6.7 Fuel Processing Systems (FPS)

6.7.1 Basic Requirements and Functions - The basic function of the Fuel Processing Systems (FPS) is to manage and process the tritium in various fuel-related systems to enable recovery and recycling of tritium as a fuel component in a safe and reliable manner. The FPS arrangement is shown in Figure 6.7.1-1. Flows and compositions of various streams in the FPS are defined in Table 6.7.1-1 for the laser or L-alternative. A similar table could be constructed for the Heavy Ion Beam or H-alternative. The main functions of the systems are also defined in Table 6.7.1-2.

6.7.2 Technology Options - Fuel processing technology has been developing rapidly over the past years with the result that new and better process options have become available at least every five years. It is anticipated that by the time an IFE type machine is built, Fuel Processing options will have improved through several generations. The present technologies proposed for this study have already reached very low tritium inventories and consequently no major improvement in inventory may be expected regardless of the eventual process selected. Table 6.7.1-2 indicates the services provided by the FPS and the proposed options considered to be optimal for each of the diverse tasks.

6.7.3 Selection of Reference Process Options - Development Trends

Isotope Separation - Although many technologies such as Thermal Diffusion[1] and Gas Chromatography are being developed for Isotope Separation, Cryogenic Distillation (CD) has been successfully demonstrated at a larger and more complex scale than that required for Prometheus. With the burn fraction in the 30% region and with the elimination of the need for producing purified deuterium streams, the overall tritium inventory has been lowered to the 48 g and 68 g range for the L and H alternatives respectively. Recent CD technology developed at Ontario Hydro has resulted in a five fold decrease in the tritium inventory for the small final product columns where most of the tritium inventory resides. Although intensive development for extending these results to large IFE applications is still not complete, it is highly probable that this will be successful. In such a case, the last column inventory of 17 and 28 g for the L and H option could be reduced to 5 and 8 g, respectively. The overall ISS inventory could then be in the 36 and 47 g for the L or H option, respectively.

Chamber Exhaust Purification (EP) - A number of options are being developed for this purpose.[2,3,4,5] Cryogenic adsorption on molecular sieve beds is the most viable competitor to the proposed permeator-based purification system. Permeation is a continuous process as compared to adsorption, which must be operated batch-wise. Thus, permeation-based technologies are considered less complex, more reliable, and have lower tritium inventory. Depending on the desired tritium recovery, permeation systems could require relatively large vacuum pumps. Present designs

For specification of streams, see Table 6.7.1-1 for L option.

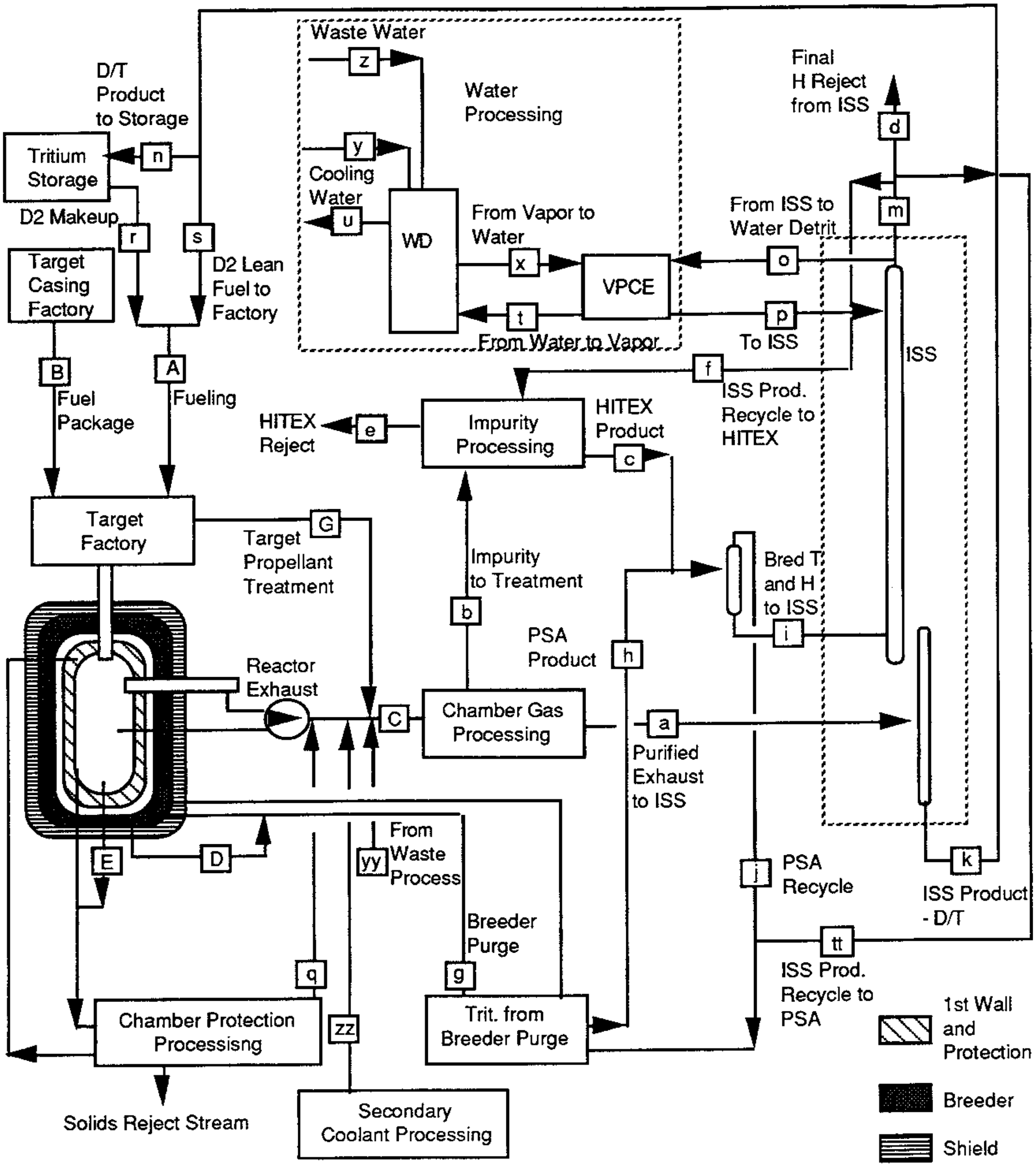


Figure 6.7.1-1. Fuel Processing Systems Arrangement

Table 6.7.1-1 FPS Design Data - L - Laser Option - Stream Identification Is Consistent with Figure 6.7.1-1

		Units			Units
Fusion Power	2807.00	[MW]	Fuel Propellant	0.00	[mol/mol]
Max. T in Coolant	1.00	[Ci/kg]	PSA H addition	5.00	[H2/HT]
T rel. -chronic	10.00	[Ci/day]	PSA H extraction	0.52	fraction
Breeding Ratio	1.20	fraction	HITEX H addition	80.00	[H2/b]
Burn-up Fraction	0.29	fraction	Pd Perm. Sep. fact	3.00	[out/imp]
H2 in Target Fuel	0.66	[mol/mol]	Propellant	0.00	[mol/mol]
H2 in Target Case	0.00	[mol/mol]	H2 in breeder purge	0.20	[%]
			H/T in Br. purge	20.00	ratio

Stream	Name	[mol/h]	H	D	T	He	CH4	NH3	CO2,Q2O
A	Fueling	20.54	2.00e-03	4.99e-01	4.99e-01				CO,N,O,A r
I	H from Casing	0.00	1.00e+00						
B	H Total Added	13.56	1.00e+00						
G	Propellant	0.00	0.00	1.00e+00					
C	Chamber Exhaust	34.10	3.99e-01	2.13e-01	2.13e-01	1.75e-01	1.12e-02	8.00e-04	4.00e-03
D	Breeder T prod.	3.57			1.00e+00				
a	Purified Exhaust	28.15	4.83e-01	2.58e-01	2.58e-01				
b	Impurity to HITEX	1.64							
c	HITEX Product	130.93	9.93e-01	3.59e-03	3.59e-03				
c+h	CD3 feed	506.21	9.91e-01	9.30e-04	7.99e-03				
e	HITEX Reject	0.55							
f	HITEX Recycle	129.84	1.00e+00						
g	He Blanket Purge	68731.55	1.04e-03	0.00	5.20e-05	9.99e-01	1.00e-06	1.00e-06	8.67e-06
h	PSA prod. to ISS	375.27	9.90e-01	0.00	9.52e-03				
j	PSA Recycle	371.70	1.00e+00						
i	HIT.+PSA to ISS	134.50	9.68e-01	3.59e-03	2.91e-02				
d	ISS Product - H2	144.49	1.00e+00						
l	ISS Product - D2	0.00		1.00e+00					
k	ISS Product - DT	18.16	2.00e-03	4.02e-01	5.98e-01				
n	DT to Storage	1.00		4.02e-01	5.98e-01				
s	DT to Factory	17.16		4.02e-01	5.98e-01				
r	D2 Make-up	3.38	1.00e+00						
o	ISS to Q2O detrit.	90.00							
p	Q2O detrit.to ISS	90.00							
x	from Q2O to VPCE	30.00							
t	from VPCE to Q2O	30.00							
z	Waste Water	1517.80	1.00e+00	1.50e-04	1.55e-07				

Table 6.7.1-2. Fuel Processing Services and Proposed Technologies for Prometheus IFE

	Fuel Processing Task	Technology Proposed	Tritium Inventory [g] IFE-L	(-H)
1	Isotope Separation	Cryogenic Distillation (CD)	48	(68)
2	Impurities from Fuel	Permeation	4	(8)
3	Tritium from Impurities	High Temp. Isotopic Exchange (HITEX)	0.5	(0.8)
4	Tritium from Breeders	Pressure Swing Adsorption (PSA)	2.8	(2.4)
5	Tritium from Water	Water Distillation + Vapor Phase Catalytic Exchange (VPCE)	0.3	
6	Tritium from Atmospheres	Recombiner + Dryer	25	
7	Fuel Storage	Uranium Getters	700	
8	Tritium from Na Coolant	Yttrium Gettering	0.5	
9	Solid Waste Detritiation	Plasma Discharge Cleaning	0.5	
		Total	781.6	(805.5)

rely on palladium-silver metallic membranes but a number of alternative permeation membranes are under development. For this reason, the permeation technology is selected as the reference process.

Tritium Extraction from Impurity Reject Streams - Fuel purification, as well as purification of other streams, will result in a tritiated impurity stream being produced containing hydrocarbons, ammonia, and other compound molecules. The reference process, High Temperature Isotopic Exchange or HITEX,[4] relies on isotopic exchange at high temperature in the presence of a catalyst, followed by permeation of the tritium enriched hydrogen. The apparent disadvantage of this process is that it dilutes the product with hydrogen. In the optimized design, however, a small distillation column is added to economically correct this deficiency. Alternative technologies such as catalytic cracking are being developed,[4] some designated to be integrated with the permeator.

Tritium Extraction from Solid Ceramic Breeder Blankets - This service requires the extraction of hydrogen, which acts as a tritium dilutent, from a large flow of helium purge gas. Early getter-based designs were superseded by a Thermal Swing Adsorption (TSA) process proposed for ITER.[6] Recently, a Pressure Swing Adsorption (PSA) process[7] has been developed. This promises low tritium inventories and is proposed for this application. Future development is most likely going to focus on membrane-based processes or high velocity adsorption processes. Unfortunately all the sorption-based processes are inherently discontinuous, and their size and tritium inventory is proportional to the length of the sorption/desorption cycle. For example, in one year of development, the cycle duration was reduced from 3-4 hours for the TSA to 10 minutes for the PSA process. The Thermally Coupled Pressure Swing Adsorption (TCPSA) process (see Section 6.7.3.1) is targeted for 20-200 pressure-sorption cycles per minute.

Tritium Recovery from Aqueous Streams - Recent studies[2] compared 16 combinations of processes suitable for extracting tritium from water. A subsequent study[8] made a detailed analysis of the best two alternatives and the Water Distillation coupled to the ISS through a Vapor Phase Catalytic Exchange was chosen as optimal. In the longer term for example, developing a laser-based tritium removal system (see Section 6.7.3.2) could replace the simple, but large and costly water distillation process.

Tritium Recovery from Atmospheres - Present systems are based on a combination of catalytic recombiners and molecular sieve dryers. For detritiation of inert atmospheres, getter-based alternatives have been developed and are in commercial use. For air, the most likely new processes may be based on permeation membranes.[9,10] These will offer continuous operation instead of the inherent batch operating mode associated with sorption processes. Getters which are tolerant to oxygen may also be developed, but will also share the disadvantage of batch operation compared to membrane processes. This would enable optimum hybrid combinations where, for example, the emergency high detritiation rates could be performed by a permeation membrane-based process and the low flow, high purity detritiation could be obtained through a conventional polishing recombiner/dryer.

Fuel Management and Storage - The getter-based hydrogen storage technology could rely on a number of metals namely uranium, zirconium-cobalt and others. Zr-Co getters have been evaluated as alternatives to the supposedly pyrophoric uranium. However, recent air exposure tests for uranium are encouraging and may result in uranium maintaining its status as the process of choice for tritium with best properties for frequent use at high capacity.

Tritium Removal from Na coolant - The use of a double-tube heat transfer system with sodium in the interspace is unique and innovative. Sodium provides a high thermal conductivity bridge between the two concentric heat transfer tubes, resulting in a relatively uninterrupted heat transfer pathway. However, high solubility of hydrogen in sodium can result in unacceptable permeation rates of tritium. A barrier must be provided for interrupting the tritium permeation flux by maintaining the partial pressure of tritium in sodium at sufficiently low level in order to lower the permeation rate to steam to acceptable levels. The low partial pressure is achieved by yttrium gettering. Future development in this area may result in advanced materials, such as silicon carbide or permeation barriers, which are compatible with the heat transfer fluid and which will eliminate the need for tritium extraction from the double-tube interspace.

Solid Waste Detritiation - Solid waste detritiation is well developed due to fission reactor needs and therefore very little development is occurring at present. One notable development is in the area of Plasma Discharge Cleaning which is consistent with the technologies used for vacuum vessels for MFE machines.

6.7.3.1 Thermally Coupled Pressure Swing Adsorption

Breeder Tritium Extraction - The breeder generates tritium which is carried in the breeder purge stream. The portion of the breeder purge gas to be treated (Figure 6.7.3-1) is first cooled countercurrently against the already treated return gas, then dried and cooled. TCPSA separator #1 extracts hydrogen from the breeder purge gas at 90% recovery. This, in comparison with the reference PSA process described in Section 6.7.5 and in comparison with data in Table 6.7.1-1, lowers the purge gas flow to be treated by approximately 40%.

