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**CONCEPTUAL DESIGN DESCRIPTION FOR THE TRITIUM RECOVERY SYSTEM
FOR THE U.S. ITER $\text{Li}_2\text{O}/\text{Be}$ WATER COOLED BLANKET**

REVISION 1.0

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ABSTRACT

The tritium recovery system for the U.S. ITER $\text{Li}_2\text{O}/\text{Be}$ water cooled blanket processes two separate helium purge streams to recover tritium from the Li_2O zones and the Be zones of the blanket, to process the waste products, and to recirculate the helium back to the blanket. The components are selected to minimize the tritium inventory of the recovery system, and to minimize waste products. The system is robust to either an increase in the tritium release rate or to an in-leak of water in the purge system.

Three major components were used to process these streams, first, 5A molecular sieves at -196°C separate hydrogen from the helium, second, a solid oxide electrolysis unit is used to reduce all molecular water, and third, a palladium/silver diffuser is used to ensure that only hydrogen (H_2 , HT) species reach the cryogenic distillation unit. Other units are present to recover tritium from waste products but the three major components are the basis of the blanket tritium recovery system.

1. INTRODUCTION

The U.S. $\text{Li}_2\text{O}/\text{Be}$ Water Cooled Blanket for the International Thermonuclear Experimental Reactor (ITER) consists of a series of zones parallel to the first wall which contain water, beryllium and Li_2O . The Be zone is always located between the breeder zone and the coolant zone to keep the breeder at a high temperature for tritium recovery. Each of these zones is isolated from the next by stainless steel clad. Since the beryllium zone is immediately adjacent to the water zone, and cracks can develop in its steel clad, water in-leakage is probable into the beryllium. The oxide layer on the surface of the beryllium will prevent further reaction between water vapor and beryllium. The water vapor establishes a steady state water partial pressure in the beryllium zone. The reference parameters for the ITER blanket are found in Table 1-1.

During a 1000 MW fusion reactor burn, tritium is produced in the Li_2O on the order of 150 g/d, if one assumes a breeding ratio of one. In the Be tritium is produced on the order of 2 g/d. Tritium is recovered from the Li_2O by means of a helium purge stream. The helium purge stream contains 1000 ppm H_2 , a tritium product at 10 ppm T_2 equivalent,* and a number of chemical and radionuclide impurities. A second helium purge stream which does not contain hydrogen recovers the tritium from the beryllium.

Table 1-1
Reference Parameters for the Tritium Recovery System
for the U.S. $\text{Li}_2\text{O}/\text{Be}$ Blanket

Breeder material	Li_2O
Neutron multiplier	Be
Structure	Stainless Steel (SS)
Coolant	H_2O
Tritium recovery method	He purge
Tritium carrier in Li_2O zones	He + 0.1% H_2
Tritium carrier in Be zones	He
H/T ratio at Li_2O outlet	100.*
Tritium flow rate, off-normal, g/d	800.**
Tritium flow rate, full power day, g/d	150.
Protium flow rate, off-normal, g/d	6000.
Protium flow rate, full power day, g/d	5000.

* The H/T ratio changes as the design progresses. In the most recent U.S. ITER design, the H/T ratio is 30.

** Assumed off-normal tritium process rate. The real off-normal tritium throughput has not been calculated.

This document describes the system designed to recover tritium from these two helium purge streams. The waste materials in the purge streams are removed and processed. The He purge is then recycled to the blanket.

2. SUMMARY

This document contains a conceptual design description of the tritium recovery system for the U.S. ITER $\text{Li}_2\text{O}/\text{Be}$ blanket. The system processes two

separate helium streams to recover tritium from the Li_2O zones and the Be zones of the blanket, to process the waste products, and to recirculate the helium back to the blanket. The components are selected to minimize the tritium inventory of the recovery system, and to minimize waste products.

The total tritium inventory for the blanket tritium recovery system is 20 g. The total capital cost of the blanket tritium recovery system is \$14 M.

The robustness of the system to either an increase in the tritium release rate or to an in-leak of water into the purge system are addressed. Neither is a problem in this system with the parameters assumed.

The technical advantages for the use of solid oxide electrolysis and a palladium/silver diffuser are presented.

3. FUNCTION OF THE PROCESSING SYSTEM COMPONENTS

The units to process the helium purge streams for both the beryllium zones and the Li_2O zones of the U.S. ITER blanket are shown in Fig. 3-1. (Heat exchangers are not shown.) Units for the Li_2O zones are these: 1) A set of cold traps is used to separate water (0.47 kg/d), and some of the carbon dioxide from the helium. 2) Two circulators and a storage system are provided to handle the helium gas. 3) A solid oxide electrolysis unit is used to decompose water. 4) A set of 5A molecular sieves at -196°C (termed X1) is used to remove hydrogen isotopes, 1% of the helium, and all remaining impurities from the helium. 5) A set of 5A molecular sieves at 25°C (termed Y1) is used to recover water, CO_2 , and other impurities from the stream leaving the X1 molecular sieves when they are regenerated and to remove entrained water from the hydrogen steam from the small electrolysis unit. 6) A palladium/silver diffuser is used to separate inerts from the hydrogen isotopes when the hydrogen is passed to the cryogenic distillation unit. 7) A SAES (ZrCoV) getter held at 350°C is used to prevent active impurities from entering the cryogenic distillation unit.

Two molecular beds, X1 and Y1, are used in series with the palladium/silver diffuser with recycle of the bleed from the diffuser going back to the cold X1 bed to ensure that impurities are collected. If the molecular sieves do not initially remove the impurities, this recycle technique will allow the concentration of the impurities to slowly increase. Eventually their vapor

Figure 3-1. Description of processing system for tritium recovery.

pressure will be high enough so that they will be absorbed on the sieves and later passed to the waste recovery unit. The total amount of CO_2 which reaches the X1 sieves is 0.01 mole % of the total hydrogen trapped. Therefore, its presence is not expected to significantly affect hydrogen trapping. (The actual effect needs to be determined.)

Units to process the helium from the beryllium zones are these: 1) A set of cold traps is used to separate water, ($10 \text{ kg/d}_{\text{max}}$) from helium. There is no source for water within the Be zone. The $10 \text{ kg/d}_{\text{max}}$ is an assumed leak rate from the blanket coolant. 2) A circulator and a helium storage system are provided to handle the helium gas. 3) Several linked solid oxide electrolysis units are used to decompose water. 4) A set of 5A molecular sieves at -196°C (termed X2) is used to remove impurities, including tritium from the helium. 5) A set of 5A molecular sieves at 25°C (termed Y2) is used to recover water, CO_2 , and other impurities from the stream leaving the X2 sieves when they are regenerated and to remove entrained water from the hydrogen stream from the linked electrolysis units. The exit hydrogen species from these sieves are routed to the Y1 sieves for recycle. The waste products are routed to the common waste recovery unit.

After purification, the protium/tritium stream is passed to ITER's common cryogenic distillation unit. Here the tritium is separated from the excess protium. The tritium product fuels the plasma while the H_2 is recycled to the helium purge stream for the Li_2O blanket.

The waste species from both helium streams go to a common waste recovery unit in which the tritium is recovered as tritiated water and non-tritiated waste is passed to the plant's stack system.

4. ITER PROCESSING DESIGN REQUIREMENTS

4.1 Feed to the Tritium Recovery System

4.1.1 Li_2O Zones

Reference elemental impurity levels for Li_2O derived from published information [1-8] are summarized in Table 4-1. The reference values in Table 4-1 were used to calculate the concentration of impurities in the helium purge stream, using methodology [9] previously developed. If one assumes an ITER

neutron spectrum, normalized to 1 MW/m^2 and a 30% duty factor, activation rates of the impurities can be calculated.

