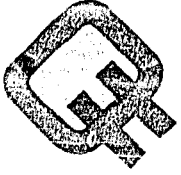
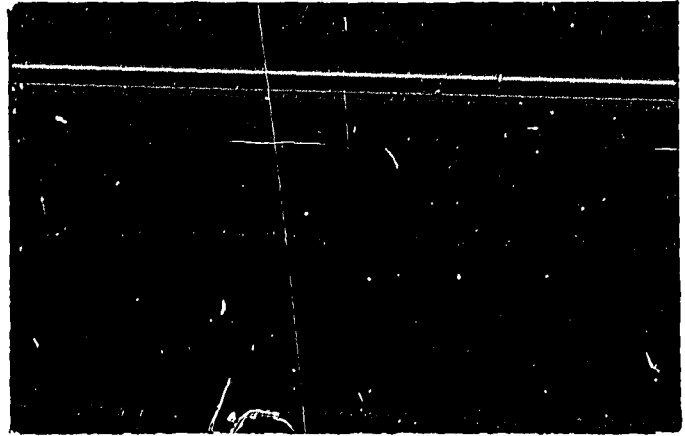
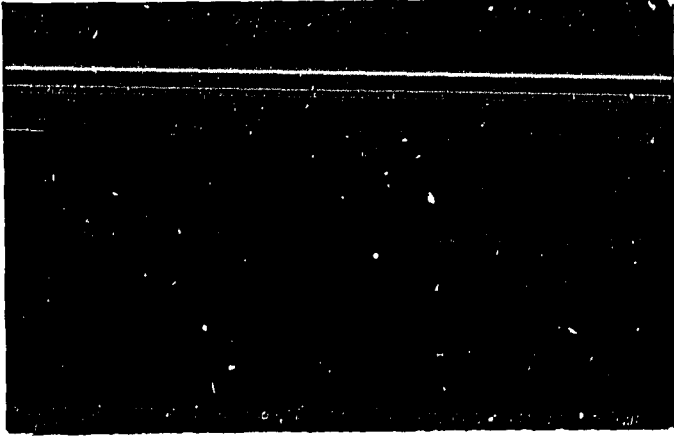


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# *Canadian Fusion Fuel Technology Project*





THE CANADIAN FUSION FUEL TECHNOLOGY PROJECT REPRESENTS PART OF CANADA'S OVERALL EFFORT IN FUSION DEVELOPMENT. THE FOCUS FOR CFFTP IS TRITIUM AND TRITIUM TECHNOLOGY. THE PROJECT IS FUNDED BY THE GOVERNMENTS OF CANADA AND ONTARIO, AND BY THE UTILITY ONTARIO HYDRO; AND IS MANAGED BY ONTARIO HYDRO.

CFFTP WILL SPONSOR RESEARCH, DEVELOPMENT, DESIGN AND ANALYSIS TO EXTEND EXISTING EXPERIENCE AND CAPABILITY GAINED IN HANDLING TRITIUM AS PART OF THE CANDU FISSION PROGRAM. IT IS PLANNED THAT THIS WORK WILL BE IN FULL COLLABORATION AND SERVE THE NEEDS OF INTERNATIONAL FUSION PROGRAMS.

A DESIGN ASSESSMENT OF TRITIUM  
REMOVAL SYSTEMS FOR THE MIRROR  
ADVANCED REACTOR STUDY

Report No. F83018

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## 1.0 SUMMARY

This study investigates the available processes for removing tritium from light water, and selects the most appropriate process for recovering tritium from the various tritiated water streams identified in the Mirror Advanced Reactor Study (MARS). A simplified flowsheet is shown for the process and the main process parameters are identified. Previous experience is utilized to predict direct capital costs and power requirement for the Tritiated Water Removal Unit (TWRU). A number of possibilities are discussed for lowering the cost of the TWRU.

An estimate is made of the direct capital cost for the Air Detritiation System that has already been selected as the reference design by MARS personnel.

The leakage from the MARS coolant loop is estimated, based on the experience obtained with Ontario Hydro's coolant systems. Design targets are identified for tritium levels in the reactor hall atmosphere and in water and air emissions. Tritium levels are predicted for these and are assessed against the previously identified targets.

## 2.0 INTRODUCTION

The objective of the Mirror Advanced Reactor Study (MARS) is to obtain a conceptual design and cost estimate for a D-T fusion reactor with an output of 1000 MWe. This study is being organised by the Nuclear Engineering Department of the University of Wisconsin who are responsible for co-ordinating the inputs of a multi-disciplinary task force.

The intent of the study is also to demonstrate that the radioactivity produced by deuterium/tritium fusion is controllable and that the tritium inventory and releases can be kept low.

In the reactor plasma, the fusion reaction results in release of a harmless helium isotope as well as neutrons. These energetic neutrons bombard and interact with the LiPb coolant blanket to create new tritium fuel which is recycled. The low solubility of tritium in LiPb keeps blanket inventory low. However, some tritium inevitably permeates into cooling water and also leaks into the reactor hall atmosphere. This study is prepared by Ontario Hydro for the Canadian Fusion Fuels Technology Project to assess appropriate designs, estimate design targets and provide a cost estimate for controlling the tritium leaks into water and air. In doing this study, we have utilized Ontario Hydro's extensive in-house knowledge of tritium control technology as well as experience with the operation of its CANDU nuclear reactors.



3.0 SCOPE

The scope of this study has been discussed with the Nuclear Engineering Department of the University of Wisconsin, and agreed to, as follows:

- (a) Review the state-of-the-art for removing tritium from light water systems and select the most appropriate system for the Tritiated Water Removal Unit of MARS.
- (b) Perform a conceptual design of the TWRU, and provide approximate size, cost and utility requirements. Produce a simplified flowsheet for the TWRU.
- (c) A catalytic oxidation/adsorption unit has been selected for the Air Detritiation System at MARS. Provide the approximate cost of this system.
- (d) Estimate the leakage from the MARS coolant loop based on the extensive data obtained by Ontario Hydro for the coolant loops in its CANDU reactors.
- (e) Identify the desired targets for tritium contamination levels in the reactor atmospheres and a desired target for tritium emission to the environment for the MARS reactors. Assess the projected performance of the proposed MARS design against these targets.

4.0 DESIGN PARAMETERS

The design parameters are shown on the attached flowchart, Figure 1.

4.1 Tritiated Water Removal Unit (TWRU)

<u>System</u>	<u>Tritium Production Rate Ci/day</u>	<u>Flow l/day</u>
Condensate from Li Pb/Steam Heat Exchanger Interspace	3300	0.001
Collectors	370	370
Halo Scrapers	950	950
Hot Cell Wash Water	100	100
Air Detritiation System Condensate	1000	200

4.2 Air Detritiation System

Five units at 5000 SCFM rated capacity for each unit. Total removal capacity of the ADS is 1000 Ci/d of tritium removed producing 200 l/d of condensate water at a concentration of 5 Ci/l.