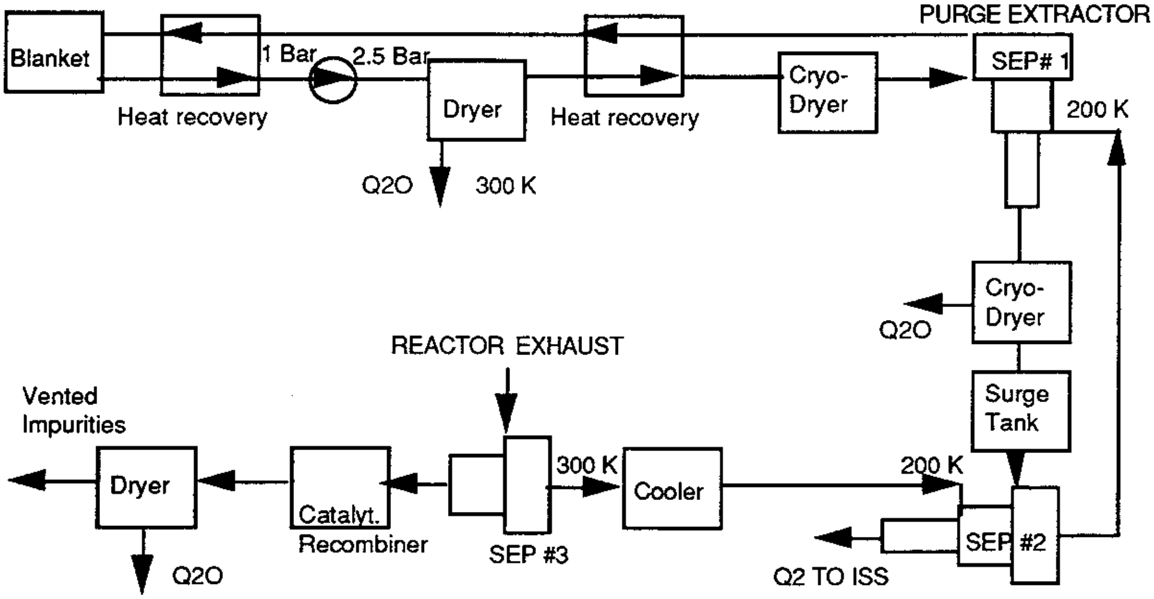


Figure 6.7.3-1. Thermally Coupled Pressure Swing Adsorption (TCPSA) for Fuel Treatment

TCPSA separator #1, by purifying the helium purge recycle flow to the breeder, concentrates the hydrogen isotope mixture to about 50% H,T in helium. Impurities such as nitrogen are concentrated with the hydrogen. TCPSA separator #1 also accepts a recycle stream of dilute hydrogen in helium from downstream processing in separator #2. The purge hydrogen extractor will normally operate at ~200 K for optimal selectivity and working capacity of the adsorbent. The adsorbent may be a hydrophobic zeolite such as silicalite. Hydrophobicity of the adsorbent is expected to be advantageous to minimize the need for periodic shutdown for adsorbent deactivation due to cumulative water uptake, to minimize reactivation due to cumulative water uptake, and also to minimize static tritium inventory with water of hydration. The adsorbent will be supported in a composite laminated structure (channel width ~50 microns) for effective mass transfer and attrition resistance at cycle frequency of 100 RPM.

Physical parameters of the hermetically-enclosed TCPSA purge hydrogen extractor (separator #1) include internal displacement of 0.7 m^3 and active zeolite adsorbent inventory of 84 kg. Estimated tritium inventory is estimated 0.4 g.

The schematic for TCPSA separator #1 represents multiple, smaller TCPSA machines in parallel. Mechanical elements are electromagnetically excited through the hermetic enclosures of the TCPSA apparatus.

During start-up procedures, the breeder purge hydrogen extractor may be operated with the helium purge at ambient temperature in order to extract air, carbon oxides, and water vapor from the breeder loop.

TCPSA separator #1 is an alternative to a vacuum regenerated PSA system operating at 77 K. The TCPSA system is more energy efficient, mainly due to reduced refrigeration load.

Hydrogen Isotope Purification - TCPSA separator #2 is provided to purify hydrogen isotope streams from separator #1, containing up to 50% helium, before admission to the Isotope Separation System. This unit will achieve final removal of helium from the hydrogen product. The unit can also accept otherwise purified hydrogen isotope streams with helium impurity at different concentrations. As shown in Figure 6.7.3-1, TCPSA separator #2 may be used to remove helium from the reactor exhaust from separator #3, after prior removal of all heavy impurities. Impurities include tritiated water, ammonia and methane, and carbon oxides and nitrogen.

With a similar adsorbent laminate and 100 RPM operating frequency as TCPSA separator #1, TCPSA separator #2 will have a working displacement of 0.05 m^3 and contain up to 15 kg of active zeolite adsorbent. Estimated tritium content is 0.9 g.

The feed gas to TCPSA separators #1 and #2 will have been dried at 200 K for removal of carbon dioxide and water vapor. Any permanent gas impurities such as nitrogen may be accepted in minor amounts by these separators and will be concentrated into the hydrogen product. Larger amounts of permanent gas impurities could be removed by another TCPSA separator (not shown in the figure) operating at about 300 K in cascade with TCPSA separator #2. Residual amounts of permanent gas impurities in the hydrogen product of TCPSA separator #2 may be removed by a palladium diffuser, whose reject may be processed by TCPSA separator #3 to recover tritium bearing hydrogen from the total impurity stream.

Reactor Exhaust Purification - The reactor exhaust contains heavy impurities (more strongly adsorbed than hydrogen) and the light impurity of helium isotopes. TCPSA separator #3 removes the heavy impurities including tritiated compounds and delivers a rich stream of hydrogen isotopes and helium to the hydrogen purification module of

TCPSA separator #2. The impurity stream containing tritiated compounds must be processed further, either by catalytic oxidation to recover all tritium as water, or by catalytic isotope exchange to concentrate tritium into the reduced phase.

TCPSA separator #3 also uses zeolite adsorbent laminate beds operated at 100 cycles per minute and has a displacement volume of 0.012 m^3 and active zeolite inventory of 2 kg. Estimated tritium inventory is 0.18 g.

6.7.3.2 Laser-Based Hydrogen Isotope Separation - The laser-based detritiation system is based on the isotopically selective multiphoton dissociation of trifluoromethane, CF_3H. At wavelengths around 9 micrometers in the infrared, tritiated trifluoromethane, CF_3T, is a strong absorber of infrared radiation, while the non-tritiated component, CF_3H, is almost transparent. By irradiating mixtures of CF_3H and CF_3T with intense pulses of laser radiation in this wavelength region, it is possible to excite the absorbing CF_3T molecules so that they dissociate as follows:

$$2CF_3T \rightarrow 2TF + C_2F_4$$

Under the right conditions, the above process is 10,000 times more likely than the equivalent dissociation process for CF_3H. Consequently, by this process one can transform a dilute mixture of CF_3T in CF_3H to a concentrated photoproduct (TF/HF) which has a T concentration 10,000 times higher than the original feedstock.

In the conceptual design of a complete water detritiation system based on the laser idea, the separation would be performed in a cyclic three stage process.

The first stage of the process is an exchange unit where the tritiated water feed exchanges hydrogen with the process gas, trifluoromethane. In this step of the process, tritium would pass from the water feed to the trifluoromethane.

The second step of the process is the laser dissociation cell where isotopically selective dissociation of the tritiated component of the trifluoromethane occurs. After passing through this cell, the majority of the tritiated trifluoromethane would be converted to TF and C_2F_4 as described above.

The final step of the process is a chemical separation unit where the TF/HF photoproduct is removed from the trifluoromethane. Following removal of the TF/HF, the detritiated trifluoromethane is then returned to the exchange unit to begin the cycle again.

Over the last few years, a complete conceptual design for a water detritiation system has been developed based on the above cycle, and all the essential process elements have been tested at lab scale.

A schematic diagram of the process is shown in Figure 6.7.3-2. The exchange step of the process is carried out in the exchange liquid regenerator and exchange tower shown on the left hand side of the schematic diagram. In the exchange liquid regenerator, the feed water would be vaporized and contacted with an exchange liquid consisting of water, DMSO, and sodium hydroxide. The exchange liquid would then pass to the exchange tower proper, where it would be contacted with trifluoromethane. This unusual two-step approach to transferring tritium from water to trifluoromethane has been shown to be superior to one step processes.

After leaving the exchange tower, the trifluoromethane is dried and then decompressed and cooled so that it enters the dissociation cell at a temperature of around -70°C and a pressure of around 100 torr. These conditions of temperature and pressure are known to lead to efficient and highly selective dissociation of the tritiated component of the gas.

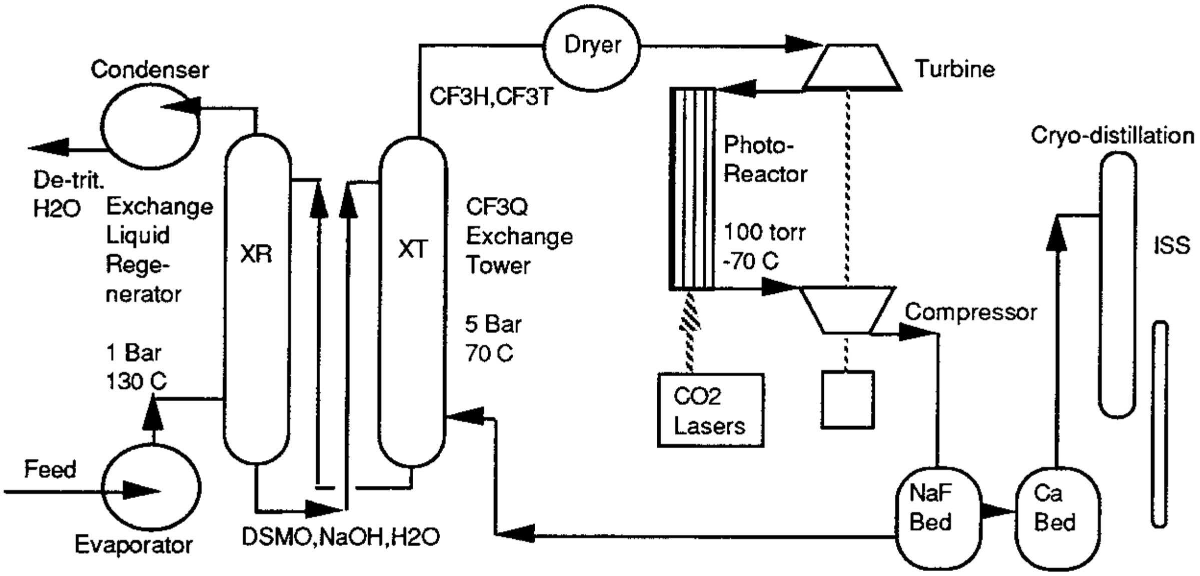


Figure 6.7.3-2. Laser-Based Isotope Separation System

The essential design problem in the dissociation cell is that fluences (laser energies per unit area) in excess of acceptable limits for long life of optical components are required to trigger the dissociation process. Consequently, one must devise a scheme where large volumes of gas can be exposed to high fluences without exposing optical components to unacceptable levels of fluence. A number of solutions to this problem have been proposed, and a selection process to determine the best solution is currently underway. All the proposed solutions rely on waveguiding of the laser radiation to create a large, high fluence region.

The final stage of the process, the separation of the HF/TF photoproduct, is the simplest step of the whole process. It is well known that, when cooled, NaF is a very selective absorber of HF/TF, and that this HF/TF can be recovered later by heating the NaF. In a continuous process then, one would have two beds—one cooled and connected in the process loop to absorb the HF/TF from the trifluoromethane stream and one heated and connected to a separate post-processing system. In this post-processing system, the HF/TF evolving from the heated NaF bed would first be converted to an H_2/HT/T_2 mixture by passing over a bed of Ca, before entering a small conventional cryogenic distillation column where the final stage of isotopic enrichment would be performed.

6.7.4 Chamber Exhaust Purification (EP) and Impurity Treatment - The use of permeation as the main tool for separating hydrogen from impurities is motivated by the following considerations:

- It is a simple and continuous process
- Has been used on an industrial scale
- Can deliver high purity hydrogen for direct feed into the ISS
- Has very low tritium inventory
- May promote cracking of ammonia[3]
- Produces no waste other than the membrane
- Can be made insensitive to poisoning.

The process has a disadvantage—the membrane can fail suddenly; but research into alternative materials and frequent replacement of the relatively inexpensive membranes will make this the most desirable alternative.

6.7.4.1 Process Description and Control - The process is suitable for a wide range of flows. The nominal mass throughput is determined by the chamber exhaust flow which is 34 and 150 mole/h for the L and H options, respectively. In addition to the 5-6 mol/h of helium, the chamber exhaust gas flow also contains impurities estimated to be in the range of 1-2%. The main constituents are expected to be hydrocarbons, ammonia, CO_2, water vapor, CO, N, O and traces of Ar. A schematic of the proposed process is in Figure 6.7.4-1. It can be seen that the permeator produces a tritiated impurity stream from which tritium must be removed before it is discharged. The process proposed for this application is based on high temperature isotope equilibration in the presence of a catalyst. First, helium may be removed from the chamber exhaust stream. This can be conveniently done to reduce volumetric throughput, but is not absolutely necessary for the process.

