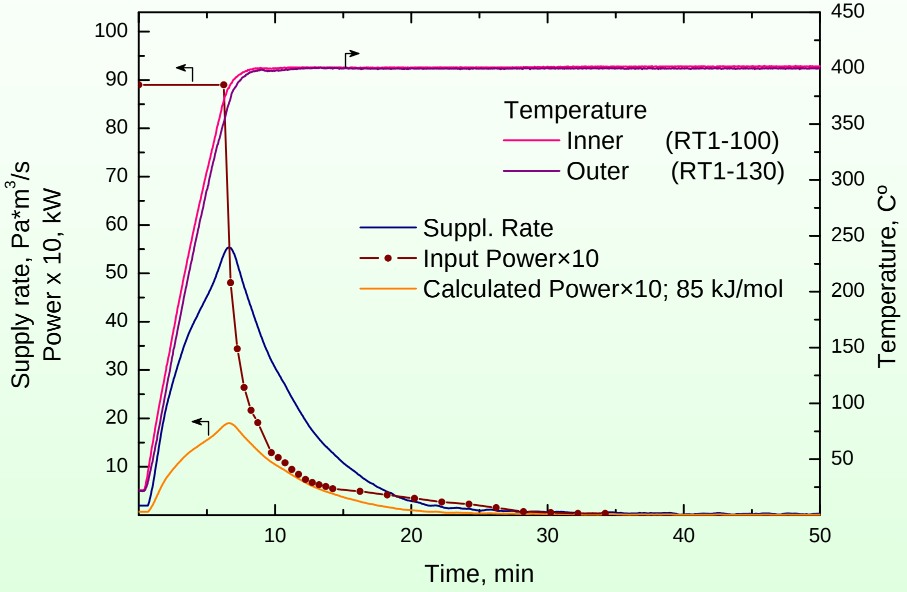
Fast delivery getter beds for ITER

T_2 and DT are stored in metal hydride getter beds, ZrCo hydride current reference material

- **$2\ ZrCo + 3T_2 \rightarrow 2\ ZrCoT_3$ + Heat**

  (low absorbtion pressure at room temperature)
- **$2\ ZrCoT_3$ + Heat $\rightarrow 2\ ZrCo + 3T_2$**

  (dissociation pressure >1 bar at 300-400°C)



- **Full size (100g T_2) fast-delivery getter bed has been designed, manufactured and currently tested at FzK**
  - **Disproportionation: $2\ ZrCoQ_3 \rightarrow ZrCo_2 + ZrQ_2 + 2Q_2$**
  - **Reproportionation possible under certain conditions**