4.3 Implications of No Tritium Removal

At this stage, it is useful to assess whether removal of tritium from aqueous streams is required at all, and what would be the consequence of not removing tritium from these streams. In the combined coolant stream from the Collectors and the Halo Scrapers, the following would result:

$$\begin{aligned} \text{Tritium Production} &= 1320 \text{ Ci/day} = 1320 \times 365 \times 0.8 \\ &= 385,440 \text{ Ci/yr assuming 80\% capability factor} \end{aligned}$$

$$\text{Coolant Mass} = 66,000 \text{ kg}$$

$$\begin{aligned} \text{Production Rate R} &= \frac{385,440}{66,000 \times 365 \times 24} \\ &= 6.667 \times 10^{-4} \text{ Ci/kg/hr} \end{aligned}$$

Tritium Concentration A (t) at time t is

$$A(t) = A (1 - e^{-\lambda t})$$

where  $\lambda =$  tritium decay constant  $= 6.42 \times 10^{-6} \text{ hr}^{-1}$

$A =$  concentration at equilibrium where tritium decay equals production

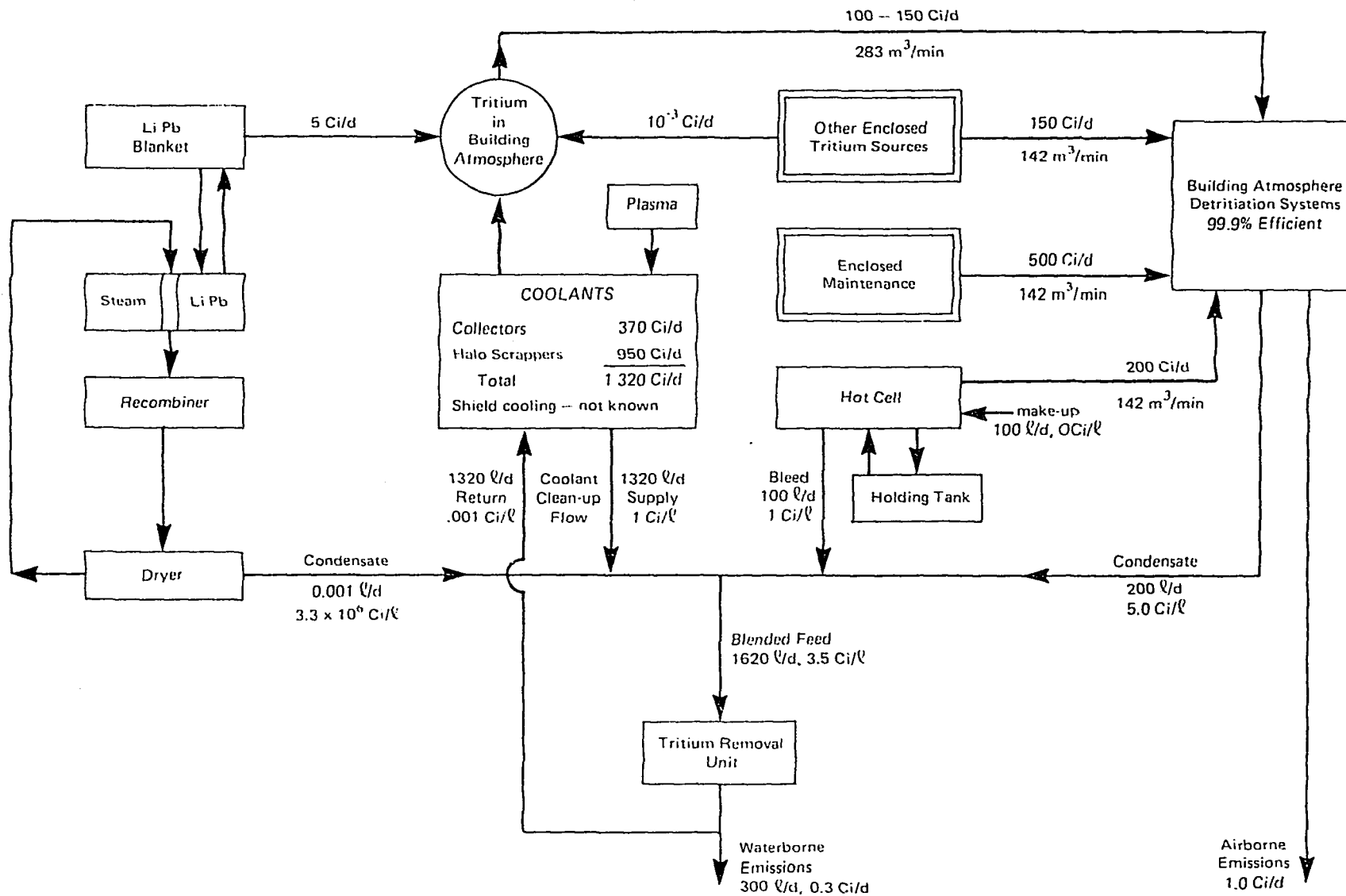


FIGURE 1  
Building Atmosphere and Waterborne Pathways for Tritium – MARS

It can be shown that,

$$A = \frac{R}{\lambda} = \frac{6.667 \times 10^{-4}}{6.42 \times 10^{-6}} = 104 \text{ Ci/kg}$$

After 30 years operation, the Concentration will reach approximately 77 Ci/kg.

#### 4.4 Basis for Sizing the TWRU

- (a) Remove 1320 Ci/d from the coolant stream going to the Direct Converter and the Halo Scraper keeping the concentration at 1 Ci/kg.
- (b) Remove 3300 Ci/day from the condensate produced by tritium permeation into the interspace of the Li Pb/Steam Heat Exchangers.
- (c) Process 200 kg/day from the Air Detritiation System Condensate at 5 Ci/kg.
- (d) In order to reduce tritium emissions and to reduce the amount of water that needs to be processed we suggest the following improvement to the method of washing the Hot Cell. We recommend that the Hot Cell wash water be recycled into a holding tank and used repeatedly until a concentration of 1 Ci/kg is reached. At this point, 100 l/day must be processed to remove approximately 100 Ci/day. The tritium-free make-up water would be used for the final wash cycle.

The total flowrate to be treated by the TWRU is (1320 + 200 + 100) or approximately 1620 l/day at an average concentration of 3.5 Ci/l.

#### 5.0 SEPARATION PROCESSES

The separation of tritium (present in the form of parts per million of HTO) from H<sub>2</sub>O must depend on the difference in behaviour of compounds containing the tritium (T) atoms and the same compounds containing the hydrogen (H) atoms. Chemically, tritium and hydrogen are expected to be similar since tritium is a hydrogen isotope. However, since tritium has a mass three times larger than hydrogen, we would expect the physical properties of compounds containing tritium and hydrogen to be appreciably different. This difference can be utilized to separate the isotopes. There is extensive literature on the separation of hydrogen isotopes(1,2,3).

#### 5.1 Processes Considered for the TWRU

Since it is desired to produce high purity T<sub>2</sub> for recycle into the fuel stream, cryogenic distillation of H<sub>2</sub>/HT/T<sub>2</sub> at around 20 K is the only practical final step for the separation process. Tritium is radio-

logically much less hazardous in the elemental form than in many other compound forms, such as the oxide. Additionally, cryogenic distillation offers a good separation factor (e.g. for  $H_2/HT$ ,  $\alpha = 2.11$  at 21.5 K) and is proven in industry.

The problem of process selection then resolves around selecting the front-end process to convert the isotopes from the oxide to the elemental form to make them suitable for feeding the cryogenic distillation system.

Among all the various processes available, the following are considered to be the most proven in industrial or pilot-scale operation:

(a) Catalytic Exchange of  $H_2O/HTO$  against  $H_2/HT$

This can be performed either in the vapour phase (VPCE) or the liquid phase (LPCE) using a proprietary wet-proof catalyst developed by Atomic Energy of Canada Ltd (AECL). VPCE has been used at the Grenoble tritium removal facility in France and is also the front-end process for Ontario Hydro's Darlington Tritium Removal Facility. The LPCE process is being used by AECL for a smaller tritium removal plant to be built in Chalk River, Ontario. All of the above facilities transfer tritium from DTO into  $D_2$ . The above catalytic processes can also be extended to the hydrogen/tritium system and will produce an  $H_2/HT$  mixture that is isotopically weaker than the source HTO. This is more pronounced for  $H_2/HTO$  transfer than for  $D_2/DTO$ . Tritium being the heavier isotope prefers to stay in the water phase as opposed to being transferred into the gas stream. Additionally, the gas to liquid flow ratio is approximately 4:1 for  $H_2/HTO$  in VPCE as compared to approximately 2:1 for  $D_2/DTO$  separation. This means that the cryogenic unit for an equivalent  $H_2/HT$  separation using the VPCE front-end, is approximately twice the size as for a  $D_2/DT$  separation.

(b) Electrolysis of  $H_2O/HTO$

Electrolysis produces an  $H_2/HT$  stream of the same molar flowrate and isotopic composition as the  $H_2O/HTO$  feed. Thus for the same separation a cryogenic unit coupled to an Electrolysis system is significantly smaller than a cryogenic unit coupled to VPCE or LPCE.