Available thermodynamic data [10] were used to calculate equilibrium vapor pressures of volatile species at various temperature, 400°C (blanket outlet temperature), 25°C , and -196°C . Most of the impurities are deposited in the elemental form at temperatures $>200^\circ\text{C}$, within the blanket lines. The rest are removed at the filters which are water-cooled to cool the purge gas to 25°C . These filters, located in front of the helium circulators will remove the particulates which reach this point. Two parallel sets of filters are provided, to remove particulates with a bimodal distribution with peaks centered at $\sim 1 \text{ }\mu\text{m}$ and $50\text{-}100 \text{ }\mu\text{m}$. (These are best estimates and need to be verified.) The circulators behind the filter should be adequately protected. (A similar system, which handles a lower gas throughput, is found on the purge gas for the beryllium zones.) The species which pass the filters are carbon dioxide, water and the radionuclide species, SO_2 , Ar and Kr. The distribution of these species is presented in Table 4-2 (chemical species). Table 4-3 shows the radionuclides which could be released in the purge stream for the Li_2O zones.

4.1.2 Be Zones

Reference elemental impurity levels for Be derived from published information [11-14] are summarized in Table 4-4. Chemical species and radionuclide species expected after the filters are listed in Tables 4-5 (chemical species) and 4-6 (radionuclides). The amount of impurity which is transported in the purge gas from the beryllium zones is significantly greater than that found in the purge for the Li_2O zones. Most of these species, except CO_2 , SO_2 , Xe, Kr and Ar, are trapped in the filters.

4.2 Flexibility of Tritium Recovery System

4.2.1 Increase in Tritium Release Rate

The tritium release rate from the Li_2O can be increased by an increase in the fusion power or by an increase in the temperature of the Li_2O . To determine the flexibility of the tritium recovery system, a five-fold increase in the tritium release rate was assumed. More detailed analysis will be required to document the real tritium release rate during a transient. The effect of different temperature profiles within the blanket, which could have a subtle influence on impurity concentration and the amount of water and total oxygen that must be processed, was not considered.

Table 4-1. Impurities in Li₂O (wppm)

Element	Li ₂ O [1-4]	Other [5-7]	Recom. [8]	Reference	Comments
Be	<10.	<10.	--	1.	uncertain
B	<10.	<10.-5.	--	1.	uncertain
C(a)	~100-400.	~100.	?	100.	CO ₂ < 8 [6]
N	--	--	?	2.	uncertain
F	80.	--	<5.-120.	0.1	uncertain
Na	20-1000.	50-500.	50.	60.	30-100
Mg	1-10.	<1-80.	--	10.	
Al	10-200.	30-100.	20.	50.	
Si	10-200.	100-500.	10.	50.	
P	<1000.	<1000.	--	1.	uncertain
S	--	--	5.	0.1	uncertain
Cl	80-100.	<10.-2000.	80.	10.	heat ~10
K	<100.-1100.	18.	400.	20.	highly uncertain
Ca	50-500.	20-100.	200.	100.	
Sc	--	--	--	0.1	uncertain
Ti	<1-100.	<10.-65.	--	10.	
V	<30.	<50.	--	1.	uncertain
Cr	<30.	<1.-30.	--		typ ~1
Mn	4-100.	1-10.	20.	1.	typ ~1
Fe	10-100.	7-500.	100.	50.	
Co	<30.-100.	0.2	--	0.2	neutron act. 0.2 [7]
Ni	<1-20.	<2.-30.	20.	10.	typ. 10-20, some ~1
Cu	1-13.	1-40.	6.	10.	typ. ~10
Zn	<50.	50.	--	10.	uncertain
Ga	<10.	2-16.	--	1.	LiAlO ₂ 16 [7]
Ge	<10.	--	--	0.1	uncertain
As	<500.	0.04-3.	--	0.1	uncertain
Br	--	0.08	--	0.1	neutron act. [7]
Rb	<100.	<50.	--	0.1	uncertain
Sr	<1000.	4.9	--	1.	neutron act. [7]
Zr	<1000.	<300.	--	1.	uncertain
Mo	<10.	<30.	--	0.1	uncertain
Ag	< 10.	<1.	--	--	
Cd	<50.	<100.	--	0.1	uncertain
In	--	0.03	--	--	
Sn	<30.	<30.	--	1.	uncertain
Sb	<50.	1.2	--	1.	neutron act. [7]
Ba	<100.	<100.-40?	--	5.	uncertain
La	--	0.11-2.?	--	--	
Au	--	0.00051	--	0.0005	neutron act. [7]
Pb	<1-80.	<10.	20.	0.1	uncertain
Bi	<10.	<10.	--	--	
U	~ 1.	0.19	--	0.1	Li ₂ O~1 [4], LiAlO ₂ 0.19 [7]

a- Source of the carbon is Li₂CO₃ formed due to exposure of LiOH to air or that present in the starting material. Methane impurity is not present in the fabricated Li₂O.

Table 4-2. Species in Helium Purge Stream from Li₂O Zones (g/d of element)

Element	Species	Blanket Exhaust 400°C	Filters ^a 25°C	Cold Trap -100°C	Mol. Sieves -196°C	Trapped in Mol. Sieve
He	He	10 ⁷	10 ⁷	10 ⁷	10 ⁷	0.0
H ^b	H ₂	4964.	4964.	4964.	0.0	4964.
H ^b	H ₂ O	50.	50.	0.0	0.0	0.0
T	HT	148.5	148.5	148.5	0.0	148.5
T	HTO	1.5	1.5	0.0	0.0	0.0
O	H ₂ O	400.	400.	0.0	0.0	0.0
C	CO ₂	4.7	4.7	4.2	0.0	4.2
Na	Na	0.1	0.0	0.0	0.0	0.0
c,d	c,d	c,d	c	0.0	0.0	0.0

a- The filters are water-cooled to reduce the purge gas temperature.

b- In-pile extraction experiments report > 95% of the tritium in the form HT when excess H₂ is added to the purge gas, our reference case.

c- Impurities present but <1.0 g/d at 400°C - K,Cl,N,P,As,Br,Rb,Mo,S,F.

d- Impurities not identified as present, <0.1 g/d at 400°C - Ca,Fe,Al,Si,Mg,Ni,Cu,Zn,Ti,Ba,V,Cr,Be,B,Mn,Ga,Sr,Zr,Sn,Sb,Co,Sc,Cd,Pb,U.

Table 4-3. Volatile Radionuclides in Helium Purge from Li₂O Zones

Isotope	Decay t-1/2	Decay Mode	Transport Element	
			Ci/d	ug/d
S-35	87.2 d	B-	0.7638	17.8
Xe-135	9.10 h	B-,g	0.13019	0.051
Xe-133	5.3 d	B-,g	2.9651E-2	0.160
C-14	5370. y	B-	4.4150E-3	928.
Ar-39	269. y	B-	2.0847E-3	61.2
Kr-85	10.7 y	B-,g	2.9249E-4	0.744
Kr-88	2.84 h	B-,g	1.4045E-4	0.00001
Kr-83	1.86 h	g	9.8359E-7	0.0
Kr-87	76. m	B-,g	7.6044E-8	0.0

Table 4-4. Impurities in Be (wppm)