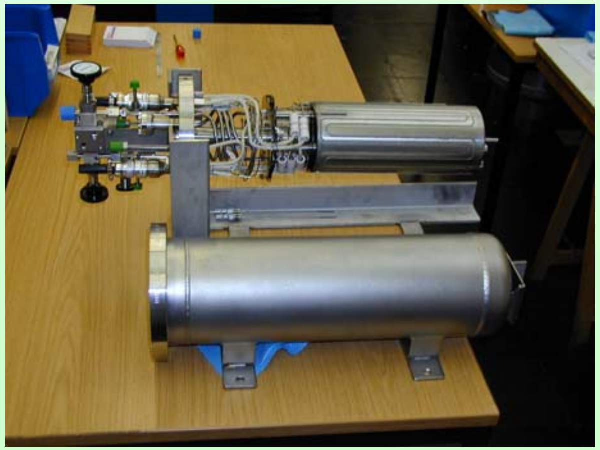
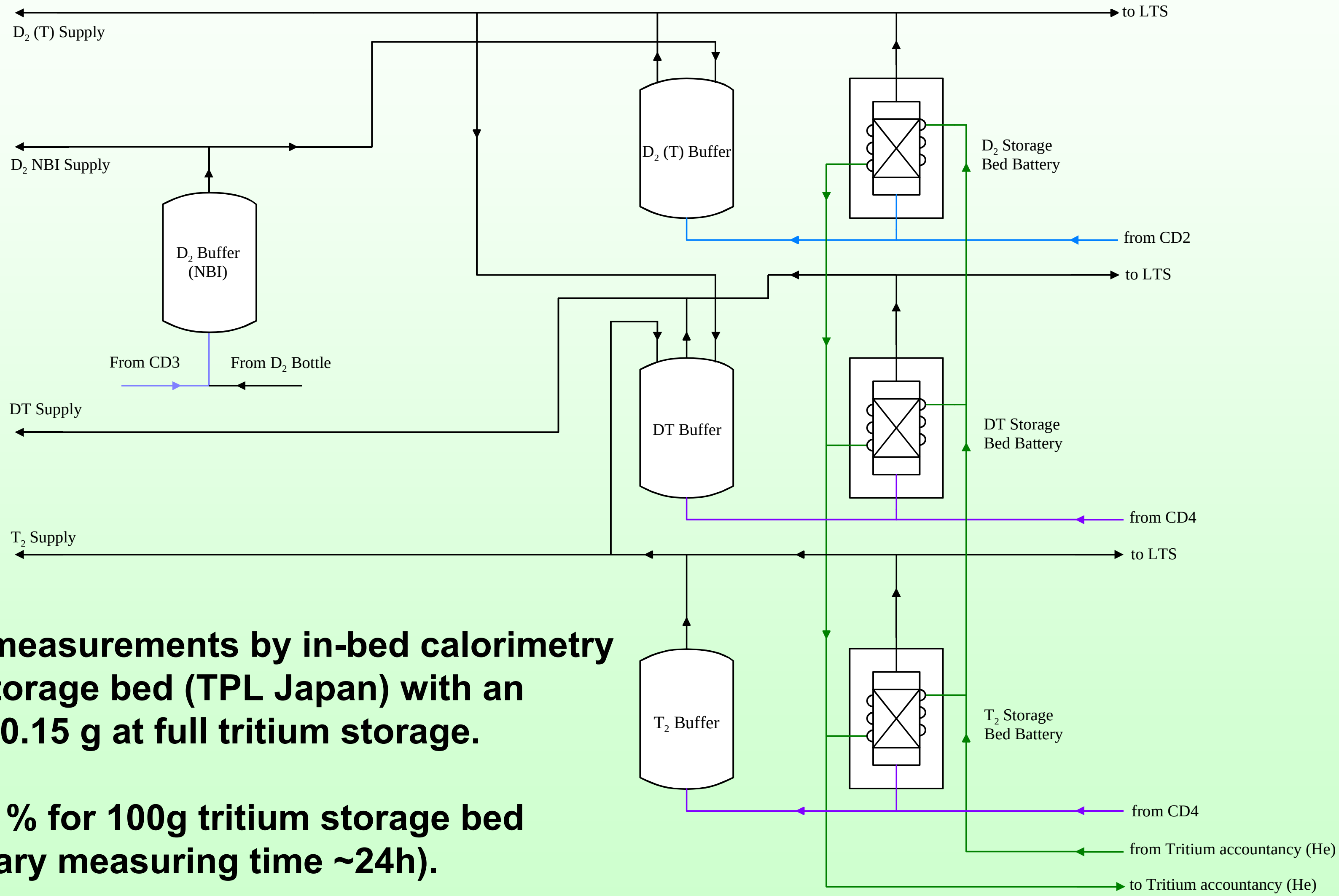