(c) Combined Electrolysis and Catalytic Exchange (CECE) of  $H_2O/HTO$

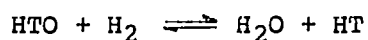
This produces an  $H_2/HT$  stream richer in tritium than the feed  $HTO/H_2O$ . However, it has the disadvantage of concentrating tritium in the electrolyte to higher than feedwater concentrations. The catalyst employed in this process is the wet-proof catalyst developed by AECL.

Each of the above 'front-end' processes will be considered in greater detail when coupled with cryogenic distillation.

## 5.2 Process Description and Status of Technological Development

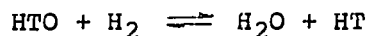
### (a) Vapour Phase Catalytic Exchange + Cryogenic Distillation

This is illustrated in Figure 2. The VPCE consists of a number of discrete stages. Each stage contains an evaporator, a superheater, a catalyst bed and a condenser. The water is evaporated, superheated to 200°C and mixed with hydrogen gas before passing over a catalyst bed where the following exchange reaction takes place.



The steam is condensed in the condenser and flows to the next stage. Flow of hydrogen and water is co-current within a stage, but counter-current over the VPCE as a whole. Essentially pure hydrogen enters the VPCE at the bottom of the cascade and picks up HT from the water, providing a suitable feed to the cryogenic distillation system, which separates a 99 percent T<sub>2</sub> product and returns almost pure H<sub>2</sub> to the VPCE. A VPCE system requires a comparatively large cryogenic distillation unit because of the low concentration stream produced by the catalytic exchange and because of the large G/L ratio necessary.

The equilibrium constant for the vapour-phase reaction



is  $K = 0.309$  at 150°C  
 $K = 0.366$  at 200°C (5)

We have considered a case where the VPCE operating at 200°C, is fed with water at 3.37 Ci/kg (61 Ci/Kmol).

Our simulation shows that a six-stage VPCE is required to detritiate water from 61 Ci/Kmol to 1 Ci/Kmol (0.05 Ci/kg). The L/G ratio is 0.2. In other words, the molar gas flow to the cryogenic unit is five times the water flow to the VPCE. Also, the feed concentration to the cryogenic unit is 11.8 Ci/Kmol, which is approximately one-fifth of the feedwater concentration. Clearly, the cryogenic unit for the VPCE is large.

### (b) Liquid Phase Catalytic Exchange + Cryogenic Distillation

This is illustrated in Figure 3. The LPCE operates below 100°C, therefore, vaporization and condensation of water is not necessary. This also eliminates the requirement of having discrete stages in separate vessels, and, in fact, a continuous column can be used to provide a number of LPCE stages. However, the LPCE is disadvantaged in that the equilibrium at lower temperatures favours tritium staying in the water form.