El. Grade	S-65 ¹¹ FINESSE ⁸	BCSS ¹²	Various Fabrications ¹³				Industry ¹⁴	Refer.
			Flake	VacCast	Leach	VacMelt		
Li	--	3.	3.	1.				1.
B	--	2.	2.	0.5	1.2			1.
C	400.	1000.	1000.	4000.	400.	1900.	100.	100-1500.
N	--	300.	300.	10.		80.	12.	< 100.
O	4500.	7000.	7000.	4000.			2240.	4500.
F	--					30.		< 20.
Na	--			100.		100.		60.
Mg	100.	800.	800.	30.	500.	20.	15.	100.
Al	100.	900.	900.	30.	600.	40.	25.	100.
Si	200.	600.	600.	30.		30.	40.	200.
P	--							0.1
S	--							0.1
Cl	--			250.		200.	70.	< 20.
K	--			30.				0.1
Ca	--	200.	200.	100.			25.	100.
Ti	--							1.
V	--							0.1
Cr	--	100.	100.	6.	90.	6.	8.	50.
Mn	--	150.	150.	130.	70.	7.	25.	50.
Fe	500.	100.	600.	140.	1100.	200.	60.	500.
Co	--	5.	5.		2.			0.1
Ni	--	300.	300.	150.	130.		70.	50.
Cu	--	200.	100.	60.			145.	100.
Zn	--	100.	200.	30.				4.
Se	--							0.1
Br	--							0.1
Rb	--							0.1
Sr	--							0.1
Zr	--							0.1
Nb	--	5.	5.					0.1
Mo	--	20.	20.					0.1
Ag	--	1.		7.	5.			1.
Cd	--	2.	2.	1.	0.5			0.1
Sn	--			10.				0.1
I	--							0.1
Ba	--							0.1
Ta	--							0.1
Pb	--	20.	20.	50.				10.
oth	<400.							

Table 4-5. Species in Helium Purge Gas from Beryllium Zones (g/d of element)^a

Elem.	Species	Blanket Exhaust 400°C	Filter ^b 25°C	Trapped in Filter	Mol. Sieves ^c -196°C	Trapped in ^c Mol. Sieve
He	He	1.33E5	1.33E5	0.0	1.33E5	0.0
H	HT, H ₂	1.	1.	0.0	0.0	1.0
T	HT, T ₂	2.0	2.0	0.0	0.0	2.0 (Maximum)
Be	Be	1.4 E-4	0.0	0.0	0.0	0.0
O	BeO	9. E-28	0.0	0.0	0.0	0.0
C	CO ₂	4.0	4.0	0.0	0.0	3.6 ^c
Mg	Mg	1060.	0.0	4.3	0.0	0.0
Na	Na	2760.	0.0	59.3	0.0	0.0
Cl	BeCl ₂	2300.	0.0	2300.	0.0	0.0
F	BeF ₂	16.	0.0	0.0	0.0	0.0
Pb	Pb	12.5	0.0	0.042	0.0	0.0
Zn	Zn	184.	0.0	2.4	0.0	0.0
Li	Li	40.	0.0	0.12	0.0	0.0
Br	BeBr ₂	4.5	0.0	0.4	0.0	0.0
Rb	Rb	4.5	0.0	4.	0.0	0.0
K	K	4.5	0.0	0.2	0.0	0.0
Cd	Cd	4.5	0.0	4.	0.0	0.0
I	BeI ₂	4.5	0.0	1.	0.0	0.0
d	d	d	0.0	d	--	--

a- All species are g/d. The amount of impurities present in the beryllium are significantly greater than those in the Li₂O.

b- The filters are water-cooled to reduce the purge gas temperature.

c- Some of the carbon dioxide is retained in the cold trap prior to the molecular sieves held at -196°C.

d- Impurities <5 g/d at 400°C - N, P, As, Mo, S, Ca, Fe, Al, Si, Ni, Cu, Zn, Ti, Ba, V, Cr, B, Mn, Ga, Sr, Zr, Sn, Sb, Co, Sc, Cd, Pb, U.

Table 4-6. Volatile Radionuclides in the Helium Purge from Be Zones

Isotope	Decay t-1/2	Decay Mode	Transport Ci/d	Element ug/d
S-35	87.2 d	B-	31.941	23.37
Xe-135	9.1 h	B-,g	1.99E-2	0.0078
Xe-133	5.3 d	B-,g	2.6 E-3	0.014
C-14	5370. y	B-	2.3 E-3	484.
Kr-85	10.7 y	B-,g	2.53E-4	0.0076
Ar-39	269. y	B-	5.65E-5	1.66

The impact of an increase in tritium release rate was found to be minimal both for the required size and scale of each component since the size of units which process the Li_2O 's helium purge stream are dominated by the magnitude of the helium flow rate, and to a lesser degree, by the total hydrogen isotope throughput. A 4% increase in the hydrogen flow rate has little effect on the size or the capacity of units like, molecular sieve beds, compressors, etc. Although the tritium inventory is proportional to the tritium throughput, it only increases slightly. Components that process impurities or water in-leakage are not affected. For the Li_2O zone in which tritium is bred, an increase in temperature would have a negligible effect on the amount of impurity released. In addition, impurities would still be trapped at the 25°C filter. For the Be zone, an increase in temperature has a minor effect because of the long residence time, 2.8 hr, of the purge gas. The results are summarized in Table 4-7.

Components that process hydrogen are affected by the 4% increase in throughput, specifically the cryogenic isotope separation system (ISS). Since the distillation columns have multiple feed points, a five-fold increase in tritium throughput might require a different feed point than the reference case. Nonetheless, since the major function of the ISS is to remove the protium, the difference between H_2 -1%T and H_2 -5%T is not significant, if the total amount of H_2 remains constant.

Thus, the tritium recovery system for the $\text{Li}_2\text{O}/\text{Be}$ blanket is not significantly affected by a five-fold increase in the tritium release rate. The total hydrogen throughput to the cryogenic distillation column, does increase 4%.

4.2.2 Massive Water Leak into the Be Zones

The routine water in-leakage into the U.S. water cooled $\text{Li}_2\text{O}/\text{Be}$ breeder blanket is assumed to be equal to the maximum water production rate, 0.5 kg/d. However, to provide additional robustness to the tritium recovery system the effect of major water in-leakage into the blanket was assessed. The parameters examined were: the site of water intrusion, and its effect on the conditions within the blanket zones. The upper limit selected on water in-leakage was equal to the expected water out-leakage in the coolant system external to the reactor, 10 kg/d. Again, this leakage rate is assumed to be a maximum upper bound.

Table 4-7.
Effect of Five-Fold Increase in Tritium Release Rate
for the ITER Li₂O/Be Blanket

Component	Factor	Effect	Impact
Blanket Purge	He, H isotopes	H-4% increase	Minimal
Cold Trap	H ₂ O leak, He	No effect	None
He Separator	He, H isotopes	H-4% increase	Minimal
MS (25°C)	H ₂ O leak	No effect	None
Electrolysis	H ₂ O leak	No effect	None
Getter	Impurities	No effect	None
Waste Treat	Impurities	No effect	None
Isotope Sep.	Isotope ratios	T-500% increase	Minimal
		Feed point-change	
		Enrichment-minor change	
		Throughput-4% increase	

The parameters for the U.S. ITER design for a Li₂O/Be water cooled blanket containing 189 modules are given in Table 4-8. The residence time for the helium purge gas in the beryllium zones is 2.8 hours, whereas, the residence time for the helium purge gas in the Li₂O zones is 7.3 seconds. The water vapor which would enter the beryllium zone of a module in 2.8 hours would occupy 0.0077 m³ which is much less than the free volume, 0.169 m³, in the beryllium zone.

The Li₂O zones are separated from water coolant by two zones of steel and a beryllium zone. Water headers do not contact the steel clad of the Li₂O zones or the helium purge lines for the Li₂O zones. Thus, the only source of water leakage into a Li₂O zone is from the beryllium zone via a crack in the common stainless steel clad. The driving force for water ingress into the Li₂O zone is the steady-state water vapor pressure in a beryllium zone. The water vapor pressure in the beryllium zone is 8-10 kPa for the conditions of a purge flow rate of 0.84 L/s and a water in-leakage rate of 10 kg/d. The maximum calculated water ingress assuming viscous flow through a rectangular crack [15], with the dimensions (μm) 35 × 190 × 2920, is 16 g/d.