Diagram of Storage and Delivery System for ITER

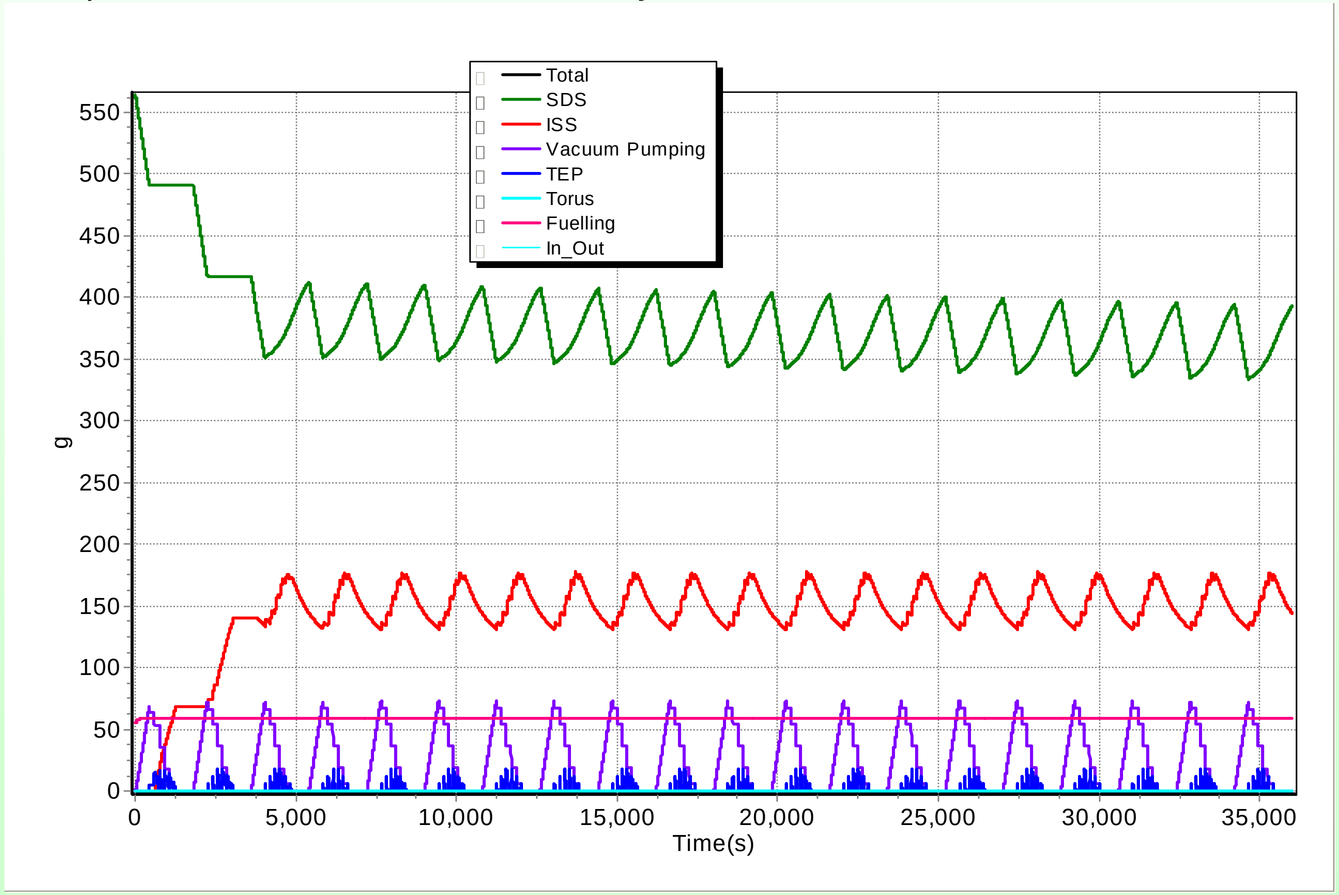


Tritium inventory measurements by in-bed calorimetry on a 25 g tritium storage bed (TPL Japan) with an accuracy of about 0.15 g at full tritium storage.

ITER target value 1% for 100g tritium storage bed (estimated necessary measuring time ~24h).

