3.1 Tritium Plant and Detritiation

3.1.1 System Description

The functions of the tritium plant can be summarised as:

- processing all tritiated gas streams from sources within the plant to produce the gas streams for fuelling (at specified flow rates and isotopic compositions);
- confinement of tritium with multiple barriers (such as a primary component, secondary enclosures and rooms);
- detritiation of a number of tritium-containing waste streams and contaminated room air, and detritiation of tritiated waste water to reject the detritiated remnants to the environment.

The main design guidelines for the tritium plant are:

- minimisation of tritium inventories;
- reduction of occupational exposure;
- low generation of effluents and wastes;
- reduction of costs by standardisation of components.

The design is based upon well-proven technology to ensure the safe handling and credible accountancy of tritium, and high reliability.

3.1.1.1 Tokamak Fuel Processing Subsystems

The outline flow diagram, shown in Figure 3.1-1, depicts the tokamak fuel processing subsystems, which consist of the storage and delivery, tokamak exhaust processing, hydrogen isotope separation, and the tritium plant analytical systems. The diagram identifies and defines all interfaces within this group of subsystems, enabling the process conditions at the interfaces to be defined systematically and consistently. In addition, there are further subsystems which participate in the fuel processing: glow discharge gas processing, gamma decay and auxiliaries.

The diagram also indicates the connections between these systems and the fuelling system, torus, torus exhaust pumps, and the water detritiation system.

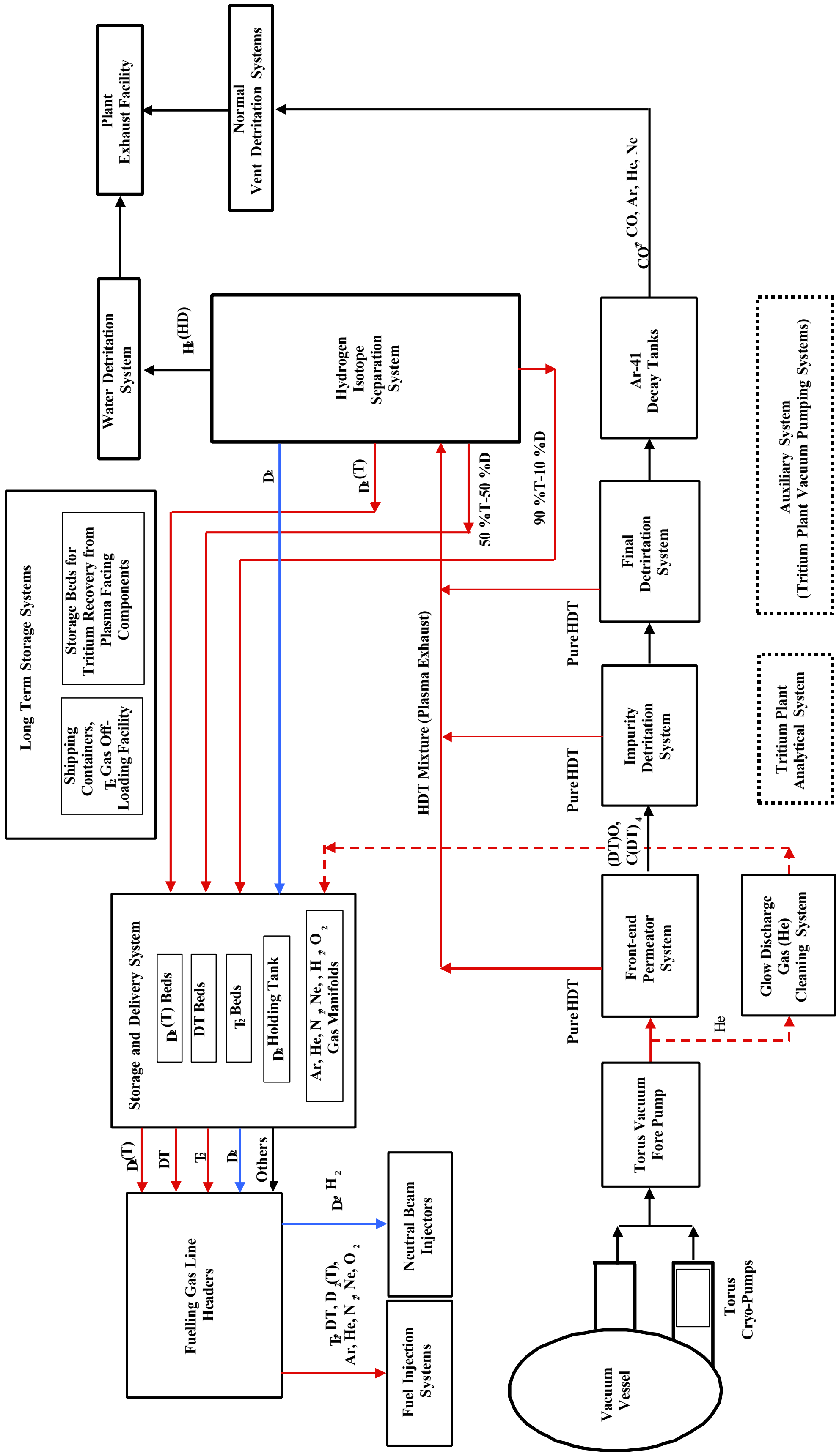

Figure 3.1-1 Outline Flow Diagram of ITER Fuel Cycle Systems and Interfaces

Storage and Delivery Systems

These systems include the long-term storage, and the short-term fuel storage and delivery systems. Transport beds containing tritium delivered from off-site are unloaded in the long-term storage. Prior to unloading, calorimetric determinations of the amount of tritium contained in the transport beds are made. Tritium is transferred as required for machine operation to the short-term storage and delivery system. In addition, between operational campaigns, when tritium is recovered from plasma-facing components, it will be necessary to transfer much of the tritium to the long term storage, which requires a capacity of 1,000 g. At the maximum tritium concentration available from the isotope separation system (purity of T ≥ 90%) this will correspond to ~ 200 moles.

The short-term storage and delivery system receives tritium containing hydrogen gases from the isotope separation system, tokamak exhaust processing system, and long term storage, at specified isotopic compositions (10/90 DT, 50/50 DT, and two D_2(T) streams for the NB injectors and gas puffing) during plasma operation, and stores them on getter beds and in holding tanks. The gases are delivered on demand to the fuelling system at specified isotopic compositions and flow rates. The design delivery rate from each bed is 20 Pam^3s^{-1}. The delivery of DT mixtures with compositions other than those listed above involves mixing the gases evolved from the storage beds, the proportions of each component being metered by mass flow controllers. For D plasma operation, D_2(T) may be delivered to the fuelling system from storage beds, the holding tank or from both these sources.

The storage beds in the storage and delivery system are each equipped with an integral calorimetric capability, achieved by temperature differential measurement in an external loop in which helium is circulated at a precisely controlled flow rate.

A further requirement is the recovery of the ^{3}He tritium decay product, which is achieved by periodically releasing the gas inventory from each of the beds in turn and transferring it to a dedicated getter bed which pumps the hydrogen isotopes, allowing the helium to pass through and be directed to a collection tank. The hydrogen absorbed by the getter bed is then returned to the main battery of storage beds.

Tokamak Exhaust Processing System

The main function of the tokamak exhaust processing system is to recover unspent DT fuel yielding a product stream suitable for transfer to the isotope separation system, or for transfer to the storage and delivery system during all modes of tokamak operation, including plasma operation, pump-down, wall-conditioning, leak detection, and tritium recovery from the plasma-facing components. In addition, tritiated gaseous process wastes from other sources (NB injector cryopump impurities, fuelling system purge, tritium plant analytical system, regeneration of helium glow discharge cleaning molecular sieve beds, and ultimately from the test blanket module purge gas loop) are also accepted and decontaminated by the tokamak exhaust processing system. The tokamak exhaust during plasma operation also includes inert gas activated by neutrons. The expected overall detritiation factor verified by R&D[1] is ≥ 10^8. The waste gas stream from the tokamak exhaust processing system, although it contains an extremely low level of tritium (less than 1 mCi/d), is sent to the normal vent detritiation system.

[1] H. Yoshida et al. "ITER R&D Auxiliary Systems", Fus. Eng. Design 55 (2001), pp 313-323

The tokamak exhaust processing system (see Figure 3.1-1) is composed of the following three processing subsystems:

- front end permeator;
- impurity processing;
- final clean-up.

The first subsystem (once-through process) comprises front-end membrane permeators (palladium/silver alloy) for separation of elemental hydrogen isotopes from tokamak exhaust gas during plasma operation and wall conditioning with D_2 gas, and a nickel catalyst reactor for direct conversion of tritiated impurities into elemental tritium during plasma operation and co-deposited tritium recovery campaigns. A separate permeator receives the NB injector cryopump regeneration gases and separates this stream into a pure molecular hydrogen stream, which is mixed with the tritiated protium stream from the water detritiation system and sent to the protium column of the isotope separation system. The impurities are sent to the impurity processing subsystem of the tokamak exhaust processing system.

During the special operation mode for tritium recovery from the plasma-facing components, the tritium recovery gas may include high concentrations of tritiated hydrocarbons, water vapour (DTO), CO, CO_2, O_2 and carrier gas (N_2 or Ar). The tritiated impurities are directly converted into elemental hydrogen (DT) in the nickel catalyst reactor, and the product gas sent to one of the front-end permeators for separation of DT from impurities and carrier gas. The DT stream is transferred to the isotope separation system. The major portion of the carrier gas is sent to the normal vent detritiation system via the impurity processing system.

The second subsystem (re-circulation loop process with continuous feed and bleed) comprises a small nickel catalyst reactor and a small membrane permeator for continuous recovery of elemental tritium from tritiated impurities by heterogeneously catalysed cracking or conversion (chemical) reactions. This subsystem also treats impurity streams from other sources including during glow discharge cleaning, cryogenic molecular sieve bed regeneration, and the analytical system.

The third subsystem (once-through final cleanup process) comprises a small counter-current membrane reactor for final detritiation of waste gas by means of isotopic exchange with protium. The detritiated impurity gas is then routed to the gamma-decay system. These three subsystems and gamma-decay system are placed in a shielded room.

Gamma Decay System

A system of tanks equipped with γ activity monitors and transfer pumps has the function of temporary retention of activated (short half-life) inert gas species to allow for their decay to an acceptable level, at which point they are discharged through the normal vent detritiation system to the environment.

Glow Discharge Gas Processing

During glow discharge cleaning, deuterium and helium will be purged over prolonged periods (up to 100 h) through the plasma vacuum vessel, at a flow rate of ~ 50% of the nominal fuelling rate for plasma operations. The gas stream from the torus roughing pumps during the helium glow will be processed through one of a pair of 77K liquid nitrogen-cooled molecular sieve beds to trap the impurities, and the helium is recycled directly back to the tokamak. The molecular sieve beds will be regenerated every 24 h, by warming to room temperature for elemental hydrogen desorption, and (at a lower frequency) to higher temperatures for tritiated moisture desorption. The desorbed gas is directed to the impurity processing loop of the tokamak exhaust processing system. This processing system will also be used for helium plasma operation.

Hydrogen Isotope Separation System

The isotope separation system utilizes cryogenic distillation to separate hydrogen isotope mixtures. The feeds originate from the sources shown in Table 3.1-1 with the indicated schedules.

