Conf. 751125 . . 46

SCOPING STUDIES OF TRITIUM HANDLING IN A TOKAMAK
EXPERIMENTAL POWER REACTOR*

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For presentation at the Sixth Symposium on Engineering Problems of Fusion Research, San Diego, California, November 21, 1975

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Abstract

Tritium handling techniques in an experimental fusion power reactor (EPR) are evaluated to determine the requirements of the system and to compare different equipment and techniques for meeting those requirements. Tritium process equipment is needed to (1) evacuate and maintain a vacuum in the plasma vessel and the neutral beam injectors, (2) purify and recycle tritium and deuterium for the plasma fuel cycle, (3) recover tritium from experimental breeding modules, and (4) provide tritium containment and atmospheric cleanup. A development program is outlined to develop and demonstrate the required techniques and equipment and to permit confident design of an EPR for operation by the mid-1980s.

1. Introduction

The experimental power reactor (EPR) operating at 150 MW(t) from fusion reactions would consume 200,000 Ci, or 20 g, of tritium per day. If the fraction burned is 1%, this would correspond to a tritium process rate of 20 MCi, or 2 kg, per day. This will be, by far, the largest tritium handling system built by the mid-1980s for a fusion experiment. The tritium handling system will include equipment to evacuate the reactor vessel, purify and recycle fuel to the reactor, separate deuterium and tritium for injection, extract tritium from the breeding blanket, and control tritium releases by containment and atmosphere cleanup. In size and complexity, the EPR system will represent significant extrapolations from the Tokamak Fusion Test Reactor (TFTR) tritium system; this will include larger quantities of tritium, more complete and more reliable containment, and larger equipment, as well as additional process steps. The EPR may provide the first realistic demonstration of all major components of a fusion power reactor tritium handling system. It will be the first operating fusion device to provide on-site purification and recycle of unburned fuel. (TFTR plans currently call for collection of unburned fuel on solid getters. The fuel will be recovered and purified off-site.) The EPR will include the first on-site isotope separation equipment and, probably, the first on-line experiments for recovering tritium bred in a CTR blanket.

2. Radiological Hazards

Tritium in the form of tritiated water, represents the more serious hazard than elemental tritium. Large, hot metal surfaces abound in the EPR, and many tritium removal mechanisms which may be used in safety systems rely on oxidizing tritium. Thus, safety-related dose calculations for this study of an EPR assumed that all tritium is in the form of tritiated water.

In calculating doses resulting from tritium, the important quantity to be developed is the total energy absorbed per gram of affected body tissue, considered to be the entire body. Essentially all the emitted low-energy beta radiation is absorbed in the body.

The International Commission on Radiological Protection (ICRP) and National Council on Radiation Protection^{1,2} have formulated recommendations concerning maximum radiation doses to both the population-at-large and workers in the nuclear industry. The federal government has established and continually revised regulations in accordance with these recommendations. The bulk of these are contained in Title 10 of the Code of Federal Regulations (10 CFR).³ The portions of 10 CFR most relevant to power plants are Parts 20, 50, and 100. As a government-operated facility, the EPR would not be legally bound to conform with these standards; but it seems reasonable to expect the predecessor of fusion power plants to be designed to operate within limits specified for fission power plants. A proposed Appendix I covers those portions of the plant that affect the normal releases of radionuclides to the environment. Note that the design criteria are not expected to be applied in an absolutely rigid manner³ and that Appendix I has not yet been formally adopted.

3. Radiological Safety Criteria

Performance criteria for the EPR were established concerning tritium concentrations and releases which lie within the numerical limits of these regulations. Design criteria were then formulated to determine the various features that the tritium handling systems and related auxiliaries must have to ensure compliance with the performance criteria and to minimize the probability of accidental tritium releases.

3.1 Performance Criteria

The reactor building will be a restricted area; the applicable regulatory limit for tritium is 5×10^{-6} μ Ci per cubic centimeter of air.

The criterion chosen was a reactor building atmosphere that should contain no more than 5×10^{-7} μ Ci of tritium per cubic centimeter during maintenance periods so that the tritium would not contribute significantly to the dose received by maintenance personnel.