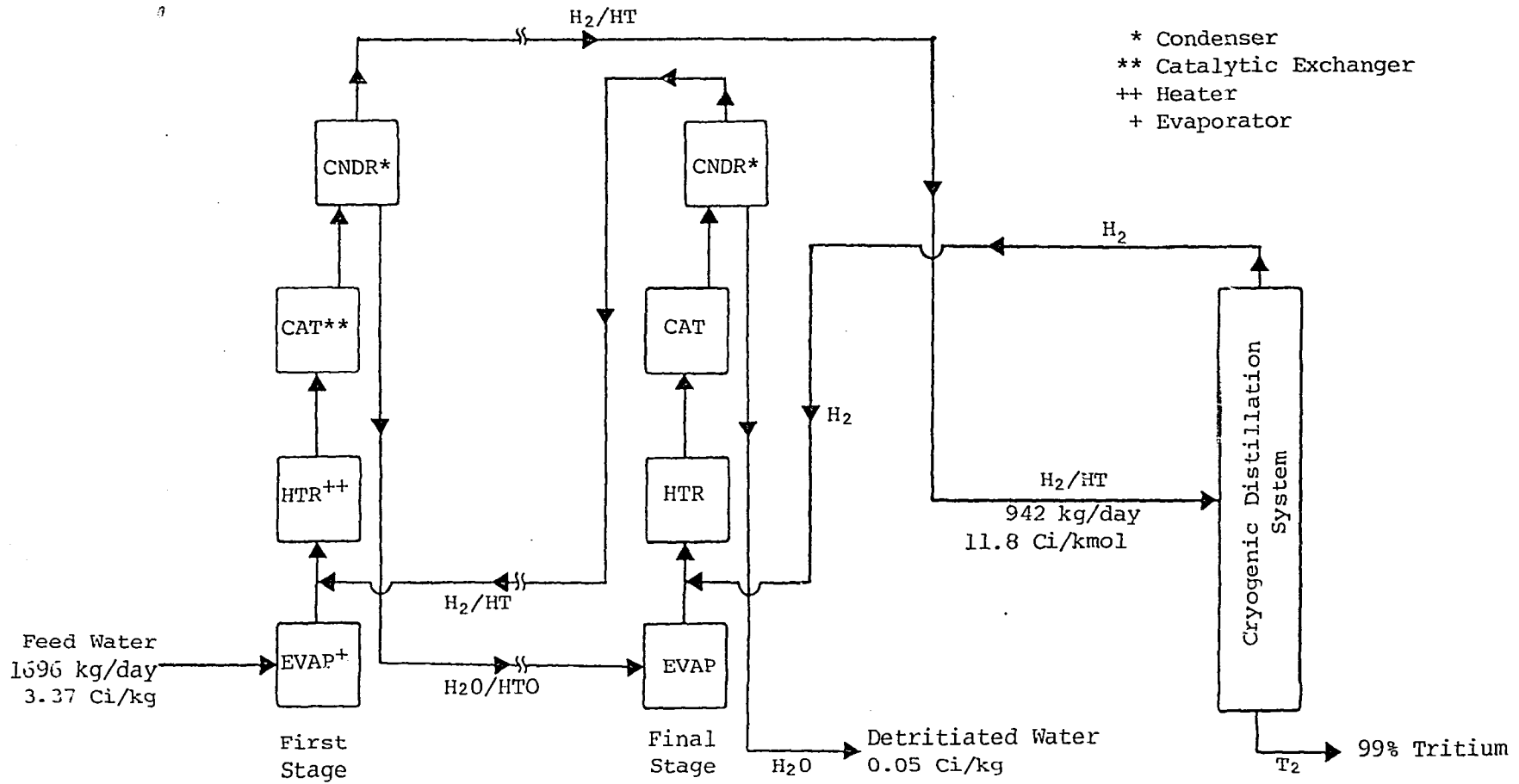


Figure 2

Vapour Phase Catalytic Exchange & Cryogenic Distillation

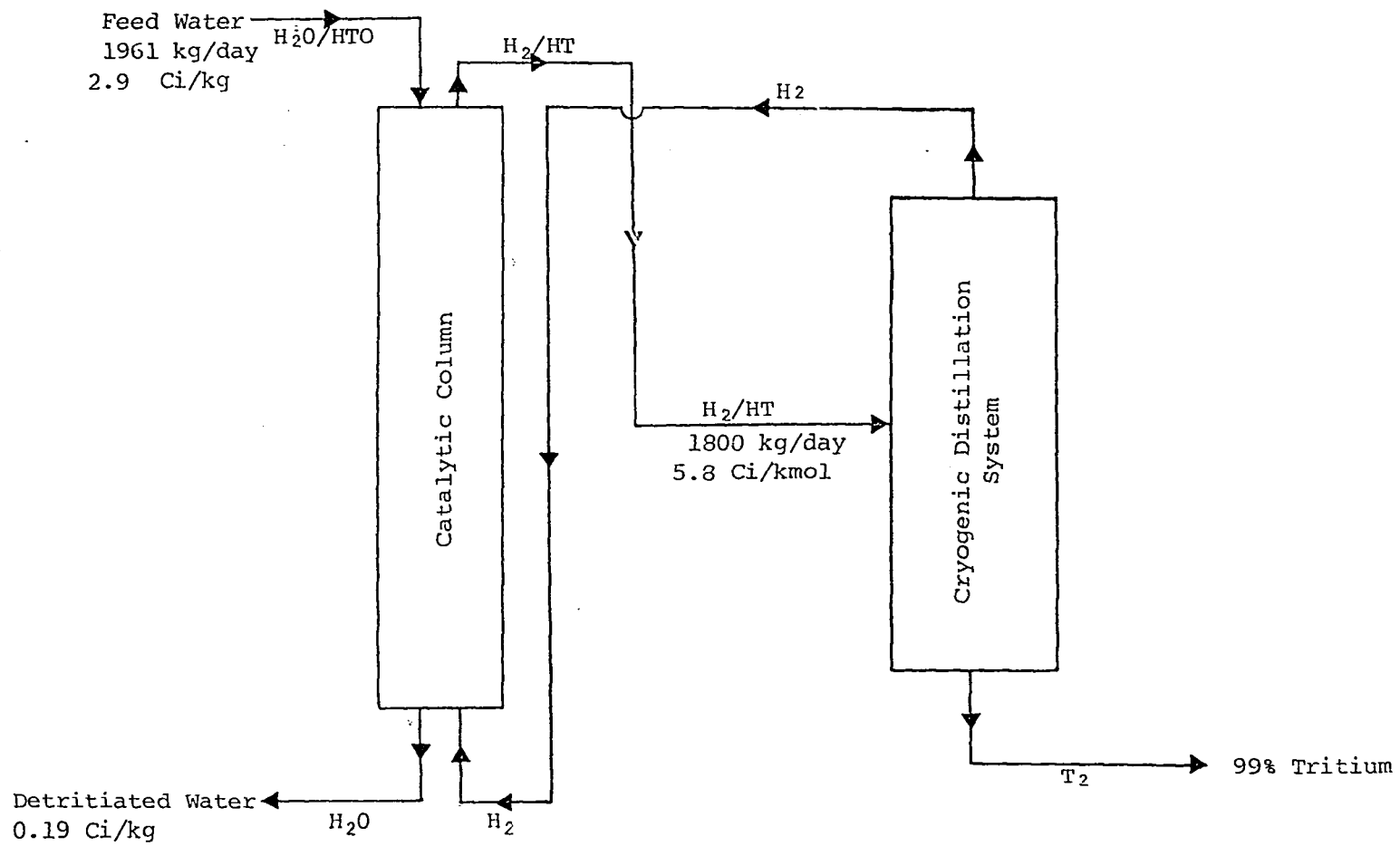
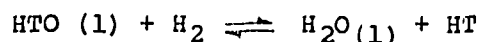


Figure 3

Liquid Phase Catalytic Exchange & Cryogenic Distillation





$$K = 0.143 \text{ at } 25^\circ\text{C}, K = 0.189 \text{ at } 60^\circ\text{C} \quad (4)$$

Thus, the K value is smaller than for the VPCE and a large gas flow and a lower than feed tritium concentration is sent to the cryogenic distillation unit, resulting in a cryogenic unit which may be larger even than for the VPCE.

We have simulated this case. The flow to the cryogenic unit is 1/0.121 or approximately 8.26 times the feedwater flow, and the detritiation can be achieved with seven stages to 3.5 Ci/Kmol (0.19 Ci/kg H<sub>2</sub>O). With more stages, a lower outlet water concentration could be achieved. The tritium concentration in the hydrogen gas going to cryogenic distillation is 5.8 Ci/Kmol.

The LPCE has been demonstrated on a pilot scale at AECL for H<sub>2</sub>/HDO exchange. A tritium demonstration plant is being constructed by AECL for startup in 1986. This plant will utilize the LPCE front-end process for removal of tritium from D<sub>2</sub>O.

(c) Electrolysis of H<sub>2</sub>O/HTO + Cryogenic Distillation

Electrolysis of water is well established in industry, being used routinely for hydrogen production. There are many different types of electrolysis cells available, not all of which are suitable for tritium service. There have been many surveys of electrolysis cells in the literature<sup>(6)</sup>. Petek et al<sup>(7)</sup> have proposed the use of bipolar electrolysis cells for tritium removal. The combination of Electrolysis and Cryogenic Distillation is illustrated in Figure 4.

The basic types of electrolysis cells and some of the manufacturers are as follows:

(1) Unipolar (tank type)

The advantages of this type are:

- o Simple construction
- o Common electrolyte with no shunt currents
- o Ease of maintaining electrolyte concentration
- o No electrical contact surfaces within the cell
- o Lower material cost per unit cell area
- o Low gasket length
- o High reliability

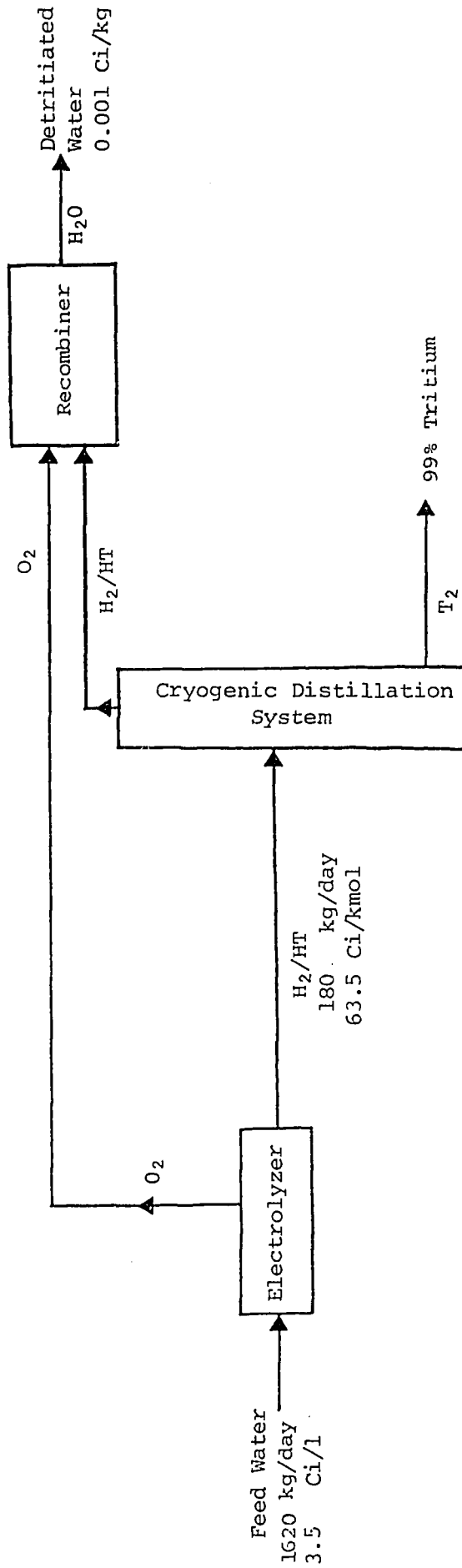


Figure 4

Direct Electrolysis & Cryogenic Distillation

This type is manufactured by the Electrolyser Corporation Ltd, Toronto, Ontario. The cell operates at nominally atmospheric pressure, so requires gas holders and gas compressors for H<sub>2</sub>, O<sub>2</sub> transfer.

(2) Bipolar Electrolyser (Filter Press)

The advantages of filter press electrolysers are:

- No external busbars required to connect individual cells
- Lower currents and higher voltages are required, simplifying the power conditioning and controls
- Operation at high pressure possible, i.e. no compressors, gas holders

The major disadvantages are:

- More sophisticated, and hence expensive
- Longer gasket length, more chronic leakage

Some manufacturers of filter press cells are:

Lurgi Apparate Technik GmbH  
Brown Boveri Co Ltd  
CJB Developments Ltd, UK  
Oronzio de Nora  
Teledyne Energy Systems

(3) Solid Electrolyte Cell

General Electric manufactures this solid polymer electrolyte (SPE) cell the advantages of which are:

- Elimination of corrosive liquids
- Compact design
- Pressurized operation

However, as of the present, the SPE cells are only available for small scale applications and are still considered to be in the development stage for large scale industrial applications.