Table 3.1-1 Isotope Separation System Operation Schedules for Different Feeds

Feed	Schedule
Plasma exhaust	Intermittent
Neutral beam injection	Intermittent
Water detritiation	Continuous
First wall conditioning	Occasional (not simultaneously with intermittent feeds)

These feed streams are introduced at two feed locations in the column cascade to produce up to five different products. These are a detritiated protium effluent for discharge to the environment, two distinct deuterium streams for gas fuelling and NB injector source gas, and two tritium fuelling streams, one with 50/50 DT and one with 10/90 DT isotopic composition. The column cascade consists of four distillation columns (CD1, CD2, CD3 and CD4). The purpose of the first column (CD1) is to remove tritium from predominantly protium-rich streams and to produce a virtually tritium-free protium stream as the overhead product. The function of the second column CD2 is to separate H and D from the CD4 overhead stream, and produce a partially-purified D_2 stream which is used for gas fuelling and as the feed to the third column CD3. CD3 removes tritium and protium from the deuterium for NB injector source gas. The bottom product of CD2, a D_2-DT mixture stream, is fed into the high-tritium-column CD4, which also receives elemental hydrogen separated in the tokamak exhaust processing system from the plasma exhaust stream.

Dominant design inputs for the isotope separation system are (1) the dynamic characteristic of some of the feed stream flow rates and compositions, and (2) tritium (and total hydrogen) inventory minimisation. These necessitate optimisation of the cascade configuration and column design to reduce column diameters and lengths to the maximum extent consistent with maintaining product quality. In addition, the cascade is equipped with several equilibrators, which are small catalytic reactors operating at ambient temperature to promote isotope exchange reactions. These reduce the required number of theoretical stages and therefore the total inventory of the cascade. The circulation pumps for equilibrator loops and transfer pumps are located in ambient temperature locations. As a result, the entire isotope separation system has no moving parts operating at cryogenic temperatures. This, with the use of redundant electric reboiler heaters, minimises the maintenance needed for components inside the cold box.

In order to facilitate the transition from standby to intermittent plasma operations, a set of recycle lines is provided to permit temporary operation at closed recycle without external feed and product flows.

Tritium Plant Analytical System

In addition to local instrumentation, a central analytical system is an integral part of the tritium plant with the main functions:
i) verification or additional control of the correct functioning of various processes by determination of the composition of various gas mixtures,
ii) determination of tritium concentrations in various gas mixtures for inventory accounting,
iii) monitoring and calibration of local instrumentation, e.g. ionisation chambers.

Samples from the storage and delivery system, tokamak exhaust processing system, and isotope separation system, are sent to the analytical system via interconnecting lines. Four manifolds are installed in the analytical system to receive samples, and are organised to minimise cross contamination between samples of different compositions. The samples to be analysed are injected into analytical gas chromatographs for determination of their gas composition.

Five gas chromatographs (three micro-gas chromatographs and two cryogenic micro-gas chromatographs) are chosen to perform the analytical tasks required, i.e. determination of the tritium concentration, as well as of the six hydrogen molecular species and of the other impurities expected.

The exhaust gases of the five gas chromatographs containing carrier gas, and injected samples are either sent for final detritiation to the normal vent detritiation system or to the tokamak exhaust processing system, depending on their tritium concentrations.

The gas chromatographs, manifolds and pipework connected to the tokamak exhaust processing system are placed in a shielded barrier.

Auxiliary System

The auxiliary system (see Figure 3.1-1) is composed of a high vacuum manifold and a vacuum manifold. The former receives high vacuum pump exhaust from the tritium process component vacuum jacket. The latter receives vacuum pump exhaust from various other sources. Gases collected by this system are delivered to an appropriate point in the tokamak exhaust processing system, depending on their composition.

3.1.1.2 Tritium Confinement and Detritiation Subsystems

The heating, ventilation and air conditioning systems (HVAC) and detritiation systems form an essential part of the ITER tritium confinement. HVAC and detritiation subsystems for the tokamak building, tritium building, hot cell and radwaste buildings are operated in various modes depending on the plant operation states, such as normal operation, maintenance and off-normal events.

Tokamak Building HVAC and Detritiation Systems

The HVAC and detritiation systems for the tokamak building are composed of two dedicated heating, ventilation and air conditioning systems for the gallery areas (HVAC-I) and for the containment volume (the tokamak cooling water system vault and annex, CVCSs area, NB cell, upper and lower pipe chases, and vertical pipe shafts) (HVAC-II), and various atmosphere detritiation systems such as the normal vent detritiation system, the standby room air vent detritiation system, the standby room air detritiation system, and the tokamak vent system for these areas. As an additional function of the HVACs for the gallery and the containment volume, local air coolers are incorporated for continuous removal of the heat load from various equipment and lighting.

Figures 3.1-2 and 3 show the integrated confinement and detritiation system configurations for the tokamak building. During plasma operation and baking, a negative relative pressure of - 1 mbar in the gallery areas is maintained by HVAC-I. Through a small duct the gallery area is connected with the tokamak pit free volume (~ 5,000 m^3, leakage rate 10 vol%/d) in between the cryostat outer surface and the bioshield inner surface. This ensures that air leakage between the crane hall and the pit free volume (~ 20 m^3/h) is always in the direction of the pit.

Ducts are installed between the bioshield inner wall and the cryostat outer wall enclosing the port openings. This effectively seals off the port area from the pit free-air volume and prevents the cross-contamination from one port to another.

To avoid condensation of the moisture, which is included in the external air, onto the cryostat surface, a forced air circulation system with a small rotary air dryer unit (throughput 150 m^3/h) composed of a compressor and an internal gas/water heat exchanger is utilized.

As schematically shown in Figure 3.1-2, the port cell pressure is kept at - 2 mbar differential pressure by continuously extracting air by the normal vent detritiation system to form a pressure gradient from the gallery areas (-1 mbar) to the ports. With this confinement configuration, it is possible to localise tritium contamination, and to eliminate the risk of tritium release to the environment during port maintenance.

It is intended to route all tritium-bearing pipes, e.g., vacuum and fuelling lines, that interconnect the vacuum vessel with the tritium plant, and hence cross the gallery areas, inside the floor slabs of the galleries, such that their secondary containment volume is either pumped or purged to the tritium plant. This design configuration makes release from these lines into the gallery areas a beyond-design-basis event, and avoids the need to have emergency isolation valves in the gallery areas HVAC system.

HVAC-II (Figure 3.1-3) for the containment volume (volume 51,000 m^3, air leakage rate 10 vol%/d at a room internal pressure of 2 bar(abs)) is not operated during plasma operation and baking, and a differential room pressure of – 3 mbar is maintained by the normal vent detritiation system by extracting room air with a flow rate equivalent to the volume air leakage rate.

