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A Tritium Systems Test Facility Volume I

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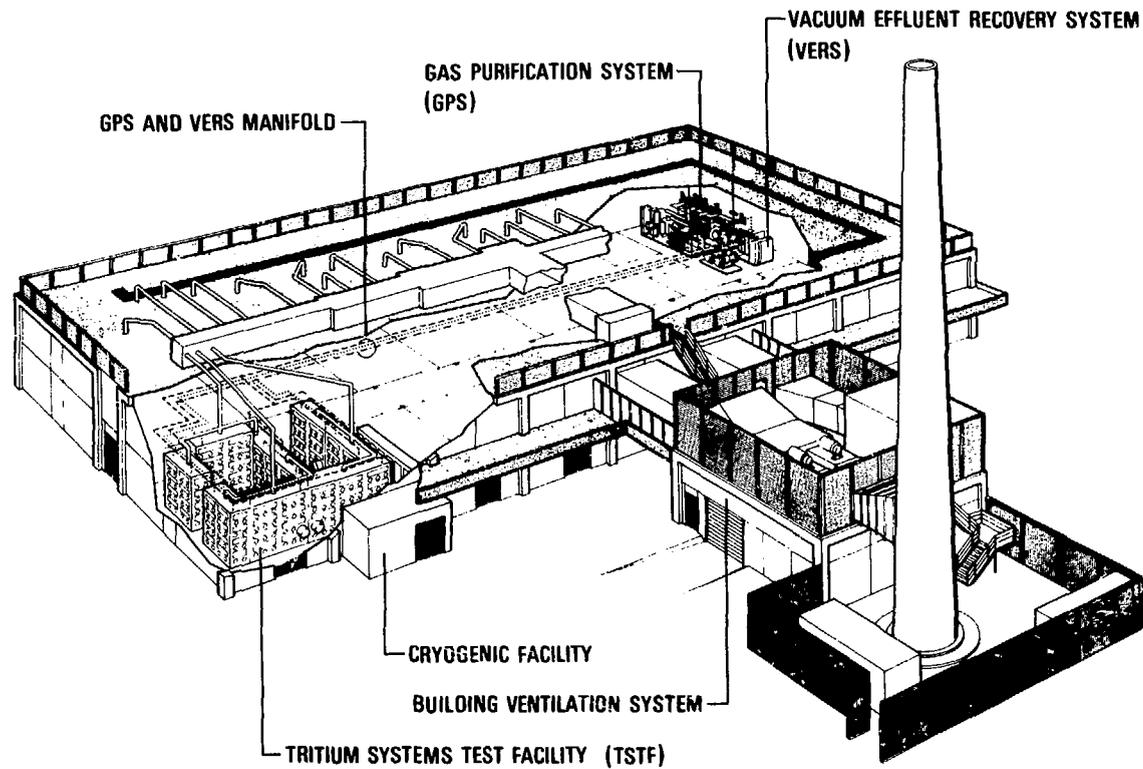
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A TRITIUM SYSTEMS TEST FACILITY
VOLUME I

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The Tritium Systems Test Facility (TSTF) will occupy approximately 13% of the floor space in the Tritium Research Laboratory at Sandia Laboratories, Livermore

PREFACE

This proposal is written in response to an invitation by James M. Williams, Assistant Director for Development and Technology, Division of Magnetic Fusion Energy, to submit a proposal to design, build, and operate a facility to demonstrate the tritium fuel cycle and environmental control systems for an Experimental Power Reactor.

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ABSTRACT AND SUMMARY

Sandia Laboratories proposes to build and operate a Tritium Systems Test Facility (TSTF) in its newly completed Tritium Research Laboratory at Livermore, California (see frontispiece). The facility will demonstrate at a scale factor of 1:200 the tritium fuel cycle systems for an Experimental Power Reactor (EPR). This scale for each of the TSTF subsystems--torus, pumping system, fuel purifier, isotope separator, and tritium store--will allow confident extrapolation to EPR dimensions. Coolant loop and reactor hall clean up facilities are also reproduced, but to different scales. It is believed that all critical details of an EPR tritium system will be simulated correctly in the facility. Tritium systems necessary for interim devices such as the Ignition Test Reactor (ITR) or The Next Step (TNS) can also be simulated in TSTF at other scale values.

The active tritium system will be completely enclosed in an inert atmosphere glove box which will be connected to the existing Gas Purification System (GPS) of the Tritium Research Laboratory. In effect, the GPS will become the scaled environmental control system which otherwise would have to be built especially for the TSTF.

There are two basic goals of the Sandia TSTF design. The first is to simulate the tritium-related functions of a fusion reactor fuel processing loop. The second is to provide a facility for the evaluation of prototype or experimental EPR components in a realistic tritium environment. Examples of features included in the Sandia TSTF are:

- Several types of pumps suitable for tritium usage are incorporated.
- The torus section allows for addition of simulated neutral beam injectors and diverter elements.
- The plasma gas load will be simulated in temperature and pressure by thermal heating of the gas prior to pumping.
- Gas purification will be accomplished by Pd/Ag membranes in conjunction with traps, filters, and metal hydride beds.

- Separation of hydrogen isotopes will be accomplished by a cryogenic distillation process.
- The two most critical aspects of the coolant loop will be simulated: permeation of tritium from the primary coolant into the power cycle working fluid, and extraction of tritium from a helium coolant.
- Instrumentation will monitor tritium concentration at a number of locations to permit easy inventory assessment and provide necessary data for accurate simulation of the EPR fuel cycle.
- Models for loop behavior will be developed to allow eventual computer control of the facility operations.

Schedules developed for this program call for completion of design by July 1978, beginning of H-D operations in December 1978, and start of tritium operations in August 1979. PERT analysis of this schedule (Figure 1) shows that acquisition of the cryostill is the critical path. The TSTF will be designed, constructed, and operated within the existing organization framework of Sandia Laboratories, Livermore (SLL).

The TSTF will be housed in a facility built to comply with the strictest environmental controls envisioned for the foreseeable future. The scaled version of the EPR tritium fuel cycle proposed here will provide all essential data necessary for design of an EPR tritium processing system, and for development of environmentally acceptable fuel handling procedures for fusion power plants.

In summary, we propose to establish an operational TSTF by 1979 within an existing tritium research laboratory incorporating full environmental safeguards.