The maximum tritium release limit can be expressed in terms of site boundary dose. It would be desirable to choose a dose limit far below 25 rems - in fact, as close to 170 millirems as possible.⁴ However, we decided to focus on the more nominal goal of a whole body dose of 1.0 rem because detailed design data are unavailable; as a result, many arbitrary assumptions were made in dose calculations, including the

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amount of tritium released to the reactor building, the site boundary distance, and the meteorology. A limit of 5 millirems/year for the whole body dose at the site boundary from normal releases was selected in accordance with the intent of the guidelines set forth in Appendix I of 10 CFR 50.³

3.2 Design Criteria

The following criteria were formulated to provide guidance for the design of the tritium handling systems:

- (1) All systems containing tritium in either gaseous or potentially gaseous form in significant quantities shall be enclosed. The atmosphere of these enclosures shall be maintained at a slight negative pressure and processed through a cleanup system designed to remove tritium. This criterion was established to limit normal leaks to the reactor building as well as to reduce the probability of large leaks due to accidents. It is consistent with present practice for all new systems being constructed to handle large quantities of tritium.
- (2) Tritium-bearing systems shall not release their inventories as a result of design-basis earthquakes, tornadoes, or the missiles generated by them. Protection must be provided for support systems, such as cryogenic refrigerators or electric power supplies, which could affect tritium containment. This criterion was established to reduce the likelihood of releases resulting from natural disasters.
- (3) If possible, all tritium handling systems shall be located in the reactor building. In any case, such systems shall be enclosed within containment structures that are reasonably leak-tight (comparable to BWR secondary enclosures), maintained at a slight negative pressure, are missile protected, and are of seismic one design.⁵ All containment structures shall have elevated release points. This criterion, which is aimed particularly at mitigating the effects of the maximum credible accidents, also leads to the control of releases caused by normal leaks and smaller accidents.
- (4) All containment buildings shall be equipped with atmosphere cleanup systems which remove tritium at a rate and an efficiency necessary to meet the site boundary dose criterion (1 rem) for a maximum credible accident and the air concentration criterion for normal maintenance conditions (5×10^{-7} $\mu\text{Ci/cc}$) established above.
- (5) Where possible, tritium handling systems shall operate at temperatures and pressures below those at which significant diffusion of tritium through metal walls occurs.
- (6) Monitors shall be provided throughout containment structures, particularly at possible tritium leakage points. All release points from the containment structures shall be monitored. Monitors will be needed to protect personnel. Local monitors at potential leak points will provide fast

response, aid in the protection of personnel, and help locate failures. Monitors at release points will aid in evaluating the performance of the containment and cleanup system and in determining the environmental impact of any release.

- (7) Those systems containing significant quantities of highly flammable materials shall have inert gas as a blanket in their enclosures.

4. Tritium Containment and Atmosphere Cleanup Systems

The tritium containment and atmosphere cleanup systems minimize tritium leakage and its consequence. These systems consist of (1) enclosures around tritium-bearing components and piping; (2) cleanup devices that maintain a slight negative pressure and remove tritium from the atmosphere in these enclosures; (3) the reactor containment building and the concomitant atmosphere cleanup and high-vacuum equipment; and (4) other tritium containment structures, if any, plus their atmosphere-cleanup and high-vacuum components.

Several criteria were formulated for performance and design of tritium containment and atmosphere cleanup systems and include the following: a limit of 5×10^{-7} $\mu\text{Ci/cc}$ for tritium in the containment building atmosphere during maintenance, a maximum annual dose of 5 millirems from normal tritium release at the site boundary, and a whole body dose of 1 rem at the site boundary for 2 hr following the maximum credible tritium release. These criteria result in the following design requirements: double enclosure of tritium systems; provisions to ensure resistance against seismic and tornado damage; containment structures, atmosphere cleanup systems, low-temperature and -pressure operation where possible; adequate monitoring; and inert-gas blankets for flammable systems.

4.1 Selection of Techniques

Because of the size and complexity of the various systems that will handle large quantities of tritium, some leakage will be inevitable. Therefore, the use of double enclosures at slight negative pressures with cleanup systems to remove tritium from their atmospheres is considered to be the only way to ensure minimum leakage to the reactor building. With inert-atmosphere enclosures, the potential fire hazards of uranium beds or gas storage of tritium are reduced. Many systems for removing tritium from enclosure or reactor building atmospheres are commercially available, but no attempt has been made to choose the most promising of these in the scoping study.

A containment building with a slight negative pressure and a controlled, elevated exhaust was judged to be more effective in reducing doses from a maximum credible tritium accident and would probably be more economical than a PWR-type containment building. However, future studies of the effect of the normal release of air activation products and the costs of PWR- and BWR-type containments might alter this conclusion.

The atmosphere cleanup system for the reactor building will contain heaters and catalytic or perhaps CuO beds to oxidize tritium to tritiated

water. The tritiated water will then be collected on dryer beds. The system flow rate will probably be on the order of 0.25 to 0.5 building volume per hour for rapid tritium removal. A tritium decontamination factor (DF) of 100 is considered both achievable and desirable. Addition of hydrogen or steam for isotopic dilution may be necessary to achieve this DF for low concentrations of tritium.

