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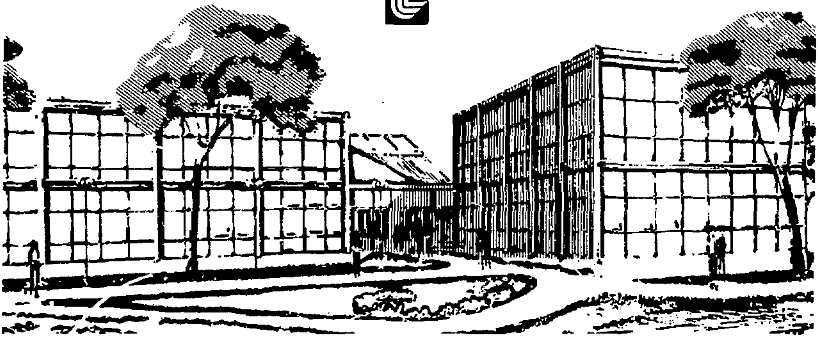

TRITIUM CONTROL IN A MIRROR FUSION CENTRAL POWER STATION*

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We describe tritium-containment systems for the blanket and power systems of a mirror-fusion reactor. These systems are designed to reduce emissions to below 1 Ci/d. The overall conceptual design uses air as the reactor-hall atmosphere. A continuous catalytic oxidizer-molecular sieve adsorber cleanup system would be used to control a 180-Ci/d leakage from reactor components, energy recovery systems, and process piping. Such a system would maintain a 40 $\mu Ci/m^3$ tritium level (5 $\mu Ci/m^3$ HTO) in the hall.

The blanket considered contains submodules with $Li_2Be_2O_3$-Be for tritium breeding. This canned breeding material is scavenged with a lithium-vapor-doped helium gas stream. The container consists of molybdenum alloy (TZM) tubes and tube sheets with the breeding material packed and sintered in the shell surrounding the tubes. Potassium vapor coolant (also lithium-doped) passes through these tubes to recover the heat at 950 Leakage following an intermediate TZM exchanger would result in a loss of 0.7 Ci/d into the steam through the Haynes-25 alloy boiler (potassium boiling). A moving getter bed is used to recover the tritium from the LiT and Li_2T scavengers in both the helium blanket scavenging flow and the potassium vapor coolant.

REACTOR HALL CONTAINMENT GOALS

Environmental Impact

The accumulated tritium emissions from the 1500 1-GW(e) fusion reactor power plants to be built in the world by the year 2025 would not significantly add to the present tritium background if emissions were kept below 1 Ci/d-GW(e).(1,2) With 10 000 plants by the year 2050, the emission will have to be below 0.1 Ci/d.

Emissions from a reactor hall with an approximate volume of 350 000 m^3 can only be kept at such a low level if the tritium concentration within the gas cover (inside the reactor hall) is kept low (i.e., 40 $\mu Ci/m^3$) and if the entire wall surface is hermetically sealed. At ambient temperatures, a stainless steel shell (alloys 304, 316, or 321) 2 mm thick would provide the necessary seal.(3) This shell

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would meet our low-permeation standard (<1 Ci/d) even in the case of an incredible accident where 2.3 kg of T_2 might be ignited and dumped, releasing HTO, T_2O, or both into the reactor hall and quickly increasing the concentration up to 24.5 ppm (65 Ci/m^3). (Less than 200 Ci of tritium can be released if we are to *remain below LWR criteria of 5 mrem at the* fenceline under poor dispersion conditions.)

The hermetic stainless steel liner would be constructed on standoffs or studs cast into the concrete shell of the building. Thus, there would be a space between the liner and the building itself; contamination within this space would be kept at around 5 μCi/m^3. If we postulate that the facility must have the containment and *removal capability necessary to reduce the* high level of contamination described above to a level of 200 μCi/m^3 for reentry with light suits into the building after 7 d of reactor-hall air processing, then the length of the standoff must be 79 cm. This design concept would be economical and safe, and it would provide acceptable secondary containment for the reactor hall.