Tritium Inventories

- Dynamic modeling allows trade-off studies between Fuel cycle subsystems for tritium inventories minimization
- It constitutes an important tool for tritium accountancy

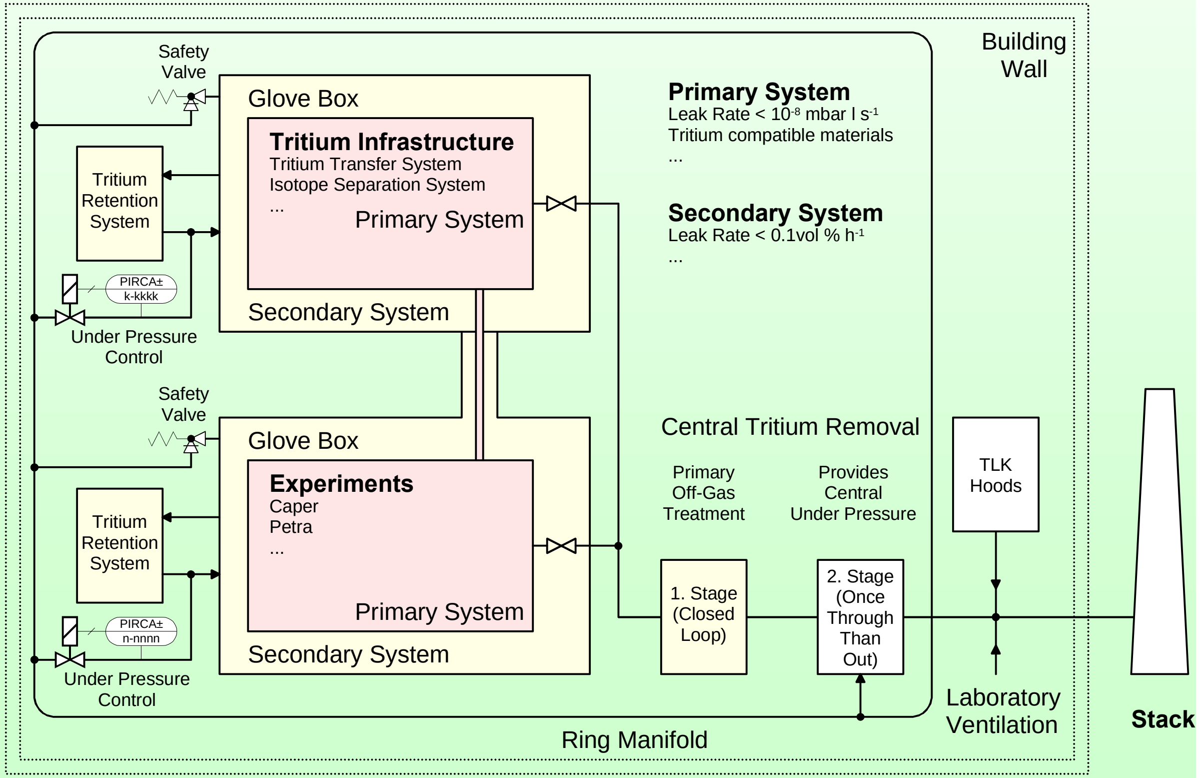


Effluents and Releases

- **Multiple confinement barriers implements Defense in Depth principle**
- **Implementation of ALARA in the ITER design was intensively checked**
  - **Detailed studies of all effluents and releases from ITER as specified in GSSR**
    - **Site specific layout considered**
    - **Local meteorological conditions taken into account**
      - Consequences analyzed for normal and accidental releases
      - Low limits on tritium in liquid effluents
- **Project guidelines for ITER tritium releases during normal operation**
  - **1 ga^{-1} as HT**
  - **0.1 ga^{-1} as HTO**
- **Estimated ITER tritium releases**
  - **0.18 ga^{-1} as HT through protium discharge of the Isotope Separation System (ISS)**
  - **0.05 ga^{-1} as HTO**
    - **0.0004 ga^{-1} will be waterborne, 85% out of that is due to blow down of the cooling tower**
- **Tritiated water will be produced in all ITER atmosphere detritiation systems (ADS)**
  - **ITER will operate a Water Detritiation System (WDS) with a capacity of $\leq$ 20 kgh^{-1} to process the water from the regeneration of ADS molecular sieves**