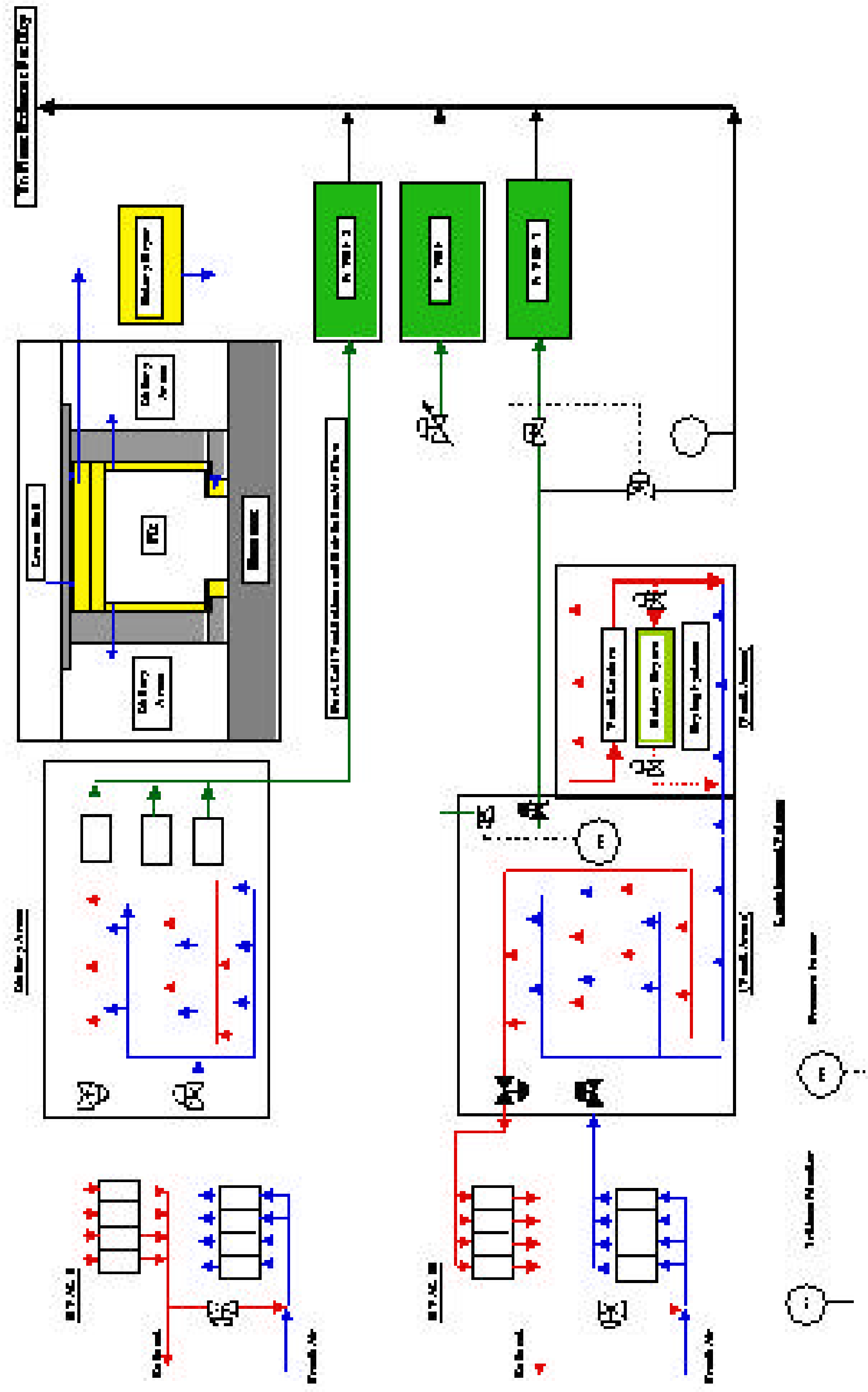

Figure 3.1-2 Configuration of HVAC Systems

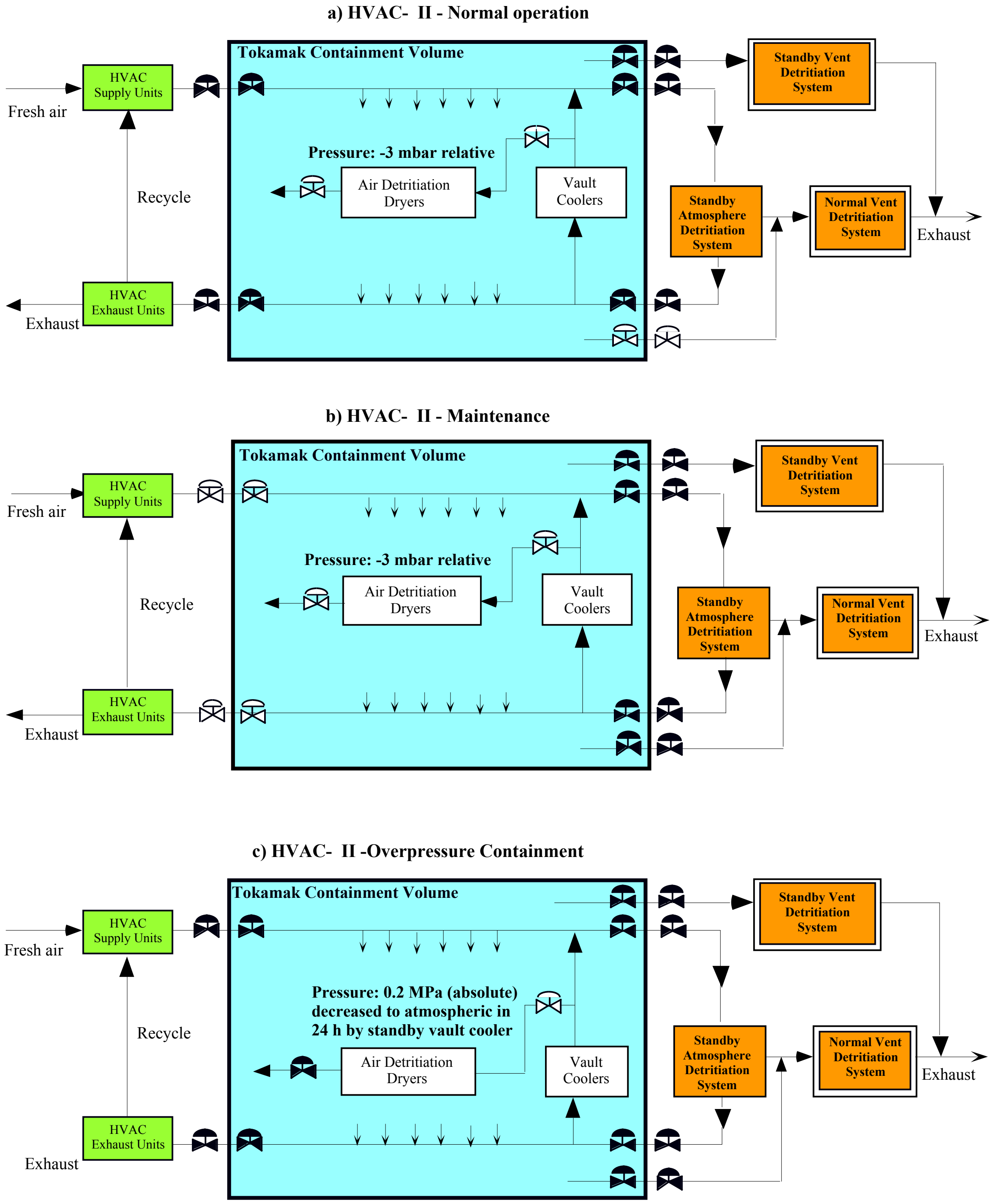

Figure 3.1-3 Tokamak Building Confinement and Detritiation System Configuration of HVAC II (TWCS Vault and Vault Annex Upper and Lower Pipe Chases, Vertical Pipe Shafts, NB Cell)

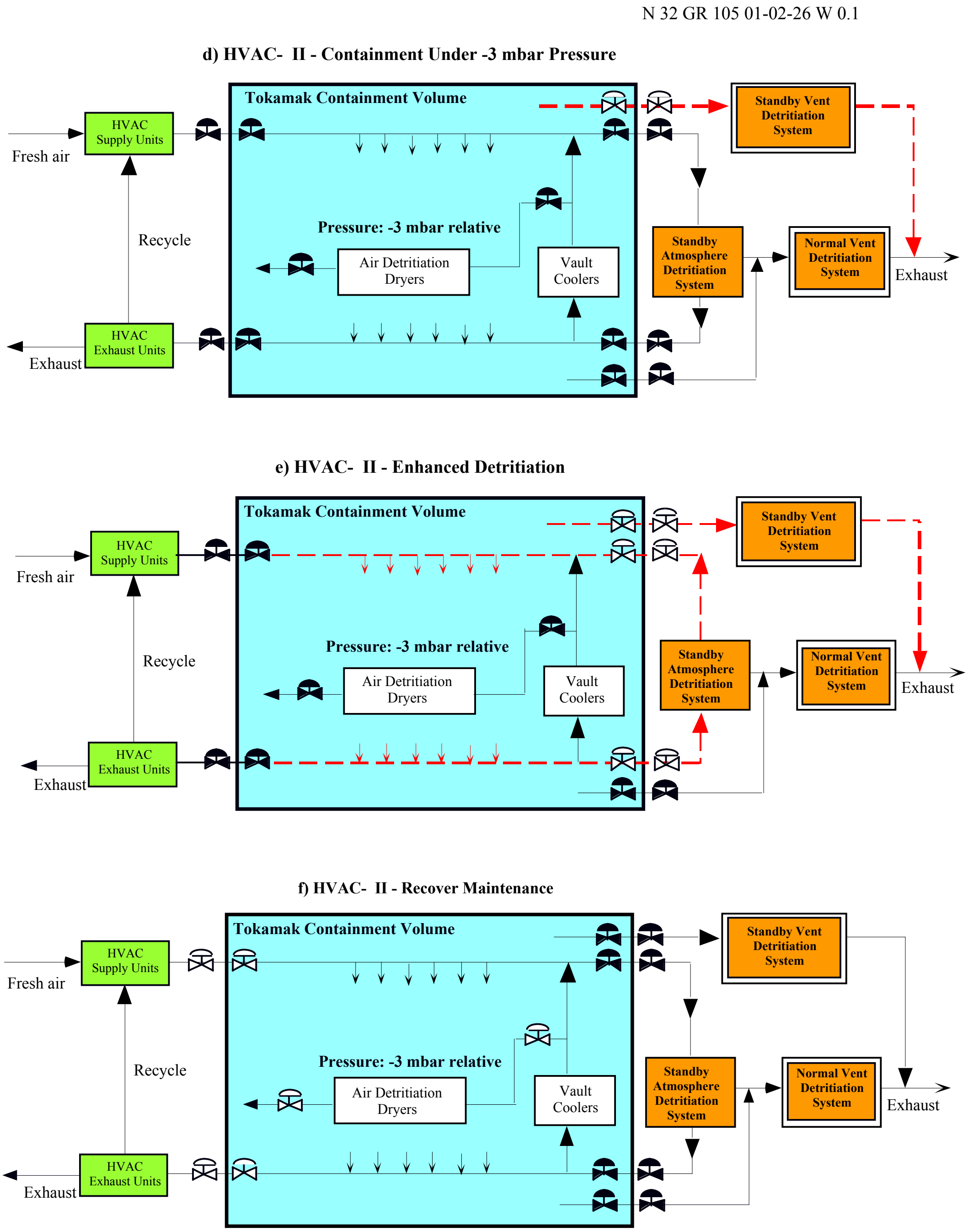

Figure 3.1-3 Tokamak Building Confinement and Detritiation System Configuration HVAC II (continued) (TWCS Vault, Vault Annex, Upper and Lower Pipe Chases, Vertical Pipe Shafts, and NB Cell)

The heat load (plasma operation: 0.8 MW, baking: ~ 1 MW) in the containment volume generated by pump motors and losses through the thermal insulation around pipes and components of the tokamak cooling water system, is continuously removed by the containment volume air coolers (cooling capacity 1.2 MW). Moreover, in the case of a large ex-vessel coolant leak (~ 100 m^3 water), the resulting steam pressure (below 0.2 MPa) is reduced to ambient within 24 h by steam condensation at the containment volume coolers.

Tritiated moisture leaking from the tokamak cooling water system is also continuously removed by air detritiation dryers. The condensate of the coolers and the air detritiation dryers may include tritium, thus it is sent to the water detritiation system before its rejection to the environment. Tritium permeation into the tokamak cooling water system coolant is estimated to be relatively small, therefore the air detritiation dryers will be installed later when required in the operation programme.

In case an ex-vessel leak occurs and/or a wet bypass event (bypass between the tokamak cooling water system vault to the vacuum vessel interior via a failed tokamak cooling water system loop) is caused as a consequence of an ex-vessel coolant leak, the normal vent detritiation system is isolated and the standby vault cooler (0.2 MW capacity) is started up. When the normal temperature and pressure in the containment volume are regained in 24 h, the standby vent detritiation system (throughput 3,000 m^3/h) and the standby atmosphere detritiation system (throughput 4,500 m^3/h) will be operated to enhance detritiation, which may allow early entrance to the vault areas to repair and/or replace failed piping and components.

An emergency water holding sump tank system of 400 m^3 capacity is installed in the basement room of the tritium building, to collect tritiated water generated (~ 100 m^3/month) by the operation of these detritiation systems.

Another type of wet bypass scenario (opening size < 0.02 m^2) due to the failure of a vessel penetration and/or a failure of diagnostic windows (both primary and secondary confinement), which may occur as a consequence of in-vessel coolant leakage, has been considered. In this case, the tokamak vent system (throughput 150 m^3/h) connected to the normal vent detritiation system, is started up within 3 minutes to prevent the internal pressure of the vacuum vessel from exceeding the area room pressure. During this scenario the tokamak vent system receives a stream from the tokamak vessel of high temperature (up to 300°C) and high humidity (up to 0.1 MPa vapour pressure).

In the case of a small-scale dry bypass event (opening size ~ 0.02 m^2), which may be caused by a failure of both primary and secondary confinement boundary windows attached to a diagnostic or heating system, allowing penetration of both the vacuum vessel and the cryostat boundaries, the air is immediately heated by the first wall and the volumetric expansion of the air results in a back flow of tritium containing air to the port cells. A relatively high level of leak tight design (in-leakage rate ~ 100 vol %/day) is applied to all port cells, and the atmosphere of the port cells is detritiated by a permanent connection to a dedicated normal vent detritiation system.

For tokamak maintenance through the vessel ports, the standby atmosphere detritiation system is switched to tokamak maintenance mode by connecting it to the tokamak vessel via the torus vacuum pumping ducts. The closed loop through the standby atmosphere detritiation system and tokamak vessel circulates dry air and continuously removes tritium outgassing from the first wall. The flow rate is adjusted to ~ 2,000 m^3/h to avoid wide dispersion of fine particles of tokamak dust due to turbulent flow in the vessel. This maintenance loop is also connected to the normal vent detritiation system, and a small flow is extracted from the loop to maintain negative pressure in the tokamak vessel.

The atmosphere detritiation systems, HVACs and containment volume air cooler equipment are located in the tritium building. The condensate of the equipment is sent to the tritiated water holding tank systems in the tritium building.

Tritium Building Confinement and Detritiation Systems

The confinement and detritiation systems for the tritium building are composed of tritium process equipment (primary barrier), enclosures such as glove boxes (secondary barrier), and tritium process rooms (final barrier). The secondary confinement is implemented by the glove box atmosphere detritiation system and/or the dry N_2 gas purge to the normal vent detritiation system. The tritium process rooms are backed up by the tritium building HVACs, the normal vent detritiation system (500 m^3/h) and the standby atmosphere detritiation system.

Figure 3.1-4 shows the concept of the confinement and detritiation system configuration for the tritium building. It also shows the interface with the ADS and VDS units for the tokamak building. The dotted lines indicate the possibility to connect the vault volume to the S-ADS and S-VDS. The HVAC is composed of a white zone HVAC and two green zone HVACs, i.e. one for the water detritiation system room and tritiated water holding tank rooms, another one for other tritium processing subsystems rooms. During normal conditions, the room atmosphere pressure in the green zone is maintained at - 1 mbar differential by the HVAC. When the room air tritium concentration exceeds a set point, the relevant room isolation valves in the HVAC are closed, and triggers cause the isolation valves connected to the normal vent detritiation system to open.