Occupational Safety

We have selected the nominal level of 40 μCi/m^3 *as acceptable for very particular* health and safety as well as state-of-the-art hardware reasons. A worker can be exposed at 100% maximum permissible concentration (MPC) for 40 h per week without any clothing protection to contamination levels of 40 μCi/m^3 if the HTO fraction remains below 12% by volume. ERDA recommends(4) that for design purposes, levels at 20% MPC should be used. This would be quite feasible if one either restricts *work assignments to 8 h per week or pro*vides analytical evidence for HTO fractions below 2%. The workers might be further protected by light-weight suits and face masks that would not interfere with agility or dexterity. Such light-weight suits (plastic undersuit, coveralls, and a plastic oversuit) with air masks(5) can provide protection factors of 100 or more if changed hourly or *factors of 10 or more if not changed for* 8 h. Under accident conditions, ventilated suits(5) can offer protection factors up to 1900. Thus, it can be seen that the nominal level of 40 μCi/m^3 offers a large number of operational options, while still remaining close to the economic and safety optimum.

There must be some assurance that in the operational design described above, the level of 2 or less HTO can be *feasibly maintained. It is this question* that is critical to the practicality of the design. The HTO can be produced from T_2 or HT by several chemical means: isotopic exchange with H_2O in the water-laden air within the reactor hall, autoradiolysis of T_2 in air (oxygen), catalytic conversion of T_2 or HT through active metal surfaces exposed, and radiolysis of T_2 or HT in air via radiation field escaping the mirror machine. *It is because of these reactions that* planners have assumed in the past that there could be no air present in fusion-reactor halls. However, careful review of current research and technology suggests that air might be used. If care is taken to eliminate exposed, hot, precious metal (catalytic) surfaces, excess water vapor, and any buildup of T_2, then the formation of HTO can be kept at manageable levels even in an air atmosphere. Estimates of *the conversion rates have been made by* fitting available data(5,6) to a rate equation. The results are as follows:

$$HTO = T_2(0)[1 - \exp(-kT_2(0)\ )],$$

where is time for conversion in hours, $T_2(0)$ is the initial T_2 concentration in $\mu Ci/m^3$, k is the rate constant, and HTO is *the calculated concentration of HTO in* $\mu Ci/m^3$. At levels of $T_2(0)$ of 40 $\mu Ci/m^3$, the rate of formation of HTO would always be less than 1.0×10^{-6} $\mu Ci/m^3/h$ (Table 1). The conversion rate does not get significant until $T_2(0)$ levels of 65 Ci/m^3 are approached. In the "incredible accident" case described above in which such levels would be attained, 11 Ci/m^3 of HTO would be produced in the first hour. From this analysis, we see that the important goal *is to keep T_2 at low concentrations.*

BLANKET AND PROCESS PIPING LEAKAGE

Reactor Hall Processing

Now that it has been established that a tritium level of 40 $\mu Ci/m^3$ is a safe working environment within the reactor hall, we can examine the constraints that this goal places on the other components in the nuclear island. Experience in our facility at the Lawrence Livermore Laboratory and other tritium research and *development facilities in the U.S.* suggests that with a continuous air-recirculation system or a once-through air exhaust system, the ambient room tritium levels depend on the cleanliness of the worker, on the outgassing of tritium from leaking equipment, and on de-adsorption *from room and hood surfaces. The ambient* level for a given room volume depends on the replacement rate of the air within this volume and on the tritium outgassing rate. The relationships are fundamental with the mass balance, as shown in Table 2.

These outgassing rates can be compared favorably with available estimates(7) for tritium leakage loss (including permeation) from a state-of-the-art energy *recovery system (process piping, pumps,* heat exchangers, turbines, etc.). For example, a conventional energy recovery system constructed of stainless steel for a 470-MW(e) plant would release about 70 Ci/d of tritium gas into the reactor hall.(7) Thus, typical for a 1-GW(e) reference reactor design, air flows of around 60 m^3/s (100,000 cfm) are required. This rate is typical of moderate size office buildings with conventional off-*the-shelf air-conditioning hardware. For*

TABLE 1. Oxidation of T_2 to HTO in Reactor Hall (Initial Concentration = 40 $\mu Ci/m^3$) (HTO Concentration in $\mu Ci/m^3$)

Time (h)	Dry Air	Humid Air	Steel Catalyzed[a]	Rad. Field on Steel(b)
1	9.96×10^{-7}	4.01×10^{-6}	9.75×10^{-5}	0.6×10^{-3}
2.5	2.49×10^{-6}	1.00×10^{-5}	2.44×10^{-4}	1.58×10^{-3}
50	4.98×10^{-5}	2.01×10^{-4}	4.88×10^{-3}	3.1×10^{-2}
2 000	1.99×10^{-4}	8.00×10^{-3}	1.92×10^{-1}	5.0
10 000	9.98×10^{-3}	4.00×10^{-2}	0.96	25.0

(a) With humid air.