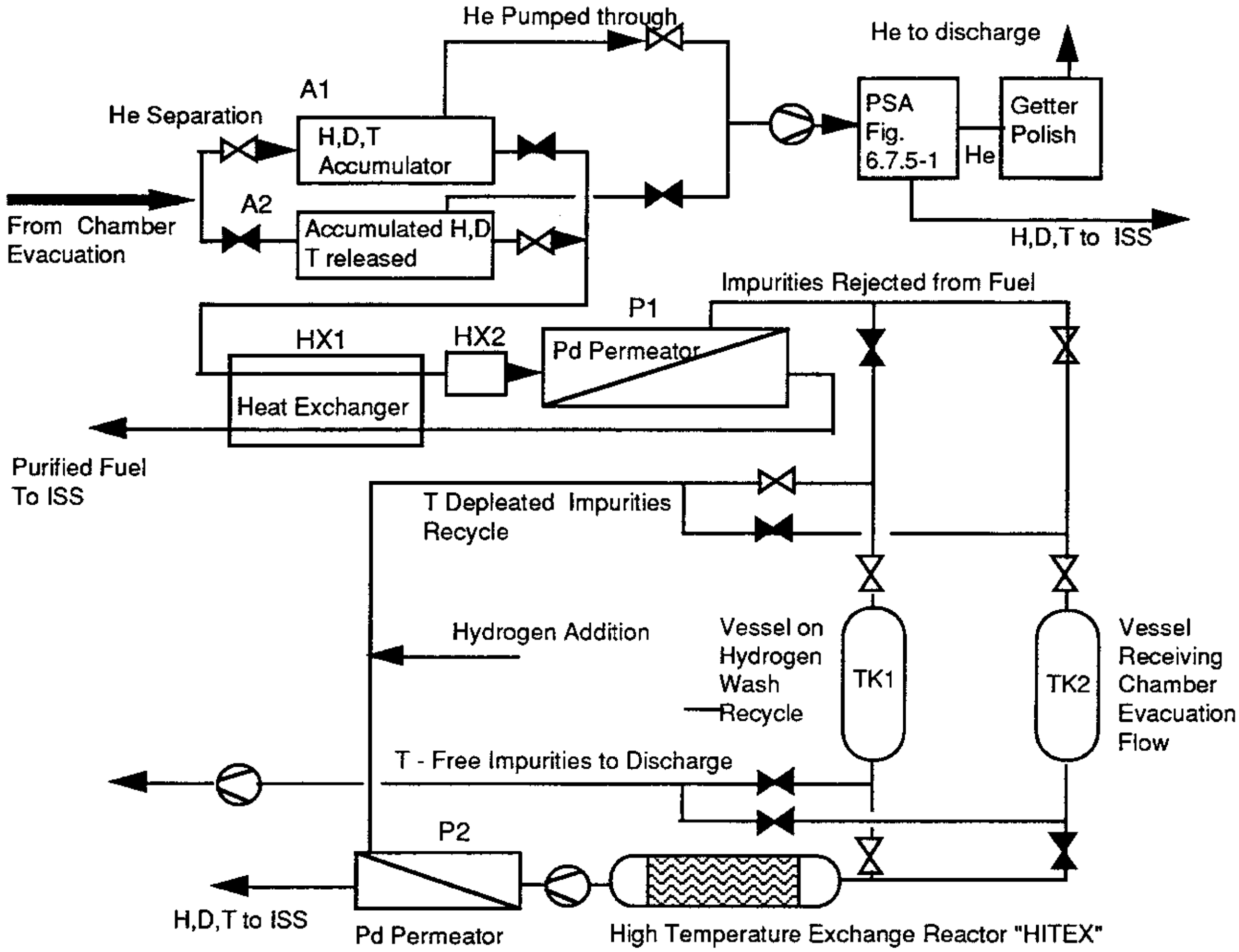


Figure 6.7.4-1. Chamber Exhaust Purification and Impurity Treatment System

The chamber exhaust is pumped through a heat recovery exchanger, HX1, and trim heater, HX2, into the permeator from which the permeate is sent directly into the ISS after heat recovery in HX1. The impurity stream is collected in TK2. In the meantime, the previously filled TK1 operates in a purification mode as follows. Impurities are mixed with hydrogen and pumped through the HITEX reactor where the hydrogens are equilibrated. Tritium in compound molecules is replaced with hydrogen, and free hydrogen (now contaminated with tritium) is separated in the permeator P2 and sent to the ISS. The remaining impurity stream is recirculated through TK1 and new hydrogen is added as required until the tritium level is reduced to below releasable levels. Then the TK1 is pumped out and its function is reversed with TK2.

The following equipment design data are proposed:

Parameter		Dimension L-Option	Value H-Option
P1 Surface	[m^2]	1	2.5
Hydrogen Pressure P1	[kPa]	100	100
P1 Operating Temperature	[C]	400	400
P2 Surface	[m^2]	2	6
Hydrogen Pressure P2	[kPa]	300	300
P1 Operating Temperature	[C]	400	400
TK1,TK2 Size	[m^3]	10	10
HITEX Volume	[m^3]	0.25	0.5

6.7.5 Tritium Extraction from Breeder Blanket (PSA) - Pressure Swing Adsorption (PSA) is a well established industrial process for separating and purifying industrial gases. For the tritium extraction from breeder blankets, however, the hydrogen dilution (0.2% of H and 0.01% T in He) requires extreme design parameters for the proposed system.

The PSA process has an inherent advantage over a recently proposed Temperature Swing Adsorption (TSA) design because it allows much faster cycling (10 versus 480 minutes) and therefore has correspondingly lower tritium inventory. For this application, the PSA process has reached proof of principle[7] with molecular sieve 5A at 77 K, with pressure cycling from 1-2 MPa during the adsorption cycle, to a rough vacuum during regeneration. Research with potentially better performing adsorbents still continues. A dynamic simulation model has been developed to facilitate system design and optimization. Simulation results indicate that a single-pass hydrogen isotope recovery of 50-80% is achievable but 52% was used for the optimized design. Hydrogen purity of more than 99% is possible to obtain in the stream regenerated from the beds.

6.7.5.1 PSA - Functional and Performance Requirements - In a recirculating system, there is no need for complete hydrogen isotope removal from the He purge stream on each pass through the PSA column. Secondly, the pressure ratio required for enriching the 0.2% hydrogen isotope concentration in the feed to greater than 99% in the product is unusually high (>10^3). Finally, H_2 is added to the column at the beginning of the evacuation cycle in order to displace adsorbed HT, and thus increase the HT partial pressure during column pump-out.

The dynamic simulation of the PSA process for H_2 and He separation was broken down into four distinct steps:

(1) Initial pressurization of the PSA column from vacuum to the adsorption pressure
(2) Flow of the hydrogen/helium gas mixture through the PSA column
(3) Depressurization and initial pump-out of He
(4) Hydrogen addition and evacuation of the PSA column to recover the HT and H_2 species.

The gas mixture withdrawn from the column during evacuation is greatly enriched in hydrogen isotopes as compared to the feed. The results of the simulation are in Figures 6.7.5-1 and 6.7.5-2.

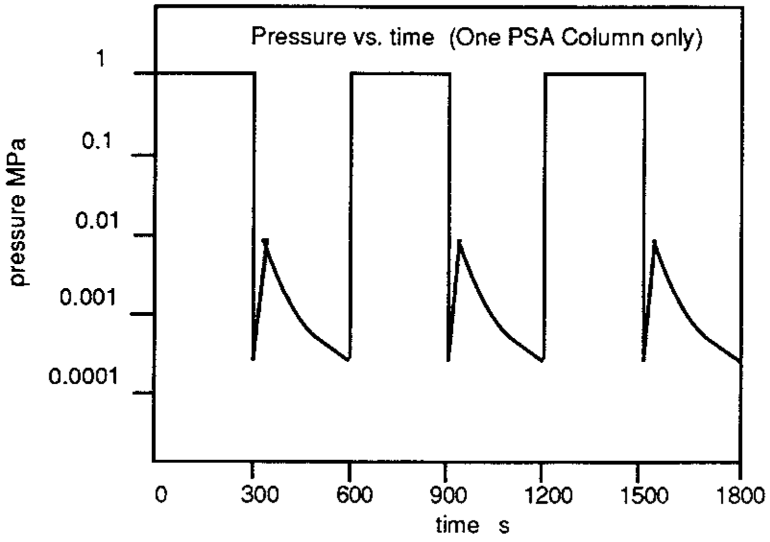


Figure 6.7.5-1. PSA Column Pressure Variation with Time

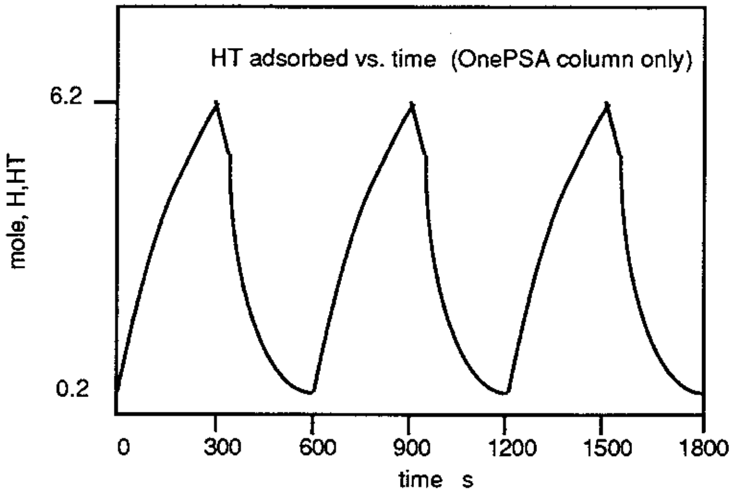


Figure 6.7.5-2. PSA HT Adsorbed as Function of Time

Figure 6.7.5-1 shows the PSA column pressure variation for the 1 MPa feed pressure. At the start of each evacuation cycle, the initial rapid drop in pressure corresponds to He being removed from the column. The following sharp rise in pressure is due to H_2 addition, and the subsequent slower drop in pressure is due to hydrogen isotope product pump-out. The purpose of H_2 addition at the beginning of the evacuation cycle is to promote the desorption of HT. Without H_2 addition, only a small fraction of the hydrogen isotope desorption occurs at a hydrogen isotope partial pressure above approximately 0.6 kPa. Experimental results suggest that further desorption by vacuum pumping is impractical.

Figure 6.7.5-2 shows Q_2, the quantity HT (mole), adsorbed within the PSA column as a function of time. The rise in Q_2 corresponds to the adsorption phase of the PSA cycle, and the fall corresponds to desorption. The maximum tritium inventory for a 10 minute PSA cycle is less than 0.5 g.

The Prometheus PSA design is greatly simplified by operating it to complete breakthrough. The formation and movement of concentration profiles down the column is of little concern. It is only necessary to ensure that sufficient feed is passed through the column to achieve near saturation of the adsorbent.

6.7.5.2 <u>PSA - Process Description and Control</u> - During PSA column pressurization and feed flow, the feed rate to the column is kept constant (see Figure 6.7.5-3). The purge gas pressure in the breeder is kept under 10 Bar. This is suitable for the PSA sorption process, and consequently a gas circulator is needed only for recirculating the purge flow through the sorption beds. Column pump-out proceeds in three stages:

(1) He Removal – He is much less strongly adsorbed than hydrogen and most of it can be removed before significant desorption of hydrogen isotopes occurs. Therefore, for a short initial evacuation time, the exhaust from the vacuum pump P1 is recycled to the blanket through V2 (with V1 closed). After helium removal, valve V2 is closed and the column is ready for hydrogen isotope pump-out.

(2) H_2 Addition – Pure H_2 is introduced into the column through valve V3 to reach a partial pressure of about 20 kPa. The effect of this is to displace adsorbed HT and increase HT partial pressure during pumpout. The only penalty associated with this procedure is further dilution of the T in H, thus increasing the ISS feed. In the optimized design, this increase is compensated by adding a small pre-enrichment column which reduces the ISS feed from this stream by a factor of 4-5. This CD column would have only 0.57 g of T_2 and reduces the ISS inventory by approximately 5 g.

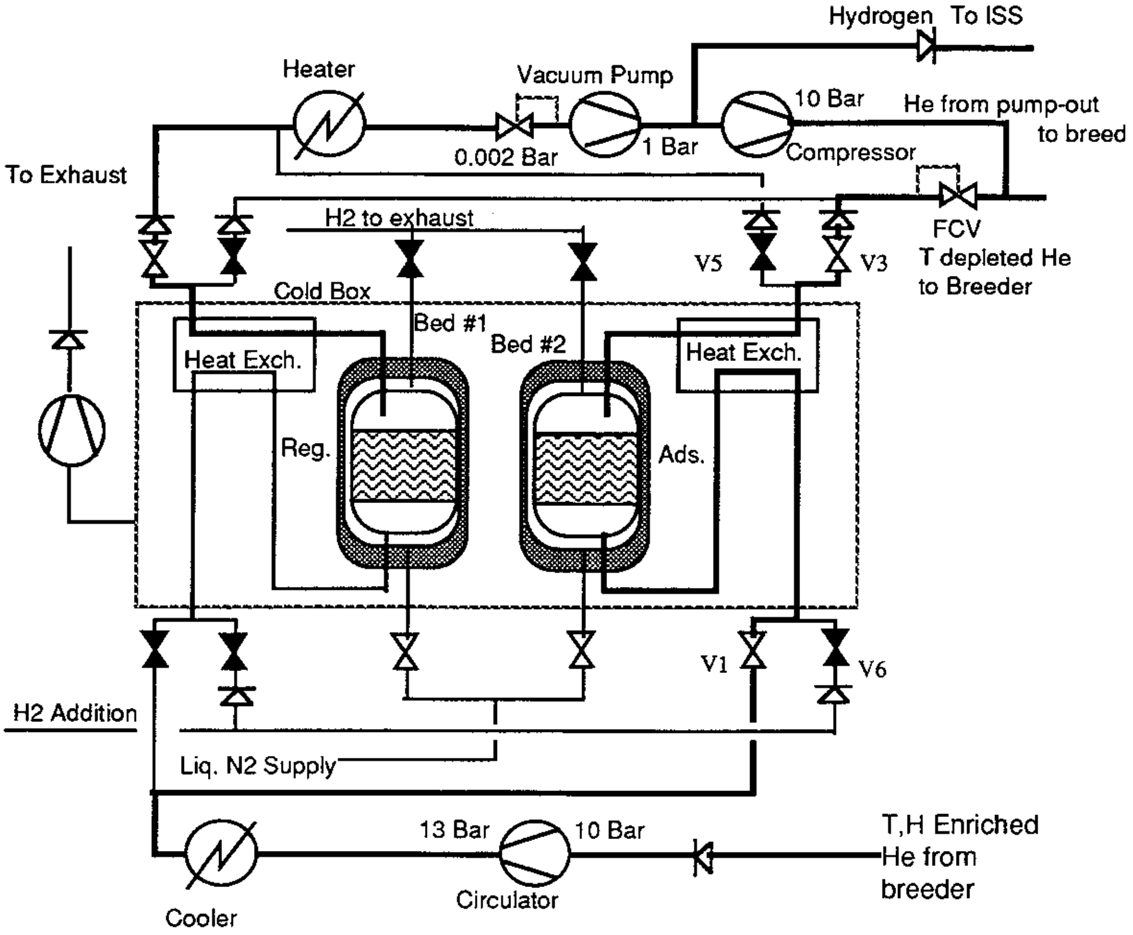


Figure 6.7.5-3. PSA for Tritium Extraction from Breeder

(3) H_2, HT Product Pump-out – Valve V1 is opened and the H_2 and HT contents of the PSA column are pumped out in order to withdraw product and to prepare the column for the next cycle.

The PSA column pump-out time is the same as the pressurization and feed time. For this design, in order to provide continuous processing of feed, two PSA columns are operated simultaneously. The feed flow is to one column while the other column is being evacuated. The flow in the columns is in the same direction during feed and evacuation.

The vacuum pumping requirements can be met by commercially available tritium compatible pumps. For example, two Model 600 Normetex pumps operated in parallel would give the pumping speed required for this application.