In the case that large room areas are contaminated simultaneously, the standby vent detritiation system (3,000 m^3/h) will be operated with a required flow rate. The standby vent detritiation system can be switched to three main areas, i.e. the tokamak building gallery area, the containment volume, and the tritium building green zone areas. The standby atmosphere detritiation system (4,500 m^3/h) is operated to enhance decontamination of the contaminated rooms to ensure early entry to reestablish normal conditions.

In addition, the normal vent detritiation system (throughput 500 m^3/h) receives various exhaust gases from different sources depending on their operation modes, maintenance schedule and their off-normal conditions. The normal vent detritiation system has a standby capacity (~ 200 – 300 m^3/h) to meet such intermittent gas sources.

Figure 3.1-5 shows the concept of an integrated atmosphere detritiation for both the tokamak and tritium buildings. The equipment of all atmosphere detritiation systems is located in the tritium building. Figure 3.1-6 shows an integral configuration of the glove box atmosphere detritiation system (throughput 150 m^3/h) and glove boxes. All glove boxes are purified by re-circulating the atmospheric gas (N_2) through the glove box atmosphere detritiation system during normal conditions. In case the tritium concentration in one of the glove boxes exceeds a set point (1 mCi/m^3) due to a failure of equipment or process piping, other glove boxes are isolated from the glove box atmosphere detritiation system gas circulation loop, and the full glove box atmosphere detritiation system capacity, is dedicated to the contaminated glove box for enhanced detritiation. Even if the maximum tritium inventory of 100 g in the tritium storage bed is instantaneously spilled in a representative glove box (volume 30 m^3), 99.9 %

recovery is achieved in a few hours. The resulting tritium permeation into the room through the gloves will be less than a few Ci, and retained by the normal vent detritiation system.

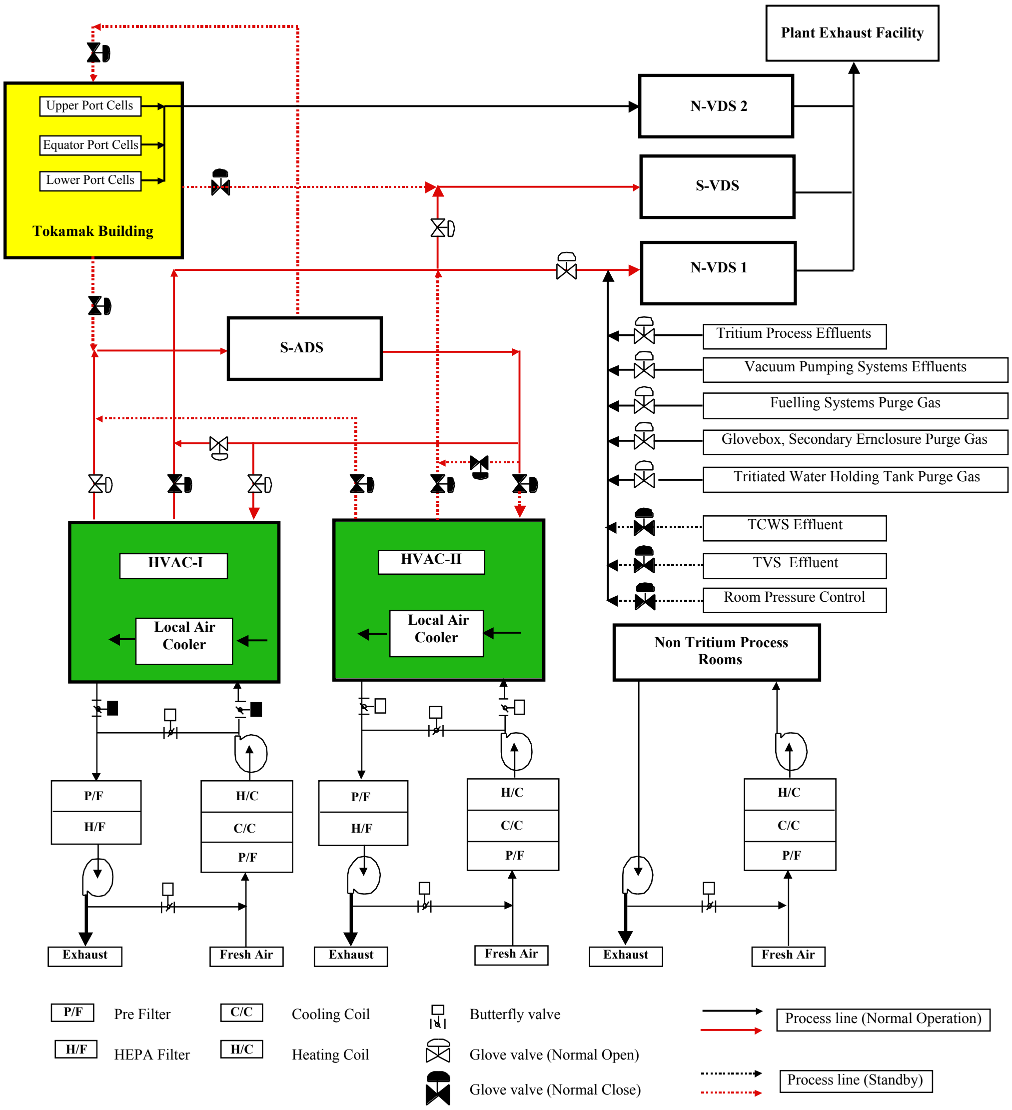

Figure 3.1-4 Concept of Confinement and Detritiation System Configuration for the Tritium Building

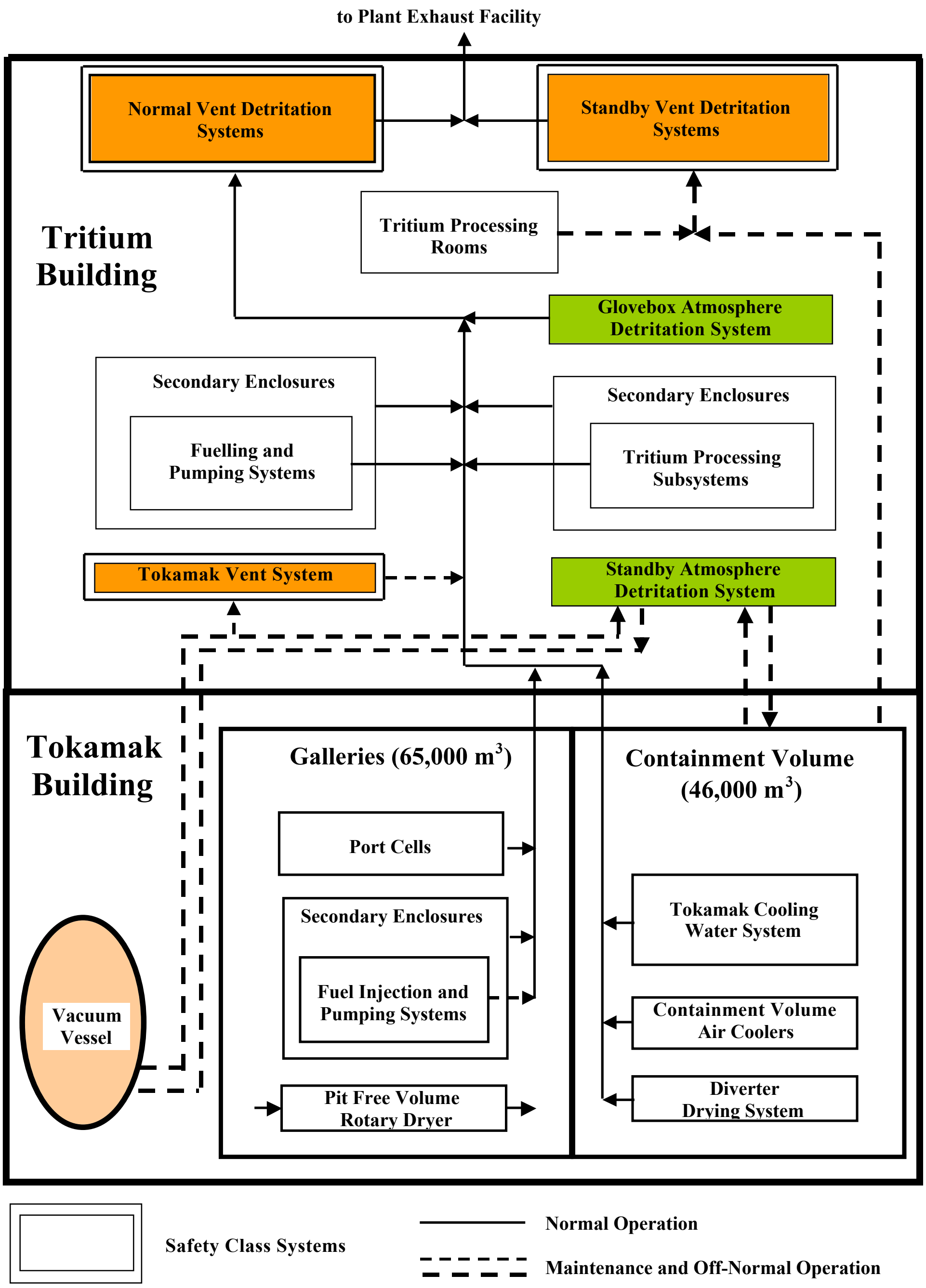

Figure 3.1-5 Integrated Atmosphere Detritiation System Configuration for the Tokamak and the Tritium Buildings