(b) Radiation field taken to be 40 000 R/hr. on steel catalyzed surfaces in humid air.

TABLE 2. Maximum Tolerable Outgassing Within Reactor Hall to Maintain 40 μCi/m^3

Air Flow (m^3/s)	Air Flow (cfm)	Volume Changes Per Hour	Outgassing Tolerated (Ci/d)
0.36	607	1/24	1.0
5.88	10 000	0.05	18.0
58.8	100 000	0.5	180.0
2352	4 000 000	20.5	7200.0

this flow a catalytic processor to oxidize and remove the tritium would cost about 3 million dollars for a complete process using about 5 m^3 of precious metal catalyst.

It is clear that relative to tritium leakage and permeation, there will be an optimum tradeoff between the size of the reactor-hall waste-gas handling system and the design of the thermal energy recovery system. Doubly or triply contained process piping and heat exchangers represent one extreme while thin steel at high temperature represents the other. Multilayer composite tubing looks feasible for low permeation (i.e., 1/20) uses.(8)

Indicated in Table 2 is the air flow that would release 1.0 Ci/d at 40 μCi/m^3 (607 cfm). This fact tells us that the operation of conventional "air flush" air locks through the reactor hall wall to the outside would result in releases of more than 1 Ci/d. Pump-down locks could solve this problem. If one expects to change 16 blanket sections per year, this would represent a flow of only 2 m^3/h (1 cfm) if the lock were the pump-down variety and if 100 personnel accesses were required per day. The resulting release would amount to 8 m^3/h (4 cfm).

Spill Accident

The demands imposed by our "incredible accident" upon the reactor-hall and the waste-gas processing systems must now be discussed. Worker reentry time following cleanup of the accident must be estimated as well. This problem is a difficult one because the cleanup transient behavior is difficult to predict. The sudden increase in T_2O concentration will drive T_2 and HT into many materials and create adsorbed layers of T_2O on all exposed surfaces totaling around 5100 Ci.

As a practical rule,(9) in addition to the conventional dilution time, 40 changes of air are required to reduce the surface accumulations. This amounts to an additional 3 days. There are procedures for surface cleaning designed to enhance tritium outgassing, such as steam cleaning, a smooth, polished surface, electro-cleaning, etc.

Spill Cleanup

Neglecting the adsorption-controlled outgassing problems discussed above, we can make an estimate of the processing time required to reduce the [illegible] Ci/m^3 to the 40-μCi/m^3 operating level. Using the study at Mound Laboratory(10) for the determination of the catalytic oxidation kinetic rate data, we developed a process system model.

The plug flow reactor design equation can be written(11) as

$$\frac{T_1(\ )}{T_2(\ )} = \exp\left[-k\,\frac{Vc}{\eta}\right],$$

where Vc is the catalyst volume and k is the first-order kinetic rate constant,

$$k = 2.27 \cdot 10^5 \exp[-7100/RT],$$

as determined at Mound.(10) Although this plug flow approach is simplistic in that it neglects pore diffusion and dispersion effects, low-temperature (300 K) operation causes these effects to be insignificant.

Eliminating $i_1(\ )$ results in

$$T_2(\ )\left[1 - \exp\left(-k\frac{Vc}{Q}\right)\right] = -\frac{V}{Q}\,\frac{dT_2(\ )}{d} \ .$$

Integrating

$$\int_{T_{2,0}}^{T_2(\ )} \frac{dT}{T_2} = -\left[1 - \exp\left(-k\frac{Vc}{Q}\right)\right]\frac{Q}{V}\int_0 d$$

results in

$$\frac{T_2(\ )}{T_{2,0}} = \exp\left\{-\left[1 - \exp\left(-k\frac{Vc}{Q}\right)\right]\frac{Q}{V}\ \right\}.$$

In Fig. 1 we show model results illustrating the reactor hall tritium content as a function of time for systems with various catalyst volumes. Because of expense, catalyst beds larger than 10 m^3 are not practical; thus safe reentry times (40 MPC with light suits) could range from around 3 days to 1 month for reasonable bed designs. Costs (plant plus catalyst) for such a recirculatory system are shown in Table 3.