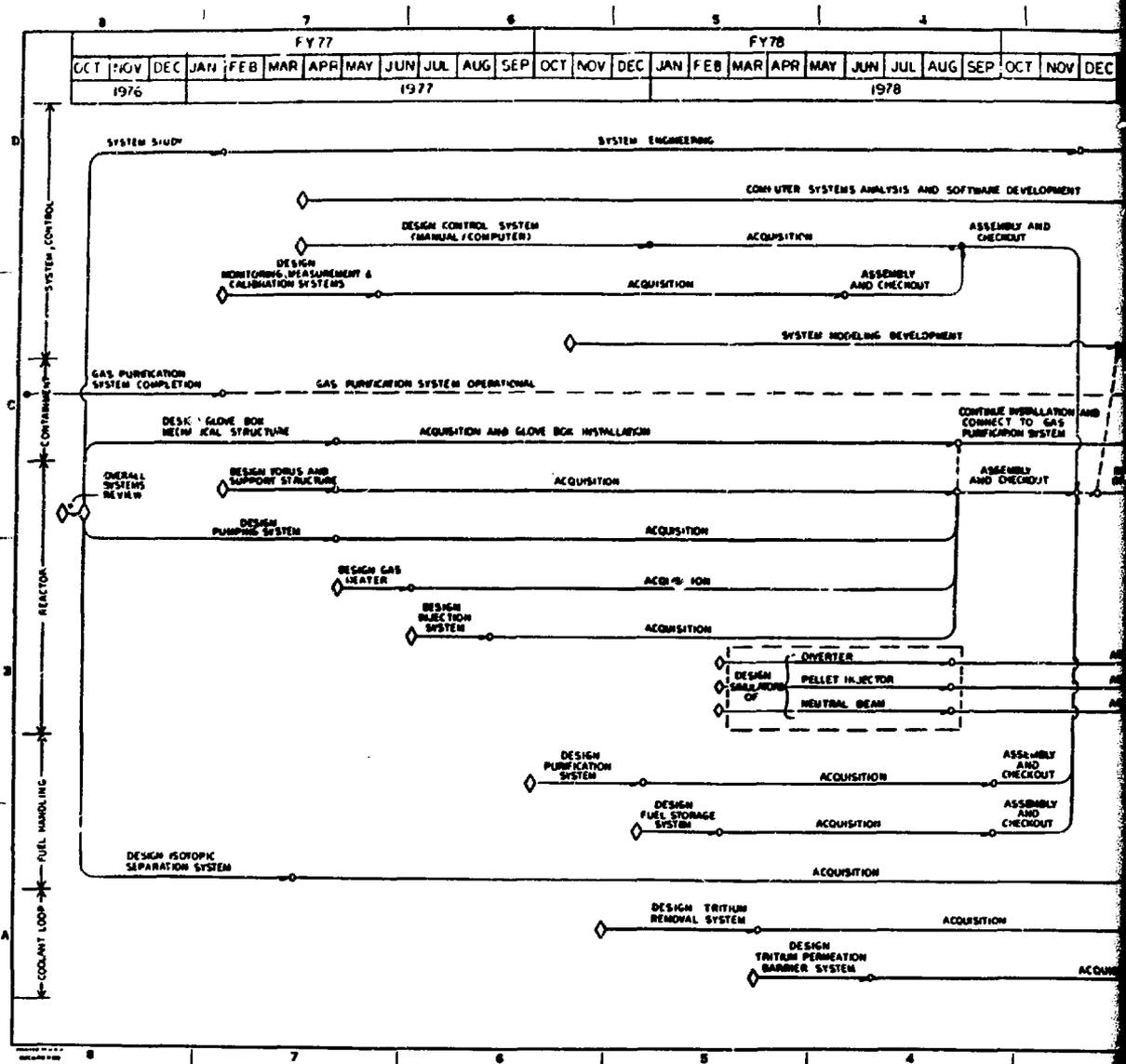


Figure 1. TSTF Program Schedule

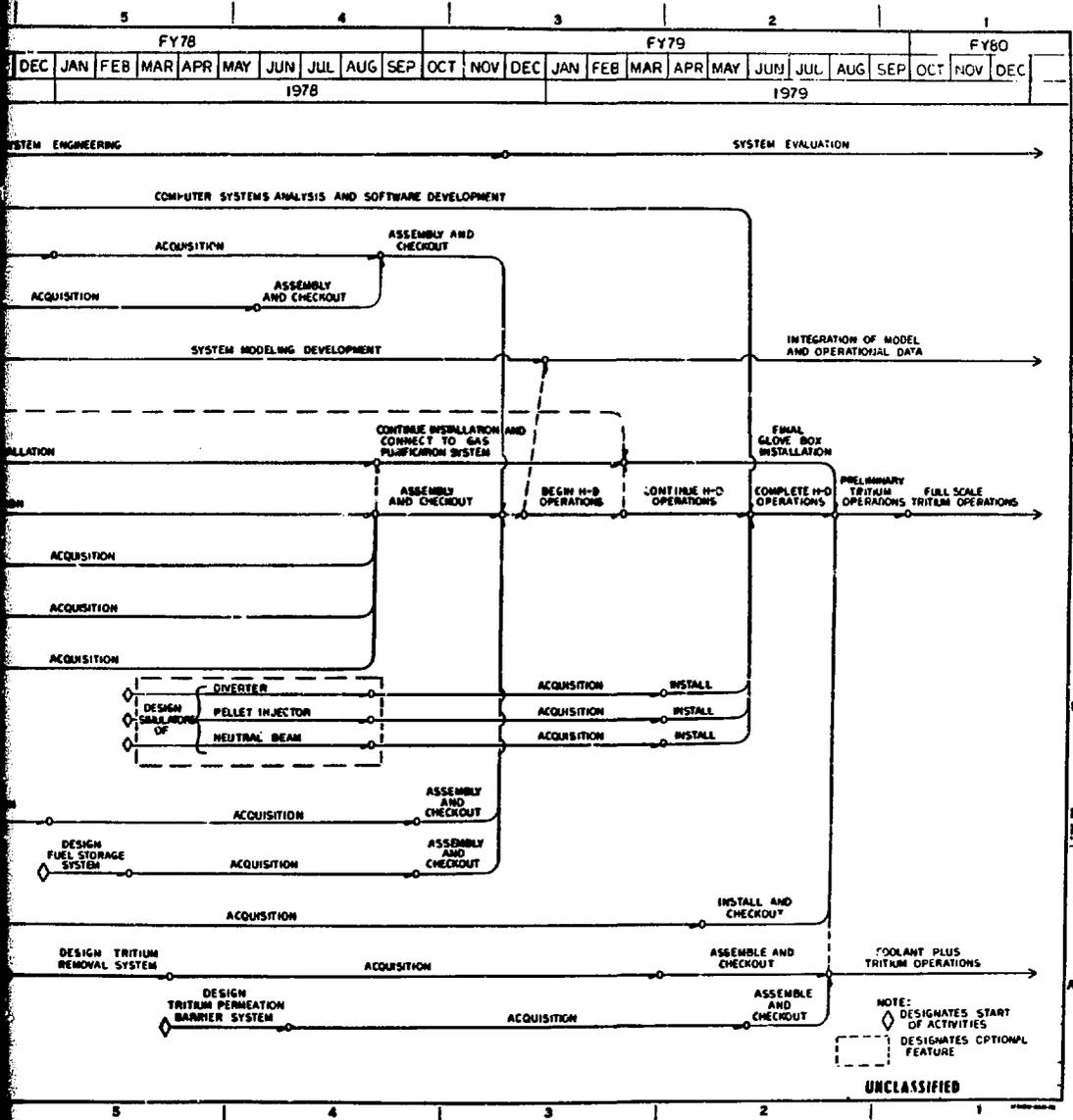


Figure 1. TSTF Program Schedule

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TSTF DESCRIPTION AND SCALING FROM EPR

Tritium Handling

Tritium handling in the TSTF can be broken into three broad categories: fuel loop, coolant loop, and containment.

Fuel Loop

Simulated tokamak EPR operation⁽¹⁻⁹⁾ will begin by pumping the reactor vessel from atmospheric pressure to $\sim 10^{-9}$ torr prior to initiation of a series of simulated "burn" cycles. After this base pressure has been achieved, deuterium and tritium will be extracted from the fuel store, blended, and injected into the torus. This fueling process will be accomplished by controlled flow of a predetermined mixture of deuterium, tritium, and impurities into the reactor in a period of a few (~ 5) seconds. During this period, reactor pressure will rise to ~ 3 mtorr. At the end of the simulated operating cycle (~ 60 s), a one-meter-long molybdenum shell will heat the fuel mixture to typical first-wall temperatures (~ 700 K) as the gas is exhausted to the vacuum pumps. The hot gases will continue to be exhausted until the pressure reaches 10^{-5} torr, simulating removal of unburned gas and ash. The reactor is then ready for the next injection of fuel. To provide a more complete test of vacuum system design, representative impurities, including ^4He , H_2 , CO , and deuterated and tritiated hydrocarbons, will be mixed with D-T fuel prior to injection. If desirable, injection of D and T by neutral beams or pellets will also be simulated. A representative pressure-time sequence is provided in Figure 2.