With a radiolysis yield of 0.25 molecules of H_2 /100 eV of absorbed radiation, the amount of hydrogen produced during radiolysis of the water vapor present in the beryllium zones if 10 kg/d of water leaks into the beryllium zone is about 0.05 mol/d. This is equivalent to a hydrogen pressure of 0.7 Pa (179°C), much less than the hydrogen pressure (100 Pa) in the Li_2O zones during normal operation.

Within the beryllium zones, 2 gram of tritium is bred each full power day. At the end of reactor life (three full power years), 2.2 kg of tritium is produced, out of which 1.2 kg is retained in the Be, 0.7 kg is decayed, and 0.3 kg is released to the purge. Since the tritium release will be in contact with water vapor at 179-365°C, significant isotope exchange can occur. If all the tritium is converted to the oxide form, the tritium concentration in the 10 kg/d water is 270 Ci/kg.

The water would be decomposed using solid oxide electrolysis units. Units with a 10 kg/d capacity are under commercial development but would have to be qualified for tritium work. Electrolysis of 10 kg/d of water will generate approximately 1 kg/d of protium. This represents a 20% increase in the protium throughput in the blanket tritium recovery system. This increase can be accommodated in a common fuel cycle cryogenic distillation unit.

5. CRITICAL DESIGN ISSUES

5.1 Advantages of Solid Oxide Electrolysis

Three types of electrolysis cells, conventional wet electrolysis cells, solid polymer cells [16] and high temperature solid oxide cells [17-19] were examined to decide which was the most desirable. The main disadvantage of a conventional cell is its inventory of liquid tritiated water. The main disadvantage of solid polymer cells is that they experience significant radiation damage, at tritiated water concentrations >200 Ci/L, thus generating significant amounts of waste.

Solid oxide cells are the preferred electrolysis option since they have no liquid water inventory, are not damaged by radiation, have minimal waste, operate at high temperature which is more efficient for electrolysis, and can completely separate hydrogen and oxygen. Their main disadvantage is the status of tested prototypes. Two groups are testing these units [17-19], but

Table 4-8. Parameters of $\text{Li}_2\text{O}/\text{Be}$ Water Cooled Blanket

Characterization of Li_2O Portion of Blanket^a

He Flow	L/s	650
Residence Time ^b	s	7.3
Water from Be	g/d	16
Water due to Breeding	g/d	450

Characterization of Beryllium Portion of Blanket

Temperature	C	179-365
He Flow	L/s	0.84
Residence Time ^b	hr	2.8
Water In-Leakage	kg/d	10
Water Vapor (STP)	m^3/hr	0.52
Water Press. at Temp.	kPa	8-10
H_2 from Radiolysis ^c	g/d	0.1
H_2 Press. at Temp.	Pa	0.7
Tritium Release	g/d	0.3

Description of Beryllium Zone - One Module

He Flow	cm^3/s	4.46
Surface Area	cm^2	2250
Length	cm	100
Effect. Linear Veloc.	cm/s	0.002
Actual Linear Veloc.	cm/s	0.01
Residence Time ^b	hr	2.8
Free Volume ^b	m^3	0.169
H_2O Vapor in 2.8 hr	m^3	0.0077

a These values are for a full-power day; flow rates are at STP.

b Residence time derived from the ratio length/actual linear velocity. The free volume for one module of beryllium is an average derived from the total volume of beryllium at 80% theoretical density.

c Refers to the radiolysis of gaseous water vapor within the beryllium zone. This value assumes that there is a 10 kg/d leak rate of water into the beryllium zone; 64.82 mole of water would be present due to the long residence time. A $G(\text{H}_2) = 0.25$ molecules of $\text{H}_2/100$ eV absorbed neutron irradiation energy and a total neutron energy of 10^{18} eV/s, were assumed.

only one [19] has coupled individual cells. When ten tubular oxide cells were coupled, the output was 0.607 m³ (STP)/hr of hydrogen which is equivalent to 11.7 kg/d of water. Thus, the solid oxide electrolysis units have the capacity to process the expected water in-leakage. Reliability testing of tubular cells is in progress. In addition, cells containing flat solid oxide units are also under development [19].

The gas-shift reaction has been studied extensively, both using iron oxide catalysts [20] and copper oxide catalysts [21-25]. However, if one processes small volumes of water, 10 kg/d, one introduces significant amounts of impurities (CO, CO₂) and greater complexity in the processing system using this technology. Both excess CO and unreacted water must be recycled. The waste product, CO₂, must be handled as radioactive waste since C-14(CO₂) is present as an impurity and is diluted when additional CO₂ is generated. To achieve the needed separation [24] six zeolite beds are required and their size depends on the needed residence time to effect absorption.

An evaluation of the different electrolysis units and the gas-shift process is given in Table 5-1. The weighting system which is used is explained at the bottom of Table 5-1.

Table 5-1. Advantages of Electrolysis Units

Characteristic ^a	Conv. Elec. ^b	Polymer Elec.	Ceramic Elec.	Gas-Shift
Tritium Inv.	N	N	Y	N
Waste Generated	C	N	Y	N
Size Incl. Aux. ^c	C	C	C	N
Complexity	Y	Y	Y	N
Reliability	Y	N	Y	Y
Radiation Damage	C	N	Y	Y
Technol. Basis ^d	Y	Y	N	Y
Rating ^e	2	-2	4	-1

a- Y = Positive Factor; N = Negative Factor; C = No effect.

b- Included within the conventional category are cells being developed which attempt to reduce the tritiated water inventory. They would have a lower efficiency since they operate at <90°C.

c- Each solid oxide cell [19] is composed of 20 tubes each 15 cm long.

d- Includes both the industrial capacity to produce cells on a reliable basis and experience with tritium to determine lifetime. In the case of cells being developed and included under the conventional category, there may not be sufficient data to give these units a Y factor. For these cells then, the total rating would be 1.

e Weight of 1 given to Y; weight of -1 to N; weight of 0 to C.

5.2 Advantages of Palladium/Silver Diffuser

All impurities have to be removed from the hydrogen stream before it is passed to the cryogenic distillation unit. The use of a palladium-silver diffuser as the final purification step is advantageous since the hydrogen pressure is about an atmosphere at this stage in the process, a pressure regime in which the diffuser is most effective [26-30].

A zirconium type of getter, if used in place of the palladium/silver diffuser, has several disadvantages. It would require a two step operation to remove impurities, would generate significant waste, and would increase the tritium inventory. Since the HT product stream and impurities have to be absorbed, the formation of oxides could hinder the sorption of impurities. During desorption at 600-700°C, the hydrogen partial pressure would be 0.1 MPa, which could result in high permeation losses through the primary container of the getter.

A comparison of these two methods of purification is found in Table 5.2.

Table 5-2.
Advantages of Palladium/Silver Diffuser to
Remove Impurities from Hydrogen

Characteristic	Pd/Ag Diffuser	Zr Type Getter
Impurity Level Volume	medium	medium
Surface Oxide Problem	no	yes
Removal Inert Impurity	yes	no
Waste Generated	low	high
Tritium Inventory	low	high
Temperature Operation	medium	high
Process Type	continuous	batch

5.3 Diffuser Design

There are two cases presented for the diffuser in this system design description: the base case which assumes that 100% of the hydrogen passes to the diffuser and the alternative case, which has to be tested, in which only the last 10% of the gas regenerated from the X1 molecular sieves at -100°C passes to the diffuser. The surface areas required for these two cases at hydrogen partial pressures of 0.2 MPa and 0.5 MPa, are shown in Table 5-3.