6.7.6 Air Detritiation Systems (ADS) - In principle, the fuel systems are designed to prevent chronic leaks from equipment, and therefore, rooms are normally intended to be ventilated without continuous tritium recovery. However, ADS systems are provided to service a room where tritium escape has been detected. The rooms are also isolated from each other in order to minimize cross contamination and facilitate clean-up operations. However, there may be exceptions where equipment is under inert atmosphere with no access during operation. The tritium processing equipment is, from the containment point of view, divided into the following categories:

- Concentrated tritium gas under pressure – In double containment such as the cryogenic distillation unit and fuel storage system.
- Concentrated tritium gas at sub- or atmospheric pressure– In single containment.
- Hydrogen with less than 1% tritium at less than 20 bar – In single containment.
- Tritiated water at atmospheric pressure – In single containment.

The design approach will assume that during normal operation there are no chronic releases from the system. This is complemented by operating the rooms at a sub-atmospheric pressure of just a few millimeters of water column with the ADS on stand-by. All rooms are independently monitored for tritium and, in the event of tritium excursion, the ADS is activated and valved into the affected room. The following kind of systems will be used:

- Conventional Ventilation System (VS).
- Exhaust Atmosphere Detritiation System (EADS) - Such a system will be connected in series with RADS and will detritiate the air to be discharged into the atmosphere. This will keep the room(s) affected by a tritium release at mild under-pressure for tritium spread containment purposes.
- Recirculating Air Detritiation System (RADS) - These systems will be in normal operation on stand-by and will be activated only during emergencies such as during tritium release into a room. In some areas where chronic tritium release occurs, part of the RADS may operate continuously.

In addition, there will be a need to remove tritium from a process and its purge gas. Where possible, this will be carried out by the process itself, but final polishing will be done in a Gaseous Waste Processing System which is similar to the system described in Section 6.7.4.

Figure 6.7.6-1 indicates the functional arrangement of these systems. Normally the flow-through ventilation will keep the rooms well ventilated through a flow pattern directed from the clean zone, kept at atmospheric pressure, to the potentially contaminated zones maintained at progressively increasing negative pressure. The ventilation system will also be able to immediately isolate the system from a room in which any trace of activity is detected. In such event the normally stand-by RADS will be activated and valved-in to the affected zone. The function of the EADS is to maintain negative pressure in the potentially contaminated zones by processing a small amount of the building air and discharging it into the environment through the

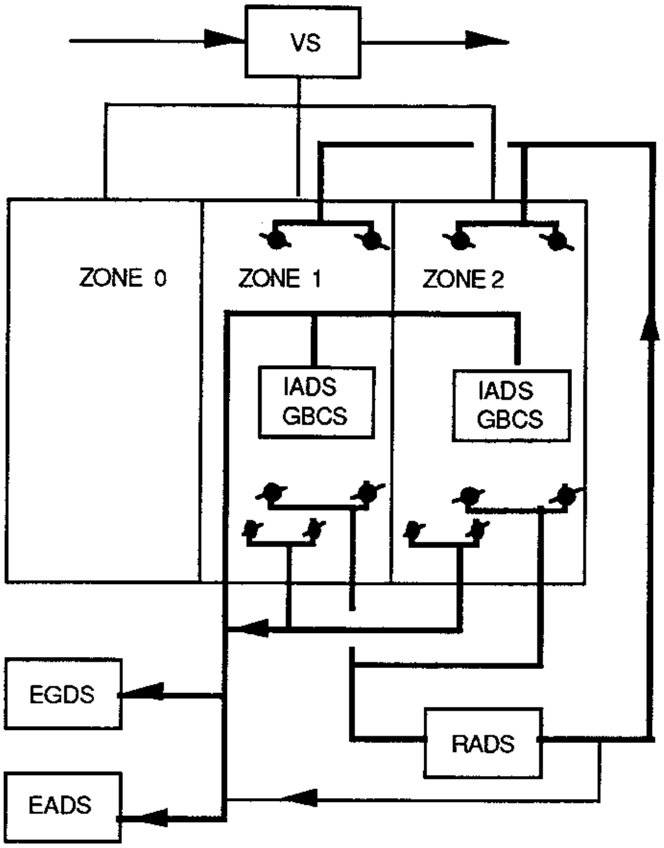


Figure 6.7.6-1. Functional Arrangement of ADS

stack. With the exception of attention to leak tightness and the room isolation feature, the VS is conventional and, in this design, is considered to be part of the HVAC system included in the balance-of-plant systems design.

6.7.6.1 **ADS - Functional and Performance Requirements** - The ADS requirements for the facility are summarized in Table 6.7.6-1.

The following general equation applies for the tritium clean-up time:

$$C = C_{max} * e^{-Q*t*f/V}$$

where:

C - Tritium concentration in building air (Ci/m^3) at time t
C_{max} - Initial release tritium concentration in building air (Ci/m^3)
Q - Flow of air to the extraction facility (m^3/h)
t - Time into the clean-up cycle (h)
f - Fraction of tritium removed from the clean-up flow, at decontamination factor 900, $f = (1-1/900) = 0.99888$
V - Size of the room to be cleaned (m^3)

Table 6.7.6-1 ADS Design Parameters

Room/Space Name	Volume (m^3)	Tritium Inventory (kCi)	Single Failure Release (kCi)	Release Conc. (Ci/m^3)	Clean-up Time to 1 MPCa (h)	RADS Flow for 3 Days to 100 MPCa (m^3/h)	EADS Flow (m^3/h) 1% Max.
Reaction Chamber							
L-Option	7050	n/a (1)	3 (2)	0.43	5.5	600	70
H-Option	7050	1000	10 (3)	1.42	3.1	900	70
Driver Building							
L-Option	180000	1000	10	0.56	6.7	10000	1800
H-Option	2x16000	1000	3	0.19	3.7	1800	300
Vacuum Pump Room	8000	1000	1000	8	4.5	1000	80
Coolant Recirculation Room	120000	0	0	0	0	0	0
Contaminated Pb	2500	10	10	4	4.6	300	25
Contaminated Na	2500	192	192	76.8	4	400	25
Pb Coolant Room	10000	10	10	1	4.4	950	100
Breeder Purge Processing	6200	40	40	6.45	4.4	800	60
Fuel Factory	20000	7x10^4	3500	174	5	3300	200
Fuel Processing Water Dist.	4000	0.128	0.128	0.032	7	200	40
Tritium Storage	2000	2x10^4	1500	750	3.8	400	20
ISS							
L-Option	2500	480	480	192	4	450	25
H-Option	2500	700	700	280	6	300	25
FCU							
L-Option	1500	80	40	27	3.7	250	15
H-Option	1500	160	80	53	3.9	250	15
Turbine Building	130000	0	0	0	0	0	
Auxiliary Building	130000	0	0	0	0	0	

(1) Total tritium content in the chamber is not evaluate
(2) Gas content of chamber only
(3) Fuel injector failure, no chamber failure

The exhaust detritiation flow is designed to be in the range of 1% of room volume per hour. This is primarily to cope with air infiltration. The proposed sizes of RADS are defined in Table 6.7.6-1.

From Table 6.7.6-1, it is evident that the total amount of RADS capacity in the reactor building is 10,000 m^3/h. This is required if the fuel injector fails and releases 10 kCi of tritium into the large mirror building for the L-option. The largest RADS requirement for the Fuel Factory is up to 3300 m^3/h of air but up to 330 g of tritium could be released into the room. It needs to be reiterated that the large tritium releases could occur only in missile type of events since there are several layers of containment, and consequently, there will be no tritium release into accessible areas from a single component failure.

6.7.6.2 ADS - Process Description and Control - The ADS requirements shown above are met by modular design. This allows operation of different numbers of modules depending on the room volumes to be serviced. The arrangement of these modules could be flexible and reliability could be achieved by providing redundancy in the inherently less reliable components such as rotating equipment-blowers or entire units. Typical Recombiner-Dryer module schematics is shown in Figure 6.7.6-2 and a membrane-based module is in Figure 6.7.6-3. Such modules will have a capacity in the range of 7,000 to 10,000 m^3/hr. The deployment strategy is based on the following assumptions:

- It is not credible that a large spill will occur simultaneously in all rooms with risk potential.
- The capacities required by some of the rooms may be too small to warrant a dedicated system.
- Common units allow for high reliability of the system and economically increased redundancy.

All ADS units will be skid-mounted for easy factory assembly, pre-testing, commissioning, and replacement/maintenance.

Recombiner-Dryer Based System - The Recombiner-Dryer based air detritiation is shown in Figure 6.7.6-2. The major components are designated with the following acronyms:

FR1	Inlet filter
B1	Blower(s)
FR2	Activated charcoal filter
HTR1	Preheater(s)
RB1	Recombiner
CD1,2	Condensers
TK1	Condensate collection tank
HX1	Air/air heat exchanger
DY1,2	Dryer beds with molecular sieves, regeneration loop, diagnostics (temperatures, flows, humidity, tritium)

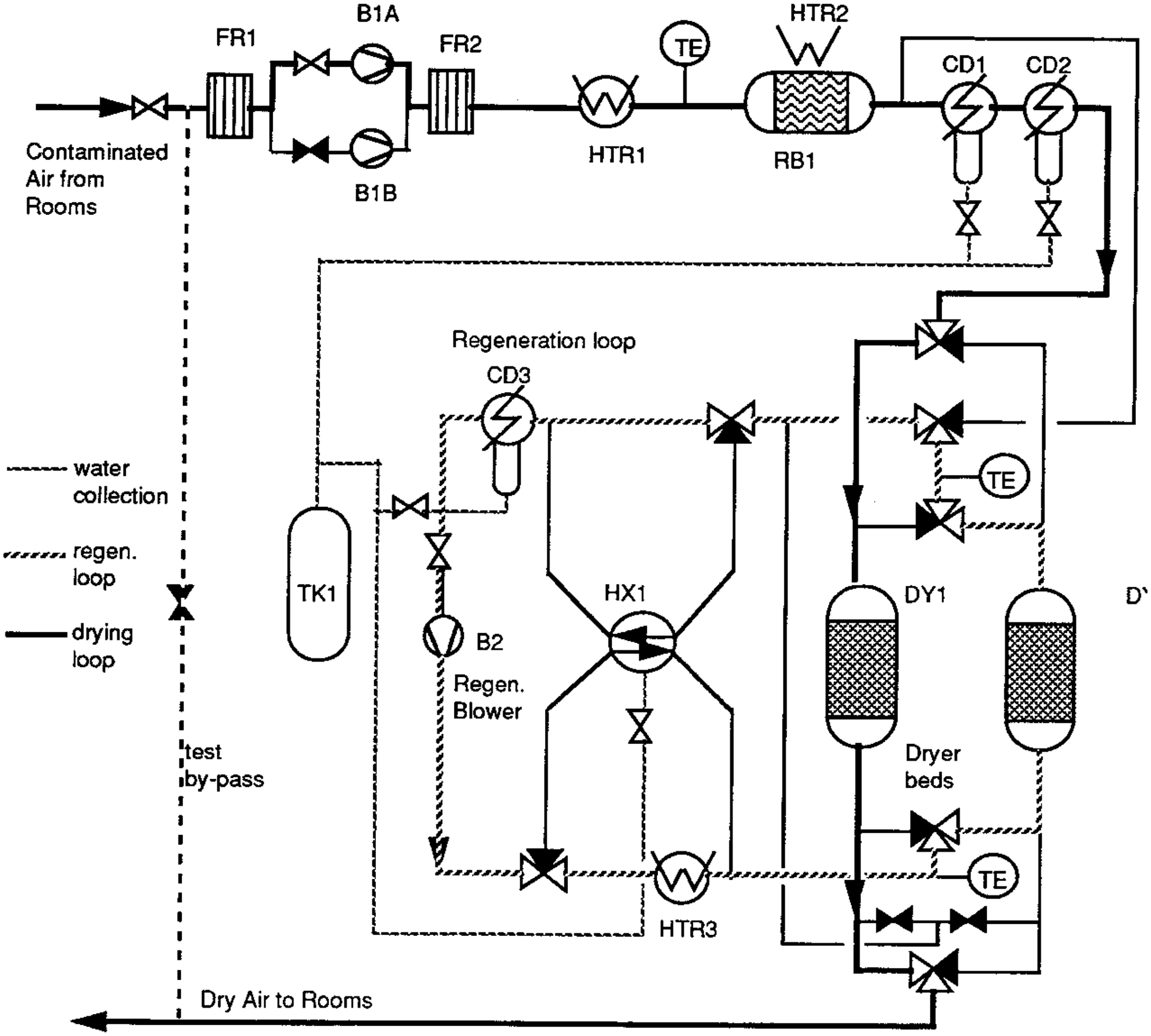


Figure 6.7.6-2. Recombiner-Dryer Based Air Detritiation System

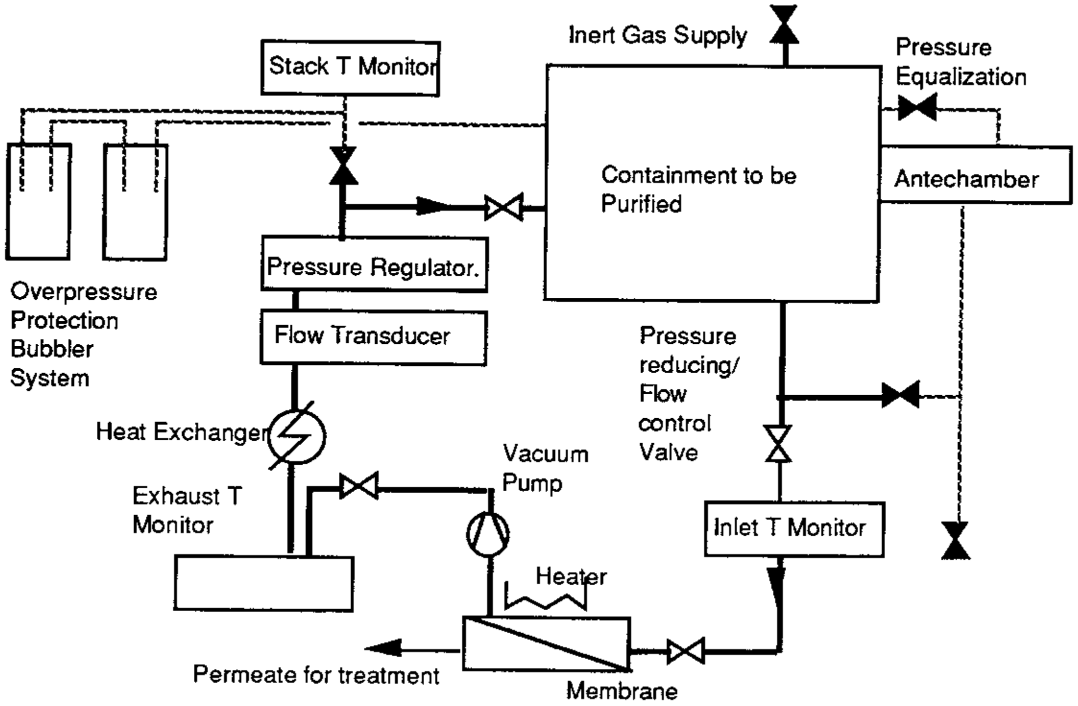


Figure 6.7.6-3. Membrane Based Air Detritiation System

The detritiation cycle is initiated by high tritium readings in an affected space. First, the affected area is isolated from the ventilation system. The contaminated air is then directed to a RADS unit. The air entering RADS is heated partially by the heat of compression and trim heated to approximately 150°C. At this temperature, the catalytic recombiner converts H, D, and T into water vapor which can be adsorbed in the molecular sieve beds. Prior to entering the beds, free moisture is separated in the upstream condensers cooled and chilled to 5°C. The return air from the dryers is up to 99.998% moisture free with a discharge dewpoint as low as -65°C. The on-line capacity of a single adsorption bed is 12 hours before requiring regeneration. A small amount of dry air from RADS is further processed in the EADS and discharged into the environment. This flow is used for controlling the negative pressure in the affected area of the facility.