Leakage of water and hydrogen from electrolysis cells needs to be as low as possible for tritium service. Due to this reason, Ontario Hydro eliminated filter press electrolysers from consideration during conceptual design of its Tritium Removal Facility. The SPE electrolyser was not selected due to its unavailability for the size required and the relatively complex auxiliary systems associated with it.

(4) Low Inventory, Low Leakage Cell for Tritium Service

The process of selecting an electrolysis cell for the first tritium removal facility in Canada revealed the disadvantage of existing cells for tritium service. For this reason, Ontario Hydro jointly with AECL, initiated a development program to develop an electrolyser suitable for tritium service. Such an electrolyser must have the following characteristics:

- o low leakage, minimum gasket length
- o explosion proof design
- o pressurized operation for elimination of gas holders, gas compressors
- o simplicity, low maintenance requirement
- o high current density and low tritium holdup
- o compatibility of materials with tritium service.

The test cell is a 7.2 kA cell with a specific inventory of 2 to 2.4 l/kA. The cell internals are contained in a tank with a single circumferential gasket. The cell is currently undergoing testing. It has performed continuously for approximately six months at a steady voltage of 2.1 V with excellent H<sub>2</sub>, O<sub>2</sub> purities. Leakage measurements are due to be performed in the near future. The results obtained so far confirm that it meets the stringent requirements for tritium service.

Electrolysis of H<sub>2</sub>O/HTO has an advantage as compared to catalytic exchange, in that, the molar flow of hydrogen to the cryogenic unit is equal to, and not higher than, the feedwater flow to the front-end. Additionally, the tritium concentration in the hydrogen is equal to, and not lower than, the concentration in the feed water. These two facts lend to a lower capital cost and power requirement for the cryogenic unit associated with an electrolysis front-end.

(d) Combined Electrolysis and Catalytic Exchange (CECE)

The CECE process, as the name implies is partly based on the reaction



The equilibrium favours transfer of tritium from the tritiated gas phase into the water phase. This is the reason that the LPCE process, previously described, is unattractive.

In the CECE process, as shown in Figure 5, a stream of tritiated water is fed to a column packed with hydrophobic catalyst. In the column, this feed stream mixes with a liquid reflux stream flowing counter-current to

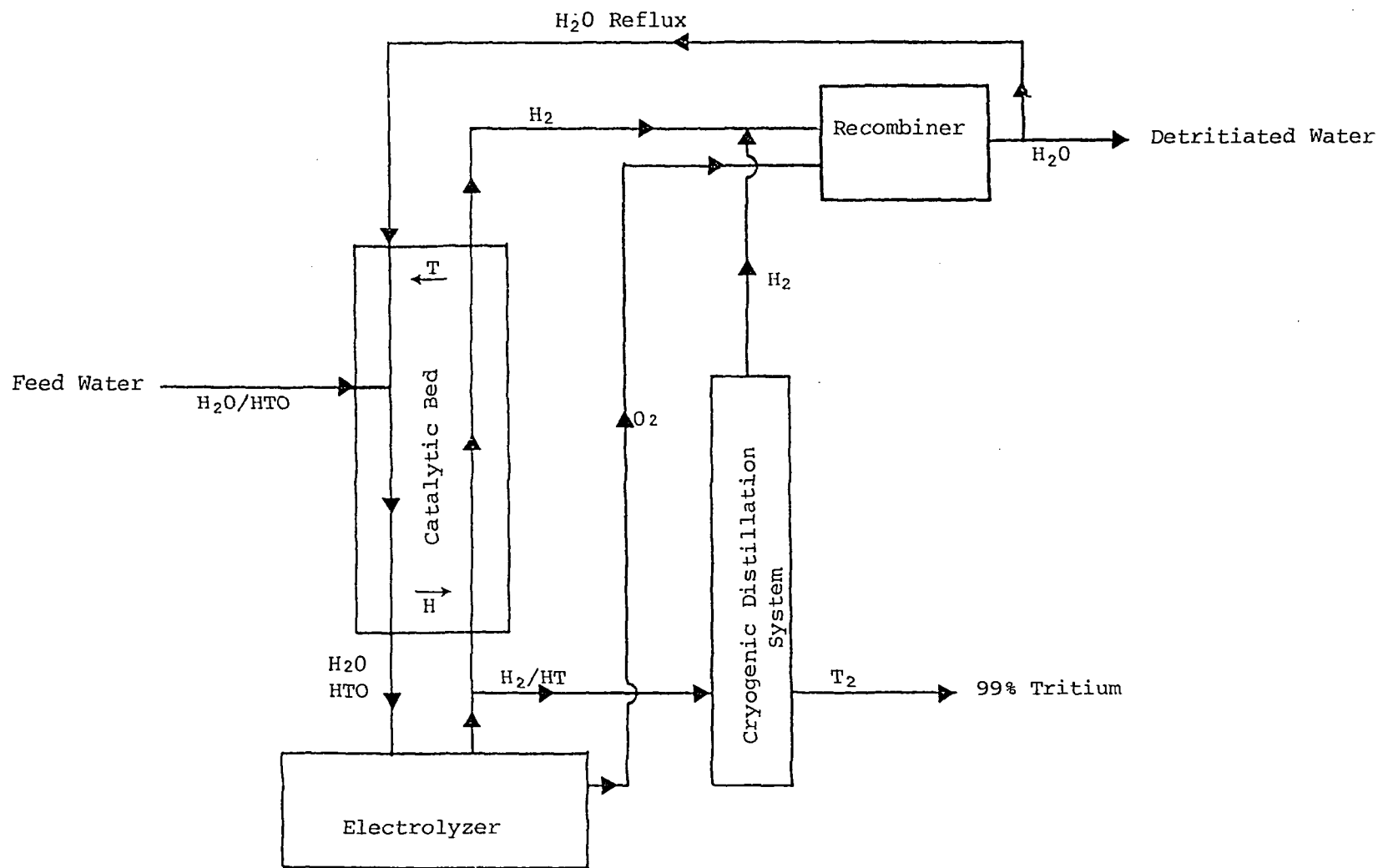


Figure 5

Combined Electrolysis Catalytic Exchange & Cryogenic Distillation

a gaseous hydrogen stream. Tritium is transferred from the gas to the liquid, so that as the streams leave the column, the liquid stream is enriched in tritium and the gas stream depleted. Outside the column, the liquid is electrolysed to provide not only the hydrogen stream for the exchange reaction, but also a product hydrogen stream which is enriched in tritium. At the opposite end of the column, the depleted hydrogen stream is recombined with oxygen from the electrolysis cell to form a detritiated water steam which provides liquid reflux to the column and the detritiated water product.

The chief advantage of CECE is that the cryogenic unit, operating on the relatively high tritium feed coming from the electrolyser can be drastically cut in size relative to the other processes described.

Disadvantages are the need for an even larger electrolyser than in the case of direct electrolysis, due to the need for reflux  $H_2O$  at the top of the column, the need for a lengthy catalytic column and the added hazard of having electrolysis cells full of  $H_2O/HTO/KOH$  at about 10 to 20 times the concentration of the feed streams. The tritium inventory in the CECE system is much higher and the tritium is in the more hazardous oxide form.

The CECE process was developed by AECL. A pilot scale CECE unit has been operated at Mound Laboratories, Ohio, since 1979. The catalyst used is the AECL wet-proof catalyst, and lifetime and activity tests on this catalyst are continuing at AECL at present.

### 5.3 Process Selection

The CECE process is the only one of the four candidate processes which concentrates tritium in the water form to greater than the feedwater concentration. This increases the radiological hazard which can be overcome by putting secondary containment around the cell. However, since more than one cell will be required in all likelihood, and since heat dissipation from the cells is necessary, secondary containment of the cells increases complexity and cost. Additionally, periodic maintenance and electrolyte replacement of the cells will cause radiological exposure to personnel. In studies previously carried out by Ontario Hydro for the DTO/ $D_2$  system, CECE without secondary containment was not found to be significantly lower in cost than other processes. On this basis, CECE is not recommended as the choice for the front-end of the TWRU.