Table 5-3.
Surface Area Requirements for Palladium/Silver Diffuser

Operating Conditions	Surface Area (m ²)
Base case	
100% H ₂ /0.2 MPa	4.6
100% H ₂ /0.5 MPa	2.7
Alternate case	
10% H ₂ /0.2 MPa	0.46
10% H ₂ /0.5 MPa	0.27 ^a

a- This is the size of the unit required to process the hydrogen throughput at TSTA. A unit capable of doing this is now being tested.

The surface areas required for all four cases are not enormous. It may be feasible to use commercial units since the tritium flow through the diffuser is 16 Ci/s. However, since the effect of tritium on the diffuser is a function of total tritium it sees rather than the ratio of T/H, tests would be needed to determine the lifetime of commercial diffusers at this tritium flow rate. A circulator is required for the palladium diffuser, as well as secondary containment enclosures for all components of the diffuser system.

6. PROCESS DESIGN DESCRIPTION

6.1 Major Components

A detailed schematic of the blanket tritium recovery system is shown in Fig. 6-1. Within the schematic, the lower unit of a set of two units shows the major regeneration sequences. For the purge for the Li₂O stream, only the regeneration at -100°C is shown.

6.1.1 Filters, Cold Traps, Heat Exchangers, Circulators

The composition of the major species in the helium purge streams as they leave the two blanket zones are listed in Table 6-1. Water-cooled filters are used between the blanket and the circulators for the blanket tritium recovery unit to remove particulates, vapor species, and other impurities and to reduce the purge gas temperature to 25°C.

U.S. ITER $\text{Li}_2\text{O}/\text{Be}$ BLANKET TRITIUM RECOVERY SYSTEM (2nd LEVEL) -
SHOWS REGENERATION*

Figure 6-1. Schematic of blanket tritium recovery system: regeneration shown.

For the purge from the Li_2O zones, a regenerative heat exchanger prior to a cold trap reduces the helium purge gas's temperature from 25°C to -80°C ; cold nitrogen within the cold trap reduces the temperature of the purge gas to -100°C . The cold trap removes water and 10% of the carbon dioxide. The gas leaving the cold trap goes to a second regenerative heat exchanger which reduces the purge gas temperature from -100°C to -186°C .

The order for equipment to process helium from the Be zone is: 1) water-cooled filter; 2) regenerative heat exchanger to reduce the gas temperature to -80°C ; 3) cold trap at -100°C ; 4) compressor/circulator; and 5) regenerative heat exchanger to cool the gas to -186°C . The filters, regenerative heat exchangers, the cold traps, and circulators are conventional devices. The presence of tritium will require the use of non-elastomer seals.

Table 6-1.
Composition of Li_2O and Be Zone Helium Purge Streams

Parameter	Be Zone	Li_2O Zone
Flow L(STP)/s		
He	0.84	650
H_2	0.00022 ^a	0.65
H_2O	0.144	0.0065
H/T ratio	10^3 b	10^2
Radionuclides ($\mu\text{g/d}$)		
S-35 (SO_2)	46	36
C-14 (CO_2)	1500	3000
Ar-39	2	61
Kr-85	<0.01	0.74
Xe-135	0.01	0.05
Xe-133	0.014	0.16
Residence Time(s)	10^4	4

a- Total hydrogen isotope.

b- This is ratio if 10 kg/d of H_2O leakage is assumed.

6.1.2 Water Collection and Decomposition by Electrolysis

Separate helium circulators are used to maintain the helium flow from the Li_2O and from the Be zones since the different purge gas conditions for the two zones makes this advantageous. These conditions are: the presence of 0.1% protium in the Li_2O stream, the possibility of a water leak into the Be stream, and the long residence time (2.8 hr) in the Be zones. The location of the circulator is prior to a cold trap for the Li_2O purge stream and after a cold trap for the Be purge stream. The difference in location was deemed advantageous to handle the potential for water leaks in beryllium's helium stream.

For both the Li_2O 's and the Be's purge, cold traps at -100°C remove >99% of the water and 10% of the carbon dioxide from the purge streams before the streams pass through 5A molecular sieves (X1 and X2, respectively) held at -196°C . The water in the cold traps is recovered by warming the trap and using hydrogen as a carrier gas to pass the water to solid oxide electrolysis units. The cold traps are warmed every two hours in the Li_2O stream and every two days in the Be stream during normal operation. In the event that water leakage into the beryllium is of the order of 10 kg/d, then the beryllium cold trap would be regenerated every two hours.

The flow rate of hydrogen species in the helium streams from the Li_2O and the Be zones leaving the cold traps is shown in Table 6-2. A small amount of water passes through the cold trap used with the beryllium helium stream if 10 kg/d of water is the magnitude of the water in-leakage; under normal conditions, no detectable water would pass the cold trap.

Table 6-2.
Species Flow rate (L(STP)/s) After a Cold Trap

Parameter	Be	Li_2O
He	0.84	650
H_2O	0.0014 ^a	--
H_2	0.00022	0.65

a- Present only in the event that 10 kg/d of water is being processed.

Electrolysis is used to decompose the water trapped in the cold trap into hydrogen (tritium) and oxygen. (The type of electrolysis units used were discussed in Sec. 5.1.) The hydrogen stream which also contains CO₂ is sent to the 5A molecular sieves at 25°C (Y1 and Y2) to remove entrained water while the oxygen streams are sent to the waste tritium recovery unit. The composition of the streams to Y1 and Y2 are shown in Table 6-3.

Table 6-3.
Impurities Which Reach Y1 and Y2 Molecular Sieves

Parameter	Be (Y2)	Li ₂ O (Y1)
Flow L(STP)/s		
He	0.00086	0.066
H ₂ O	0.0075	0.00032
H ₂	0.44(max) ^a	0.65
Radionuclides(ug/d)		
S-35(SO ₂)	46	36
C-14(CO ₂)	1500	3000 ^b
Ar-39	2	61
Kr-58	<0.01	0.74
Xe-135	0.01	0.05
Xe-133	0.014	0.16

a- This is the hydrogen produced from the electrolysis of 10 kg/d of water.

b- Only the radioactive CO₂ is shown here.

6.1.3 Helium Separation - Molecular Sieves at -196°C

For the helium purge stream from the Li₂O zones, two conditions must be met. First, >90% of hydrogen has to be removed from a 10³ excess of helium. Second, the helium must be continuously recycled. The best processing solution appears to be the use of 5A molecular sieves at -196°C. Under these conditions, the sieves will adsorb hydrogen, effectively allowing the helium stream leaving the sieves to be recycled back to the blanket. For the helium stream entering the Li₂O zones, 0.1% hydrogen is added. A mixer tank, a

second compressor and a surge tank for hydrogen are used to return the helium/0.1% hydrogen purge to the Li_2O zones. The surge tank (2 m^3) would retain the hydrogen from the molecular sieves at a pressure of 0.3 MPa in the event of an unplanned warmup of the sieves.

The material retained in the X1 and X2 molecular sieve beds at -196°C is shown in Tables 4.2 and 4.5. The X1 beds are regenerated quite differently than the X2 beds due to the presence of 0.1% H_2 in the X1 beds.

A three step regeneration is assumed for the X1 molecular sieves. First, to recover the hydrogen, the beds are cycled between -100°C and -196°C every two hours. Warm H_2 gas is passed through the bed to assist in desorption of the H_2 (T) species, and any co-adsorbed helium. The hydrogen stream is passed to the Y1 molecular sieves and then to the palladium/silver diffuser. Only this first regeneration step is shown in Fig. 6-1. We have assumed that a multitubular reactor with an internal heat exchanger [31] would be required to achieve good temperature control of the bed.