The volume of the reactor building will be about 4,000,000 ft³. Based on data from buildings of a similar nature, it should be possible to maintain a pressure of -0.25-in. H₂O with an inleakage rate of less than 0.5 building volume (2,000,000 ft³) per day. A discharge similar in amount to the inleakage would be exhausted from an elevated release point about 100-m high. This exhaust stream would be taken from the outlet side of the reactor building's atmosphere cleanup system.

Tritiated liquids resulting from the regeneration of dryer beds of cleanup systems will be pumped to a small facility for solidification, drumming, and off-site shipment.

The allowable leak rate to the building, L, with a given removal system flow rate, W, to maintain a maximum concentration of 5×10^{-7} Ci/m³ is obtained by:

$$L \left(\frac{\text{Ci}}{\text{sec}} \right) = W \left(\frac{\text{m}^3}{\text{sec}} \right) \times 5 \times 10^{-7} \left(\frac{\text{Ci}}{\text{m}^3} \right). \quad (1)$$

If W is approximately 0.25 building volume per hour (17,000 cfm or 7.9 m³/sec), $L = 4 \times 10^{-6}$ Ci/sec or 0.3455 Ci/day. Thus, even with a substantial increase in flow or relaxation of the concentration criteria, there would still be a need for double containment of systems handling several million curies of tritium per day.

The following assumptions were used to evaluate the effectiveness of reactor building containment and atmosphere-cleanup schemes in reducing 2-hr site boundary doses:

- (1) Minimum dispersion conditions exist for 2 hr following a maximum credible accident.
- (2) A total of 5×10^7 Ci of tritium is released to the reactor building following the maximum credible accident.
- (3) The breathing rate of an individual at the site boundary is 3.47×10^{-4} m³/sec.
- (4) All tritium is in the form of tritiated water.

The two containment and cleanup system combinations evaluated were: (1) a very tight containment building which leaked at the rate of 0.01-building volume per day, had a cleanup system with a flow rate of 1-building volume per hour, and a tritium DF of 100 (or higher); and (2) a containment building which operated under a slight negative pressure, had an inleakage rate of 0.5-building volume per day, and exhausted a similar amount from the outlet side of a side of a cleanup system with a tritium DF of 100 through a 100-m high stack.

The release rate from the first system varies significantly in time, and the integrated release over a 2-hr period would be 17,900 Ci; the dose at the site boundary would be 4.9 rems.

The second system, which had the controlled exhaust from the elevated release point, was evaluated using the conservative approximation that the quantity of tritium in the building (and, hence, the release rate) remains constant for 2 hr. The release rate, Q, would be 2.84 Ci/sec. The site boundary dose would be 0.96 rem.

The dose resulting from tritium released during normal operation was also estimated. With a 100-m release point elevation, a release rate of 2,000,000 ft³ (0.5-building volume) per day (0.66 m³/sec), a concentration of 5×10^{-7} Ci/cc in the building, and a dispersion factor (X/Q) of 7×10^{-5} sec/m³ for nonfumigation conditions taken from AEC Safety Guide 25,⁴ the annual dose would be 4.6×10^{-2} rem/year.

The calculations assumed that the exhaust concentration was equal to the building concentration when, in fact, it could be a factor of 100 lower (if the exhaust tritium removal system were operating under normal conditions). Therefore, the calculation shows that, even with considerable increases in building or exhaust tritium concentration, the annual average dose rate at a 200-m site boundary due to normal tritium releases will still be below 5 millirems.

4.2 Program Requirements

Definitive designs for the double enclosures cannot begin until the designs and layouts for major tritium-bearing systems for an EPR are available. Additional information on the behavior of tritium in the environment and the modes and consequences of tritium release from fusion facilities would be useful in establishing final criteria and designs for tritium containment and atmosphere cleanup systems.

Future work on containment and cleanup systems for an EPR includes design of secondary enclosures, further detailed examination of tritium-related accidents, selection of optimum cleanup systems, design of a tritiated liquid-waste disposal system, and tritium containment in blanket modules.

5. Vacuum Systems

5.1 Main Vacuum Systems

The main vacuum system consists of the pumps, piping, and valving that are used to lower the pressure to appropriate levels before initiation of a discharge and maintain proper conditions throughout the discharge. This system must remove impurities dislodged or outgassed from the walls, fusion ash (helium), and deuterium and tritium which have left the plasma. The system may pump from a divertor exhaust chamber similar to the design described in Ref. 6 or directly from the main vacuum chamber.

5.1.1 Requirements. The system will have to meet the following nine requirements in order to achieve the goals outlined above:

- (1) It must be available in appropriately large speeds and capacities, either now or in the future, without major developments or breakthroughs.
- (2) It must provide complete tritium recovery in a reasonable manner (tritium may cost as

much as \$7000/g, and several grams will be pumped per day).