This leaves VPCE, LPCE and E.

The following are the parameters for these processes.

TABLE 1: COMPARISON OF VPCE, LPCE, E  
Basis: Remove 5720 Ci/day

	<u>VPCE</u>	<u>LPCE</u>	<u>E</u>
Feed water flow kg/day	1696	1961	1620
Feedwater concentration Ci/kg	3.37	2.92	3.5
Return concentration Ci/kg	0.05	0.19	0.001
H <sub>2</sub> flow to cryo. unit kg/day	942	1800	180
H <sub>2</sub> concentration to cryo unit Ci/Kmol	11.8	5.8	63.5

It can be seen that the flowrate to the cryogenic unit is ten times larger for the LPCE as compared to E.

Now, the internal circulation in the largest cryogenic column, V, determines the cryogenic unit size and cost.

$$V = F \left(1 - \frac{Y_W}{Y_F}\right) \frac{r}{\alpha - 1}$$

where F is the feed flow to cryogenic column Kmole/h

V is internal circulation Kmole/h

$Y_W$  - tritium concentration in return stream from cryogenic column

$Y_F$  - feed concentration to cryogenic column

r -  $V/V_{min}$ , we will use 1.3

$\alpha$  - relative volatility for H<sub>2</sub>/HT system, at 21.5 K,  $\alpha = 2.11$

	<u>VPCE</u>	<u>LPCE</u>	<u>E</u>
Internal Circulation V Kmole/h	22.93	43.84	4.388
$V^{0.366}$	3.15	3.99	1.72
$V^{0.81}$	12.64	21.37	3.31

Ontario Hydro has derived correlations for the capital cost and power consumption of cryogenic units for hydrogen isotope separation. The capital cost of cryogenic unit is proportion to  $V^{0.366}$ , and power

consumption for the cryogenic unit is proportional to  $v^{0.81}$ . The front-end process costs are not felt to be the controlling costs for process choice. For DTO/D<sub>2</sub> systems, the front-end costs were found to be comparable for the three options. For HTO/H<sub>2</sub> separations, the front-end costs are more favourable towards electrolysis. The above tabulation shows that the capital cost and power consumption is significantly lower for a cryogenic unit associated with an Electrolysis front-end than for a cryogenic unit associated with LPCE or VPCE.

Based on the above analysis, we recommend that Electrolysis + Cryogenic Distillation should be selected for the MARS-TWRU.

#### 5.4 Conceptual Design of the Reference Process

A conceptual flow sheet of the reference process (Electrolysis + Cryogenic Distillation) is shown in Figure 6.

##### (a) Front-End

Feedwater for the TWRU is collected in a storage tank. From there it is pumped to a pre-treatment section where dissolved and solid impurities are removed. The feedwater then flows into the Electrolysis Cells. The electrolysis of 1620 l/day requires 200 kWh/h. The cell being developed by Ontario Hydro/AECL can be confidently scaled up to 25 kA per module, based on the existing module. Therefore, eight 25 kA cells in parallel are required. At a voltage of 2.1 V, the power requirement for Electrolysis is 420 kW. The Electrolysis system is operated at approximately 400 kPa and 80°C.

The hydrogen stream produced by the Electrolysis Cells is cooled and dried by molecular sieve dryers before being sent to the Cryogenic Unit. The oxygen stream is sent to the Recombiner.

##### (b) Cryogenic Unit

The dry hydrogen gas stream is sent to the cryogenic unit where it passes through an adsorber operating at near liquid nitrogen temperature. This adsorber removes the last traces of moisture and also any oxygen and nitrogen. The bone dry, ultra-pure hydrogen gas enters the distillation columns after being cooled further to 21.5 K.

The Primary Column separates H<sub>2</sub> from HT. It operates at approximately 135 kPa and 21.5 K.



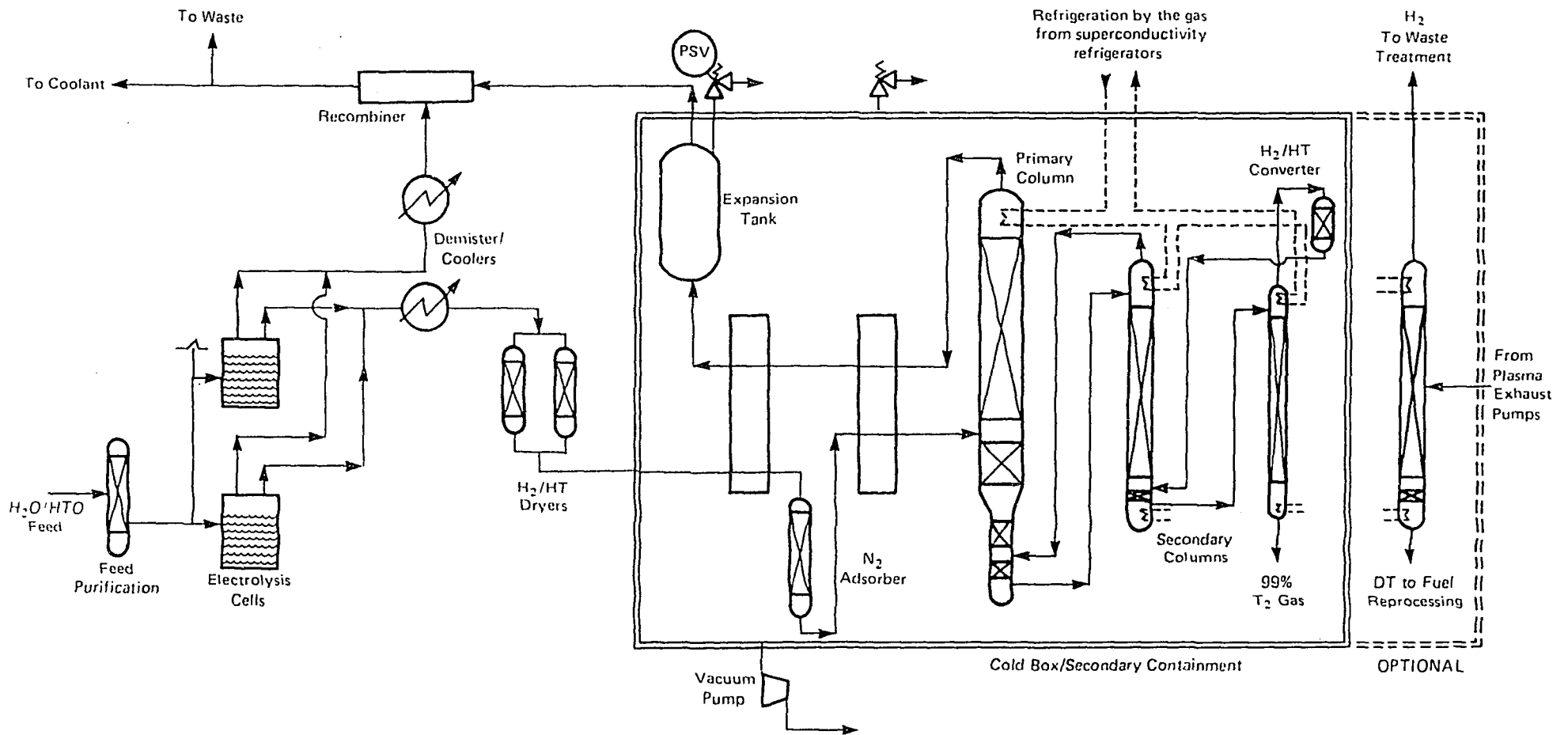


FIGURE 6  
Tritiated Water Removal Unit for MARS – Conceptual Flowsheet

Substantial detritiation is obtained in this column. We have used a computer simulation program developed and tested by Ontario Hydro to assess the performance of the Cryogenic Unit for MARS. The return hydrogen stream from the top of the column is reduced in tritium by a factor of approximately  $10^4$  so that after recombining with oxygen in the Recombiner, the resultant  $H_2O$  has a tritium concentration of approximately 0.001 Ci/kg. The Primary Column imposes the main load on the Refrigeration System. The bottoms from the primary column undergoes further distillation in a second and third column until at the bottom of the last column, a 99 percent  $T_2$  stream is produced ( 0.6 g/day).