Thus, the system presented is nearly optimally configured for both the routine leakage task and the incredible failure. Now we have to ensure that our blanket containment scheme can keep internal emissions below 180 Ci/d.

BLANKET DESIGN WITH PERMEATION BARRIERS

The problems of tritium containment in a solid blanket configuration will be examined. This configuration has a potassium-vapor-cooled niobium first wall and a blanket structure containing lithium beryllate ($Li_2Be_2O_3$) packaged and canned in TZM as a heat exchanger shell.

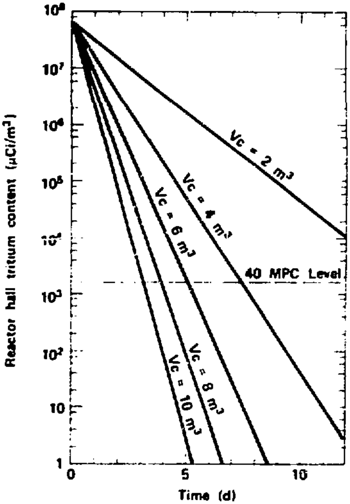

FIGURE 1. Tritium Reduction after the Incredible Accident (Q = 58.8 m^3/s (100 000 cfm); T_2O = 65 Ci/m^3; V = 350 000 m^3; Temp. = 300 K); Vc = catalyst volume

TABLE 3. Approximate Costs for Recirculating Systems as a Function of Catalyst Volume, Vc.(a)

Vc (m^3)	Approx. Recirculating System Cost (millions of dollars)
2	1.3
4	2.4
6	3.6
8	4.8

(a) Basis: Honeycomb catalyst at \$60 000/m3, 10% of recirculating systems cost.

A detailed review and analysis of Brookhaven National Laboratory(12) results suggests that the beryllium metal-lithium beryllate ($Li_2Be_2O_3$) mixture is the leading contender owing to its high melting point (1150°C), low tritium solubility, sustained breeding ratio (BR ~ 1.2), low residual radioactivity, low reactivity with air or other common chemicals (i.e., beryllium) and resistance to sintering problems. $LiAlO_2$ would qualify, were it not for its strong reactivity with beryllium or BeO.(13)

The phenomenology of tritium production within the Be-$Li_2Be_2O_3$ particle mix can be visualized as follows. Neutron multiplication in the Be (and the resulting bombardment) results in a transmutation of lithium atoms within the crystalline structure to ^3H or T, which diffuses through grain boundaries, dislocations, pores, etc., to the surface. Somewhere in this process, the oxide (T_2O) is formed, and this T_2O reaction product is chemically bound (complexed) on these internal and external surfaces. Chemical reduction of this T_2O-$Li_2Be_2O_3$ surface complex on the surrounding Be can occur, thus releasing T_2 gas into the flowing helium gaseous tritium scavenging stream.

The data are available for 650°C and can be extrapolated to our operating condition of 950°C. These results indicate that for holdup times around 5 min, 99% of the blanket-contained tritium can be removed to achieve inventories of 12 500 Ci or 1.2 g.

MOLYBDENUM ALLOY (TZM) BLANKET CONTAINMENT

Our blanket concept for the Be-$Li_2Be_2O_3$ canned with the molybdenum alloy is shown in Fig. 2. Our first task here is to estimate the permeation of tritium to the potassium-vapor coolant stream so that we

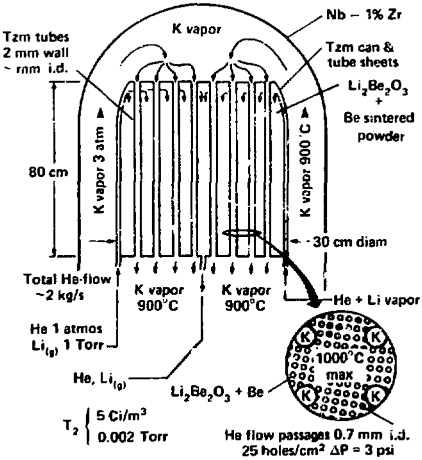

FIGURE 2. Blanket Module Design With Potassium-Vapor Cooling and Integral Secondary Tritium Containment

can size the wall thicknesses properly and obtain pressure drop estimates for the helium scavenging flow.