- (3) It must pump helium.
- (4) It must achieve low base pressures.
- (5) It must perform in a radiation field.
- (6) It must have relevance to future (i.e., beyond EPR) reactors.
- (7) It must demonstrate reliability and maintainability.
- (8) It must show reasonable economics.
- (9) It must be compatible with the general requirements and physical configuration of the EPR.

5.1.2 Selection process. The main vacuum system will consist of piping, valves, and pumps. The initial step in the selection process was to evaluate the capability of ten types of vacuum pumps to meet the requirements listed above. The results are summarized in Table 1.

Table 1. Summary of results of evaluation of ten vacuum pumps

Type of pump	Requirement met ^a								
	1	2	3	4	5	6	7	8	9
Cryosorption	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mercury diffusion	✓	✓	✓	✓	✓	✓	✓	✓	✓
Oil diffusion	✓	?	✓	✓	?	X	✓	✓	✓
Tritium gettering	✓	X	X	✓	✓	X	?	✓	X
Turbomolecular	X	?	X	✓	?	X	?	✓	?
Zirconium gettering	?	?	X	✓	✓	?	✓	✓	✓
Cryosorption panel in vessel	X	?	✓	✓	✓	X	?	✓	X
Ion	X	X	?	✓	✓	X	X	X	✓
Bare cryopanel	✓	✓	X	X	✓	✓	✓	✓	✓
Frozen sorbent	✓	?	?	✓	✓	?	?	✓	X

^a ✓ - acceptable; X - rejected; ? - applicability is in doubt.

Cryosorption pumps were found to meet all nine requirements to a reasonable degree. These pumps, which consist of an array of molecular sieves cooled by a liquid helium reservoir surrounded by liquid nitrogen-cooled chevrons, operate by adsorbing volatile gases such as hydrogen and helium on the helium-cooled array and less volatile gases on the outer chevrons. Special-order modules with speeds of about 25,000 liters/sec have been manufactured. The pumps, which function by adsorption, must be regenerated periodically by heating. A regeneration period of several hours at 300°C is required to drive off water vapor, but rapid regeneration at cryogenic temperatures may be possible if only helium and hydrogen isotopes have to be removed.

Mercury diffusion pumps were also found to be capable of meeting the nine requirements. These pumps use directed streams of mercury vapor to sweep the gas being pumped from the inlet side toward the exhaust. Liquid nitrogen-cooled baffles are required to reduce the backstreaming of mercury into the vacuum chamber. These baffled traps reduce the pumping speed by approximately 50%. Only minor developmental work is required to produce pumps of the scale needed for an EPR. Diffusion pumps, however, also require forepumps, and the two-part pump system should be considered as a unit.

Oil diffusion pumps are essentially the same as mercury pumps, except that oil vapor is used as the pumping medium. Contamination by tritium and the effects of gamma, beta, and neutron radiation on the oil were other concerns which downgraded oil pumps with respect to the mercury pumps.

Titanium gettering was found to be unacceptable, principally because of difficulties with tritium recovery and helium pumping. Titanium gettering involves evaporation of the metal, which condenses as a very thin surface film to adsorb active gases. Helium cannot be pumped because of the chemical nature of the process. The stability of the hydride and the many layered process would make tritium recovery difficult.

Turbomolecular pumps are basically similar to rotary compressors operating at 20,000 to 30,000 rpm. The largest pumps commercially available have a speed of less than 2000 liters/sec for air. Turbomolecular pumps have difficulty in achieving low base pressures for hydrogen. It is unlikely that turbomolecular pumps could be designed to achieve the required speeds and base pressures for hydrogen isotopes with reasonable outlet pressures in an economically feasible manner.

Zirconium gettering pumps use an 85% zirconium--15% aluminum metal mixture, arranged for maximum surface area, to pump gases by forming zirconium oxides, hydrides, etc. These pumps differ from titanium gettering pumps in that the getter material is in a permanently fixed configuration and is regenerable. As with all getter techniques, the zirconium pumps cannot pump helium.

A cryosorption or cryogenic panel within the vessel or the divertor chamber itself was ruled out because of the anticipated effects of bombardment by charged and energetic neutral particles. Regeneration would also involve complex equipment in a highly activated area.

Ion vacuum pumps use currents of accelerated ions to propel the gas being pumped onto a titanium gettering surface. This technique yields some effective helium pumping, but at considerable economic cost as well as increased complexity. Complete tritium recovery from these pumps would not be possible. It is unlikely that ion pumps could be scaled up to the size required for an EPR.