The Cryogenic Unit contains packed columns, and is protected from overpressure by an expansion tank which limits the pressure increase upon warm-up of the system. Insulation is provided for the columns by a vacuum of approximately  $10^{-6}$  torr. Material of construction for the Cryogenic Unit is 304L or 316L stainless steel.

(c) Recombiner

A catalytic or flame recombiner can be used for the depleted  $H_2$  stream. For the flowrate of hydrogen expected, a flame recombiner is much less costly than a catalytic recombiner, and is the recommended choice. It is also being used by Ontario Hydro in its tritium removal facility.

(d) Refrigeration

Refrigeration for tritium removal systems can be supplied by refrigerators operating with either hydrogen or helium as the working fluid. A refrigerator using hydrogen requires approximately 2.5 to 3 times less power input than a unit operating with helium. For large systems, the power saving can be significant. For this reason, Ontario Hydro's tritium removal facility uses a hydrogen refrigerator.

For the MARS-TWRU, however, we recommend the use of helium, for the following reasons:

- (a) A much larger helium refrigerator will be required at MARS for cooling the superconducting magnets for the reactor. The additional TWRU requirement for cold helium gas at 17-18K for the TWRU will only impose a small, additional load on this large refrigerator. In this manner, also, the refrigeration requirements for MARS can be integrated into one system.
- (b) The use of a hydrogen refrigerator will increase the working pressure of the cryogenic columns, reduce the relative volatility and increase the size. Since the hydrogen in the refrigeration system should be maintained at above atmospheric pressure at all points to prevent air ingress, the hydrogen in the Primary Column will have to be at a higher pressure than 135 kPa to provide a temperature difference in the column condenser.

It is estimated that the input power requirements for helium refrigeration are approximately 100 kW.

6.0 COST ESTIMATES

6.1 Cost of the TWRU

The cost of the cryogenic unit is given by:

$$C = A V^{0.366}$$

where A is a constant

V is internal circulation in kgmol/h in the Primary Column

C is the cost in millions of 1983 U.S. dollars

From Ontario Hydro's experience, the constant A for small cryogenic units of the size of the TWRU is 2.5.

$$\begin{aligned} \therefore C &= 2.5 \times 4.388^{0.366} \\ &= \$4.30 \text{ million U.S. (1983)} \end{aligned}$$

This cost does not include a separate helium refrigerator, but includes all piping and equipment within the cold box and also includes the recombiner. The cost includes the extensive engineering associated with such a system. It does not include any freight, duty or taxes and any indirect costs such as corporate overheads etc. It can be considered as the money paid to an engineering contractor for procuring such a system.

The cost of the Front-End System can be given as:

$$C_{FE} = B F^{0.7}$$

F is the feedwater flowrate to the system kg/hr

$C_{FE}$  is the cost in million of 1983 U.S. dollars of Front-End, including the Electrolysis Cells, Feed Treatment System

B is a constant

Based on Ontario Hydro's experience, the constant B has a value of 0.2.

$$\therefore C_{FE} = 0.2 \times \frac{(1620)^{0.7}}{(24)} = \$3.8 \text{ million U.S. (1983)}$$

The total cost and power consumption for the TWRU are summarized below:

Table 2: Direct Capital Cost and Power Requirement for TWRU

	Direct Capital 1983 U.S. \$	Power Consumption kW
Electrolysis Unit Front-End	$3.8 \times 10^6$	420
Cryogenic Unit	$4.3 \times 10^5$	100
Total	<u><math>\\$8.1 \times 10^6</math></u>	<u>520 kW</u>

6.2 Cost of the Air Detritiation System (ADS)

The reference design and capacity of the ADS has already been selected by U. of Wisconsin. Five modules rated at 5000 CFM air flow have been selected. Each module consists of a catalytic oxidation and drying unit.

$$C_{ADS} = 12.7 (AF)^{0.6}$$

where AF is air flow in CFM

$C_{ADS}$  is direct capital cost in thousands of 1983 U.S.\$.

Therefore, for AF = 5000

$$C_{ADS} = \$2.1 \text{ million}$$

Direct cost of ADS =  $5 \times 2.1 = \$10.5$  million U.S. (1983)

7.0 TRITIUM LEAKAGE AND EMISSION TO THE ENVIRONMENT

7.1 Design Target for the Tritium in Air Concentration in the MARS Reactor Hall

The United States Code of Federal Regulations, Title 10, Part 20\*, Section 103 gives the statutory requirements for the limitation of exposure of personnel at licensed nuclear facilities to airborne radioactivity. The maximum permissible exposure of an individual to an airborne contaminant during any period of one calendar quarter is specified by requiring that the intake during that period is not greater than the intake which would result from inhalation for 40 hours per week for 13 weeks at a uniform concentration of the contaminant as listed in Appendix B, Table I, Column 1 of Part 20. The concentration given for tritium (in either soluble or insoluble forms) is 5 micro Ci/m<sup>3</sup>. The

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\* Henceforth in this report this document will be referred to by the standard abbreviation, namely 10 CRF Part 20.

footnotes to Section 103 state that for tritium oxide the total intake permitted is twice that which would result from inhalation alone at this concentration, thus allowing for the intake by skin absorption.

The above requirements are modified by the need to maintain radiation exposures "as low as reasonably achievable" (ALARA) as specified in 10 CFR Part 20, Section 103. Implementation of the ALARA philosophy normally involves a process of optimization of the design of the facility being considered. Guidance on the application of this philosophy is provided in the Nuclear Regulatory Commission (NRC) Regulatory Guides 8.8 and 8.10. In addition, a description of the methodologies that should be employed in the optimization process is provided in Publication 37 of the International Commission on Radiation Protection, which is entitled "Cost - Benefit Analysis in the Optimization of Radiation Protection."

In the absence of information on the design of the MARS facility, it is only possible to provide general targets for airborne contamination levels. As a result of operating experience at Ontario Hydro's CANDU nuclear generating stations, a set of air quality assessment criteria have been developed for use as design targets. These criteria are part of an overall philosophy for tritium control in which one of the fundamental concepts is that contamination control is more effective and efficient when imposed at the source, both for component leakage and process emissions. One of the techniques employed at the design stage to implement this concept is to locate equipment which has a potential for significant contribution to the airborne tritium contamination in "confinement" rooms. In this way the volumes of contaminated air which need to be processed can be minimized and unnecessary exposure of personnel in other, "normally accessible," areas of the station can be avoided. The target tritium in air concentrations for normally accessible areas and confinement areas are as follows:

<u>Type of Area</u>	<u>Target Tritium in Air Concentration</u>
Normally Accessible	0.01 to 0.1 MPCa*
Confinement	0.1 to 1.0 MPCA**

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\* MPCa = Maximum Permissible Concentration in air, e.g., from 10 CRF Part 20 for tritium oxide 1 MPCa = 5 micro Ci/m<sup>3</sup>.

\*\* Ontario Hydro design practice for control of airborne contamination is based on the concept that in confinement areas the controlled use of equipment for respiratory protection of individuals is acceptable. Therefore, although in some confinement areas the actual concentration of airborne areas the actual concentration of airborne contaminants may be greater than the MPCa value based on an unprotected, 40 hour per week occupancy, the concentration to which the occupational individual is exposed is effectively maintained at less than 1 MPCa.

The rationale for setting design targets for normally accessible areas that are in order of magnitude lower than the targets for confinement areas is based on the following fundamental premises:

- (a) the exposed population is significantly larger for the normally accessible areas than for the confinement areas;
- (b) the occupancy time, i.e. hours per week, per individual in the normally accessible areas is significantly longer than the occupancy time per individual in the confinement areas; and
- (c) the targets for chronic airborne contamination must include provision for radiation exposure from other internal and external sources.