Since molecular sieves can separate hydrogen isotopes, it may be feasible and advantageous to warm up the X1 sieves between -196°C and -100°C in stages. Helium will desorb first, then protium and finally HT. If these desorptions can be controlled, it may be possible to return most of the protium directly to the inlet of the Li_2O blanket zone, never passing it to the cryogenic distillation unit (ISS). Only the last tritium rich portion of the desorbed hydrogen will be passed via the diffuser to the ISS. (This has to be verified and is not the reference case.)

The second regeneration step would be to 25°C , occurring perhaps once a week, to desorb inert impurities from the X1 sieves by flowing hydrogen gas through them. This regeneration step may not be needed.

The third regeneration to 250°C , is for two purposes: to remove absorbed water and CO_2 and to reduce the tritium inventory of the X1 beds. Again, H_2 gas is passed through the bed to assist in species desorption, perhaps once a month. Tests are needed to determine the regeneration period needed.

In the beryllium helium stream, the concentration of tritium and of all impurities is low, of the same order of magnitude as the tritium concentration in the Li_2O helium stream. Therefore, regeneration of the X2 sieve beds is handled differently. Using hydrogen as the carrier gas, the beds are warmed

to 250°C in controlled stages, once a day; the regenerated gas is passed to the Y2 beds.

6.1.4 Impurity Separation - Molecular Sieves (Y1 and Y2) and Palladium/Silver Diffuser

The function of the Y1 molecular sieve bed held at 25°C is to ensure that only hydrogen or helium species pass to the diffuser. Entrained impurities other than helium are trapped in the Y1 beds when a hydrogen gas stream from regeneration of the X1 sieves at -100°C, 25°C, or 250°C, or a hydrogen stream from an electrolysis unit is passed through them.

The regenerated gas from the X2 bed is passed to the Y2 bed at 25°C, and is then passed to the Y1 sieve bed at 25°C. Thus there are several intermediate beds between the waste stream from the beryllium purge gas processing system and the Li_2O hydrogen/tritium recovery system. The successive sets of regeneration processes should provide adequate residence time to reduce the concentration of short-lived xenon and krypton species while allowing molecular tritium to be recovered.

The Y1 and the Y2 molecular sieve beds held at 25°C are regenerated every 12 hours by flowing helium gas through them while they are at 250°C. The helium stream is passed to the waste recovery unit. The CO_2 which has been transported from the blanket is passed successively in these regenerations to the Z molecular sieves in the waste unit.

The palladium/silver diffuser unit prevents helium or small amounts of rare gases from reaching the cryogenic distillation unit. The small amount of helium, 1% of total gas, which passes from the regenerated X1 molecular sieve bed during a -100 °C regeneration has a minor effect upon the diffuser's operation. The bleed gas from the diffuser is cycled back to the X1 molecular sieves at -196°C to be reprocessed. If the diffuser develops a crack, helium passes to the cryogenic distillation unit. Fast-acting valves are need after the diffuser to minimize the amount of this gas which reaches the cryogenic distillation unit.

Oxygen plus other impurities permeate out from the gas lines and enter the hydrogen stram after it leaves the diffuser. Therefore, a SAES getter (ZrCoV) held at 350 °C is placed behind the palladium-silver diffuser to react with any active impurities while allowing the hydrogen to freely pass. A cryogenic guard be could be used in place of the SAES getter.

6.1.5 Waste Tritium Recovery Unit

The waste tritium recovery unit is used to separate species like helium, carbon dioxide, and oxygen from tritium-containing species, pass the non-tritium gases to the plant stack, and recover the tritium. The components of the waste recovery unit are a set of 5A molecular sieve beds (termed Z), a set of copper oxide beds held at 500°C and a set of cold traps held at -100°C. If the level of the gamma impurities warrants it, zeolite beds could be added to trap radioactive argon, krypton, and xenon at -196°C and a calcine solution could be added to trap carbon (C-14) dioxide as calcium carbonate.

The CO₂ desorbed from the Z beds during their regeneration at 250°C reaches the -100°C cold traps. Again 10% would be stopped by the cold trap and 90% would pass to the stack if a radiation monitor indicates that this is acceptable. If not acceptable then the calcine solution would be required. The 10% CO₂ in the cold trap is recycled back to the the purge stream for the beryllium zones.

All waste gas streams pass through the Z molecular sieve bed; the helium in the streams passes to ITER's stack system, as do all gases not trapped by the Z molecular sieves. Upon regeneration of the molecular sieves every 12 hours, using helium as a carrier gas, tritium-containing species are converted to water in a copper oxide bed and the water is collected in a cold trap. (Copper oxide was selected since oxygen from the electrolyzers is available to regenerate the copper oxide.) Non-condensibles are passed to ITER's stack system. The cold trap is warmed every 12 hours using hydrogen gas; the hydrogen and the water are cycled to the electrolysis unit, associated with the Be zone purge.

6.1.6 Controls

Localized control for processing is maintained on each unit using feedback from temperature and flow sensors. Data collection is maintained at a centralized control unit. A separate system which is linked to a centralized control unit is responsible for safety.

6.1.7 Containment Requirements

All units and process lines are assumed to have primary and secondary containment. The major components of the blanket tritium recovery system are installed in secondary containment gloveboxes. Lines between the blanket and

the compressor units will be doubly contained. Tritium release from these systems cannot occur as a result of a single component failure.

Because of the size and mass of the compressors used to circulate the helium for the Li_2O zones and the need to have access to a crane if a compressor fails, the room in which these units are located is assumed to provide secondary containment of these units.

6.1.8 Interfaces to Other Systems

The blanket tritium recovery system is interlinked with the blanket, the other subsystems of the fuel processing system, the cryogenic isotopic separation system (ISS), the general roughing vacuum system, the waste disposal unit, and the stack system. Valves and control circuits have to be provided between these systems to insure reliable operation.

The fuel streams derived from blanket test modules could be interfaced with this system, if there are no incompatibilities. This issue requires further examination once the fuel streams from these modules are better defined.

Standard interfaces have to be provided to water coolant, liquid nitrogen coolant, electrical power, vacuum systems, stack cleanup systems, glovebox cleanup systems, air supply systems, helium gas systems, etc. In addition, we have assumed that air cleanup is provided for all areas in which the components of this system are located and that crane facilities are available for maintenance activities. Access also has to be provided to solid waste disposal facilities at the plant when the end-of-life of components is reached.

6.2 Material Flows

The material flows, temperatures and pressures for the process paths shown in Fig. 6-1, as numbers 1,1',...20, are listed in Table 6-4. A minimum helium and/or hydrogen flow was assumed for regeneration of any of the molecular sieve beds.

6.3 Utility Requirements

The major power requirements of the blanket tritium recovery system are those for the helium purge stream which is used for the Li_2O zones. This purge

Table 6-4. Material Flows for the Blanket Tritium Recovery System

1. Hydrogen is used as purge gas for regeneration of coolers; molecular sieves at -196C and operation of electrolysis cell.
2. Helium is used as purge gas for regeneration of all molecular sieves at 25 C.
3. For molecular sieves, 0.01% of inert or other gaseous species are considered trapped: in -196C bed for helium, in 25C bed for H₂.
4. Assumption for electrolysis unit and palladium diffuser: 0.95 reaction or permeation of entering species.
5. Carbon dioxide has about 10% of vapor trapped at -100C cooler.
6. Cleanup of impurities prior to first cooler is not considered since this involves cleanup of gamma species.