Bare cryopanel cooled to liquid helium temperatures will pump hydrogen to low pressure at high rates. Regeneration would be simple and quantitative. Large pumps have been constructed, and scaling to any size seems feasible, but bare panels will not pump helium. This does not rule out use of these pumps for pumping excess neutralizing gas from the neutral beam injectors, but it does eliminate the use of bare panels (alone) for the main vacuum system.

Cryosorption pumping can be accomplished with bare panels containing frozen sorbent material. These systems are particularly useful when contaminants (such as oils) are present which poison solid sorbents (such as molecular sieves or carbon). This will not be a problem in the EPR. Frozen carbon dioxide is an effective sorbent for hydrogen, and frozen argon sorbs helium. The principal reason for rejecting these pumps for the EPR was that it would be difficult to prevent contamination of the plasma with the sorbent. Regeneration of the pumps and recovery of tritium would be complicated by the presence of large quantities of another gas.

The preceding evaluations indicate that cryosorption and mercury diffusion pumps are the two types most likely to be capable of meeting the requirements for an EPR. Each type would be used in a system consisting of several pumps attached to the ends of many large ducts connected either to the main vessel or to the divertor exhaust chambers. The pumps would be located outside the shield, and the ducts penetrating the shield would be bent to allow shielding against neutron and gamma streaming.

A larger number of smaller ducts and pumps could be used if physical arrangements prevent the use of ducts 1-m-diam. The pump would be about 3-m long if proportions were the same as for smaller existing pumps. However, simple extrapolation from existing designs indicates that a 1-m-diam by 3-m-long pump would have a capacity of about 300 liters (STP); it will be necessary to install more sieve in EPR pumps.

The required pumping speed can be estimated from the plasma particle-confinement time, the plasma density and volume, and the vacuum requirement. The plasma data indicated that approximately 10^{22} ions/sec would leave the plasma. Design calculations proceeded on the assumption that either a divertor or a gas blanket concept would be used. Although the gas blanket concept for Tokamaks has not yet been developed, preliminary discussions indicated that the vacuum requirements would probably be no more rigorous than for a divertor. The Princeton Reference Design^o gives the requirement for the divertor as 4.5×10^{-4} torr. This led to a pumping speed of 3.1×10^5 liters/sec, based on diatomic gas (i.e., 5×10^{21} molecules/sec). The system was then sized on the basis of diatomic gas of mass 5 at 300°K. A 1-m-diam by 5-m-long duct coupled with a 40,000-liter/sec pump had a conductance of approximately 160,000 liters/sec; ten such ducts were required.

5.1.3 Program requirements. Data required from plasma physics concern the vacuum requirements for divertors and/or gas blankets and the particle confinement time. Such data should be forthcoming from future EPR studies using input on scaling laws from plasma experiments.

Information is needed on the long-term reliability, maintainability, and performance of large cryosorption pumps and mercury diffusion pumps. Rapid regeneration capabilities and storage of cryosorption pumps should be determined.

Studies are being performed at ORNL on rapid regeneration of cryosorption pumps. The commercial development of large, high-speed cryosorption and mercury diffusion pumps should be encouraged. Reliability and remote maintenance possibilities should also be investigated.

Future EPR studies directly related to the main vacuum system will include development of roughing systems and preparation of optimum physical arrangements. Work with those involved with blanket and shield design and neutronics calculations, and with manufacturers, will further clarify research and development needs.

5.2 Injector Vacuum Systems

The injector vacuum system consists of the piping, valves, and pumps that are necessary to maintain the appropriate vacuum in the neutral beam injector drift tubes and gas cells. Because a substantial amount of tritium, perhaps tens of thousands of curies per day, will enter the system from the main plasma vessel via the drift tubes, and because the deuterium feed to the injectors may become contaminated with tritium, this system is considered to be a tritium-handling system. The quantity of tritium involved necessitates a reasonably high recovery of tritium from the injector vacuum systems.

5.2.1 Requirements. Based on preliminary injector design, a pumping speed and an ultimate pressure requirement were developed. Thus, to satisfy the above criteria, it was determined that the injector vacuum system should have the following 13 characteristics.

- (1) ultimate pressure below 10^{-4} torr;
- (2) capability for pumping small amounts of helium;
- (3) high speed in a system of reasonable size;
- (4) continuous operation or short, infrequent regeneration periods;
- (5) high degree of tritium recovery;
- (6) compatibility with the physical nature of injectors;
- (7) a design based on commercial or potentially commercial technology;
- (8) favorable economics;
- (9) high reliability;
- (10) easy maintainability;
- (11) any required regeneration should produce a reasonable outlet pressure and cause no interference with injector operation,
- (12) low contamination residue; and
- (13) low backstreaming.