Tritium Confinment phylosophy

- **Multiple barrier concept for the confinement of tritium**
  - **Detritiation of all primary exhaust gases (except from Water Detritiation System) prior to discharge into the environment**
  - **Atmosphere detritiation systems for secondary and tertiary containments**
  - **Removal of tritium permeated through hot structural materials**
  - **Recovery of tritium via the Tokamak Exhaust Detritiation System**
  - **Specifications for primary and secondary containments**
    - **Definition of leak tightness**
    - **Outer jacket for tritium bearing components heated to temperatures above 150°C**

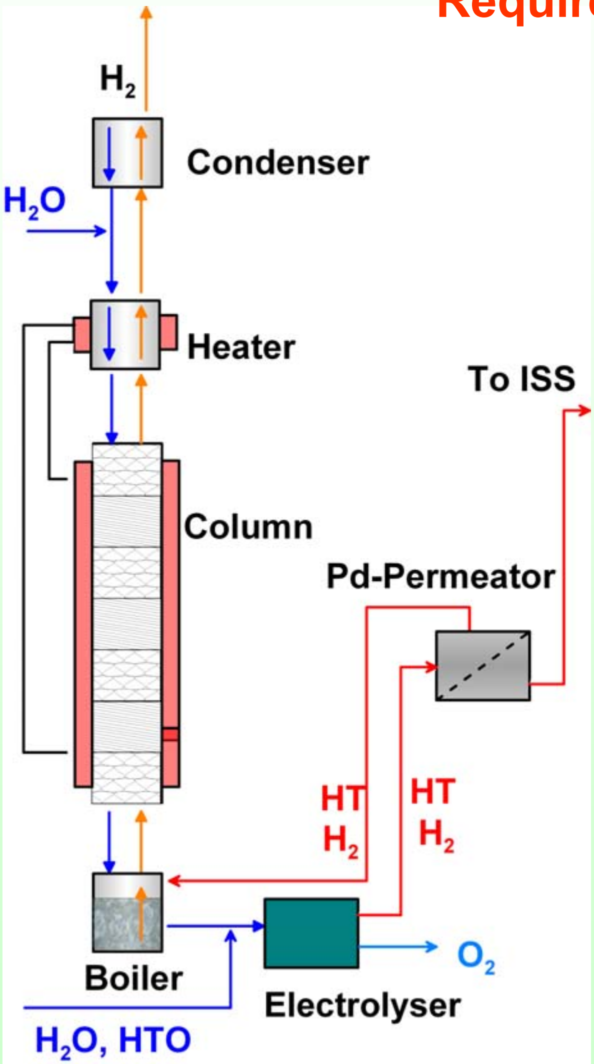


Tritium Primary System Safety for ITER

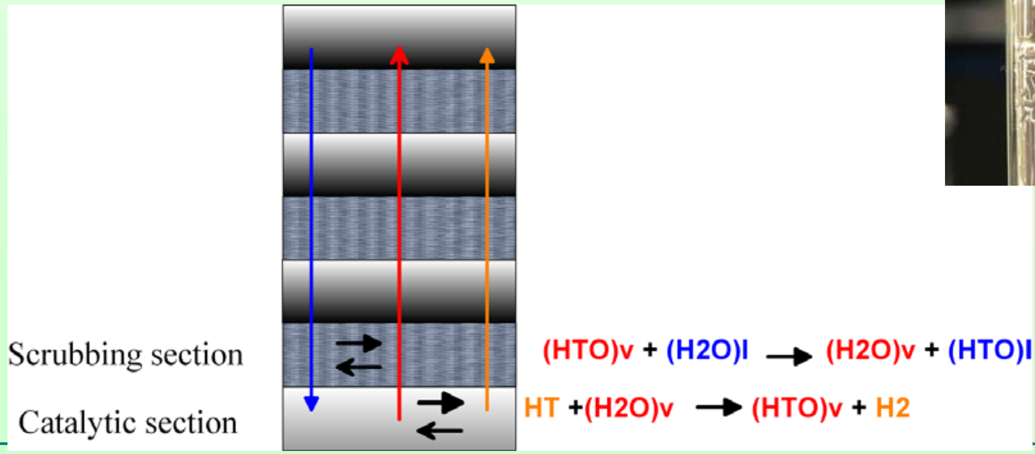
- **Management of functional safety (along with the international standard IEC 61508)**