Helium Scavenging System

A helium scavenging flow rate of 2 kg/s is selected. Such a rate will provide good scavenging characteristics, low pressure drop through the blanket, and small piping costs. The porous Be-$Li_2Be_2O_3$ bed shown in Fig. 2 must be designed to provide a low pressure drop for the helium scavenging stream so as to avoid stressing the TZM internal structures. A pressure drop around 21 kPa (3 psi) is desired. If a small fraction (1) of the blanket area can be utilized for flow passages through the Be-$Li_2Be_2O_3$ bed, the flow passage diameter and number density can be computed. A 1. area would be about 2.5 m^2 (70 ft^2) producing linear velocity of 7.6 m/s (25 ft/s). The diameter required to meet the pressure drop criteria will therefore be 0.7 mm. Thus, there would be about 25 holes/cm^2. The flow will be laminar at a Reynolds number of 5.

It should also be mentioned here that the total pressure of the helium scavenging stream is maintained around 1 atm. The potassium-vapor coolant stream total pressure will be around 3 atm. The purpose of this difference is to ensure that any failure or breeching of the TZM blanket container will result in a guaranteed flow of potassium into the helium scavenging stream. This is expected to prevent massive tritium leaks into the potassium via mechanical fractures or pores.

At this helium scavenging flow rate of 2 kg/s, the tritium production within the blanket of 3.6 × 10^3 g/s will result in a concentration of 1.8 × 10^{-6} atm or 5 Ci/m^3 in the helium flow This concentration would constitute the driving force out of the blanket across the TZM tubes into the potassium-vapor coolant flow or any other sink. However, a scavenging agent such as lithium vapor can be added to the helium flow to complex the tritium into lithium and Li_2T, which will not permeate the TZM barrier.

Data on the equilibrium distribution of gas-phase constituents as a function of temperature in the Li-D systems are available.[13] At 950°C, about 480 mol of D_2 are complexed with lithium for any single mole of D_2 freely available in the gas phase for permeation. The lithium vapor acts as a scavenging agent to reduce the effective D_2 concentration by a factor of 480. It is assumed that the Li-T system will behave identically.

It is obvious that this lithium vapor getter concept becomes feasible only at high temperature where the equilibrium is favorably shifted toward the complex above 500°C. There is one constraint, however. The amount of lithium-phase vapor cannot exceed its vapor pressure; otherwise a liquid phase will condense out. In our design, a concentration of 1.0 Torr (0.1%) was used, which is safely below its 4-Torr vapor pressure.[14]

Permeation

Available permeation data[15] for molybdenum indicate that if the TZM solid suspension system will behave as pure molybdenum and if the lithium scavenging agent performs its task in the helium scavenging flow, the 2-mm TZM tubes with an aggregated area[16] of about 2 × 10^7 cm^2 (about 50% of the heat transfer area) will permeate tritium at 3600 Ci/d to the potassium-vapor coolant.

If 5% of this loss by further leakage appeared in the reactor-hall atmosphere, the room processor could handle this load, since its maximum rating would be 180 Ci/d at 58.8 m^3/s. However, most of this loss is expected to appear in the potassium-vapor coolant loop with a flow around 2000 kg/s,(16) resulting in a tritium concentration of around 34 $\mu Ci/m^3$. This level of contamination is 17 times MPC for a controlled access area,(4) assuming that it was all converted to T_2O by the time it came in contact with operating personnel. A tritium leak from this line and a ten-fold dilution (authorized 25-rem dose) allow the unprotected emergency rescue worker about 1-min to accomplish his task.

There are other sources of tritium, however. Tritium is produced at low levels with the beryllium in portions of the blanket that would not require a lithium breeding material or an associated helium scavenging flow (added molybdenum is degrading to the neutronics). For this reactor concept, this tritium production would amount to 31 100 Ci/d. This would be intolerable if it were totally released to the potassium-vapor flow. Thus, these purely energy-producing blanket sections can be contained also with TZM tubes as before, but for the same permeation leakage at 3600 Ci/d, the wall thicknesses could be reduced by 100 or so.