5.2.2 Selection process. The injector vacuum system consists of valves, pumps, and piping. Ten types of pumps were evaluated based on their capability for satisfying the 13 requirements listed above. Table 2 summarizes the results.

Both mercury diffusion pumps and cryosorption pumps will satisfy all the requirements. The considerations involved were similar to those discussed for the main vacuum pumps, but the needs to pump helium were different. The only source of helium in the injector chamber will be from the torus, from decay from the small quantities of tritium stored on the pump system, and from inleakage. The importance of helium pumping capabilities in the injectors should continue to be analyzed as the designs of EPRs develop. Without helium pumping, the helium pressure in the injector will be approximately equal to one-half the product of the torus pressure during the burn and the fraction burned. More exact estimates would take into account such effects as the "sweep" created by the beam and would more closely estimate the composition of the plasma while the beam drift tube is exposed to the torus. Helium pumping capacity was judged to be desirable for the EPR injector system

and would probably be necessary for subsequent larger systems where higher fraction burn is expected.

Table 2. Summary of evaluation of ten types of pumps

Type of pump	Requirement met ^a												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Cryosorption	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Oil diffusion	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	✓
Mercury diffusion	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Titanium gettering	✓	X	✓	?	X	✓	✓	✓	?	?	X	X	✓
Turbomolecular	✓	?	X	✓	✓	✓	✓	X	?	✓	✓	?	?
Zirconium gettering	✓	X	?	✓	?	✓	✓	?	?	✓	✓	?	✓
Cryosorption panel in injector	✓	✓	✓	✓	✓	X	✓	✓	✓	?	X	✓	✓
Ion	✓	?	?	✓	X	✓	✓	X	?	?	?	X	✓
Bare Cryopanel	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Frozen sorbents	✓	?	✓	✓	?	X	✓	✓	✓	✓	?	?	?

^a ✓ - acceptable; X - rejected; ? - applicability is in doubt.

5.2.3 Analyses. The required overall pumping speed requirement was estimated based on a 3-MW, 150-keV injector with an ionization efficiency of 0.33. All ions were assumed to be D_1^+ . Based on preliminary criteria, the gas-cell pressure was in the millitorr range and the drift tube was kept at or below 10^{-4} torr. A pumping speed of approximately 80,000 liters/sec was required. Approximately 900 std liters would have to be pumped during a 24-hr period. This leads to a capacity requirement of about 200 std liters for each of five cryosorption pumps on a 24-hr cycle.

Calculation of the amount of tritium that infiltrates from the plasma into the injector was based on 24 injectors, 40-cm-diam by 3-m-long drift tubes, and a D-T pressure of 10^{-4} torr outside the plasma. This calculation showed that the injector vacuum system would handle about 7.5×10^5 Ci of tritium per day.

The conclusions of these analyses are sensitive to changes in the data concerning the injector efficiencies, the gas cell and drift tube pressure requirements, the injector geometry, and the pressure outside the plasma. A decrease in the ionization or neutralization efficiencies by much more than a factor of 2 would make engineering of the injector vacuum system difficult. Large increases in gas-cell pressure or decreases in drift pressure would also be difficult to accommodate.

An increased drift-tube length or a lower pressure outside the plasma would decrease the amount of tritium handled, but probably not sufficiently to eliminate the need for recovery. Shorter drift tubes or a higher pressure outside the plasma would increase the amount of tritium handled; however,

major increases (i.e., more than a factor of 5) in the mass flow rate up the drift tubes would be necessary before significant changes in the injector vacuum system designs would be warranted.

5.2.4 Program requirements. The actual beam requirements, both voltage and total power, can be determined only by utilizing plasma physics data. Needed information relative to beam technology involves the efficiency, pressure requirements, and geometry of the injectors.

6. Tritium Processing System(s)

Tritium processing systems include equipment for removing D-T mixtures from the main vacuum systems, purifying the D-T mixture for recycle to feed systems, separating isotopic (H) impurities from D-T mixtures, recovering tritium from blanket modules, preparing tritium-containing wastes for disposal, transferring feed, providing storage for tritium, and vent or atmosphere cleanup equipment directly associated with the process systems. Although the major vacuum pumps are considered with the main vacuum system they are connected directly to the process equipment and, therefore, must also be considered in process studies.

As now envisioned, the EPR tritium processing system should be designed to:

- (1) limit tritium release rates to acceptable low rates and minimize the probability and consequence of accidental releases,
- (2) contain acceptable inventories of tritium,
- (3) involve reasonable (hopefully, small) costs,
- (4) be compatible with all other portions of the EPR, and
- (5) use current technology or technology which can be expected to be developed early enough for use in EPR.