  - **P& ID`s are available for each Fuel Cycle subsystem**
  - **Risk evaluations by Hazard and Operability (HAZOP) studies**
  - **Analyze loop by loop of each safety instrumented function by a team of experts, including at least one senior, competent person not involved in the project design team**
  - **Assignment of a specific Safety Integrity Level (SIL) is to each SIF**
    - **Software solutions are accepted for low risks such as SIL 1 or in some cases SIL 2**
    - **Hardware solutions are required for SIL 3**
    - **None of the tritium primary system loops should involve the highest risk level (SIL 4)**
    - **Feedback to the design if necessary**

Water Detritiation - Combined Electrolysis Catalytic Exchange Process

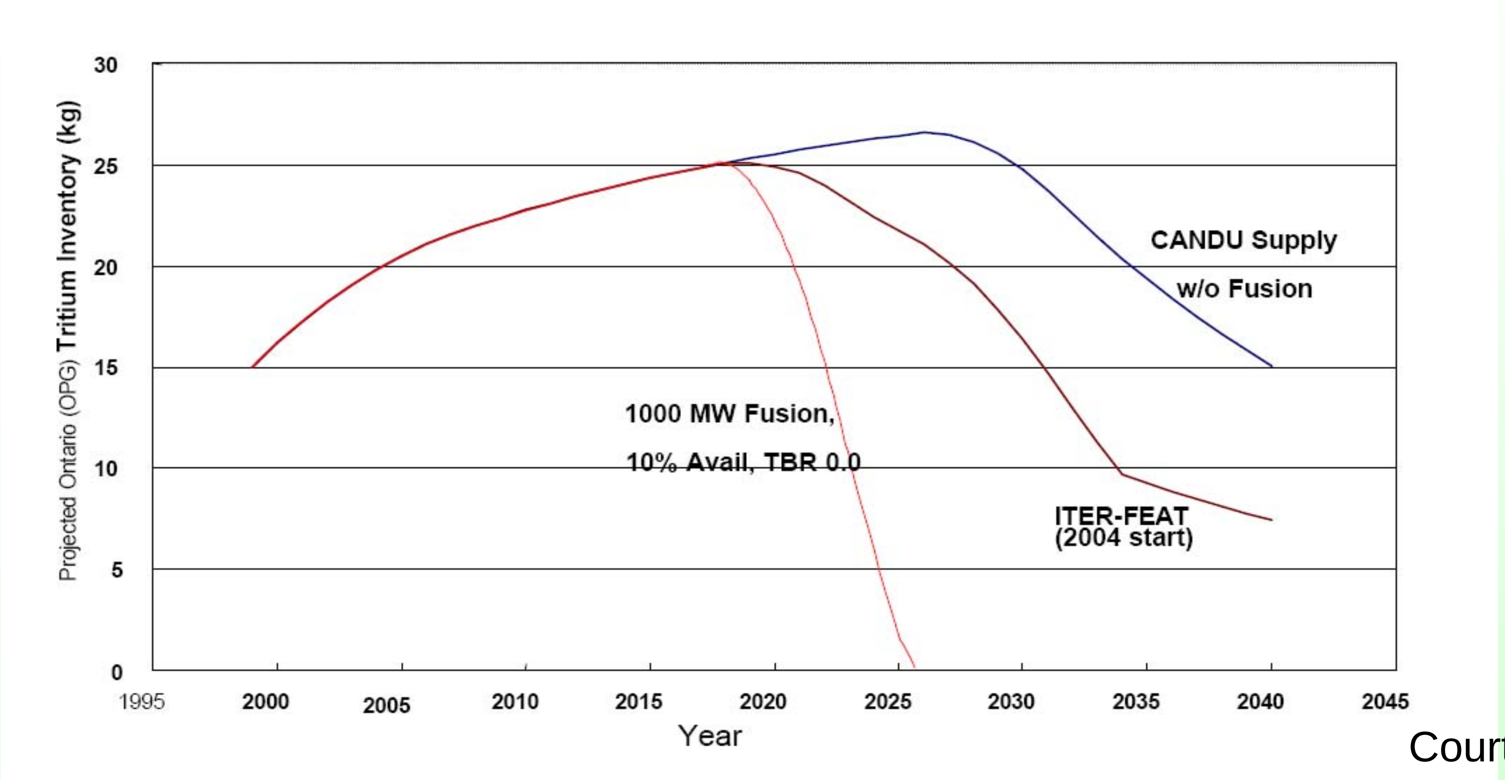
Requires a decontamination factor of about 10^8