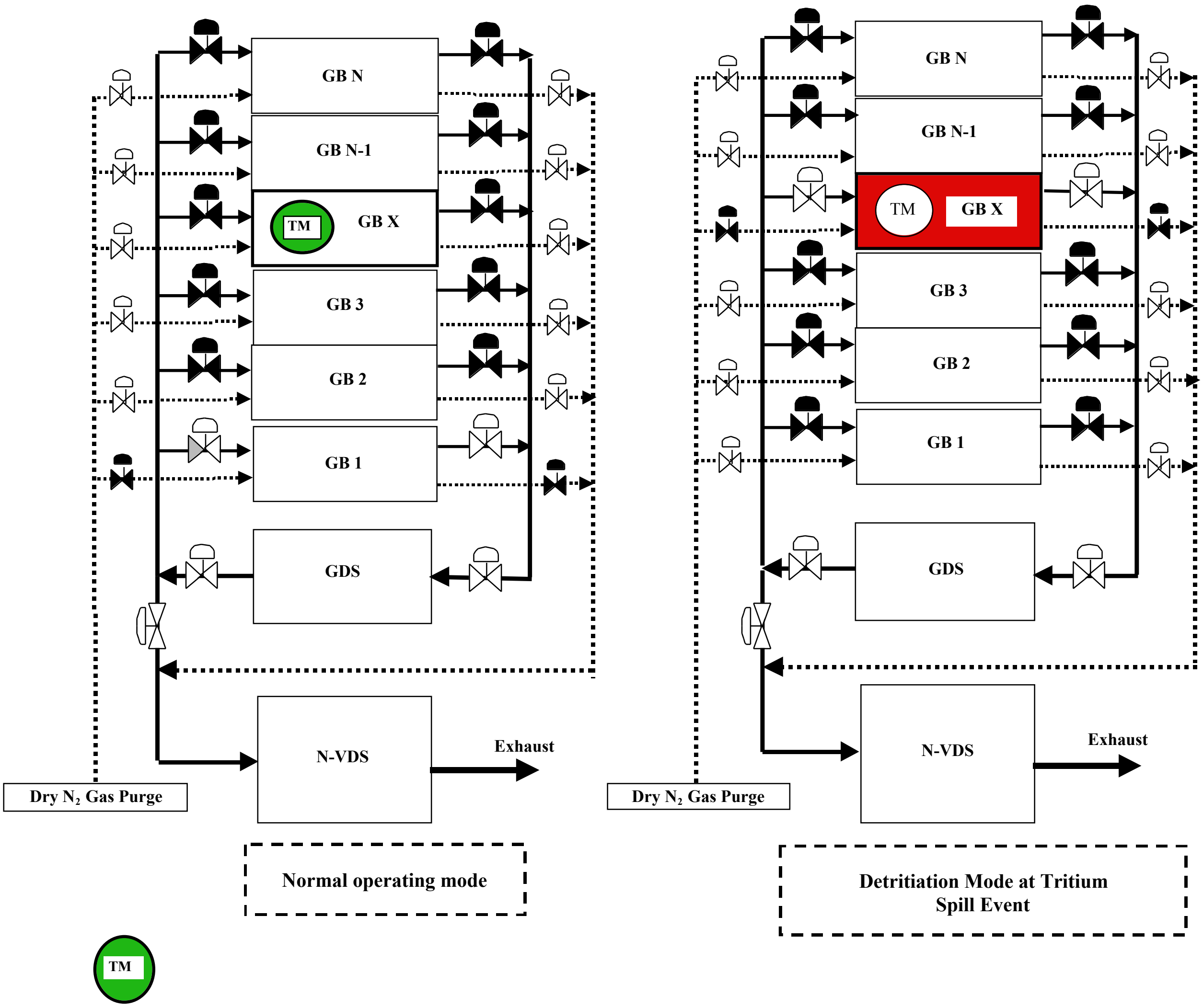

Figure 3.1-6 Integral System Configuration of the Glove Box Atmosphere Detritiation System, Glove Boxes and the Normal Vent Detritiation System

Tritiated water produced by the operation of these detritiation systems is collected by an intermediate measuring tank and then sent to the tritiated water holding tank systems after measurement of the tritium concentration levels. Condensate of the HVAC and local air coolers is sent to the tritiated water holding tanks in a similar manner.

Hot Cell and Radwaste Building Confinement and Detritiation Systems

The confinement and detritiation systems for the hot cell and the radwaste buildings are composed of their HVACs, a hot cell red zone detritiation system, and the vent detritiation system. Activated dust and decay heat from in-vessel components introduced in the red zone are separately removed by local filters and local air coolers installed in a green zone in the hot cell. Figure 3.1-7 shows the configuration of an integrated confinement and detritiation system for these buildings. The atmospheric pressure of the hot cell green zone is maintained at a differential of - 1 mbar by the HVAC during normal conditions, and the pressures in the amber and the red zone are maintained at differentials of - 2 mbar and - 3 mbar, respectively by the hot cell vent detritiation system. The hot cell vent detritiation system capacity (700 m^3/h) includes standby capacity for an emergency tritium confinement for any green zone rooms in the hot cell and the radwaste buildings, where the relevant HVAC isolation valves are closed.

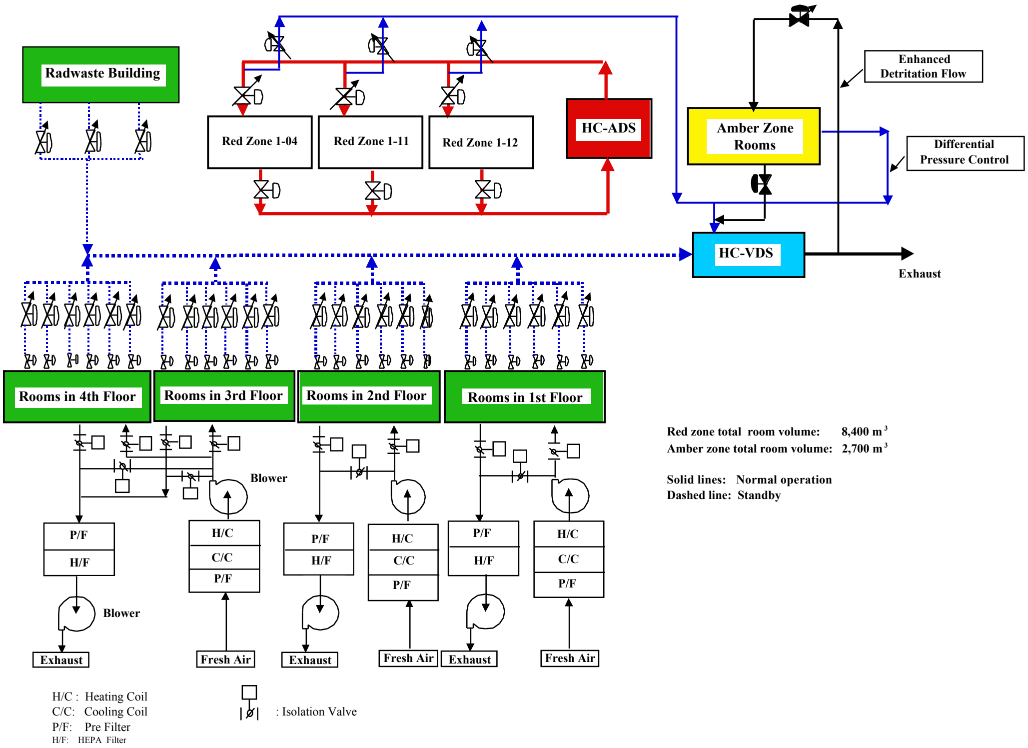

Figure 3.1-7 Hot Cell and Radwaste Buildings - Confinement and Detritiation System Configuration

The hot cell atmosphere detritiation system (capacity 4,500 m^3/h) is manifolded to all red zone rooms to control the air flow rate required in each room depending on their operation states. The achievable room air HTO concentration during occupancy by the maximum number of divertor cassettes (estimated tritium outgassing rate ~ 18 Ci/h) is 500 DAC (Derived Air Concentration: unprotected exposure to 1 DAC = 10 µSv/h), or 1.6 x10^8 Bq/m^3. The reduction rate of the HTO concentration after removal of divertor cassettes or other tritium source terms from the room depends on the decontamination characteristics of the wall surface, and based on recent R&D results, the tritium concentration can be lowered to 1 DAC within approximately 5 days using the atmosphere detritiation system at full capacity.

Saturated molecular sieve beds in these detritiation systems are regenerated by a hot cell dedicated regeneration system. The recovered condensate from the regeneration system and the HVAC is sent to the tritiated water holding tanks system located in the tritium building in a manner similar to that for the tritium plant systems.

In order to reduce the generation rate of tritiated water from hot cell operation, minimization of the leakage rate in the building walls, doors and other penetrations is being investigated. The tentative estimate of water generation based on the present design parameters (room volume, leak tightness, humidity and temperatures) is ~ 0.3 m^3/d.

Water Detritiation System

During operation of ITER, tritiated water will be produced in various systems. The expected sources are:

(a) condensate generated from the normal operation of various atmosphere detritiation systems and HVACs,

(b) tritium process component maintenance,

(c) condensate from the air coolers in the containment volume (designed to limit overpressures from an ex-vessel coolant leak),

(d) air detritiation dryers in the containment volume,

(e) the tokamak cooling water system maintenance drain and the tokamak cooling water system vent gas condensate,

(f) in-vessel component maintenance drain collected in the hot cell, and

(g) condensate from the standby vent detritiation system and the standby atmosphere detritiation system operated during tritium contamination accidents.

The source water (a) - (d) will be processed by the water detritiation system to minimize tritium-bearing waste water to be rejected to the environment, whereas the water (e) and (f) is recycled to the tokamak cooling water system. The water (g) will be stored in the emergency holding sump tanks.

The source water will be stored in the holding tank system with the following level classification:

· H Level > 100 Ci/kg;
· M Level 10^{-3} Ci/kg – 100 Ci/kg;
· L Level 1.6 x 10^{-6} Ci/kg - 10^{-3} Ci/kg;
· LL Level < 1.6 x 10^{-6} Ci/kg for direct release after assaying;
· emergency holding sump tanks: total capacity 400 m^3

The high (H) level and the medium (M) level tanks receive condensate from the atmosphere detritiation systems and the local air coolers in the hot cell building and the tritium plant building, and the process blow-down water of the water detritiation system at maintenance. In case of an event leading to a large amount of tritium contamination, condensate produced by the standby atmosphere detritiation system and the standby vent detritiation system will be stored in either the H level or the emergency holding sump tanks. The low (L) level tanks receive drainage from tritium process equipment during its maintenance. The low low (LL) level tank receives water generated in the HVACs, and the water can be directly rejected to the environment after assaying the tritium concentration.

Figure 3.1-8 shows the outline flow diagram for the water detritiation system, but does not show the LL level or emergency holding sump tanks. Tritiated water sent from the holding tank system is purified by the front-end processing system composed of demineralizer and charcoal beds to remove hazardous ions and organic species to the catalytic exchange process and electrolysis. The purified water (tritium concentration < 10 Ci/kg) is then fed (~ 20 kg/h) either to the catalytic exchange towers (tritium feed concentration < ~ 10 Ci/kg) or to the electrolysers (tritium feed concentration ~ 100 – 500 Ci/kg). Pure water is fed (~ 20 kg/h) to the top of the catalytic exchange tower.