The first goals of the tritium handling system will be to provide acceptable containment and to minimize the hazard of personnel exposure and/or machine downtime due to tritium releases. Excessive release of tritium is not only a hazard to personnel, but can also contaminate expensive equipment and jeopardize the mission of the EPR.

Tritium inventories must be limited because:

- (1) they represent a significant cost to the system,
- (2) high inventories probably imply a higher maximum environmental risk in the event that a major release occurs, and
- (3) tritium supplies available to the EPR will be limited. A 150-MW(t) EPR would burn 20 g of tritium per day (200,000 Ci/day). If the fraction burned is 1%, this suggests a tritium process rate of 2 kg or 20 MCi per day. If a 2-day inventory is maintained throughout the process and storage systems, this would correspond to an inventory of 4 kg or 40 MCi.

The principal tritium process steps required for the EPR (or any fusion reactors) are shown in Fig. 1. Vacuum pumps play an obvious and important part in the removal of tritium, deuterium, and impurities from both the plasma chamber (or divertor) and the injectors. Although vacuum pumps must be considered as part of the tritium processing system, they are more conveniently treated as part of the vacuum systems. The size and pumping characteristics of the vacuum pumps

Fig. 1. Diagram of Reference EPR Tritium System

are discussed as part of the vacuum system in Sect. 5. Recovery of D-T from the pumps is discussed as part of the tritium processing system. Cryosorption pumps permit complete regeneration of tritium and have no shaft seals to permit leakage to or from the system. They also introduce no impurities, such as lubricants or working fluids, to the system; thus, cryosorption pumps must be considered for the EPR. Mercury diffusion pumps appear to be the most likely competitor to cryosorption pumps; however, mechanical pumps and getter pumps were also investigated.

Two disadvantages of cryosorption pumps are their cyclic operation and their limited capacity for holding D-T. The cyclic nature of these pumps increases the potential tritium inventory; the pumps would have to be regenerated frequently, probably daily. The disadvantage of this type of pump system depends on the other process steps. If some of these steps are cyclic with the same period, the steps may mesh very well. The most likely purification technique, sorption on uranium beds, is a cyclic process, and thus coordinates satisfactorily with cryosorption pumping. The principal disadvantage of mercury diffusion pumps is the possibility of introducing mercury into the plasma system or downstream process equipment. Purification systems would probably be damaged by mercury accumulations. Cold traps would drastically reduce the chance of steady mercury contamination of other equipment, but the probability of a slow accumulation of mercury and the possibility of severe contamination in the event of equipment malfunction must still be considered.

Some form of protection may be needed to protect cryosorption pumps from sputtered materials. This protection may be provided by the vacuum duct walls, cold baffles inserted in the duct, or the outer chevrons which are cooled to liquid nitrogen temperatures. Very little material would be expected to reach the molecular sieve or mercury.

Once tritium is recovered from the vacuum pump, it must be purified to remove chemical impurities such as helium, oxygen, and nitrogen. Helium, which is formed from the D-T reaction in the plasma, may be about 1% of the removed gases. Other impurities may result from leakage or outgassing of the equipment. The purification technique most likely to be employed for the EPR uses uranium beds. These beds will sorb essentially all likely impurities except the noble gases.^{7,8} When heated, they release the hydrogen isotopes but retain the impurities. Uranium beds obviously have limited lifetimes determined by the impurity content of the process streams. The life of uranium in the EPR, however, is expected to be long (years). Noble gases swept into the bed can be pumped off, if necessary, additional purification can be achieved by routing the uranium bed outlet stream through a palladium membrane. Uranium beds, which are frequently used for tritium storage and purification, look promising, and the existing experience with uranium beds gives them an edge. An alternative method will have to promise significant advantages in order to be preferred for the EPR. The cyclic nature of uranium beds couples well with cryosorption pumping.

Other hydride-forming metals besides uranium will need to be considered. Since different metals have different affinities for hydrogen (isotopes as well as oxygen and nitrogen, a better combination of properties may be found. However, the existence of a more suitable material is not now apparent. Uranium beds are also proposed for storing tritium. Although palladium membranes alone can readily produce a high-purity hydrogen isotope stream, the production of a reject stream containing little or no hydrogen isotopes without larger surfaces and/or high total pressures is difficult.

It is possible to combine the purification operation with the isotope separation steps. The advantages of this operation obviously depend upon which isotope separation technique is chosen. Cryogenic distillation, one of the most promising isotope separation techniques, could separate helium as well as other impurities likely to be present. The merits of this approach, however, also depend on the throughput capacity required for the isotope separation system. All material recovered from the plasma will have to be purified before it is returned to the plasma; however, all material will not have to undergo isotope separation. The material used to fill the torus before each run and the material feed in the form of gas or solid pellets (probably) will not require isotope separation. Only deuterium (and possibly tritium) supplied through injectors need undergo isotope separation, and a separate purification step is likely to be chosen.