During regeneration the air is heated to 300°C in HTR3 and recirculated through the bed where it heats up the bed and provides heat of desorption. Humidified regeneration air flows through the heat recovery exchanger HX1 and subsequently deposits the moisture in the condenser CD3. When the bed outlet temperature reaches approximately 280°C, the heating process is considered complete. The bed is flushed with dry air from the dryer discharge. The fraction of the regeneration flow is 1/7 of the overall dryer throughput. This side stream is recirculated into the drying loop upstream of the condensers CD1 and CD2 and returned upstream of the drying bed until the regenerating bed outlet dew point of -85°C is reached. The entire regeneration process will take approximately eight hours. The subsequent cooling of the bed takes place by recirculating air in a closed loop through the CD3 which removes the residual heat until the final temperature of 28°C is reached.

Membrane-Based ADS - Figure 6.7.6-3 indicates a typical arrangement of such as system.

These types of processes are in the initial stage of experimentation with tritium, but commercial dryers based on permeation membranes already exist.[10] The system is designed as a typical permeation membrane process consisting of a gas circulator, permeation module, reject stream treatment loop, and appropriate diagnostic equipment.

The two most valuable features of the process are that:

- Permeation of hydrogen in gaseous and oxide form occur and no recombiner is needed.
- It is a continuous process.

The following characteristic process design parameters were published:[9]

Feed pressure	400–500 torr
Permeated side pressure	1.1 torr
Temperature of membrane	80–100°C
Recovery 80% T	At 0.1 of feed stream at $4x10^{-2}$ to 10^{-1} micro-Ci/cc and humidity 2,000-12,000 ppm
Recovery 70% T	At $2x10^{-1}$ micro-Ci/cc and humidity 440 ppm.

This process may feature instantaneous start-up, insignificant sensitivity to residual contamination, and continuous operation. Consequently, it will be particularly suitable for RADS operation. For the EADS service, the added security of the recombiner-dryer process may be required.

6.7.7 Inert Atmosphere Detritiation System (IADS) - A number of inert atmosphere detritiation concepts were described in References 11, 12, 13, and 14. The process of choice is the getter-based atmosphere purification system (Figure 6.7.7-1). The application of IADS will be on a modular basis where each room or secondary containment is serviced by its own dedicated system. For very large applications, the systems described for the air detritiation systems of the recombiner-dryer type shown in Figure 6.7.7-2 may offer the optimum solution.

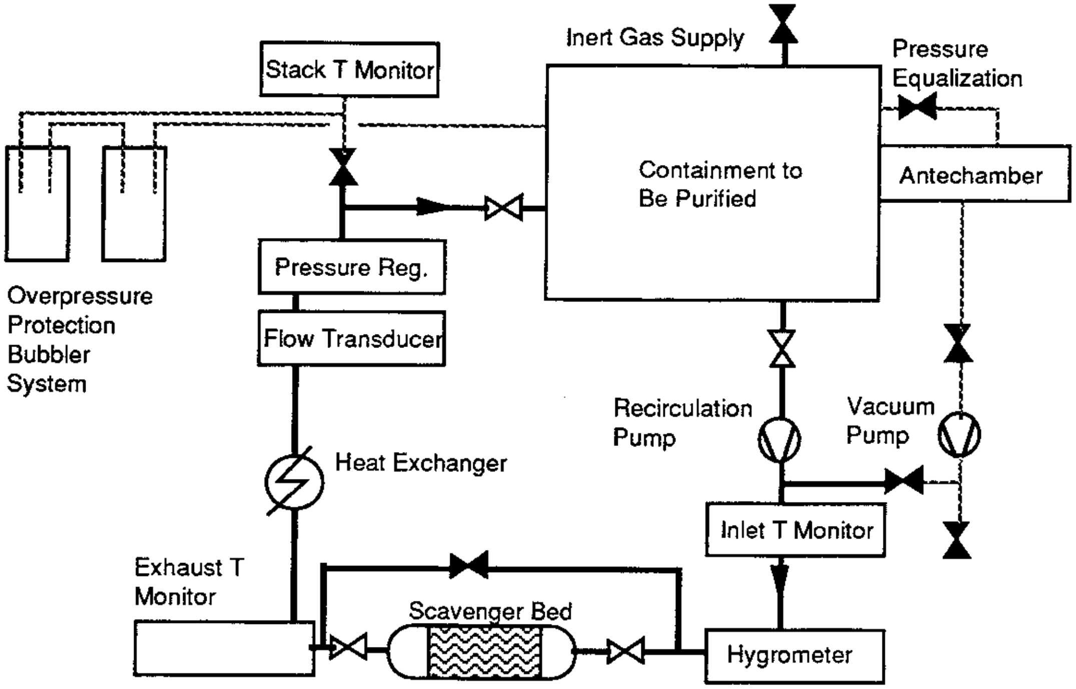


Figure 6.7.7-1. Getter-Based Inert Gas Detritiation System

Recombiner-Dryer Based IADS - The IADS will have the following components (as shown in Figure 6.7.7-2):

FR1	Inlet filter
B1	Blower(s)
FR2	Activated charcoal filter
HTR1	Preheater(s)
RB1	Recombiner
CD1,2	Condensers
TK1	Condensate collection tank
DY1,2	Dryer beds with molecular sieves
OXY1,2	Oxygen removal beds
HTR3,4	Oxygen removal bed heaters
HX1	Gas/gas heat exchanger, regeneration loop, diagnostics (temperatures, flows, humidity, tritium)

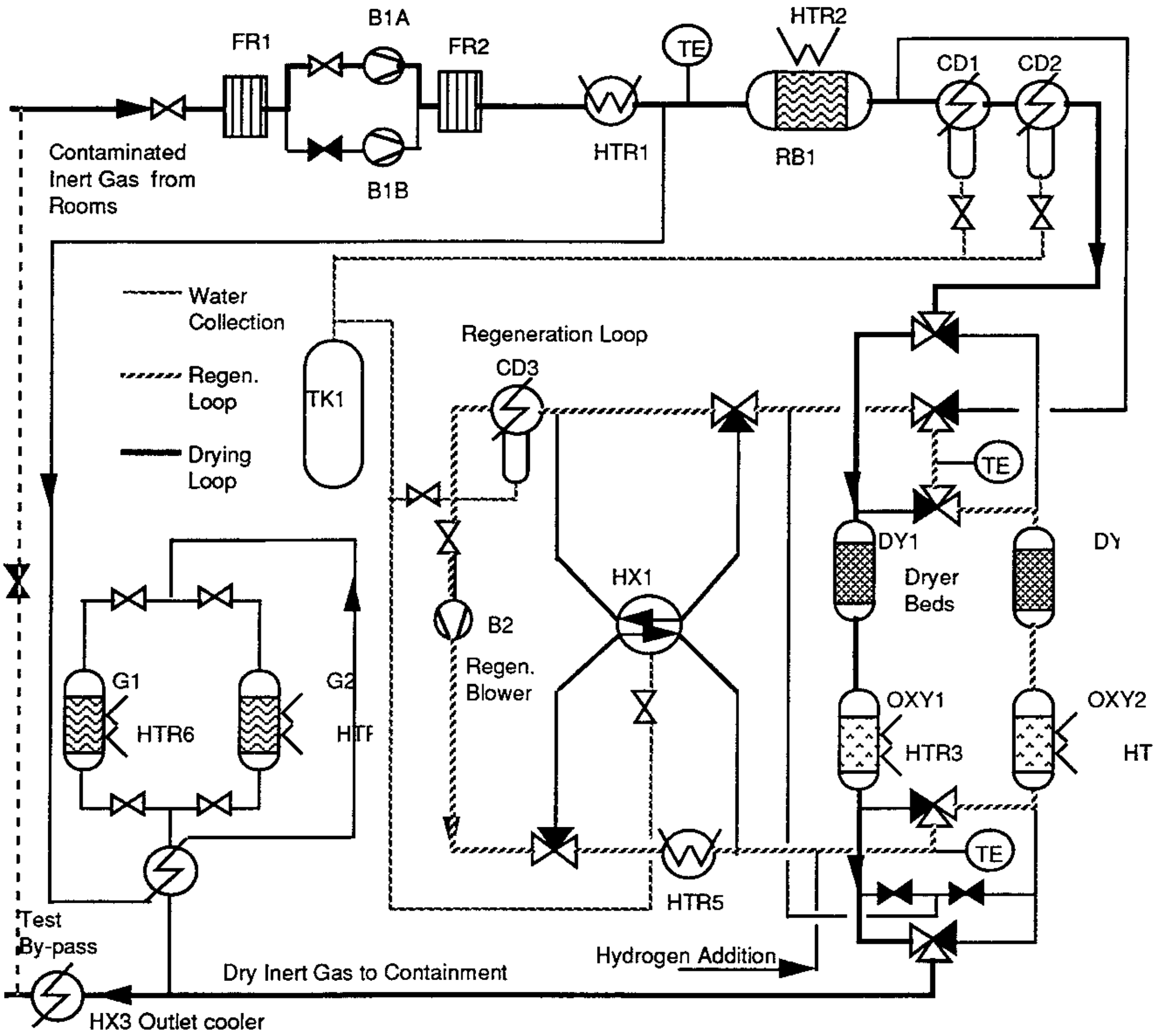


Figure 6.7.7-2. Recombiner/Dryer Based Inert Gas Detritiation System

The detritiation cycle is initiated by high tritium readings in an affected space. First, the affected area is isolated. Recombiner-dryers operate in the same manner as described in Section 6.7.6.2. In addition, downstream oxygen removal beds operate at 175°C to remove excess oxygen from the purified inert gas. The returning gas is finally cooled in HX3 to the ambient temperature.

Regeneration of the beds is similar to the process described in Section 6.7.6.2.

6.7.8 Fuel Storage and Management System (FSMS) - Fuel in the tritium concentration range (between 50–70% tritium) is required to be stored and assayed in a safe manner. This will be done in the Fuel Storage and Management System (FSMS).

6.7.8.1 FSS - Functional and Performance Requirements - In order to obtain uninterrupted production of fuel, the free tritium inventory in all the systems will be in the order of 7 kg. Table 6.7.8-1 indicates the in-process inventories of systems containing tritium. During shutdown, all the free tritium inventory will have to be stored in metal hydride storage beds. A single storage bed size is proposed to contain no more than 200 g of tritium. On the basis of 50% DT fuel, there will have to be approximately 7000/200 = 35 storage beds available for fuel storage alone. The nominal 200 g tritium per bed target for the 50% fuel overall storage capacity will be 200/6 * 2 = 67 mol of hydrogen. For the L-option, a bed could be theoretically filled with fresh fuel enriched from the ISS (59.8% T) to 67 * 0.598 * 6 = 240 g of tritium. If the 200 g limit is required, the beds for ISS-L could be deliberately undersized for 200/(6*0.598) = 55.7 mol of hydrogen. One of the largest rundown sources will be the ISS which contains approximately 860 g of hydrogen isotopes of which only 68 g is tritium (H-case). The purpose of the system is to provide:

- Storage for all free hydrogen gas contained in process for shutdown purposes.
- In-process surge capacity in the form of tanks where required.
- Storage for fuel make-up.
- Assay capability.

In addition, the tritium storage and management system will rely on a number of storage tanks for temporary shutdown storage. The following tanks are foreseen to be used and are defined in Table 6.7.8-2.

Table 6.7.8-1 Tritiated Hydrogen Storage Requirements

System	T_2%	[g] Gas	[moles]	Number of Beds
Factory Fuel, DT	50	7000(T)	2333	35
D_2 Make-Up	0	5000	1250	–
H_2 Propellant		1000	500	8
Chamber Pumping L-Option	39	28	70	1
Chamber Pumping H-Option	4	12	300	5
Isotope Separation	3	70	300	5
Impurity Extr. from Fuel L	26	4	7.26	
Impurity Extr. from Fuel H	4	8	33.3	1
Tritium Extr. from Impurity*				
Tritium from Solid Breeders	5	2.6	8.7*	
Tritium Removal from Na	4	15	60	1
Tritium from Water	–	–	5*104	**
Tritium from Atmospheres	–	–	–	–
Fuel Management and Storage	50	700	233	4
Solid Waste Detritiation	–	–	60	1
Total Number of Beds with 23% Excess Capacity				75

* Included in impurity extraction from fuel

** This amount is actually water vapor which, during shutdown, condenses. No storage is required.

Table 6.7.8-2 Tritium Storage Tank Requirements

System	Pressure (Bar)	Tank Volume (m^3)	Quantity to be Stored (mole)	Location of Tank
Fuel Factory Fuel	n/a			
D_2 Make-up	10	3	1250	Fuel Factory
H_2 Propellant	10	2	500	Fuel Factory
Chamber Pumping L-Option	n/a			
Chamber Pumping H-Option	n/a			
Isotope Separation	10	2	300	ISS
Impurity Extraction	n/a			
Tritium Recovery from Breeders	n/a			
Tritium Removal from Na	1	1.5	60	Tritium Removal Room
Tritium Recovery from Water	n/a			
Tritium from Atmospheres	n/a			
Fuel Management and Storage	1			
Solid Waste Detritiation	1	1.5	60	Fuel Storage

6.7.8.2 **FSMS - Process Description and Control** - The FSMS flow diagram is shown in Figure 6.7.8-1. The diagram is simplified to show only two of the overall number of beds required.