D-T gas and impurities regenerated from cryogenic pumps or exhausted from diffusion pumps are sent to a Pd/Ag diffuser for gas purification, as shown in Figure 3. Helium and other waste gases (with low levels of tritium contamination) will be collected and processed through the Vacuum Effluent Recovery System (VERS). The remaining gas, consisting primarily of D-T with H present in small ($< 1\%$) concentrations, will be isotopically separated by cryogenic distillation. High purity ($> 90\%$) D and T will be extracted from the cryostill and stored in separate tanks or beds.

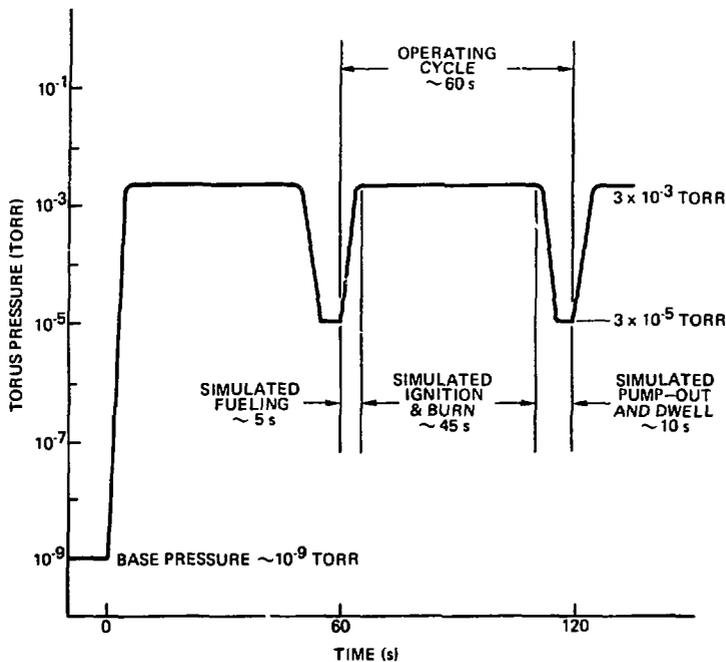


Figure 2. Pressure-vs-Time Plot for TSTF Operations

Coolant Loop

Both helium and water are being considered as primary coolants for the EPR tokamak reactor. Tritium permeation is a potential problem with either system; tritium will diffuse from the torus and wall blanket into the primary coolant loop in either case, and into a first-wall cooling jacket if one is used.

It should not be necessary to operate a scaled-down heat exchanger to evaluate tritium permeation from the coolant through the heat exchanger walls. However, the two most critical aspects of coolant loop operation will be modeled in the SLL TSTF. First, promising candidates for tritium permeation barriers will be evaluated in realistic operating environments.