On this basis, given the major potential sources of airborne contamination and external exposure are located in the confinement areas, selection of appropriate design features to achieve the above targets generally represents a cost-effective measure when considered as part of an integrated occupational dose management program.

It is suggested that the MARS reactor hall should be considered to be a normally accessible area, so that the target for the tritium in air concentration should be between 0.01 MPCa and 0.1 MPCa. If the chronic tritium in air concentration is within this range, the resulting dose commitment to an individual resident in the reactor hall for 40 hours per week for 13 weeks would be between one percent and ten percent of the permissible quarterly dose specified in Section 101 of 10 CFR Part 20, i.e., between 12.5 and 125 mrem. Over a period of a year the corresponding dose commitment would be between 50 and 500 mrem.

An area of difficulty which might arise when assessing compliance with the design target presented above is the determination of the relative quantities of elemental tritium, i.e., tritium gas, and tritium oxide in the reactor hall air. Although 10 CFR Part 20 does not distinguish between these forms of tritium, tritium oxide is a significantly greater radiological hazard than elemental tritium. The MPCa value employed by Ontario Hydro for elemental tritium is  $0.2 \text{ Ci/m}^3$ , based on a quality factor of 1.0 for tritium radiations. The U.S. practice of assigning a quality factor of 1.7 to tritium radiations would therefore yield an MPCa value for elemental tritium of approximately  $0.1 \text{ Ci/m}^3$ . Assuming that the Air Detritiation System is the only pathway for removal of tritium from the reactor hall atmosphere, with an air flow rate of  $280 \text{ m}^3/\text{minute}$  (equivalent to the 10000 cfm value specified in the data provided for this study), the maximum rate of release of tritium oxide to the reactor hall atmosphere that would comply with the proposed target is 0.0084 Ci/hour. ( $0.1 \text{ MPCa}$  of tritium oxide =  $0.5 \text{ micro Ci/m}^3$ ). However, employing the same assumptions and data, the maximum rate of elemental tritium to the reactor hall atmosphere that would comply with the proposed target is 168 Ci/hour ( $0.1 \text{ MPCa}$  of elemental tritium =  $0.01 \text{ Ci/m}^3$ ).

The following analysis indicates the procedure for assessing compliance with the proposed targets. It is based on the data available for the MARS water coolant system together with a number of assumptions related to the MARS design and tritium behaviour. One of the basic assumptions employed is that there is no segregation of the water coolant system components, i.e. all the components are located in a common air volume (the reactor hall), so that all leakage from the coolant system results in the release of tritium to the reactor hall atmosphere.

To assess compliance with the design target in a situation where there is a mixture of radioactive materials which have different radiological significance, the method described in the footnotes to Appendix B of 10 CFR Part 20 should be employed.

#### Assumptions

- (1) MARS reactor hall volume =  $1 \times 10^6 \text{ m}^3$ .
- (2) Air Detritiation System flow rate = 10000 cfm =  $280 \text{ m}^3/\text{minute}$ .
- (3) From 10 CFR Part 20, 1 MPCa of tritium oxide =  $5 \text{ micro Ci/m}^3$ .
- (4) All tritium present in the MARS water coolant system is in the oxide form.
- (5) The concentration of tritium in the MARS water coolant system is 1 Ci/kg of coolant.
- (6) All water leaking from the coolant system in vapour form is released to the reactor hall atmosphere.
- (7) The rate of leakage of water in vapour form from the coolant system is 3.2 kg/hour (see Section 6.2).
- (8) The air detritiation system is the only pathway for removal of tritium from the reactor hall atmosphere.

Since the rate of release of tritium oxide from the coolant system to the reactor hall atmosphere would be 3.2 Ci/hour, at equilibrium the rate of removal of tritium oxide by the air detritiation system must also be 3.2 Ci/hour. Therefore, an air detritiation flow of only  $280 \text{ m}^3/\text{minute}$  gives an equilibrium tritium oxide concentration of 190 micro Ci/ $\text{m}^3$ , or 38 MPCa. If tritium oxide released by other sources in the reactor hall is added to this, together with tritium oxide produced by conversion of elemental tritium, the concentration in the reactor hall at equilibrium for an air detritiation system flow rate of  $280 \text{ m}^3/\text{minute}$  could be considerably higher than this.

The minimum concentration of tritium oxide in the reactor hall atmosphere calculated on the basis of the assumptions stated is therefore already more than two orders of magnitude above the range of target concentrations of 0.01 to 0.1 MPCa. Naturally, the implications of this

result must be judged against the perceived validity of the assumptions employed. Assumptions 4 and 6 are particularly critical. However, there is an apparent need for measures to reduce the concentration of tritium oxide in the reactor hall, e.g. by segregation of equipment, improved component leaktightness or increasing the capacity of the air detritiation system.

In a given situation the ventilation flow rate will be determined by whichever of the following requires a greater flow rate:

- (a) the need for removal of excess heat from process system components;
- (b) the need for provision of a suitable working environment for personnel; and
- (c) the need to meet the design targets for airborne contamination concentrations.

#### 7.2 Estimated MARS Coolant Leak Rate

Based on operational data from Ontario Hydro's fission reactors, the average chronic leak rate from the primary heat transport systems of a reactor was approximately 5 kg/hour. Of this amount, approximately ten percent remained in the liquid form, the remainder evaporating either instantaneously on being released or subsequent to release but prior to entering the leakage collection systems. Taking this data as being reasonably representative of leakage from a modern high temperature water coolant system, the leak rate for the MARS system can be estimated. Using the respective coolant masses to derive a scaling factor, the estimated average chronic leak rate for the MARS coolant system (total mass = 66 Mg) is 1.1 kg/hour, of which approximately 0.1 kg/hour remains in the liquid form.

#### 7.3 Emissions to the Environment

We have conducted a review of suitable emission targets for the MARS project. Based on our review of literature and involvement in other fusion projects, the following tritium emission targets are recommended:

	<u>Liquid Emissions</u>	<u>Gaseous Emissions</u>
Design Targets for Normal Operation	10-20 Ci/day	10-20 Ci/day

The tritium control design of the MARS project should aim for the low end of this target range. Most fusion reactor designs have chosen values of about 10 Ci/day. Often no distinction is made between tritium emission forms in quoting targets and none is made here.

These targets, we feel, can be comfortably met by the tritium control systems included in this study.



The Air Detritiation System, assuming a reasonable detritiation efficiency of 99.9 percent, will emit 1.0 Ci/day based on an influent tritium rate of 1000 Ci/day.

The waterborne emissions can be reduced to low levels, if the electrolysis Front-End is used. We have performed a preliminary computer simulation of the Primary Column in the Cryogenic Distillation System, when it is coupled to an Electrolysis Front-end. The results show that after recombination, the water produced has a tritium concentration of 0.001 Ci/l. From a water balance, this translates to a waterborne tritium emission rate of 0.3 Ci/day.

	<u>Liquid Emissions</u>	<u>Gaseous Emissions</u>
Design Targets	10-20 Ci/day	10-20 Ci/day
Predicted Emissions	0.3 Ci/day	1 Ci/day

#### 8.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study are:

- (1) The technologies needed for tritium removal from water and air are available on the commercial market.
- (2) The combination of an electrolysis front-end together with cryogenic distillation of hydrogen isotopes appears to be the best choice for detritiating water streams in this particular application under the present economic climate.
- (3) The integration of all hydrogen isotope separation needs in one facility using parasitic cooling provided from superconductivity refrigerators would offer the lowest initial cost and operating economy and simplicity.
- (4) We suggest that the target for the tritium concentration in the reactor hall should be between 0.01 and 0.1 MPCa ( $0.5 \text{ micro Ci/m}^3$ ). Assuming that leakage from the water coolant system is released directly to the reactor hall and that the tritium in this system is in the oxide form, this target is exceeded by more than two orders of magnitude at the assumed air detritiation system flow rates.
- (5) We suggest that the emission targets should be 10-20 Ci/day in the waterborne form and 10-20 Ci/day as airborne tritium. These targets are not expected to be exceeded in the reference design.

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