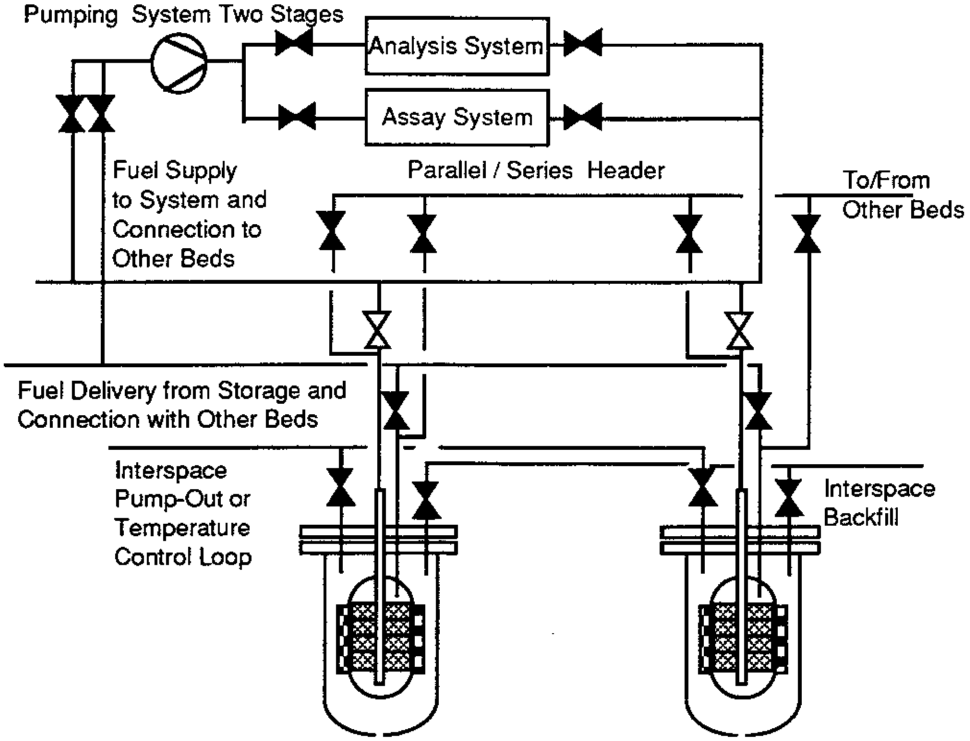


Figure 6.7.8-1. Fuel Storage and Management System Diagram

The storage medium is uranium or zirconium-cobalt.[15] The storing material is contained in the primary container which is provided with heater, temperature, and pressure control devices. Process heating is by way of built-in replaceable electric heaters. The primary envelope is enclosed in a secondary vessel designed and tested for pressure and vacuum operation. This secondary vessel provides vacuum insulation, prevents tritium release in the event of primary envelope failure, and provides opportunity for active temperature control and for tritium permeation capture and recovery. The getter assembly is located in a glove box or solid steel vessel type tertiary containment with inert atmosphere which is continuously monitored for tritium and serviced by an inert gas purification system. The entire storage capacity will have 23% redundancy for excess hydrogen and partially for compensating for lost or degraded storage capacity. In addition, each bed will be designed for 50% loading. The overloading avoidance control will rely on control by procedural means. In situ tritium assay will take place by way of calorimetric measurement of decay heat.

The conventional pressure-volume-temperature measurement can also be used. Temperature control will take place by electrical heating as described above. Heat removal from the bed will be facilitated through filling the interspace between the primary and secondary containment with inert gas. This will facilitate heat convection from the primary and radiation from the secondary. More aggressive cooling could occur if the tertiary containment gas is circulated through a cooler, or more directly if the interspace gas is circulated through a cooler.

The short term, in-process storage capacity by tanks will rely on double walled tanks with interspace leak control.

Accidental bed failure could occur only as a dual failure, namely a combination of heater run-away and failure of diagnostics to recognize this. For this purpose, rupture disc-type relief devices could be used. However, since such devices require inherently high maintenance and since any maintenance on the primary envelope is undesirable, relief devices are avoided.

Each storage bed contains the gettering material in four to five layers separated through sintered grids. Each layer locates the material in copper blocks shaped for optimum heat transfer to achieve uniform operating temperatures. At the inlet and outlet, main filters are located. The main objective of the filters is to prevent the powdered getter material from escaping from the bed. All beds will be installed to permit flow through operation.

6.7.9 Isotope Separation System (ISS) and Water De-tritiated System (WD) - A number of waste water detritiation front-end options were considered but the water distillation is proposed. The final tritium enrichment is accomplished by cryogenic distillation (CD). The entire ISS, including all the interlinked water distillation columns, VPCE, equilibrators, and CD units has been simulated using Ontario Hydro's FLOSHEET steady-state process simulator.[16]

6.7.9.1 **Functional and Performance Requirements** - The requirements for hydrogen isotope separation arise from chamber exhaust gas processing, breeding blanket tritium recovery, air cleanup, and other safety and waste processing systems. The functional relationship between the ISS and the fuel processing systems is shown in Figure 6.7.1-1, and the corresponding flows and compositions of the ISS feeds are specified in Table 6.7.1-1 for the L option, respectively. The CD system configuration represented in Figure 6.7.9-1 has undergone several refinements in order to simplify the design, to improve robustness, and to minimize tritium inventory. The specific feed and product flows and compositions are defined in Figure 6.7.9-1. The following processing streams apply for the isotope separation system:

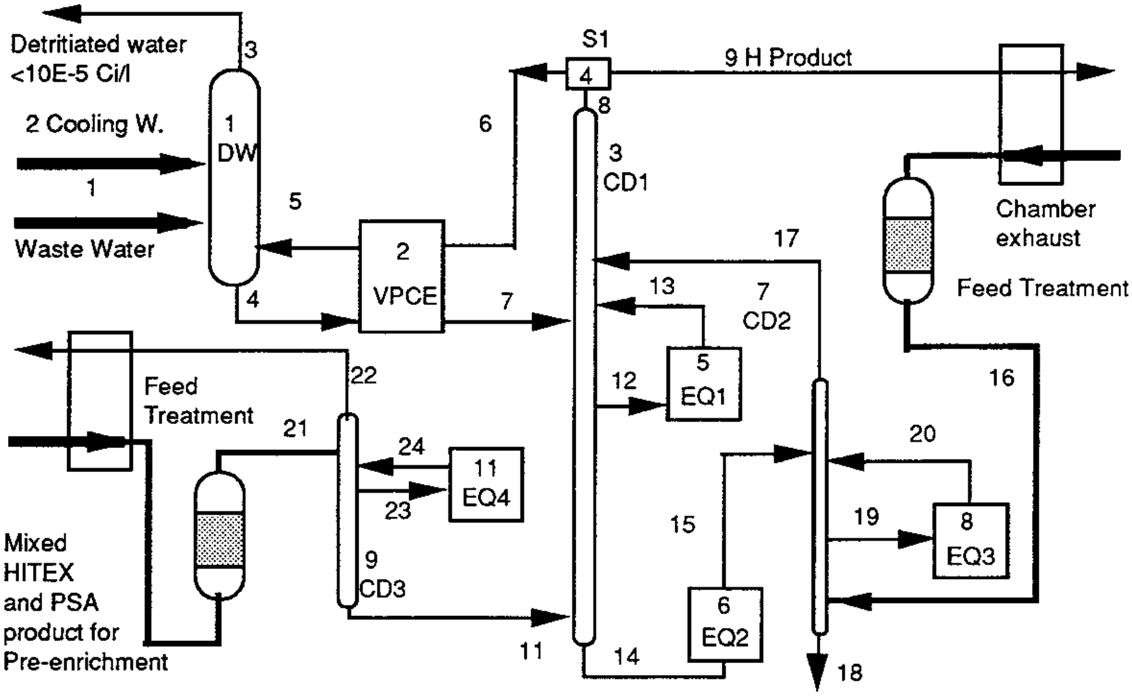


Figure 6.7.9-1. ISS and Water Detritiation - Flow Diagram

Feeds to the ISS - The elemental hydrogen streams which are external feeds to the cryogenic distillation system are assumed to be isotopically equilibrated at a temperature of 300 K.

- Tritiated Waste Water - Stream z (in Figure 6.7.1-1) or 1 (in Figure 6.7.9-1), shown as z/1.
- Solid Breeder Tritium Extraction - Stream h/21. Tritium must be extracted from the solid breeder through a He/hydrogen purge gas stream. The composition is 0.2% H and 0.01% T.

- Chamber Exhaust Gas - Stream a/16. The H/D/T mixture from plasma exhaust gas processing must be isotopically separated. This is different between the laser and heavy ion options mainly due to the significantly different hydrogen component where the heavy ion option target contains approximately ten times more hydrogen than the laser option.
- Target Injector Propellant Cleanup - This applies only to the heavy ion option. Most of the propellant gas is trapped and recovered in a chamber just before the entry shutter to the chamber. Only a small portion of the gas enters the chamber and is mixed with the chamber exhaust gas. Deuterium and protium were considered as alternative propellants. It was established that as long as the propellant component is in excess of the deuterium makeup which in this case is threefold, the excess deuterium propellant must be separated to a reasonable purity. This makes the ISS design complicated to the extent that two additional columns are required and the tritium inventory is substantially increased. Consequently, protium was selected as propellant.
- Product from the HITEX Process - Stream c/na is mixed with stream h.

ISS Products

- Detritiated Waste Water - Stream u/3. This stream must contain less than 10 micro-Ci/kg of tritium. Therefore, the mole fraction of HTO in the product must be less than 6.2×10^{-12}.
- Protium Product - Stream d/9. The tritium atom fraction in the detritiated protium stream (H_2 with Trace HD) must be less than 1.0×10^{-9}.
- DT Product - Stream k/18. Although there is no tritium enrichment required, the DT composition is still T enriched due to the addition of the T from the breeder product.

6.7.9.2 Waste Water Detritiation Options - Two waste water detritiation processes were considered for this application:

- Distillation for HTO concentration and Vapor Phase Catalytic Exchange (VPCE) process for transporting T from HTO to HT for processing in the ISS.
- Combined Electrolysis and Catalytic Exchange (CECE) process which transfers tritium from water to hydrogen in direct contact in the presence of a hydrophobic catalyst.

Final selection of the waste water detritiation process was made on the basis of factors such as cost, flexibility, and safety. The reference case for this application is the DW + VPCE option. The characteristic features of the process are:

- Tritiated water is fed near the bottom of the column (the optimum feed point is determined by feed composition), detritiated water is withdrawn from the top of the column, and a small stream of concentrated tritiated water is fed from the bottom of the column to the VPCE.

- In the single stage VPCE, tritium is transferred to hydrogen gas, which returns to the CD system for detritiation.
- The tritium-depleted water stream returns from the VPCE to the water distillation column.

The attractive features of the process are:

- Safety: Water distillation is inherently a safe process, since it involves very moderate process conditions (temperature: 50-60°C; pressure 10-30 kPa), it has no associated explosion hazard (such as electrolysis), and it has an excellent operating history with large-scale industrial units processing tritiated water.
- Reliability: Reliability of water distillation is proven by more than 20 years of large scale industrial use.
- Availability: Large scale units are available, with no extrapolations of existing technology.
- VPCE Catalyst Lifetime: Since the VPCE catalyst is operated at 200°C under conditions which are favorable for catalyst lifetime, the expected lifetime is in excess of 20 years.

The disadvantages of the DW + VPCE process are primarily that the equipment is physically large (3 columns, 25-m high, 0.6-m diameter) and the process may require up to 1600 kg/h of low grade steam. (This can be reduced if a heat pump is used.)

The following source terms for waste water were estimated:

Source	Flow [mole/h]	Tritium Concentration [mole fraction]
Chronic Drain	232	$3.1 * 10^{-8}$
Chronic ADS Collection	463	$3.1 * 10^{-8}$
Inert Atmosphere Detrit.	93	$3.1 * 10^{-10}$
Decontamination Water	463	$3.1 * 10^{-8}$
Chamber Maintenance	3.4	$3.1 * 10^{-8}$
Post Accident Drain	85	$7.8 * 10^{-7}$
Post Accident ADS	170	$7.8 * 10^{-7}$
Post Accident Clean-Up	8.4	$3.0 * 10^{-9}$

The overall flow is 1517 mole/h with blended concentration of $1.55 * 10^{-7}$ mole fraction.

6.7.9.3 ISS - Process Description

Water Distillation - Although the water detritiation equipment is large, it contains very little tritium, mainly due to the low concentration of tritium in the waste water and limited tritium enrichment in DW1. The design parameters of the distillation columns is given in Table 6.7.9-1.

Table 6.7.9-1. Water Distillation Column Parameters

		L-Option and H-Option
No. Theoretical Stages		450
Pressure (kPa)	Top	11
	Bottom	25
Temperature (K)	Top	320.9
	Bottom	338.2
Diameter (m)		0.59
Packing Height (m)		54
Reflux Ratio		27
Holdup (mole/stage) Column		110.6
	Reboiler	884.7
Total Holdup (mole)	H_2O	5x104
	D_2O	58.2
	T_2O	0.05
Steam Consumption (kg/h)		740
Feed Location, Stage	Stream 1	300
	Stream 2	350
	Stream 5	425
Drawoff Loc. Stage	Stream 3	1
	Stream 4	450

VPCE - The vapor phase catalytic exchange is carried out over a Pt on alumina catalyst at 200°C. A liquid stream is withdrawn from the reboiler of DW1, evaporated, mixed with a detritiated hydrogen stream from CD1, superheated to a temperature of 200°C, passed through the catalyst bed, and finally passed to a condenser for hydrogen/water separation. Detritiated water is returned to DW1 and tritiated hydrogen is returned to CD1.

Cryogenic Distillation - The cryogenic distillation system is comprised of three cryogenic distillation columns (CD1, CD2 and CD3), four equilibrators (EQ1, EQ2, EQ3, and EQ4), and one stream splitter (S1). The purpose of the first cryogenic distillation column, CD1, is to remove tritium from streams containing mostly hydrogen with trace tritium and to produce a highly detritiated hydrogen stream (Stream 8) as the overhead product and a D_2/DT stream as the bottom product for further processing in the final column CD2. CD1 also receives a recycle stream from the downstream columns CD2. In addition, a small column CD3 was added to reduce the H_2 content of diluted streams h and c from the PSA and HITEX processes. This reduces the CD1 size and tritium inventory by approximately 5 g.

Since the hydrogen from CD1 may be discharged to the environment, it is essential that the design of CD1 be conservative to ensure that tritium emissions will be acceptably low. The reflux ratio for CD1 is, therefore, conservatively set at 3.7—more than twice the minimum reflux ratio. This conservatism results in a somewhat larger diameter and power consumption for CD1 than the minimum possible.

In the lower portion of CD1, a side stream is taken off and passed through equilibrator EQ1 and then returned to CD1. The purpose of the equilibrator is to promote the reactions: $HT + HD = H_2 + DT$ and $HT + D_2 = HD + DT$. Immediately downstream of CD1 is equilibrator EQ2, which serves to promote the reaction $HT + D_2 = DT + HD$, in order to convert traces of tritium in the form of HT into DT.

The bottom product of CD2 is the final DT stream. A side stream is taken from CD2 and passed through equilibrator EQ3 in order to promote the reaction: $2\ DT = D_2 + T_2$.