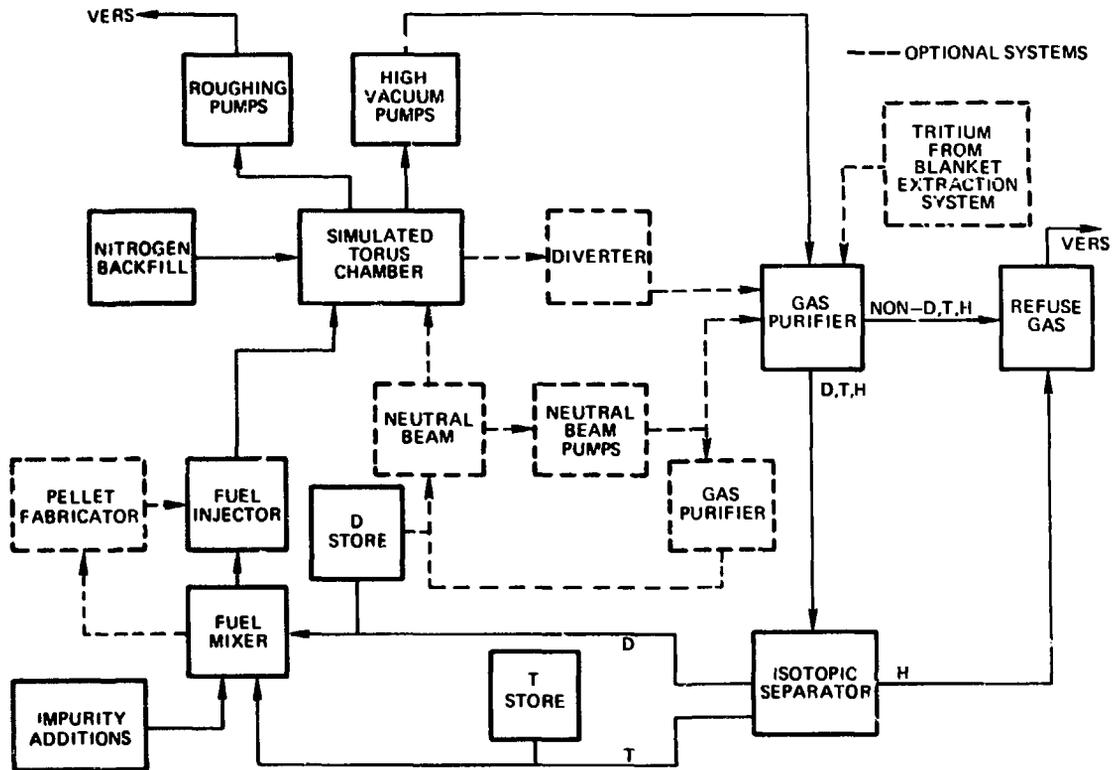


Figure 3. TSTF Schematic

Second, a system for removal of tritium from a high-pressure helium gas coolant loop will be demonstrated. This process will involve catalytic conversion of tritium to tritiated water and collection of the water vapor on molecular sieves.

Containment

The SLL TSTF will be assembled from austenitic stainless steel and other materials previously demonstrated to be compatible with long-term exposure to tritium. All joints will be welded or contain metal-to-metal seals. Where necessary, surfaces exposed to tritium will be coated with a permeation barrier, such as a thin film of chrome/chrome oxide. The entire assembly will be housed in modular glove boxes which operate at a pressure slightly negative with respect to the room.

To preclude the occurrence of an explosive mixture of hydrogen isotopes and oxygen, and to avoid oxidizing or nitriding the uranium beds, the entire glove box volume will be maintained in an argon atmosphere. Instrumentation will monitor tritium, water, and oxygen partial pressures in the glove box, and appropriate clean-up procedures will be initiated when pre-determined levels are detected. Tritium will be removed from the glove box atmosphere by circulating the gaseous contents of the module through the Tritium Research Laboratory gas purification system until a sufficiently low tritium concentration is achieved.

By interconnecting glove box modules, it will be possible to achieve a ratio of volume to decontamination rate which is representative of a well-designed reactor hall clean-up system. Thus, the operational characteristics of a fractional-scale plant decontamination process will be demonstrated using the existing Gas Purification System.

Containment of tritium associated with vacuum pumping will have significant impact on the type and design of pumps to be used. Leakage and permeation through seals and contamination of pump oil and organic gaskets are serious problems encountered in the use of most mechanical and oil diffusion pumps. Wherever possible, the SLL TSTF will avoid the use of pumps containing oil or other organics. However, the VERS is available to process contaminated waste from such mechanical pumps where their use is mandatory. Cryopumps which accumulate large tritium inventories will be doubly-contained, and they will provide secondary protection of the helium coolant from tritium sources. Pumps operating at elevated temperatures (e. g., Hg diffusion pumps) will have permeation barriers where practical, and will be doubly-contained.

The cryogenic still used for isotope separation has an inventory of ~35 gms of tritium, including both gaseous and liquid phases. The design of this apparatus includes appropriate double containment separating the tritium from the glove box and from the cryogenic coolant.

Scaling of the EPR Fuel Cycle

Since the basic flow rate in the fuel cycle is determined by the required throughput in the torus and the burn cycle in the reactor, reactor operating parameters of the different EPR designs have been collected.

Table I lists the predicted characteristics of EPR designs proposed by Argonne National Laboratory (ANL),² General Atomic (GA),³ and Oak Ridge National Laboratory (ORNL).⁴ The listed throughputs are the cycle-averaged gas loads due only to the exhaust of plasma gases at the end of the burn cycle. Also listed is the additional throughput expected in the GA EPR due to fueling and the operation of the Flowing Plasma Boundary (FPB) system proposed¹⁰ for wall impurity control. The gas flow necessary for the use of the FPB would substantially increase the gas load per cycle and would correspondingly affect the pumping speed necessary in the scaled TSTF. In scaling down the main torus pumps to TSTF sizes, the gas loads in the absence of an FPB have been used; a different scaling factor would be necessary when using the torus and its associated pumps in simulating FPB or injector module operation.

The quantities which must be properly scaled in the TSTF include the torus volume (V), the total torus pumping speed (S), and the average gas throughput (Q). As is evident, some variation exists in these parameters among the different proposals. A realistic set of characteristics can be derived from the numbers in Table I. These representative EPR parameters are listed in Table II. Based on the data of the three EPR proposals scaled to 500 MW(t), the numbers in Table II can be considered representative of maximum gas loads expected in an EPR.

The SLL TSTF parameters of gas throughput, pumping speed and reactor volumes are all scaled down by a factor of 200 from typical EPR values.