Isotope separation will probably be required at the EPR site to prepare "tritium-free" deuterium for the injectors and to remove the trace of hydrogen produced by deuterium-deuterium (D-D) reactions and outgassing from the vacuum vessels and equipment. Although these operations could be carried out in a single system, separate systems are likely to be selected because the required throughputs will be different. It is even possible that different separation techniques will be chosen. The first system (D-T separation) will be the larger. A specific design for the EPR cannot be prepared at this time because the purity requirements for the injectors and the plasma feed have not been estimated. Hydrogen isotope separations have been performed in equipment of reasonably large size, and the data and experience gained from these separations can be expected to be

used in the EFR. However, impurity requirements should be specified as soon as possible so that specific designs can be made to determine whether, as expected, the isotope requirements of the EFR can be met at modest cost with current technology. Although no unusually large expenditures for isotope separation equipment are anticipated, one could specify plasma and feed concentrations which would be difficult to meet.

Satisfactory storage of tritium either as a gas or as a solid tritide (usually uranium tritide) has been demonstrated in other ERDA programs. This is current technology, and either form should be considered "safe." Solid storage is often considered less hazardous; therefore, it will probably be used for most large-scale and long-term storage. Small-scale and especially short-term (surge) storage will be in the form of low-pressure gas.

The blanket recovery system is one of the least understood components in the EFR tritium handling system. Detailed evaluations of all of the blanket recovery systems considered for the EFR or later fusion power reactors will not be presented here since a separate report is being prepared on the subject.

The feed system has not been extensively evaluated in the EFR tritium study because the plasma physics aspects of the feed system have not been clearly defined. If subsequent developments indicate that solid pellet feed should be used in the EFR, relatively more complex tritium handling equipment would be involved. This is another area where expanded tritium studies will be recommended.

6.2 Information Required for Evaluating Tritium Processing Systems for the EFR

Plasma physics information. Many aspects of the tritium process system will have to be reevaluated as requirements and performance of the plasma system become better understood. Purity requirements must be known for all feed streams: fill, supplementary feed (solid?), and injector feed.

Several options in the EFR design could affect tritium handling equipment. The probability of adopting these techniques and their performance characteristics should be evaluated. The selection of feed systems is obviously important to the tritium handling program. Solid-feed equipment will involve different techniques and containment systems. Although no divertor is currently proposed for the EFR, some potential divertor designs would affect tritium removal techniques. Diagnostic devices can also affect tritium containment. Any opening to the plasma chamber must be considered in tritium containment studies. A graphite liner facing the plasma could lead to tritium retention and result in different sputter products and outgassing rates (and composition).

Fundamental data required. The fundamental chemical data required are usually associated with blanket recovery processes. Sputter products and tritium retention on graphite liner (if adopted) could become more important as studies proceed.

Tritium technology data required. Considerable data are needed on the recovery of tritium from vacuum pumping systems. Cryosorption pumps or mercury diffusion pumps are currently believed to be the most suitable choices for the EFR, but alternative

systems should also be considered. Cryosorption pumping is currently under study at ARL. Particular interest is centered on regeneration at low temperatures, and pump sorption capacity for hydrogen isotopes and helium at various pressures and pumping rates. If mercury diffusion continues to be a promising alternative system, study of these pumps should be initiated.

The recovery of tritium from lithium blankets is the area of most immediate interest. This is perhaps the most difficult developmental effort required for tritium handling in the EFR. However, as mentioned earlier, a minimal EFR device would not include provisions for blanket experiments. It would also be possible to use a less efficient recovery system for the EFR. This would allow breeding and material studies in some blanket modules, but it would be less effective in advancing tritium handling technology. Recovery processes for 500°C lithium blankets are limited by inventory considerations: that is, the maximum allowable tritium concentration is restricted by the allowable tritium inventory in the blanket. If only a small portion of the EFR blanket region is devoted to breeding experiments, much higher concentrations could be permitted before the inventory becomes excessive. Since heat from this module does not necessarily need to be discharged directly to a stream, tritium release rates may also be controlled even when the tritium concentrations are relatively high. Thus it may be possible to operate the recovery system at concentrations significantly higher than those required for future reactors. However, one would prefer to simulate future reactors as effectively as possible and operate the EFR blanket at comparable concentrations.

Isotope separation. Existing engineering data should be more fully evaluated before new experimental work in this area is initiated. As soon as information on allowable D-T rates, permissible concentrations, and injector feed rates are estimated, one or more conceptual designs of an isotope separation system should be prepared. This will clarify the magnitude of the isotope separation problem.

7. References

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