Tritium would also enter the potassium-vapor stream through the first wall (niobium-1% zirconium) through energetic particle implantation deep into the niobium wall. Although the peak tritium concentration level will occur only a few *micrometres*(17) into the niobium surface from the plasma, the diffusion coefficient is so very large that one must assume that the wall acts as a source of tritium at a depth of 1.5 mm and in porportion to the relative distances (1.5 μm/2 mm) could leak into the potassium-vapor stream. This leakage is expected to be 96.8 Ci/d, contributing 0.7 $\mu Ci/m^3$ to the concentration. These problems can be handled through the addition of a lithium-vapor scavenging agent to the potassium vapor. As before, lithium will complex the tritium containment through LiT and Li_2T and reduce the gaseous T_2 level some 480 times to 0.7 $\mu Ci/m^3$.

Blanket Tritium Processing

A moving bed getter(18) *of zirconium* pellets can be used to remove tritium selectively from the LiT and Li_2T in the blanket helium scavenging flow and from a slip stream taken off the main coolant potassium flow. Such getter systems(16) typically have capacities of 60 cm^3 T_2 per gram of getter at standard temperature and pressure. Thus, this moving getter bed would remove at 80% per pass (loading at 3.8 wppm), the tritium that would leak into the helium scavenging flow. The getter material would move at 55 kg/min, tying up 1900 g of tritium as inventory in the 78-m^3 bed. In railroad-car-lot quantities, zirconium (with up to 10% hafnium as impurity) as getter would cost 6.5 million dollars.

To handle the potassium-vapor flow, the moving getter bed concept can be utilized by processing a slip stream of 34 $\mu Ci/m^3$ of T_2 through the moving getter bed. This small unit would only have to process 7 g of getter per minute.

The 7.3-Ci/d leakage of tritium from the potassium coolant loop (with 34 $\mu Ci/m^3$ tritium) into the reactor hall can be estimated assuming 100 m of 2.5-mm-wall stainless steel pipe of 15-cm i.d. Most of this low-level leakage can be purged by air ducting arranged along the pipeway channels with the flow into the reactor hall processor.

The leakage of tritium from the potassium through the steam boiler heat exchanger into the steam would be an estimated 0.7 Ci/d for a Haynes-25* boiler at 600°C with an area of 5 × 10^7 cm^2 and with 3.8-mm-thick stainless steel walls. A *stainless steel boiler with a thin tungsten* clad coating of 100 μm will reduce this leakage to 0.03 Ci/d.

A summary of these various process-stream tritium concentrations and their associated leakages is given in Fig. 3. Clearly, where accidental exposure to workers from process piping failure is possible, concentrations near MPC are desirable. The tritium leakage to the

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*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

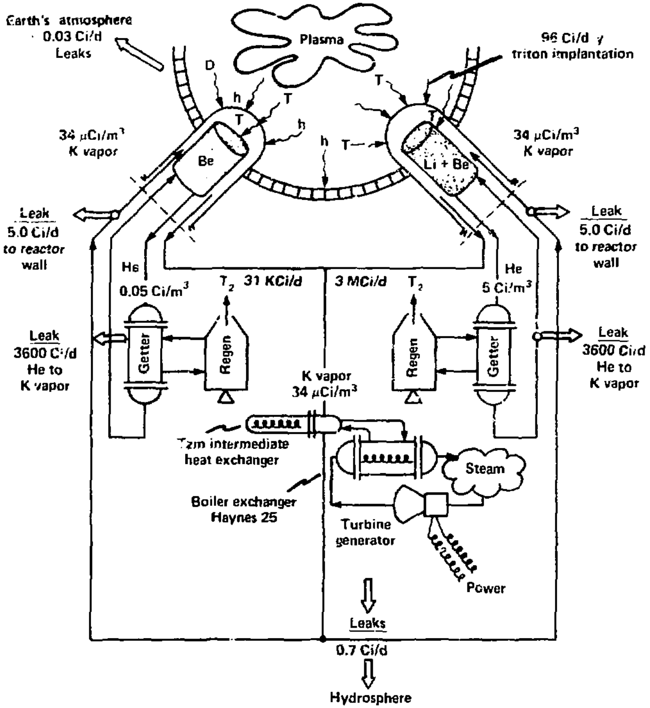

FIGURE 3. Control of Tritium Losses

environment is below our goal of 1 Ci/d. This ranges from below 0.03 Ci/d from the reactor hall under accident conditions to 0.7 Ci/d if all the leakage from the boiler appeared in the steam cycle and escaped.

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