Although this scale factor is large when compared to the factor of 10 to 20 commonly used in the chemical products industry, multiphase systems are not a problem here, and the scaling of gas mixtures is well understood both theoretically and experimentally. Consequently, we believe that a simulation with larger dimensions would result in unwarranted additional

TABLE I
PREDICTED CHARACTERISTICS OF EPR DESIGNS

	ANL	GA	ORNL
<u>Torus Vacuum System</u>			
Volume (m^3), V	711-879	441	724
Area (m^2)	592-1528	~ 350 (est.)	~800
Pump Speed (l/s), S	8×10^5	2×10^7 (max.)	1.5×10^6
$r^{-1} = S/V$ (s^{-1})	~1	~45	~2
Average DT Throughput, Q ($\text{torr} \cdot l \cdot s^{-1}$)	7.7	5.1 (945 with FPB)	7.2
Pumpdown Time (s)	10-14	~1	12 (Typ)
High Vacuum Pump Type	Cryosorb	Cryosorb	Cryosorb, Hg Diff
End-of-Burn Pressure (torr)	~3 mtorr at 70°C	20 mtorr at 700°C	---
<u>Design Parameters</u>			
Average Thermal Power (MW)	400	410	410
Burn Time (s)	30-90	125 (84% duty cycle)	100 (50% duty cycle)
Fractional Burnup	0.02	~0.03	---
Exhaust Gas Temperature (K)	700	~2000	~700
<u>Fuel Handling</u>			
Storage	Getter Bed	---	Solid UT_3 , Gas
Injection	Pellet, Blanket	Pellet, Blanket	---
Purification	Hot Getter/Pd/Ag Membrane	Pd/Ag Membrane	U Beds, Pd/Ag Membrane
Isotopic Separation	Cryostill	Cryostill	Cryostill
<u>Coolant Loop</u>			
Coolant	H ₂ O He	He	He
Maximum Temperature (°C)	302 527	600	370
Pressure (atm)	136 50	~50	~70
Purification	---	T ₂ O-Sieve (barrier)	---
<u>Neutral Beams</u>			
<u>Heat</u>			
Power (MW)	60	60	50
Energy (keV)	180	125	200
Duration (s)	3	2-3	5
<u>Sustain</u>			
Power (MW)	30	Plasma is not driven after ignition	Plasma is not driven after ignition
Energy (keV)	180		
Duration (s)	As needed to maintain burn		
<u>Pump</u>			
Speed (l/s per pump)	5×10^5	7.5×10^5	
Type	Cryosorb	Cryosorb	

TABLE II
 REPRESENTATIVE EPR AND SCALED TSTF VACUUM
 SYSTEM PARAMETERS

	<u>EPR</u>	<u>SLL TSTF</u>
Power (maximum MW-thermal)	500	---
Torus Volume: (m ³)	800	4
Plasma Volume: (m ³)	600	---
Plasma Density: (m ⁻³)	10 ²⁰ ions	---
D ₂ Fuel Flow* (torr-l s ⁻¹)	20	0.1
T ₂ Fuel Flow* (torr-l s ⁻¹)	20	0.1
T ₂ Inventory (g)	8 x 10 ² - 8 x 10 ³	~40
Operating Cycle (s)	20 - 100	60 (simulated)
DT Gas Load After Burn** (torr-l)	2.4 x 10 ³	12
⁴ He Gas Load After Burn** (torr-l)	0.3 x 10 ³	1.5
DT Gas Pressure After Burn** (mtorr @ 0°C)	3	3
⁴ He Gas Pressure After Burn** (mtorr @ 0°C)	0.4	0.4
Pump Speed (ℓs ⁻¹)	8 x 10 ⁵	4 x 10 ³
Pumpdown Time 3 → 0.03 mtorr (s)	5 - 15	~5

* Assuming duty cycle ~1, ignoring neutral beam contributions, and using plasma density at end of burn to compute pressure. All gas loads (torr-ℓ) and pressures are computed at STP.

** Assuming negligible pumping during burn cycle and using plasma density at end of burn to compute pressure.

expenditures for building space and capital equipment--primarily for containment systems. Furthermore, a larger simulation would not allow use of "off-the-shelf" components for most TSTF subsystems. On the other hand, a reduction in scale compared with 1:200 may also be feasible, and a more detailed systems study will be conducted early in the design phase to determine an optimum scale factor.

Recently, there has been increasing interest within the plasma community¹¹⁻¹³ in studying an interim device to be constructed after the Tokamak Fusion Test Reactor (TFTR) and before the Experimental Power Reactor (EPR). Preliminary concepts now being discussed are the Ignition Test Reactor (ITR) by GA¹² and The Next Step (TNS) by ORNL.¹³ Initial indications are that the ITR would operate at a reduced thermal level (tens of megawatts) compared with EPR (hundreds of megawatts) and would not have a power conversion loop. Both reactors would burn D-T fuel and, therefore, would require a fuel processing cycle similar to that of EPR.

The Tritium Systems Test Facility described in this proposal is intended to provide tritium handling technology for EPR.¹⁴⁻¹⁶ This same technology is necessary for design of ITR or TNS. The primary difference in applying TSTF results to ITR or TNS is that extrapolation to an interim device would probably require a scale factor different from the factor of 200 necessary to simulate EPR. For example, a scale factor of order 10 would be necessary to apply TSTF results to the operation of ITR.

FACILITY DESIGN

The 200:1 reduction in scale from EPR is applied throughout the simulation of the EPR fuel processing cycle, and it appears explicitly in the calculations of pumping speeds, gas loads, fuel supply rates, gas purification throughput, distillation requirements, and tritium inventory. The TSTF--consisting of the simulated torus, tritium and deuterium fuel supply, recovery, purification, and isotopic separation systems, and the blanket coolant/steam cycle system--is secondarily contained in glove boxlines schematized in Figure 4. The boxlines are compartmented into varying lengths and heights, depending upon the apparatus contained within. The choice of scale factor leads to a design that will occupy approximately 100 m³ of glove box volume in the Tritium Research Laboratory and results in a total tritium inventory of ~40 grams (Table II).

Systems Analysis

An important part of the overall program is the use of systems analysis throughout the development and operation of the TSTF. During the formulation and design stage, the analysis consists of parametric studies to determine systems design sensitivities. In the construction phase, system engineering studies will be used to optimize the configuration of the facility. Once construction of the TSTF is completed, systems performance studies will be used to evaluate TSTF operation. The evaluation of TSTF experiments will be used to determine the best configurations for the scale-up required for the EPR, ITR and TNS facilities.