- Temperature of the column: ~ 60°C;
- LPCE column is filled with mixtures of catalyst and packing;
- Achievable decontamination factor is given by the catalyst and packing separation efficiency;
- Catalyst /packings are available from different manufacturers;
- Intense R&D program to study the simultaneous H, D, T transfer;
- R&D on-going to investigate SPM lifetime, testing the mechanical properties of SPM after long-time exposure



Expected Tritium Available



Courtesy S. Willms, LANL

~ 2.5 kg/year for 20 CANDU units (Ontario OPG)
400t of heavy water in a CANDU unit (moderator+cooling) ; Generation rate 5 Ci/kgy; Recovery efficiency 90%

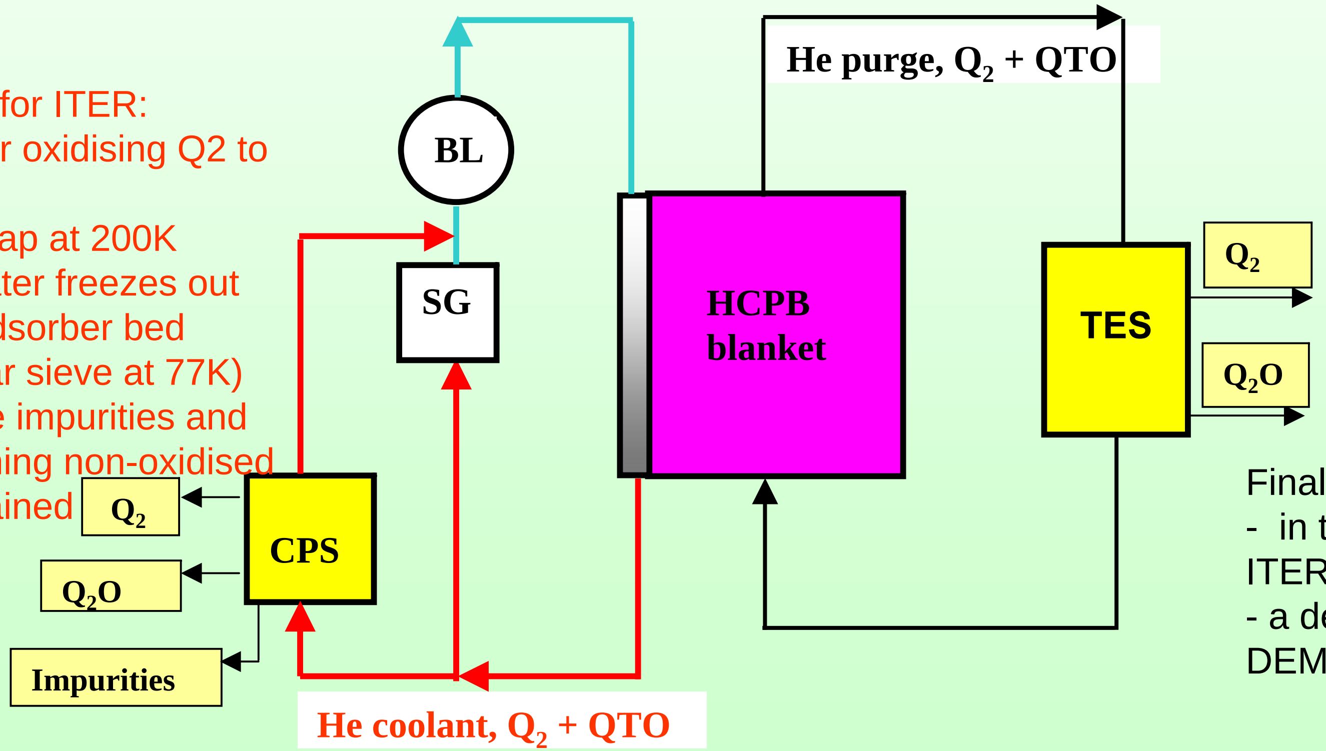
Korea is currently comissioning a Tritium Extraction facility (4 CANDU units)
Water Detritiation program undergoing in Romania (1 CANDU unit operational and 1 under construction)
China – 2 CANDU units