The CD1, CD2, and CD3 cryogenic distillation column parameters are summarized in Table 6.7.9-2. Process simulations results are shown in Tables 6.7.9-3, 6.7.9-4, 6.7.9-5, and 6.7.9-6 for the gas, liquid streams, and the L and H options, respectively.

6.7.9.4 **Water and Hydrogen Distillation - Control Description** - Control systems for the distillation units is well proven in a number of heavy water upgraders, and the same control philosophy is proposed to be adopted for this application. The operating pressure of water distillation column DW1 is controlled by automatic adjustment of cooling water flow to the column condenser. The flow of steam to the reboiler is at a constant rate and is normally set only at column startup. Withdrawal of overhead product is controlled by reboiler level. Feed forward to the downstream VPCE and associated feedback are kept constant. Since a single stage VPCE unit is used for transferring tritium to the gas phase, its control is simple. Low pressure steam to the evaporator is on evaporator level control, and the flow of high pressure steam to the superheater is controlled by the superheater exit temperature.

The CD system is the heart of the ISS and is also the most complex part of the system. The pressure in the CD cascade is designed to progressively decrease from column CD3 to CD1 and CD2. The purpose is to provide enough inter-column differential pressure to control the forward flows in the cascade. This control strategy deliberately avoids the use of pumps to transfer these enriched streams. On the contrary, return streams in the cascade which are depleted in tritium are pumped against the pressure gradient. The boil-up in each column is set by controlling the power input to the electrically heated column reboilers. Once the boil-up in a column is defined, the appropriate fraction of vapor flowing up the column must be condensed and returned within the column as reflux. Thus, the helium refrigerant flow to each column condenser is modulated to condense the correct amount of vapor and maintain the column pressure at the desired value.

Table 6.7.9-2. Cryogenic Distillation Column Parameters

		L-Option			H-(where different)		
Parameter		**CD1**	**CD2**	**CD3**	**CD1**	**CD2**	**CD3**
Number of Theoretical Stages		120	30	20			
Pressure (Pa)	Top	120	100	150			
	Bottom	125	101	152			
Temperature (K)	Top	20.98	24.74	21.79	9.2	5.2	13
	Bottom	24.74	24.54	21.91			
Column Diameter (cm)	Top	9.00	3.85	13.14			
	Bottom	–	–	–			
Packing Height (m)		6.6	1.65	1.11			
Reflux Ratio		3.7	6.5	3.5			
Intermediate Reboiler	Stage	–	–	–			
	Power (W)	–	–	–			
Holdup Profile (mol/stage)	Top	1.45	0.27	2.93	1.5	0.47	2.7
	Bottom	1.45	0.27	2.93	1.5	0.47	2.7
	Int. Reboiler	–	–	–			
	Reboiler	4.34	0.81	8.79	4.5	1.4	8
Total Holdups (mole)	H_2	95	0.6	64.21	111	1.9	58
	D_2	118	5.23	0.018	66	5.8	0.015
	T_2	4.87	2.78	0.25	6.3	4.8	0.23
	T_2 (g)	29.27	16.69	1.5	37.7	28.7	1.4
Condenser Duty (W)							
Feed Locations, Stage	Stream 7	20					
	Stream 11	70					
	Stream 13	90					
	Stream 17	80					
	Stream 25				85		
	Stream 15		10				
	Stream 16		24				
	Stream 20		15				
	Stream 21			7			
	Stream 24			15			
Drawoff Locations, Stage	Stream 8	1					
	Stream 12	93					
	Stream 14	120					
	Stream 17		1				
	Stream 18		30				
	Stream 19		17				
	Stream 9			20			
	Stream 22			1			
	Stream 23			17			

Table 6.7.9-3 ISS Liquid Flows, L-Option

Flow No.	Composition mole/h	Liquid Mole Fraction H_2O	HDO	HTO	D_2O	DTO	T_2O
1	1517	9.9985e-01			1.4998e-04		1.5398e-07
3	1518	1.0000e+00	2.7992e-06	1.1091e-10	2.0619e-12	1.5926e-16	3.2371e-21
4	30	9.4344e-01	5.5664e-02	2.8529e-05	8.6426e-04	8.6346e-07	2.2702e-10
5	30	9.5776e-01	4.2100e-02	1.3723e-05	1.2837e-04	8.1729e-08	4.9902e-11

Table 6.7.9-4 ISS Gas Flows, L-Option.

Flow No.	Composition mole/h	Gas Mole Fraction H_2	HD	HT	D_2	DT	T_2
6	90	9.8347e-01	1.6553e-02	5.8884e-09	1.1849e-09	1.4414e-14	3.5287e-20
7	90	9.7858e-01	2.1284e-02	5.1348e-06	1.3116e-04	6.6813e-08	8.7293e-12
8	234.5	9.9993e-01	7.0116e-05	2.6781e-10	1.1958e-10	1.4212e-15	3.2683e-21
9	144.5	9.8347e-01	1.6553e-02	5.8884e-09	1.1849e-09	1.4414e-14	3.5287e-20
11	134.5	9.3645e-01	6.1311e-03	5.7011e-02	7.3078e-06	1.2661e-04	5.7278e-04
13	400	4.1816e-02	2.7728e-01	2.1606e-02	5.5963e-01	9.5420e-02	4.2503e-03
14	20	2.0047e-12	8.4888e-06	2.4313e-04	3.8808e-01	5.6965e-01	4.2023e-02
15	20	2.0225e-08	1.7362e-04	7.6331e-05	4.5365e-01	4.3642e-01	1.0968e-01
16	28.2	2.5227e-08	2.3839e-01	2.2403e-01	6.8565e-02	1.4100e-01	7.5745e-02
17	30	1.7276e-01	4.0969e-01	1.3610e-01	2.4262e-01	3.7804e-02	1.0335e-03
18	18.2	2.1246e-04	5.0948e-03	2.1720e-02	9.6937e-02	5.4140e-01	3.3464e-01

Table 6.7.9-5 ISS Liquid Flows, H-option.

Flow No.	Composition mole/h	Liquid Mole Fraction H_2O	HDO	HTO	D_2O	DTO	T_2O
1	1517	9.9985e-01			1.4998e-04		1.5398e-07
2	1	9.9985e-01			1.4998e-04		3.0995e-07
3	1518	1.0000e-00	4.3791e-06	1.1110e-10	5.0464e-12	2.4958e-16	3.2483e-21
4	30	8.4174e-01	1.5109e-01	2.6038e-05	7.1372e-03	2.3976e-06	2.1196e-10
5	30	8.5143e-01	1.4671e-01	1.2548e-05	1.8535e-03	3.0116e-07	4.6928e-11

Table 6.7.9-6 ISS Gas Flows, H-option.

Flow No.	Composition mole/h	Gas Mole Fraction H_2	HD	HT	D_2	DT	T_2
6	90	9.2056e-01	7.9439e-02	1.5895e-08	4.0323e-08	1.1603e-13	7.2425e-20
7	90	9.1757e-01	8.0429e-02	4.9519e-06	1.9975e-03	2.5968e-07	8.6585e-12
8	597	9.2056e-01	7.9439e-02	1.5895e-08	4.0323e-08	1.1603e-13	7.2425e-20
9	507	9.2056e-01	7.9439e-02	1.5895e-08	4.0323e-08	1.1603e-13	7.2425e-20
11	377	9.9883e-01	5.6002e-04	6.1022e-04	5.6516e-08	1.3611e-07	1.5325e-08
12	600	3.2983e-03	2.5315e-01	2.7941e-02	6.8033e-01	3.4830e-02	4.5453e-04
13	600	2.3933e-02	2.3156e-01	8.2627e-03	6.8191e-01	5.3245e-02	1.0861e-03
14	20	3.2864e-13	4.5734e-06	9.2436e-05	4.1303e-01	5.6776e-01	1.9114e-02
15	20	3.0304e-09	6.9679e-05	2.7324e-05	4.8765e-01	4.1845e-01	9.3803e-02
16	145	5.8848e-01	2.6336e-01	8.3067e-02	3.5871e-02	2.4758e-02	4.4641e-03
17	150	5.2008e-01	3.5310e-01	7.7214e-02	4.7537e-02	2.0404e-03	2.2101e-05
18	15	3.4561e-04	4.1748e-03	7.2594e-03	1.1175e-01	6.1039e-01	2.6608e-01

The overhead vapor product from a column is withdrawn through a control valve which controls the reboiler level in that column at the desired value and thus ensures that mass balance is maintained within the column. This control strategy ensures a mass balance for each column, provides for pressure and reboiler-level control for each column, ensures the correct column internal flows, and allows transfer of tritium-rich streams without the use of circulating pumps.

6.7.9.5 **Safety Analysis** - The ISS contains most of the free or releasable tritium in the fuel processing systems. For this reason, this system was selected for sample safety analysis. Safe design and operation of the ISS requires that the process fluids contained within the ISS equipment not be released or leaked to the surrounding environment under any postulated event. In considering the safety of the Isotope Separation System, the effect of possible failures on equipment groups has been analyzed to show that the system design is safe. The following generic failure modes have been considered and have been applied where applicable:

- Utility failure as a common mode failure: loss of power, loss of chilled water, loss of liquid nitrogen or gaseous cold or hot nitrogen, and loss of vacuum in coldboxes.
- Closed valve at equipment outlet.
- Controller failure: level control, flow control, temperature control, pressure control.
- Catalyst poisoning (loss of efficiency).
- Failure of composition analysis.
- Failure of interlocks.

The evaluation of the above failures is summarized in Table 6.7.9-7.

6.7.10 **Heat Transfer Media Detritiation** - The major heat transfer media from the reactor to the steam generators are helium and lead. The helium coolant handles the largest portion of the reactor power with a minimal transfer of tritium to the steam cycle. However, the higher solubility of tritium in the lead poses a problem which must be addressed. Approximately one third of the heat produced in the reactor (750 MW) will be removed by liquid lead and transferred into the ultimate heat transfer medium, steam, which will convert this into electrical energy in a steam turbine or generator. The permeation rate from the Pb side of the heat exchanger was analyzed and the data is summarized in Table 6.7.9-8. The lead steam generators are equipped with double-walled heat transfer tubes with the interspace filled with sodium. The tritium permeation control will be facilitated by maintaining the partial pressure of tritium in the sodium channels below a value that would prevent the permeation rate to increase above the 10 Ci/day limit. The parameters shown in Table 6.7.9-8 apply.

The tritium solubility in Pb was obtained from Reference 17 which quoted a temperature independent value of 1.2×10^{-2} (appm H in Pb/torr$^{1/2}$).

Table 6.7.9-7 Failure Modes and Effects Analysis (FMEA) for the ISS

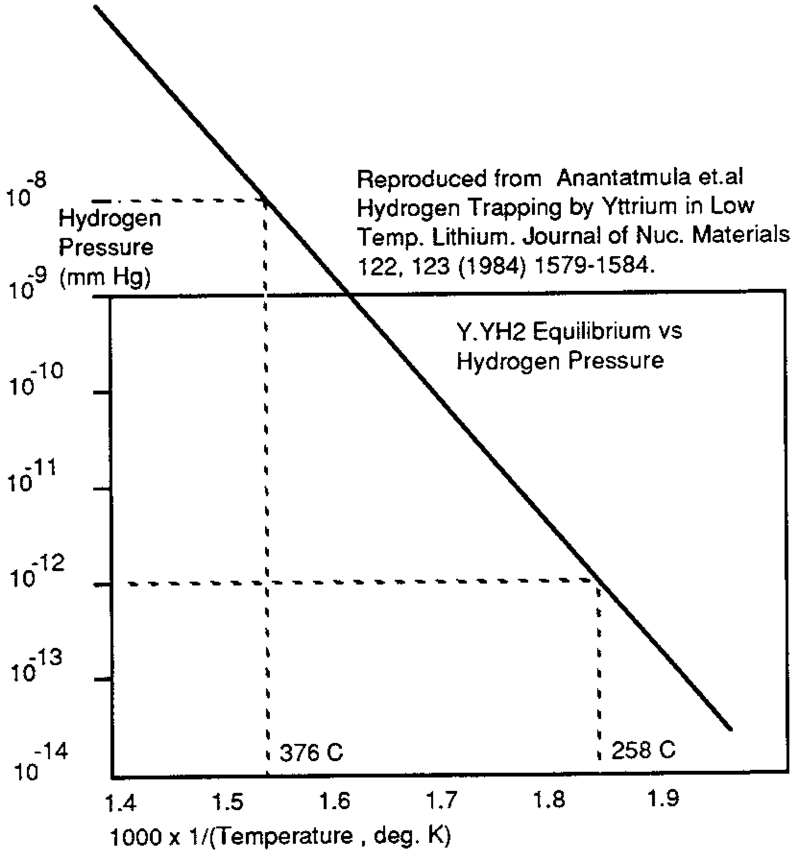
Equipment	Purpose	Failure Mode	Effect	Detection	Mitigation
CD1, CD2, CD3, CD4	Distill. columns	Lost power	Warm Up	High pressure	Expansion tanks limit pressure
		Loss of cold-box vacuum	"	"	"
		Loss of refrigeration	"	"	"
		Closed outlet valve	Higher pressure	High pressure	Design pressure adequate, shut heat to reboil.
DW	Condenser	High water level, LC failure	Water in product line	High level alarm	Lower setpoint
VPCE	Cooler	No chilled water	High temperature	Temperature alarm	Restore water flow
	Cryogenic adsorbers	LN_2 failure	High bed temperature	High T alarm	System shutdown
		Hot N_2 failure	Long regeneration time	Low T persists	Switch beds
		Closed outlet during regeneration	High pressure	High P alarm	Relief valve to expansion tank
VPCE, EQ1, EQ2, EQ3, EQ4,		Low catalyst efficiency	Off-specification product	Analyses	No hazard
Pumps, Compressors		Closed outlet	High pressure	High pressure alarm	Relief valve to suction

Table 6.7.9-8 Heat Transfer Media Must Be Processed to Keep Tritium Permeation Within Acceptable Limits

Parameter	L-option [g/h]	H-option [g/h]
Amount of tritium dissolved in Pb and transported from chamber into steam generator	0.321	0.797
Permeated from Pb through the first tube or amount to be removed from interspace to prevent permeation to steam	0.11	0.28
Tritium returned from steam generator in cooled Pb coolant	0.211 torr	0.51 torr
Required partial pressure of tritium in Na loop to keep permeation below 10 Ci/day	3.6×10^{-11}	3.6×10^{-11}

6.7.10.1 **Tritium Extraction from Sodium-Filled Heat Transfer Tube Interspace** - In general, the following options for maintaining low partial pressure of tritium in Na below 3.6×10^{-11} torr are available: cold trapping, solvent (Salt/Electrolysis) extraction, distillation, adsorption, purging and isotopic dilution, and gettering. From these options, only the last one is proposed to be used for the reference design.