Simulated Torus

A principal component of the TSTF design is a 0.61-m (24-in.) diameter, 13.8-m long stainless steel cylinder which represents the EPR torus. The volume of the simulated torus is 4 m³. Four 0.15-m-inside-diameter ports will be located around the cylinder at 1-m intervals along

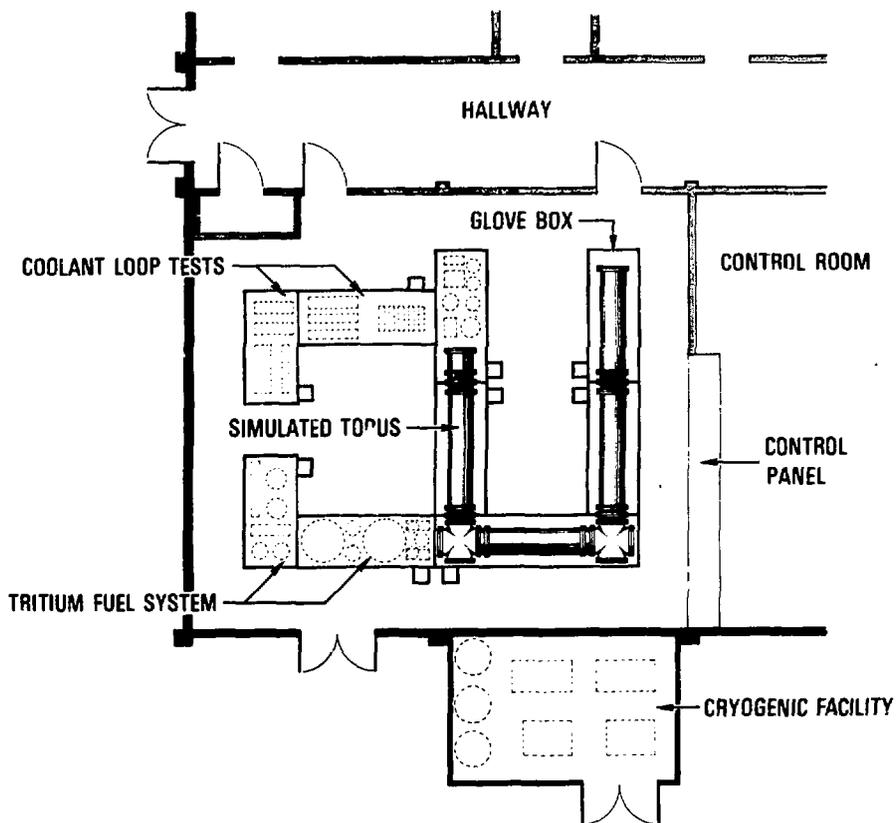


Figure 4. TSTF Floor Plan

the length, resulting in a total of ~50 ports. These ports will provide access to the reactor for pumps, gas injectors, and diagnostic instrumentation. This large number of ports allows a maximum of flexibility for future changes and additions with minimal downtime and cost. The chamber will be assembled from ~3-m long sections joined with 0.61-m Wheeler® flanges, and will be enclosed in a modular glove box line. All-metal sealed valve pairs are provided on one half of the available ports so that pumps and other devices can be removed or installed while maintaining the tritium containment integrity of the simulated torus and the piece of equipment. Heating elements and thermal insulation will be installed on the outside torus wall for bakeout.

TSTF Vacuum Pumping

Vacuum pumps are an integral part of the D-T processing loop in the TSTF. The required pumps fall into three categories: high vacuum; foreline; and roughing and auxiliary high vacuum.

High vacuum pumps are used to achieve base pressures in the torus chamber and to pump out the torus chamber between simulated burn cycles. Foreline pumps transfer gas from the high vacuum pumps to the purifier where impurity gases, including ash and unwanted reactive gases such as CO, are separated from the D-T fuel. The roughing and auxiliary high vacuum pumps are normally used only in chamber pump-downs after the vacuum chamber has been backfilled with nitrogen to atmospheric pressure. Roughing pumps are used to evacuate the chamber to a pressure of ~0.1 mtorr, a pressure regime where the auxiliary high vacuum pumps can be started.

Using the gas throughput and pumping speed requirements developed above, it would be possible to proceed directly into evaluation and selection of pumps required in the three (vacuum, foreline, roughing) TSTF pumping systems. These choices, however, are influenced by recommendations in the EPR reports. These pumps are listed in Appendix A, and span the spectrum of pump technology from older, well-tested designs (e.g., rotary mechanical, blower, mercury diffusion) to newer, more compact systems (e.g., getter canisters, liquid-helium-cooled cryopumps). As a result of reviewing the pumping requirements of the EPR proposals, we have generated a set of criteria to be applied to the TSTF pumps. These requirements are that TSTF pumps:

- be tritium compatible and organic free,
- can be doubly-contained if necessary,

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- have proper pumping speeds for all required gases in all required pressure regimes,
- can be scaled up to meet EPR requirements,
- can be easily maintained,
- have acceptable cycle times, capacity/cycle, power consumption, and cost/unit pumping speed.

Each of these criteria is discussed in detail in Appendix A.

Based on our assessment of available pump data, a recommended TSTF pumping system is shown schematically in Figure 5. The system characteristics are summarized in Table III. Note that no components containing organics are exposed to high levels of tritium, and that the system is closed; i. e., no gas is released to the environment. Although a getter/cryosorb system appears optimum, the torus and associated vacuum plumbing will be flexible enough to test other pumping systems. The getter/cryosorb system proposed to meet the pumping needs of TSTF requires several areas of development. These areas are delineated under Research and Development.

Rough pumping of the system is performed by a liquid-nitrogen-cooled molecular sieve/dry carbon vane pump combination. A combined getter/ion pump continues pumping the nitrogen-backfilled chamber to $\sim 10^{-6}$ torr. Two sets of combined getter/cryosorb pumps are used to provide high (and ultra-high) vacuum pumping capability: while one set is pumping, the other set can be regenerated. With existing getter/cryosorb combinations, a total gas capacity of $\sim 1.5 \times 10^4$ torr- ℓ can be pumped before outgassing of the pumps will be necessary. This in turn implies that the pumps can operate more than one thousand simulated burn cycles of 60-s duration before regeneration; i. e., about one day of continuous use.

After one getter/cryosorb set has become saturated, it is valved off from the torus volume and the other combination valved in. Desorbed gas from the first set is pumped to a surge tank from which it flows through a hot uranium bed into a Pd/A_g diffuser. Purified D-T-H then proceeds to the cryogenic still for separation.

The TSTF is designed to be able to test the operation of the cryosorb pump in the mtorr pressure range. Testing of the pumps in this pressure regime will permit quantitative evaluation of the potential problems of gas-caused thermal shorts between the liquid nitrogen and liquid helium baths and "icing" of the sieve surface by frozen gas layers. These tests are needed in light of the widespread desire of reactor designers to use cryo-pumps in their systems.