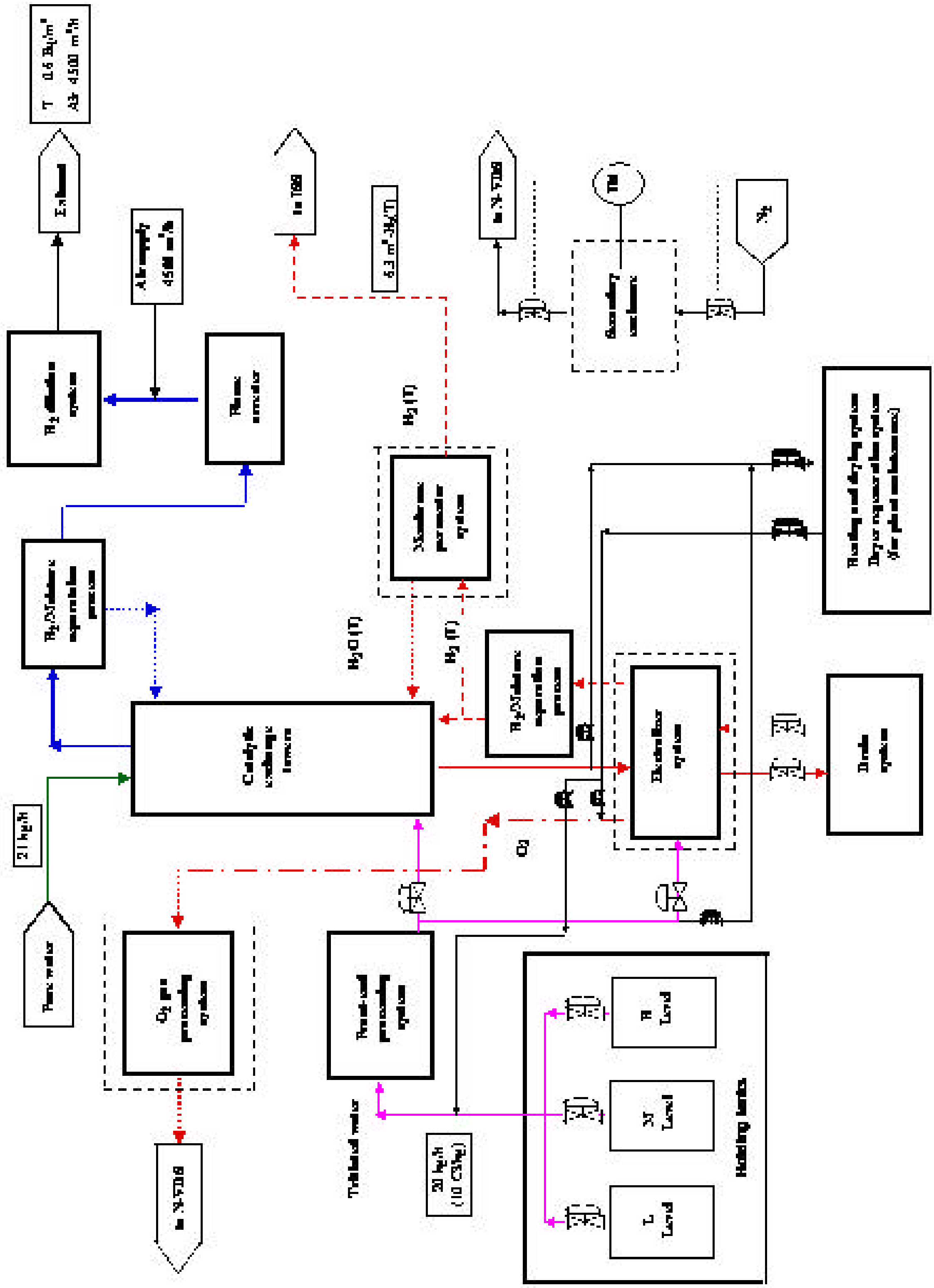

Figure 3.1-8 Outline Flow Diagram for the Water Detritiation System

The catalytic exchange towers are composed of hydrophobic catalyst-packed sections and a hydrophilic-packing section (sieve tray). The isotopic exchange reactions taking place in each section are:

HT (G) + H_2O (V) = H_2 (G) + HTO (V): Hydrophobic catalyst section

HTO (V) + H_2O (L) = H_2O (V) + HTO (L): Hydrophilic packing section

where, G, V and L in these equilibrium reactions mean gas, vapour and liquid phases, respectively.

Through these counter-current catalytic exchange reactions, tritium (T) is enriched in the water which is flowing to the bottom of the towers, and hydrogen gas which contains virtually no tritium is flowing to the top of the tower. The enriched water is then dissociated into hydrogen gas H_2 (T) and O_2 gas by the electrolysers. The H_2 (T) is returned to the bottom of the tower, and a part of the hydrogen gas stream (280 mol/h) is sent to the hydrogen isotope separation system to recover tritium via a membrane permeator system. The hydrogen stream from the top of the tower is rejected to the environment through the flame arrester. The O_2 stream from the electrolysers is sent to the normal vent detritiation system via the O_2 gas processing system composed of molecular sieve dryers.

The membrane permeator and molecular sieve dryer, which are operated at elevated temperature, and electrolysers, are placed in a secondary enclosure to avoid tritium leakage/permeation to the room. The atmosphere (dry N_2 gas) of the secondary enclosure is sent to the normal vent detritiation system with a small flow rate.

The water detritiation system can be operated with high availability (more than 300 days/year). Demineralizers and charcoal beds require frequent replacement (every two years), and the electrolyser, based on solid polymer electrodes, may need electrode replacement once per year due to expected deterioration caused by β-ray exposure from tritium-enriched water. A detailed maintenance procedure, which can handle components contaminated by highly concentrated tritiated water, has been developed and reflected in the water detritiation system design.

3.1.1.3 Design Integration

General

Components have been standardised across the whole tritium plant to the maximum extent consistent with the functional requirements of each application, in order to minimise the costs of spare parts and maintenance.

Process interconnections between systems located in different glove boxes consist of stainless steel piping/tubing within a secondary enclosure. The atmosphere of the secondary interspace will communicate with the secondary confinement volume of either the upstream or downstream system, and a bulkhead at the other end of the secondary jacket will ensure segmentation of these volumes as necessary.

Plant Layout

A detailed layout of the tritium plant in the building (which also houses other equipment, such as the roughing pump system and the HVAC systems for both the tritium plant and tokamak buildings) has been developed. The arrangement of the constituent process systems, together with their secondary confinements, and the infrastructure systems, has been optimised in terms of minimising the length of interconnections, and has taken into account provision of adequate space for operation and maintenance, incorporation of shielding (for some specific systems), separation of areas of the building into zones, assurance of satisfactory working conditions in all locations by the HVAC systems, and definition of access and escape routes. Analysis of the layout is essential to ensure that the functionality of the tritium confinement by the HVACs and the atmosphere detritiation system / vent detritiation system is maximised, and that the potential for and consequences of hydrogen deflagration/explosion are reduced to acceptable levels. The building design and locations of equipment within it enable the seismic response at the locations of critical components to be calculated, to serve as a basis for seismic analysis of components as necessary.

3.1.1.4 Performance Analysis/Design Integrity

The principal design features, which have been implemented to preclude or mitigate hazards common to multiple systems in the tritium plant, are reviewed briefly in the following.

Overpressure Protection

Pressurization from external systems is avoided by backflow prevention units in the supply lines which close at a pressure well below that needed. In addition, the feed gas pressures are limited by pressure relief valves in the respective systems.

Primary system vacuum pumps and compressors are equipped either with a relief valve which opens a bypass from the discharge side to the suction side of the pump, or with two redundant pressure transducers on the pump discharge which trip the pump at a preset pressure.

In systems operating at cryogenic temperatures, such as the isotope separation system and the glow discharge cleaning gas processing system, the dominant potential cause of overpressurisation is a malfunction of the refrigerant supply, leading to regeneration of the inventory, and/or failure of pipes or valves leading to plugging of gas exhaust lines. The protection against this is an expansion vessel downstream of a rupture disc. The rupture disc is designed to burst at a pressure below the system design pressure, and the expansion vessel is sized to accept the gas expanded from the process system under the most severe combination of inventory and warm-up postulated.

Over-temperature Protection

Each heater is thyristor-controlled and the temperature of adjacent components monitored by thermocouples, which causes the programmable logic controller (PLC) to give a warning at high/low deviations from the set point. If the temperature reaches a second set point closer to the design temperature, the heater is tripped and an alarm given by the PLC.

In parallel, other thermocouples give a warning if the temperature is above a certain level. Heater trip and alarm functions are redundant for the above-mentioned thermocouples.

The readings of the two thermocouples are continuously compared by a virtual instrument in order to detect any off-normal condition in either of them.

Tritium Permeation Mitigation

Heated components in the fuel cycle subsystems such as permeators and catalytic reactors, in which the working tritium inventory exceeds 1 g, are equipped with internal thermal shields and a vacuum jacket which is held at close to ambient temperature at which no measurable hydrogen permeation occurs. The evacuated interspace allows confinement and recovery of tritium which has permeated through the primary vessel wall. The presence of permeated gas can be detected either by pressure monitors in the interspace, or by a deterioration in the thermal insulation performance of the vacuum interspace, which can then be pumped out and the gas returned to the primary circuit.

Redundancy/Diversity

The system design embodies no redundant components for the purpose of enhancing availability. Due to the fact that, wherever possible, commercially available components are employed, a certain margin of over-capacity exists in some systems, which will mitigate short-term failures or unavailability of components. The control system incorporates redundant and, where possible, diverse components and cable routes in order to provide a fully independent hard-wired alarm and emergency shut-down function.

3.1.2 Assessment

3.1.2.1 Fuel Cycle Subsystems Design

The design of the fuel cycle subsystems is based on either well-proven processes and components, or on comprehensive R&D carried out at near ITER scale over the full range of anticipated parameters.

The storage and delivery system utilizes ZrCo as the metal hydriding material. This has been tested under the full range of operating conditions to ensure that the potential drawbacks of this material will not compromise performance. Combinations of pressure and temperature under which disproportionation can occur can be avoided, and even if under upset conditions this took place, the getter material can be reproportionated at moderate temperatures (450°C). The tendency for deviations in isotopic composition as the beds deliver gas has been demonstrated to be acceptable (within ~ 2%). Determination of in-bed tritium inventories can be made by calorimetry with an accuracy of 3% within a working shift and to within 1% over longer periods. The capability of the reference-bed design to maintain required delivery rates (20 Pam^3s^{-1} per bed) consistent with ITER fuelling scenarios over extended ranges of bed-loading fractions should be demonstrated with a full-scale prototype, in order to confirm the results of laboratory tests with a 1/5 scale unit.

The mechanical integrity of Pd/Ag membrane permeators used in the tokamak exhaust processing system (and other systems) has been demonstrated at representative tritium and impurity concentrations over operating periods of several years. The poisoning effects (in presence of CO) have been shown to be fully reversible. System optimization studies, supported by R&D on the overall detritiation achievable by the tokamak exhaust processing system[1], have enabled permeator pumping requirements to be considerably reduced compared with earlier designs. The design of the impurity processing module has been simplified by combining the reactors for cracking (for hydrocarbons) and shift reactions (for water), and by the adoption of a single catalyst (nickel on kieselguhr, a naturally occurring material used as a catalyst carrier) for all duties (chemical and isotope exchange reactions) throughout the tokamak exhaust processing system. The evolution of the design into an essentially once-through process has contributed to a reduction in tritium inventory and improvement in detritiation performance (by maintaining nearly constant isotopic compositions at specific locations within the system, thereby minimizing memory effects). The ability of the process to achieve the required detritiation factor of 10^8 with a reasonable margin in steady state has been proven. Further tests are required to confirm the performance over the full range of operating conditions.

The process used for separation of the impurities from the circulating He during glow discharge cleaning (trapping on cryogenic molecular sieve beds) is well-established technology.

Hydrogen isotope separation by cryogenic distillation has been demonstrated under steady-state conditions in fission applications and by R&D over many years. For ITER, recent R&D has focussed on tritium inventory minimization by the selection of optimized column packing materials and operating conditions. A consensus has been reached on the database to be used for design and safety analysis, and the tritium inventory of the whole system has been reduced by refinement of the column sizes and detailed design improvements of other components. R&D to demonstrate that the design is capable of handling the expected rapid fluctuations in feed compositions and flow rates has been successfully completed. The development of steady state and dynamic simulation computer codes has enabled design calculations and R&D results to be benchmarked against each other.

Advances in the development of analytical techniques have been incorporated in the design for the tritium plant analytical system. Substantial progress in micro-gas-chromatography performance enables quantitative measurements in ~ 60 s for hydrogen isotope mixtures and ~ 160 s for impurity mixtures to be achieved with very small samples, in the nanolitre range.

[1] H. Yoshida et al. “ITER R&D Auxiliary Systems”, Fus. Eng. Design 55 (2001), pp 313-323

Developments in laser Raman spectroscopy include the application of an external resonator which enables quantitative analysis of hydrogen isotope mixtures to be carried out. This technique is proposed for periodic calibration of the on-line pressure and temperature measurement techniques used for the product quality control of the isotope separation system.

The layout of tritium plant systems within the building has been reviewed to ensure that all requirements for space, access, and environmental conditions are met. The effect of the equipment on the building design such as mechanical loads and heat dissipation requirements, have been taken into account. Access routes for the introduction of deferred equipment and for the replacement and removal of components during maintenance and routine operations, such as the import of tritium transport containers, have been checked. The design of the building is conventional, and consistent with the practice followed at existing tritium laboratories, upgraded where necessary to provide additional features such as shielding capability.