The final design does not rely on permeation barriers which, in the oxide form, could be applied only at the steam side. For a 1000 and 100 fold improvement due to the permeation barriers, according to Bell,[18] the partial pressure will be 3.6×10^{-5} torr and 4×10^{-4} torr, respectively. Considerable work was done in yttrium gettering from lithium. The yttrium gettering capability is best expressed in Reference 19 from which Figure 6.7.10-1 was reproduced. It is evident that tritium levels in the 1 ppm range need to be maintained if the permeation rate is to be kept below the 10 Ci/day limit. This can be achieved through the following design parameters:



Reproduced from Anantatmula et.al Hydrogen Trapping by Yttrium in Low Temp. Lithium. Journal of Nuc. Materials 122, 123 (1984) 1579-1584.

Figure 6.7.10-1. Y.YH2 Formation vs. Equilibrium Hydrogen Pressure

- No permeation barriers, partial pressure 10^{-11} torr is needed which requires getter temperature of 546 K or 273°C.
- Permeation barrier with 100 fold improvement; this will need partial pressure 10^{-7} torr which is achievable with getter operating at 680 K or 407°C.
- Permeation barrier with 1000 fold improvement; this will need partial pressure 10^{-5} torr, achievable with getter at 730 K or 430°C.

The proposed system parameters for the L-option (and H-option) are:

- For removing 0.3 (0.8) g, T_2 per hour.
- 2 wppm equilibrium concentration in the Na-filled interspace.
- 1 wppm concentration of returning purified stream.
- Required Na processing rate is 300 (800) [kg/h].
- Yttrium getter needed is in the order of 0.4 (0.7) kg.
- Cycle length is approximately 24 hours.
- Vessel size is approximately 0.25 (0.5) m^3.
- Getter temperature is 270°C; no reliance on permeation barriers.

The system is indicated in Figure 6.7.10-2.

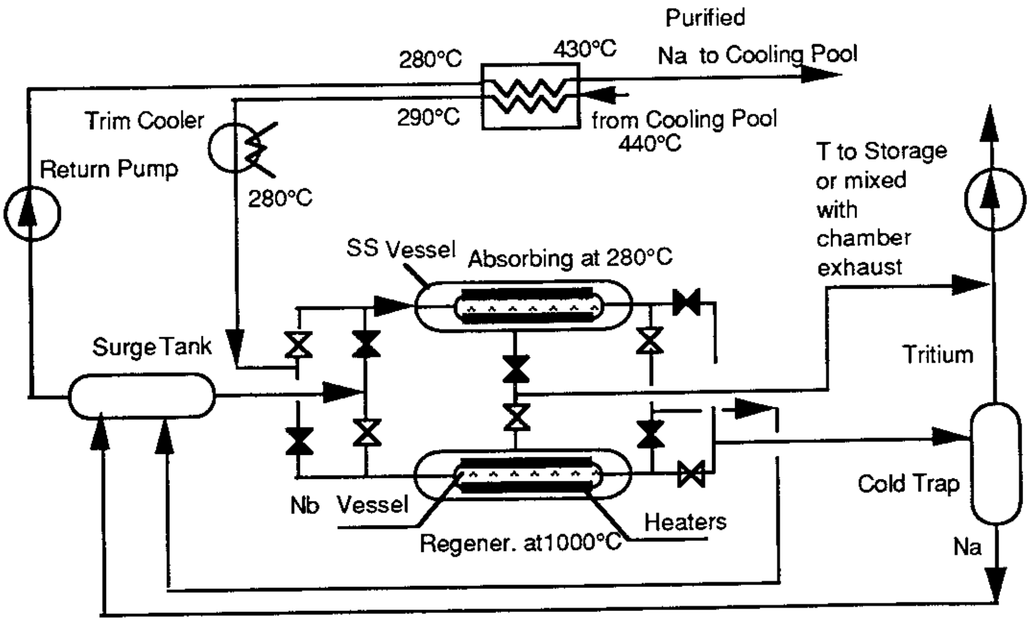


Figure 6.7.10-2. Recovery of Tritium from Na by Yttrium Gettering

6.7.10.2 <u>Permeation Through SiC - From Breeder Purge Gas to He Coolant</u> - Permeation from the breeder purge gas (at atmospheric pressure) to the coolant would take place through the silicon-carbide heat transfer area. The conditions on the breeder side are determined by the breeder purge gas-helium which is at 10 Bar. The permeation investigation was done with the following parameters:

- Partial pressure of tritium is estimated to be in the range of 1-10 Pa; namely, there is 0.1% hydrogen in the purge gas and the tritium dilution is 1:20.
- Breeder temperature is 725 K.
- Size of the heat transfer area is assumed 4×10^5 (m^2).
- Wall thickness is 3 mm.

The permeation was found to be in the range of 40 milli-Ci/day. This is substantially less than the 10 Ci/day release limit and consequently no tritium recovery from the helium coolant will be required.

6.7.11 Solids Removal from First Wall Protection - It is assumed that the lead used for first wall cooling will be purified to the degree required prior to use in the reaction chamber. The in-process generation of impurities can be recognized in the following categories:

- Gaseous Impurities – These are assumed to be not soluble in Pb to the extent that such removal is required. It was analyzed that the only substance of concern, tritium, will not be possible to remove from Pb to the extent that tritium permeation through the first layer of coolant wall can be avoided. For this reason, no gas removal of dissolved gases is foreseen to be required.
- Solids – The most consistent solid material to be deposited in the Pb is carbon originated from fuel target material, with a laser direct-drive target deposition rate of 160 g/h. The heavy ion, indirect-drive option would have nearly an order of magnitude higher deposition rate. In addition, there could be fractions of structural material corroded, ablated, or otherwise mobilized from the surfaces with which the first wall coolant is in contact. All this material is expected not to form an alloy and will be experienced as free material floating on the surface (C, SiC) or depositing in areas of low turbulence (metals). The light impurities will easily be separated by a static skimmer or alternatively in cyclone type separator. The bottom Pb drain in the reaction chamber will have to be designed to avoid accumulation of C by securing sufficient turbulence to carry the light and insoluble carbon from the chamber. Alternatively, where the Pb flow can be slowed down below the level of turbulence when carbon can separate, in situ separation can be applied.
- Impurities Forming an Alloy – One such impurity is potentially identified as bismuth. The normal concentration of bismuth in commercially purified lead is approximately 100 ppm. In addition, the production rate of bismuth during operation is approximately 10 ppm/MW-yr/m^2. The goal of the initial and on-line separation system is to maintain bismuth concentration at the 1 ppm level, mainly to improve on the hazard potential. The bismuth separation will not be a simple task since its occurrence is as an alloy with Pb.

6.7.12 Tritiated Waste Processing - Tritiated solid waste processing will rely on conventional fission processes. Large tritiated components such as breeder blanket modules will be removed only after in-situ surface and internal decontamination occurs to the optimum degree. Decontamination of the first wall will consist of removing the Pb coolant and, subsequently, plasma discharge cleaning, with inert gas purge to follow. The tritium-carrying inert gases would be purified in processes described in Sections 6.7.6 and 6.7.7. Internal decontamination will take place through continuing recirculation of the purge gas and its subsequent purification in the PSA process described in Section 6.7.5.

When the in-situ decontamination is completed, the module is removed and placed into a hot cell for dismantling or packaging for reprocessing The hot cell atmosphere, depending on its composition, will be treated in ADS-type equipment. Breeder material could be de-tritiated by combination of heat, purging, and evacuation. Metal components may be helium glow discharge decontaminated as indicated in Figure 6.7.12-1. [20] The main components of such a system are a furnace, purge gas recirculation loop, tritium extraction system which could be similar to the breeder purge gas separation described in Section 6.7.5, and tritium monitoring devices.

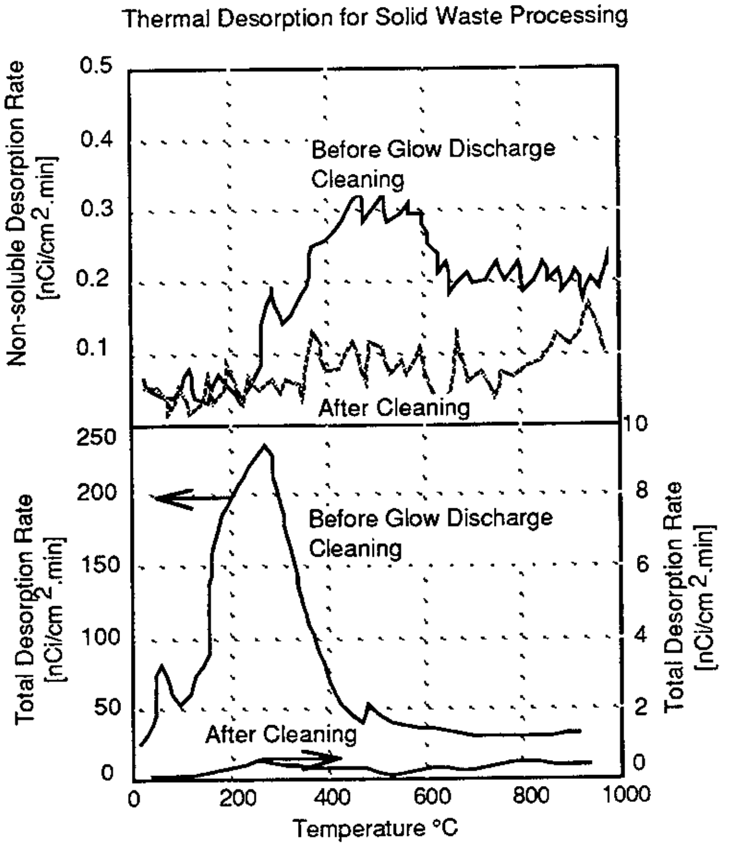


Figure 6.7.12-1. Effects of Glow Discharge Cleaning on the Total Thermal Desorption Spectra

References for 6.7

1. J. Mitsui, Y. Okada, F. Sakai, T. Ide, I. Yamamoto, A. Kanagawa, K. Hirata, T. Yamanishi, K. Okuno, and Y. Naruse, "Separation of Hydrogen Isotopes by an Advanced Thermal Diffusion Column Using Cryogenic Walls," Fusion Technology Vol. 19, May 1991.

2. S. K. Sood, O.K. Kveton, et al., "Tritium Systems Concepts for the Next European Torus (NET)," CFFTP 86-020, October 1986.

3. M. Glugla, R. Penzhorn, "Tritium Experiments with Catalytic Fuel Cleanup Loop," Fourth Topical Meeting on Tritium Technology in Fission, Fusion, and Isotopic Applications, Albuquerque NM, 29 September-4 October 1991.

4. R. S. Wilms, A. Busigin, S. K. Sood, K. M. Kalyanam, B. Dean, "ITER Fuel Cleanup System," Conceptual Design Description, 20 June 1990.

5. J. W. Barnes, et al., "Experience with International (Japanese American) Fusion Fuel Processing Hardware Project," Fourth Topical Meeting on Tritium Technology in Fission, Fusion, and Isotopic Applications, 29 September-4 October 1991, Albuquerque NM.

6. D. K. Sze, R. Clemmer, P. Finn, L. Greenwood, M. Billone, Y. Gohar (Argonne National Laboratory), "Blanket Fuel Processing - Solid Breeders," Presented at the ITER Fuel Cycle Workshop, 1-11 August 1989.

7. S. K. Sood, C. Fong, K. M. Kalyanam, A. Busigin (Nitek Corp.), O. K. Kveton, D. M. Ruthven, "A New Pressure Swing Adsorption (PSA) Process for Recovery of Tritium from the ITER Solid Ceramic Breeder Helium Purge Gas"

8. A. Busigin, S. K. Sood -OH, O. K. Kveton (CFFTP), R. H. Sherman, J. L. Anderson (TSTA/LANL), "ITER Isotope Separation System," Conceptual Design Description Revision 2.0, ITER-IL-FC-9.2-0-18, 5 June 1990.

9. H. Ito, T. Suzuki, T. Takanaga, Y. Matsuda, S. Konishi, Y. Naruse (JAERI) and S. Hirata (Kawasaki Heavy Industries, Ltd), "Separation of Tritium Using Polyimide Membrane."

10. R. W. Spillman, M. B. Sherwin, "Grace Membrane Systems: Gas Separation Membranes: The First Decade," Chemtech, 378-384, June 1990.

11. W. T. Shmayda, N. P. Kherani (OHRD), B. Wallace (CFFTP), F. Mazza (SAES), "Inert Gas Secondary Enclosure Clean-up System."

12. W. T. Shmayda, N. P. Kherani (OHRD), F. M. Ghezzi, G. Bonizzoni (SAES), "St 737 For Tritium Service: An Experimental Evaluation."

13. N. P. Kherani, W. T. Shmayda, R. A. Jalbert, "Tritium Removal from Inert Gases Using ST 198 Alloy," CFFTP 88-039, October 1988.

14. T. Yamanishi, M. Kinoshita, K. Okuno, and H. Yoshida, "A Brief Review of Tritium Recovery from Inert Gases by Uranium Getter Beds," Report JAERI-M85-174, Japan Atomic Energy Research Institute, 1985.

15. G. R. Longhurst, A. G. Heics, R. L. Rossmassler, W. T. Shmayda, "Experimental Assessment of the Consequences of Air-Ingress Accidents in Uranium Beds," 4th Topical Meeting on Tritium, Fission, Fusion, and Isotopic Applications, 29 September-4 October 1991.

16. A. Busigin and S. K. Sood (Ontario Hydro), "Process Simulation with Microcomputers: A Generalized Simulation Code for Application to Fission and Fusion Systems," CNS Bulletin, Vol. 9, No. 3, May/June 1988.

17. E. M. Larsen, M. S. Ortman, K. E. Plute (University of Wisconsin), "Comments on the Hydrogen Solubility Data for Liquid Lead, Lithium, and Lithium-Lead Alloys and Review of a Tritium-Solubility Model for Lithium-Lead Alloys," UWFDM-415 (1981).

18. J. T. Bell, J. D. Redman (Chemistry Division, Oak Ridge National Laboratory), "Tritium Permeation Through Steam Generator Materials," American Chemical Society, 8412-0513- 2/79/0779-331, 1979.

19. R. P. Anantatmula, H. Katsuta, "Hydrogen Trapping by Yttrium in Low Temperature Lithium; Westinghouse Hanford Company, P.O. Box 1970, Richland, Washington 99352," Journal of Nuclear Materials 122 & 123, 1579-1584 (1984).

20. A. B. Antoniazzi, W. T. Shmayda (OHRD), R. A. Surette (AECL), "Decontamination of Tritiated Stainless Steel," CFFTP G-9114, Fourth Topical Meeting on Tritium Technology in Fission, Fusion, and Isotopic Applications, Albuquerque NM, 29 September-4 October 1991.