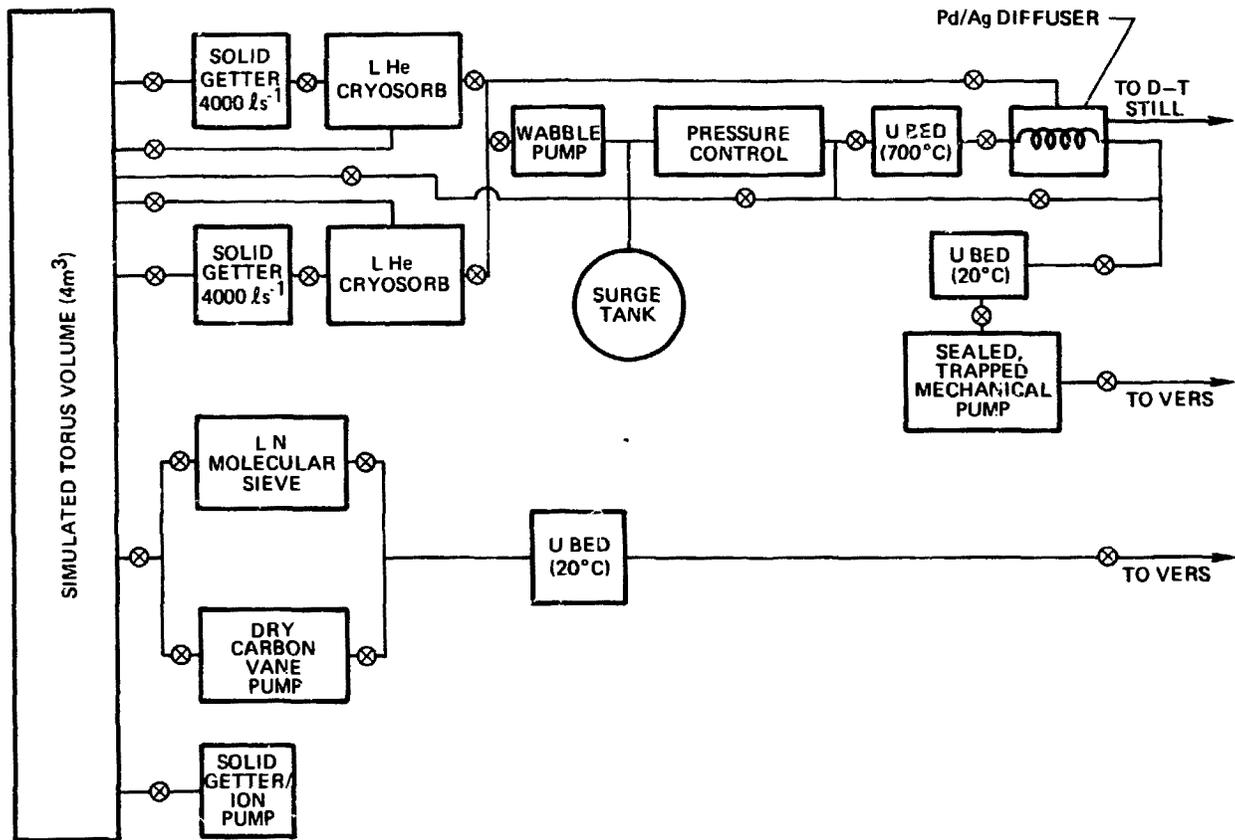


Figure 5. Recommended Pumping Systems for TSTF

TABLE III
PUMPING SYSTEM SUMMARY

Scaling for Tritium Handling System (factor of 200)

Chamber Volume

D_2 fuel flow: 3.5×10^{-4} mole/min = 1.4×10^{-3} gm/min = 0.1 torr-ℓ s⁻¹

T_2 fuel flow: 3.5×10^{-4} mole/min = 2.1×10^{-3} gm/min = 0.1 torr-ℓ s⁻¹

Assumed operating cycle: 45 s burn, 60 s total duration

Gas load after burn: 12 torr-ℓ D-T
1.5 torr-ℓ ⁴He

Gas pressure after burn: 0.003 torr DT
0.000375 torr ⁴He

Chamber Pumps

D-T high vacuum pumps: two solid getter/cryopumps with 6-inch gate valves

Base pressure: $\sim 10^{-9}$ torr

Time to base pressure: ~ 4 days (includes 2 days bakeout at 150°C)

Pump capacity: 15,000 torr-ℓ each

Pump cycles: 1100

Pump speed: 4000 ℓ s⁻¹ each

Pumpdown: $\tau^{-1} \sim S/V \sim (4000 \text{ ℓ s}^{-1})/4000 \text{ ℓ} = 1 \text{ s}^{-1}$, implying
 ~ 5 s from 3×10^{-3} torr to 3×10^{-5} torr

Pump recycle time: < 3 hours

Daily operation time: 24 hours

Roughing pumps: Carbon vane pump + liquid-nitrogen-cooled molecular sieves

Auxiliary high vacuum pump: combined getter/ion (used only after nitrogen backfill of chamber)

Gas Purification

Goal: separate H-D-T gas from other gases

Input: 15,000 torr-ℓ per cryopump recycled in 1 hour

System: Pd/Ag filter, 0.013 cm thick, 30 cm² area, operating at 600°C, 1 atm differential

Forepump/transfer pump: Wabble® pumps, staged in series

®Société de Recherches Techniques et Industrielles, Route de Guyancourt, 78530 Buc, France.

Separation of Hydrogen Isotopes

In an EPR, hydrogen isotope separation requirements will be strongly dependent on the method of reactor fueling and impurity control. Proposed fueling methods include pellet injection, gaseous blanket flow, and neutral beam injection. Impurity control may be accomplished with a flowing plasma boundary, or diverters. Each of these methods places different demands on the fuel processing systems, including isotopic separation.

Currently cryogenic distillation appears to offer the best throughput at high output concentration with low inventory and low power consumption. For an EPR, the degree of separation required is uncertain; however, purity requirements of the Fusion Engineering Research Facility (FERF)⁽⁷⁾ (\cong 90 percent isotopic purity) are achievable with current technology.

Combining published information with the design parameters of the Sandia TSTF, the characteristics of a continuously operating cryogenic distillation system can be estimated. For a system with negligible protium, preliminary sizing studies indicate that a 40-stage column with a packed height of 2.84 m (9.3 feet) will yield 91.5 percent D_2 and 91.5 percent T_2 at the top and bottom, respectively, when DT is withdrawn at the 80 percent concentration level for equilibration ($D_2 + T_2 \cong 2$ DT) in a catalytic converter and then recombined with the feed stream. The 25-mm-diameter column will have sufficient capacity to process the anticipated gas load (Table III).