The distributed control system with PLCs and a hardwired system for alarm and emergency shut-down developed for the ITER tritium plant (Figure 3.1-9) is consistent with systems currently in operation in tritium laboratories. It is to be expected that advances in system and hardware design will occur prior to the implementation of the ITER tritium plant and these will be reviewed and adopted where appropriate.

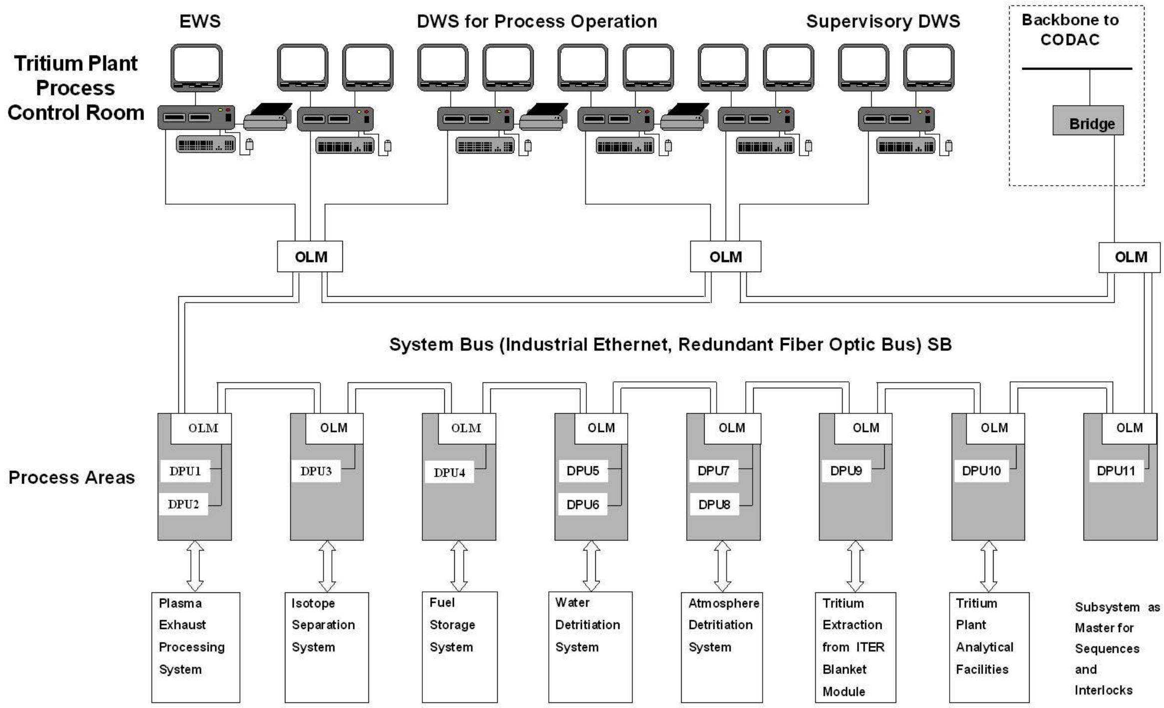

Figure 3.1-9 Tritium Plant Automated Control System Configuration
DWS: Display Work Station, EWS: Engineers' Work Station
OLM: Optical Link Module, DPU: Distributed Process Unit

3.1.2.2 Development of Tokamak Fuel Cycle System Dynamic Simulation Code

The fuel cycle dynamic simulation code CFTSIM[1] was developed during the ITER EDA through a design task. This code provides an integrated dynamic simulation of the ITER fuel cycle. It presents the user with a graphical representation of the ITER tritium plant. The code models the ITER fuel cycle pathways for deuterium and tritium, including the following system models, in varying degrees of detail.

(i) Fuelling System Model (Storage and Delivery System Model);
(ii) Codeposited Layer Dust Model;
(iii) First Wall Model;
(iv) Tokamak Model;
(v) Tokamak Chamber Model;
(vi) Tokamak Exhaust Processing System Model;
(vii) Hydrogen Isotope Separation System Models;
(viii) Neutral Beam Injectors Model.

3.1.2.3 Analysis of the Tritium Inventory Dynamics for DT Pulsed Plasma Operations

For the purpose of design improvement in the interfaces between the SDS, TEP and ISS, a series of preliminary studies of the tritium inventory dynamics were implemented by using the CFTSIM code. The following cases of DT plasma operation were selected as being representative of the plasma operation:

(i) Short DT pulse operation (450 s burn, 1,350 s dwell) with 200 Pam^3/s total fuelling flow rate (deep fuelling 50 $Pam^3s^{-1}T_2$, shallow fuelling 100 Pam^3/s DT + 44.5 Pam^3/s D_2 + 5.5 Pam^3/s T_2),
(ii) Long DT pulse operation (3,000 s burn, 9,000 s dwell) with 200 Pam^3/s total fuelling flow rate (deep fuelling 50 Pam^3/s T_2, shallow fuelling 100 Pam^3/s DT + 44.5 Pam^3/s D_2 + 5.5 Pam^3/s T_2). Table 1-7 summarizes the input parameters selected for these representative cases.

Figures 3.1-10 (a) and (b) show the results of the tritium inventory dynamics over five repetitive pulses. In the present preliminary analysis, the entire column cascade of the ISS was started up with pure D_2 gas immediately after receiving the feed stream (tokamak exhaust stream) via the front-end permeator. The time to establish steady-state concentration profiles of the 6 possible hydrogen isotope mixtures (permutations of H, D and T) in cascade, will require a distillation time of 1,000 s or more.

The total tritium inventory shown in these figures does not include the following inventory elements:

(i) tritiated impurities trapped in the torus cryo-pump during the five pulses,
(ii) tritium trapped by the plasma-facing components, and co-deposited material in the vacuum vessel.
(iii) tritiated impurities processing in the tokamak exhaust processing unit.

[1] A. Busigin and P. Gierszewski, "CFTSIM-ITER dynamic fuel cycle model", Fus. Eng. & Design 39-40 (1999), p 909

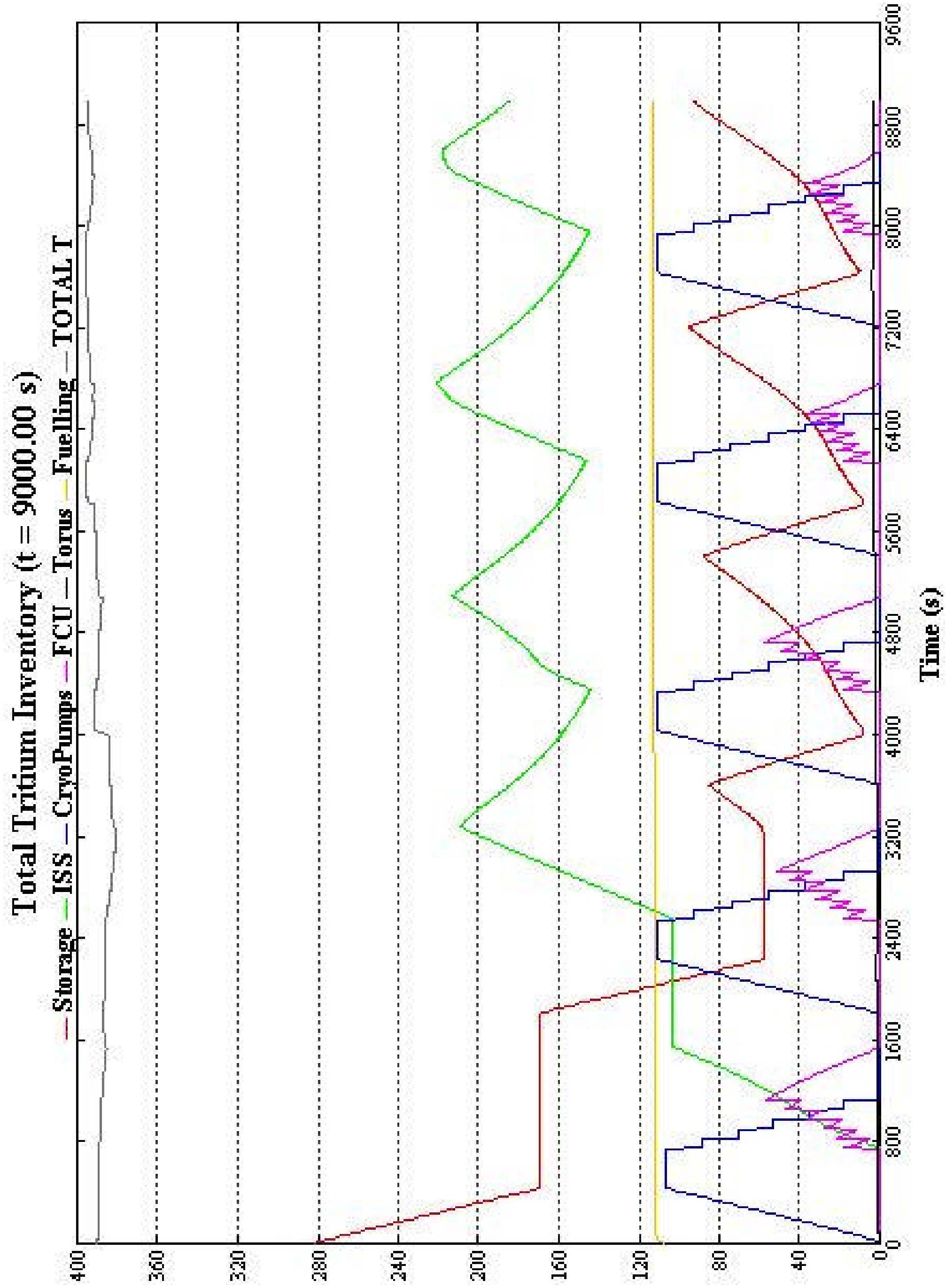

Figure 3.1-10 (a) Tritium Inventory Dynamics in the Fuel Cycle System (for Short DT Pulses)