Common Section of Processing																			
Blanket	HX	Filter	Cooler	Cooler(R)	MS(-196C)	MS(R 25)	Electrolys	MS(25C)	MS(R300)	PD-thru	PD-bleed	SAES/ISS	WMS(25C)	WMS(R300)	CuO(1)	CuO(2)	Cooler	Cooler(R)	Stack
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1.04E+05	1.04E+05	1.04E+05	1.04E+05	1.04E+05	1.04E+05	10.40001	10.53851	0.105	280.6925	14.77329	280.6925	2.531526	2.531526	2.531526	2.531526	2.531526	2.531526	2.531526	5.062053
103	103	103	103	103	103	220.7733	3.068	295.4658	1.12	1.064	0.056	1.064	1.265263	0	1.265263	0	1.265263	0	0
1.03	1.03	1.03	1.03	1.03	1.03	1.086	0.0995	1.12	0.052	1.064	0.056	1.064	1.265263	0	1.265263	0	1.265263	0	0
H ₂ (mol/hr)	1.04	1.04	1.04	1.04	1.04	1.086	0.0995	1.12	0.052	1.064	0.056	1.064	1.265263	0	1.265263	0	1.265263	0	0
T ₂ (mol/hr)	1.04	1.04	1.04	1.04	1.04	1.086	0.0995	1.12	0.052	1.064	0.056	1.064	1.265263	0	1.265263	0	1.265263	0	0
H ₂ O(mol/hr)	0.01	0.01	0.01	0.01	0.01	0.018	0.002	0.018	0.005	0.018	0.005	0.018	0.04	0.04	0.04	0.04	0.04	0.04	0.036
T ₂ O(mol/hr)	0.01	0.01	0.01	0.01	0.01	0.018	0.002	0.018	0.005	0.018	0.005	0.018	0.04	0.04	0.04	0.04	0.04	0.04	0.036
CO ₂ (mol/hr)	0.02	0.02	0.02	0.02	0.02	0.018	0.002	0.018	0.005	0.018	0.005	0.018	0.04	0.04	0.04	0.04	0.04	0.04	0.036
Na(mol/hr)	0.00018	0.00018	0	0	0	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875
O ₂ (mol/hr)	0.00018	0.00018	0	0	0	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875	0.48875
H/T	100.0385	100.0385	100.0385	100	312	0	203.2903	312	263.8088	104	263.8088	263.8088	263.8088	263.8088	263.8088	263.8088	263.8088	263.8088	263.8088
Temp.(C)	850	400	25	-100	25	-196	25300	600	25	300	350	350	350	350	350	350	350	350	350
Press.(MPa)	0.1-0.15	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Blanket portion of blanket

Blanket	HX	Filter	Cooler	Cooler(R)	MS(-196C)	MS(R 25)	Electrolys	MS(25C)	MS(R300)
1	2	3	4	5	6	7	8	9	10
Blanket	400C	HX(25C)	Cooler	Cooler(R)	MS(-196C)	MS(R 25)	Electrolys	MS(25C)	MS(R300)
1.385	1385	1385	1385	1385	1384.862	0.1385	0.1385	2.426526	2.426526
0.021	0.021	0.021	0.021	0.021	46	0.042	71.58253	71.62453	71.62453
0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.0105	0.0245	0.0245
23	23	23	23	23	23	23	1.213263	1.213263	1.213263
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.000553	0.000553	0.000553
0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.0102	0.0056	0.0102
5	5	5	5	5	5	5	11.53125	11.53125	11.53125
959.2083	959.2083	959.2083	1.5	2302.1	0	3	6386.286	2923.45	2195.429
400	400	25	-100	25	-196	25300	600	25	300
0.1-0.15	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.2	0.1
Temp.(C)									
Press.(MPa)									

stream has a helium flow rate of 29 mol/s; the hydrogen flow rate after the large molecular sieve beds at -196°C is only 0.08 mol/s. The helium purge stream for the Be zones has a flow rate of 0.04 mol/s. Power requirements are found in Table 6-5.

The first component, water cooled filters, reduces the temperature of the helium purge stream to 25°C . The first regenerative heat exchanger lowers the helium purge temperature to -80°C . The first liquid nitrogen cooler is used to maintain -100°C in the cold trap. The second regenerative heat exchanger lowers the temperature of the helium to -186°C . The second liquid nitrogen cooler is used to maintain -196°C in the molecular sieve bed.

There are two large compressors, which maintain the helium pressure within the Li_2O zones of the blanket and within the tritium recovery equipment. A smaller compressor is needed for hydrogen to compress it prior to the palladium/silver diffuser. The electrical power needed is listed in Table 6-5.

The other major electrical requirement is the power needed to warm and cool the molecular sieve in beds X1. For a 40 minute warmup and cool-down, 10 kW of power is required. Finally, an additional 20 kW is required to operate the components which process beryllium's helium purge stream and to regenerate all small molecular sieve beds (Y1, Y2, Z). The total power requirement is about 0.5 MW.

6.4 System Layout

The space requirements for the blanket tritium recovery system are listed in Table 6-6. Access space if components are dismantled for maintenance is not included. A system layout of the components is shown in Fig. 6-2; here access space around each unit is shown. The three rooms shown, one for the Li_2O 's purge, one for the Be's purge, and one for tritium/hydrogen handling are respectively $13 \times 12 \times 4$ m, $13 \times 7 \times 3$ m, and $8 \times 11 \times 3$ m.

The large compressor units and regenerative heat exchangers for the helium purge stream for the Li_2O zones are in the Li_2O room which has a crane that can be operated remotely, to ensure that these units can be maintained in the event that they experience gamma contamination. Other units in this room are the low temperature molecular sieve beds, the regenerative heat

exchangers, and the cold traps. In an adjacent room, are the units used to recycle the helium stream for the Be zones. The units which purify the tritium and recover the waste tritium are in the third room.

Table 6-5.
Major Power Requirements for the Blanket Tritium Recovery System

Component	Power kW	Area/Volume m^2/m^3	Delta Temperature $^{\circ}\text{C}$	Coolant/Flow mol/s
Water Cooler	241	---	400	H ₂ O/ 127
Reg. HX-1	78	2/1	130	He/ 29
Liq. N ₂ Cooler-1	12	---	20	N ₂ / 11
Reg. HX-2	52	2/1	86	He/ 29
Liq. N ₂ Cooler-2	6	---	10	N ₂ / 11
Compressor He-1 ^a	65	---	---	-----
Compressor He-2 ^a	33	---	---	-----
Compressor H ₂ ^a	0.5	---	---	-----
MS(X1) cycling	10	---	---	-----
Miscellaneous (Be)	20	---	---	-----
Total	510			

a- Compressor head is respectively: 0.1-0.2 MPa, 0.1-0.15 MPa, 0.-0.2 MPa.

6.5 Hydrogen and Tritium Inventories

An estimate of the tritium and the hydrogen inventories within the components of the blanket tritium recovery system has been generated from available data. These estimates are found in Table 6-7. A two hour regeneration is assumed for the cold trap and the -196°C molecular sieves for the Li₂O purge. For the Be purge, a two day regeneration is assumed for the cold trap and a one day regeneration for the -196°C molecular sieves. Four grams of tritium is released in two days from beryllium. Since the chemical form, T₂ or T₂O is unknown, the four grams is listed under both classifications. For the other components, the inventories listed are upper limits.

Table 6-6.
Space Requirements and Physical Dimensions for the Components of the
Blanket Tritium Recovery System

Component	Vol (m ³)	Dimensions			No. of Units
		L(m)	W(m)	H(m)	
Filters	2	1	1	1	2
Heat Exchangers	2	1	1	1	2
Li₂O					
He Compressors	16 ^a	2	2	2	2
He Storage	8 ^b	2	2	2	1
He/H ₂ Mix Tank	1	1	1	1	1
H ₂ Surge Tank	2	2	1	1	1
Cold Trap	4	1	1	2	2
Electrolysis	1	1	1	1	1
MS (-196°C)	16	2	2	2	2
MS (25°C)	2	1	1	1	2
Be					
He Compressors	1	1	1	1	2
He Storage	8	2	2	2	1
Cold Trap	2	1	1	1	2
Electrolysis	4	2	1	2	1
MS (-196°C)	2	1	1	1	2
MS (25°C)	2	1	1	1	2
Diffuser	6	3	1	2	1
Waste	6	3	1	2	1
Total	85	--	--	--	--

a- The compressor volume is given, not the room volume.

b- The gas is assumed to be held at ≤ 0.6 MPa.