Blanket Tritium Cycle for HCPB from DEMO

Coolant Purification System (CPS)
- process the tritium permeated from the blanket into the primary helium coolant
  - a fraction of only 0.01-1% of the helium coolant stream is fed in CPS

Tritium Extraction System (TES)
- extraction of tritium from the blanket purge gas
- a Cold trap combined with Thermal Swing Adsorption using a cryogenic molecular sieve bed
- the advantage is that tritiated hydrogen is not converted into tritiated water

Proposal for ITER:
- a bed for oxidising Q2 to Q2O
- a cold trap at 200K where water freezes out
- a cryoadsorber bed (molecular sieve at 77K) where the impurities and all remaining non-oxidised Q2 is retained



Final tritium recovery:
- in the existing TEP/ISS for ITER
- a dedicated ISS is needed for DEMO

Extraction/removal of tritium from breeding blanket

	TES		CPS	
	ITER	**DEMO**	**ITER**	**DEMO**
• **Tritium generation rate during pulses [g tritium/d]** • **Tritium permeation rate from purge gas stream [g tritium/d]**	**< 0.1** **-**	**385** **-**	**-** **0.000012**	**-** **12.6**
Purge gas flow rate [Nm^3/h] **CPS feed flow rate**	**12.1** **-**	**8000** **-**	**-** **0.107**	**-** **48400**

Significant conceptual, modelling, experimental and design activities are needed for DEMO !!!

Conclusions

- **Concepts, technical solutions and detailed design for ITER Fuel Cycle systems are available**
- **Separation performances already proven for certain Fuel Cycle systems**
  - **Challenging due to the high decontamination factors required**
  - **Broad range of input gas compositions and flow rates**
- **Control system is rather complex due to:**
  - **Safety instrumented functions**
  - **Rapid fluctuations in composition and flow rates**
- **Instrumentation**
  - **Accurate and fast-response analytics is still a goal**
  - **Methods for accurate and stable flow-rate measurements of complex gas mixtures need further development**
- **The inner Fuel Cycle technology of ITER constitutes a good basis for DEMO**
  - **However, processes for extraction and recovery of bred tritium (and tritium permeated into cooling systems) will have to be developed**
  - **Quantification of tritium trapped in materials will become available during ITER operation**