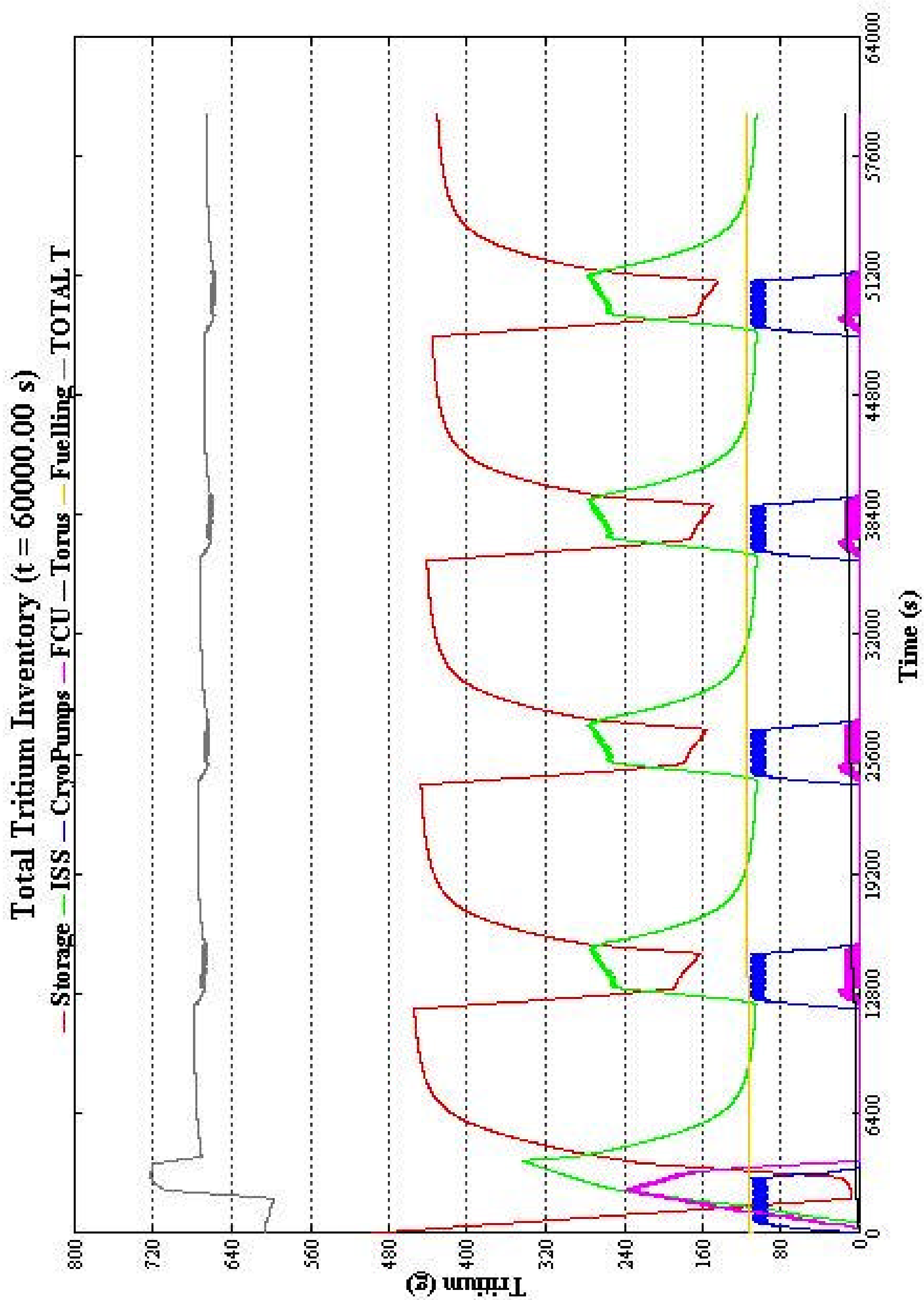

Figure 3.1-10 (b) Tritium Inventory Dynamics in the Fuel Cycle Systems (for Long DT Pulses)

3.1.2.4 Tritium Confinement and Detritiation Subsystems

HVAC

Because of their functional requirements during off-normal events in the tokamak, tritium, hot cell and radwaste buildings, the HVAC systems are safety classified systems - therefore there are 2 emergency room isolation dampers (high leak tightness butterfly valves) in series backed up by emergency power and/or emergency compressed gas (N_2). However, all HVAC equipment such as blowers, heating and cooling coils, pre-filters and HEPA (high efficiency particulate) filters, emergency isolation dampers, and fire isolation dampers are industrial items, and no specific R&D has been required for their use in ITER.

Atmosphere Detritiation Systems

As described in 3.1.1.2, different atmosphere detritiation systems are employed to meet the confinement and detritiation requirements at different operation states of the tokamak, tritium, hot cell and radwaste buildings. The process configurations of these atmosphere detritiation systems are different, based on the confinement strategy and safety requirements (off-normal event scenarios).

Figure 3.1-11 shows a conceptual process flow diagram of the standby atmosphere detritiation system, which is a typical safety classified atmosphere detritiation system similar to the normal vent detritiation system, standby vent detritiation system, hot cell atmosphere detritiation system and the hot cell vent detritiation system. The standby atmosphere detritiation system is designed to process various tritiated source gases containing high levels of elemental tritium, tritiated hydrocarbons, and saturated moisture. The process configuration is characterised by the three loops described below.

a) Recombiner loop composed of inlet filter (F-1), inlet blower battery (BL1-A/B/C: 50% capacity/each blower; one blower is redundant), two stage recombiners (Rec-L, Rec-H), two stage recuperative heat exchangers (HX-1, HX-2), one stage electric heater (EH-1), one stage condenser (CX-1), and one-stage molecular sieve dryer bed battery (DX-A/B/C). Elemental tritium included in the source gas/air is catalytically converted (conversion factor > 10^4) into tritiated water molecules by the first stage recombiner (operating temperature 150°C), and tritiated organic species are oxidised (conversion factor > 10^3) to tritiated water molecules and CO_2 by the second stage recombiner (operating temperature 500°C). The converted tritiated water molecules are adsorbed by the molecular sieve dryer bed. Thus, overall tritium permeation through vessel walls and pipe lines in the recombiner loop can be minimised by the two-stage recombiner configuration. This configuration was selected as an essential design feature to process tritiated source gases containing elemental tritium and organic tritium. The glove box atmosphere detritiation system process uses only a one stage recombiner (operating temperature 150°C) because the expected tritiated species in the glove box atmosphere are elemental tritium and tritiated moisture (HTO).

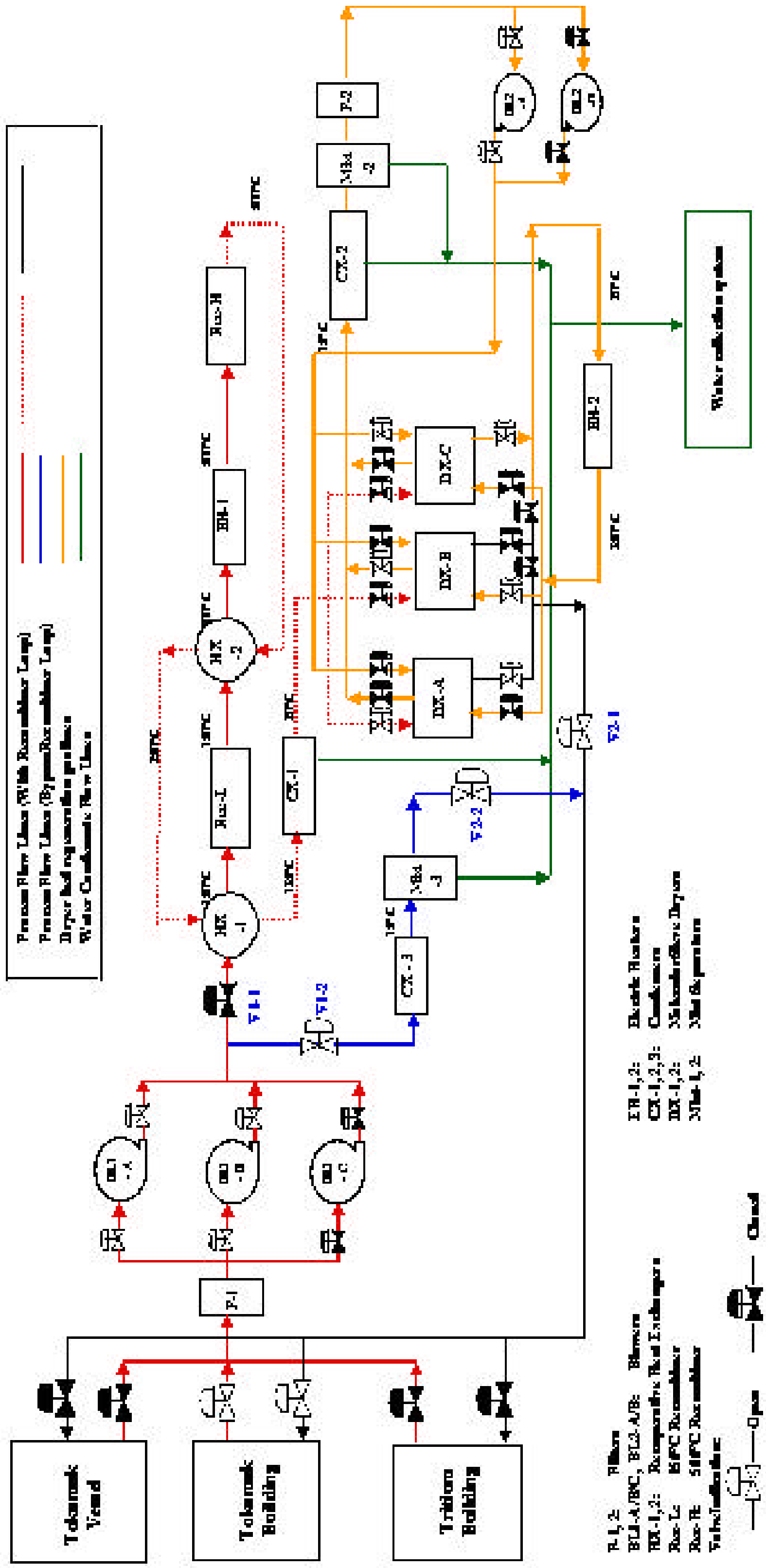

Figure 3.1-11 Conceptual Process Flow Diagram of the Standby Atmosphere Detritiation System

(b) Molecular sieve dryer regeneration loop composed of regeneration gas heater (EH-2), dryer bed cross-over valve headers, one-stage condenser (CX-2), mist separator (Mis-2), filter (F-2) and blower battery (BL2-A/B). Tritiated water produced in the recombiner loops and/or included in the source gas/air is adsorbed by the dryer bed. When the decontamination factor (DF) defined by the tritium concentration ratio between inlet and outlet streams around the dryer is > 100 (design value 10^2 – 10^4), the saturated dryer bed is then switched to the regeneration mode.
(c) Direct condensing loop composed of a one-stage condenser (CX-3) and mist separator (Mist-3). In case humidity in the source gas/air is very high or saturated, this bypass loop is started for direct condensing of the moisture, and the recombiner loop is isolated until the room moisture level is reduced to an acceptable level for the standby atmosphere detritiation system dryer bed battery capacity.

The use of the direct condensing loop is an important design feature which results in a large reduction of water load on the molecular sieve dryer regeneration loop.

All atmosphere detritiation systems utilise proven technology and components such as canned type blowers, recuperative gas/gas heat exchangers, gas/water heat exchangers, electrical gas heaters, catalytic recombiners and molecular sieve dryer beds.

The design value of the detritiation factor of these atmosphere detritiation systems (glove box atmosphere detritiation system > 10^2; standby atmosphere detritiation system > 10^3; normal vent detritiation system, standby vent detritiation system > 10^4) has been well proven in the existing tritium facilities, and no further R&D is required.

Common Dryer Regeneration System

It is expected that the usage of dryer regeneration systems, which is required for all atmosphere detritiation systems, will be very low for the standby detritiation systems (S-VDS, S-ADS). To maximize the effective usage of the dryer regeneration system, a common dryer regeneration system was employed for ITER instead of a distributed regeneration system in each detritiation system. A similar design (use of common regeneration system) was applied to the atmosphere detritiation systems located in the hot cell building.

Water Detritiation System

The water detritiation system selected for ITER is based on the existing plant technology using catalytic exchange towers and electrolysers, which has been operated over 13 years in a Japanese fission reactor. The advantages of the plant technology are compact size due to its very high separation efficiency, no production of tritium-bearing waste water due to a complete decomposition of the water into molecular hydrogen and oxygen, and operation flexibility over a wide range of tritium concentration (1 mCi/kg – 500 Ci/kg) by the combination of a tritium-scavenging catalytic exchange process with tritiated water electrolysis. The long-term operation of the existing plant has indicated that tritium levels in the exhaust hydrogen stream can be directly rejected to the environment with suitable air dilution to meet the deflagration limit (1 vol% in air).