The total tritium process inventory is <20 g. The total residual tritium inventory trapped in the 5A molecular sieves after several years of operation can reach 134 g. To obtain release of this tritium requires prolonged heating of the bed at 250°C while hydrogen is circulated [32]. We have chosen this method to regenerate these molecular sieve beds, so we expect the actual bed inventory to be appreciably less than this value.

- R - Regenerative Heat Exchanger
- MS - Molecular Sieve Bed
- F - Filter
- C_n - Compressor
- SHe - Helium Storage
- T - Cold Trap
- EI - Electrolysis Unit
- Su - H₂ Surge Tank
- M - Mixer
- G - Getter
- P - Pd/Ag Diffuser
- W - Waste Recovery

Figure 6-2. Layout of processing system for components of blanket tritium recovery system.

Table 6-7.
Maximum Tritium and H₂ Inventories in Components

Component ^a	Inventory(g)		H ₂ Process
	Tritium Process	Residual	
Li ₂ O			
Cold Trap(2)	0.1	---	---
Electrolysis	<0.1	---	---
MS (-196°C)(2)	12.4	134 ^b	414
MS (25°C)(2)	<0.1	1.4 ^c	---
Be			
Cold Trap(2)	4.	---	---
Electrolysis	<0.1	---	---
MS (-196°C)(2)	2.	0.7 ^d	2
MS (25°C)(2)	<0.1	1.4 ^c	---
Diffuser	0.1	---	---
SAES	<0.1	---	---
Waste	0.1	1.4 ^c	---
Total	<17.2	138.9	416

a The symbol (2) indicates two units.

b This is the steady-state value for beds each containing 192 kg of sieves, and with no added water to the bed.

c This is the steady-state value for beds each containing 0.06 kg of sieves, with maximum tritium exchange with retained water.

d This is the steady-state value for beds each containing 1 kg of sieves, and with no added water to the bed.

6.6 Reliability/Availability

There is a general lack of qualification data for most components for tritium operation. Palladium/silver diffusers need extended testing at the tritium concentrations and pressures expected in ITER. Ceramic electrolysis units, consisting of series of 10-20 cells currently under commercial development for protiated water, require tritium qualification. The purpose of these qualification tests is to obtain data which indicate the reliability of individual components in tritium service, the time between failures, the type of maintenance schedules to be followed, and any synergistic effects between components when they are linked in system operation. The overall goal of this work will be to ensure 99% availability of the blanket tritium recovery system, including planned maintenance.

6.6.1 Maintenance Requirements

Maintenance of the components of the blanket tritium recovery system may require gamma shielding, especially for the filters located immediately after the outlet of the purge gases from the blanket. To provide ease in maintenance, components which have a high probability to become gamma activated, i.e., those used to recycle the helium streams, are located in separate rooms. A crane which can be remotely directed is used in the room in which large units, the compressors and the molecular sieve beds for the helium purge for the Li_2O zones, are located to minimize worker exposure to gamma contamination. In addition, components are designed as modular units to minimize downtime if replacement of a unit is required.

6.6.2 Accident Scenarios

There are three accident scenarios which could prevent operation of the blanket tritium recovery system. These are: 1) failures within the Li_2O or Be blanket zones, 2) failures or upsets which arise within the components of the blanket tritium recovery system, and 3) failures in the cryogenic distillation unit.

Two major failures are anticipated in the blanket zones: 1) a high leak rate of water into the blanket zones and 2) major/minor fragmentation of the Li_2O or the Be.

The consequences of a high leak rate of water into the blanket was addressed in section 4.2.2. The leak will be in the Be zone of the U.S.

blanket design. A large-scale electrolyzer is provided to handle a leak rate of ≤ 10 kg/d. Above a 10 kg/d water leak rate, the blanket would need repair, so flow to the blanket tritium recovery unit would be interrupted. Valves on purge lines between the blanket zones and the blanket tritium recovery system would close to isolate the two systems. (A leak rate > 10 kg/d should be a decision criteria to require shutdown for blanket repair.)

The consequences of minor fragmentation of the blanket materials are alleviated through the presence of two parallel sets of filters in front of each helium circulator unit. The blanket gas flow can be switched from one set of filters to the other set through a control circuit. Afterwards, the first set of filters can be easily replaced.

Major fragmentation of the blanket materials can be detected by means of the replacement time for two sets of filters. If replacement is required of both sets in a few hours to a day, then again valves on purge lines between the blanket zones and the blanket tritium recovery system would close to isolate the two systems. (A particulate transport rate of this magnitude should also be a decision criteria to require shutdown for blanket repair.)

The most crucial component in the blanket tritium recovery systems is the compressor for the helium purge for the Li_2O zones. If this unit fails, then there is a static gas atmosphere in the Li_2O zones which may allow the tritium to concentrate in cold areas of the blanket. This would be undesirable. Therefore, a spare compressor would be in storage.

The second most crucial component is the palladium/silver diffuser. If the diffuser ruptures, the maximum amount of helium which would pass to the cryogenic distillation unit (ISS) is 10 mol/hr (Table 6-4, flow 12). This amount of helium is 5% of the total hydrogen flow (294 mol/hr - Table 6-4, flows 11 and 12) entering the ISS from the blanket tritium recovery system. This influx of helium should have a minor effect on the operation of the ISS since the total input from the blanket is a small fraction of the ISS's total load.

Some failures, within the blanket tritium recovery system, can be tolerated due to the long regeneration times for many components. For molecular sieve beds Y1, Y2, and Z, 12 hours is required; for beds X2, 24 hours, and for the Be cold trap, 48 hours. If a failure occurs in the X1

beds, the helium purge gas could be recycled to the Li_2O zones for four days, the net result being a 4% increase in the hydrogen partial pressure of the purge stream.

The consequences of a failure of the cryogenic distillation system (ISS) would not be severe for the blanket tritium recovery system, if the ISS were repaired within a few days. The hydrogen which permeates through the palladium/silver diffuser could be rerouted to the helium purge stream, without removing the tritium. The tritium concentration would increase ~100% each day, but this corresponds to only a 1% increase in the total hydrogen content of the purge stream.

6.7 Estimated System Cost

Component costs were extrapolated from experience at TSTA, JAERI, and other groups. The total capital cost of the blanket tritium recovery system is \$ 14 M. The component costs are listed in Table 6-8 and include secondary containment and distributed control costs.

Table 6-8. Capital Cost of Major Components

Component	Cost (\$M)	Source
Be Compressor	0.2	TSTA Air Detritiation System
Be Cold Trap(2)	0.2	Estimate
Be Electrolysis-Large	2.0	JAERI/TSTA
Be MS (-196°C)(2)	0.4	Estimate
Be MS (25°C)(2)	0.2	Estimate
Li_2O Compressor(2)	3.0	TSTA Air Detritiation System
Li_2O Cold Trap(2)	0.2	Estimate
Li_2O Electrolysis-Small	0.5	JAERI/TSTA
Li_2O MS (-196°C)(2)	2.0	Estimate
Li_2O MS (25°C)(2)	0.2	Estimate
Pd/Ag Diffuser	2.0	JAERI Unit/Estimate
SAES Getter	0.1	Estimate
Waste Tritium Recovery	0.5	TSTA Scaling
Miscellaneous	0.5	Estimate
Safety Controls	1.0	Estimate
Instrumentation	1.0	Estimate
Grand Total	14.0	

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