The thermal design of a representative single distillation column is illustrated in Figure 6. The coolant is gaseous helium, which leaves a helium refrigerator at approximately 14 K, and is moved by means of carefully insulated transfer lines to section A. Electrical heaters are used to adjust the temperature of the gas before it flows through the cooling coils surrounding the condenser and reboiler. Two separate vacuum jackets surround the distillation column to minimize heat leakage. Liquid nitrogen is used to provide additional thermal protection to the column and helium coolant. The equipment required to support the operation of the distillation column is shown in Figure 7.

The complexity of the distillation apparatus will be a direct function of the extent to which protium in the form of HT is present in the feed and output streams. To remove the protium contamination, the TSTF has been designed with a double (sequential) cryostill system. Further discussion appears in Appendix C.

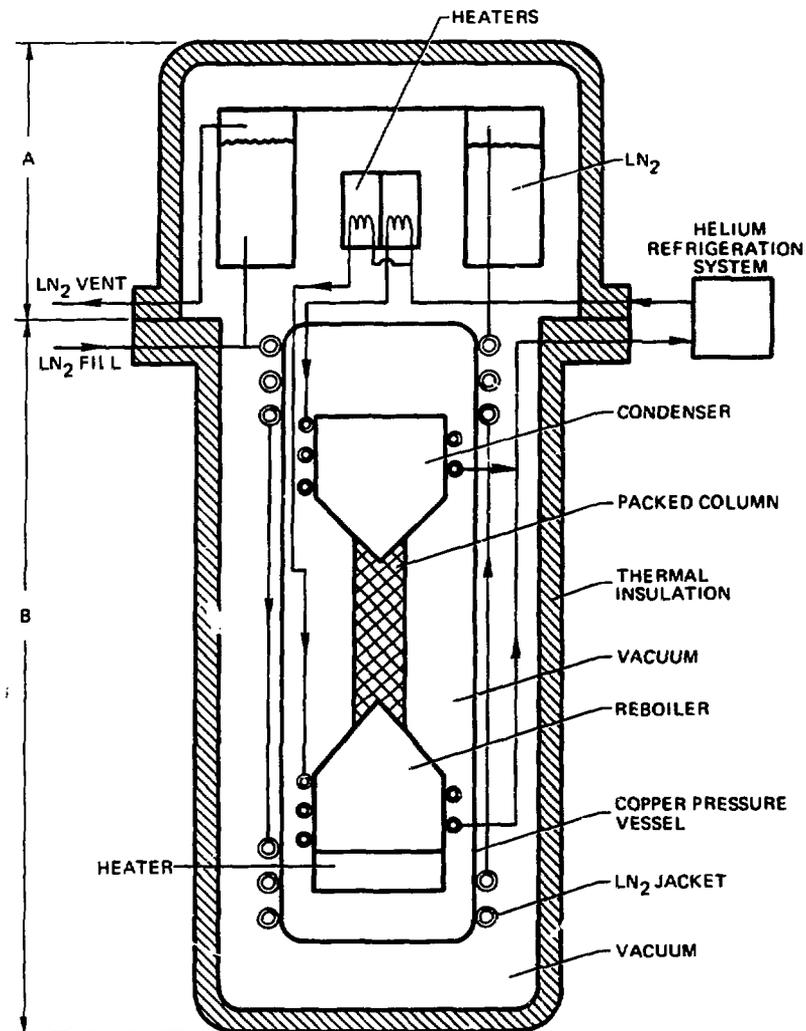


Figure 6. Typical Thermal Design for Hydrogen Isotope Distillation

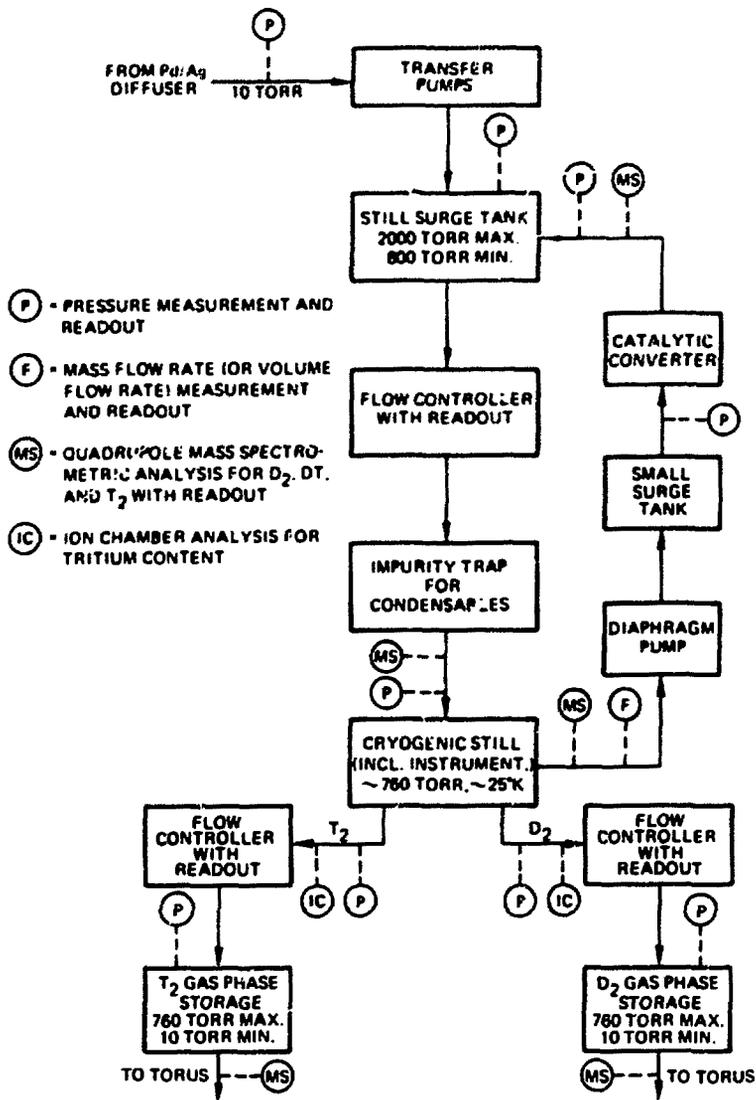


Figure 7. Distillation Column Flow Sheet

Before firm cost estimates can be established, a parametric study of still performance using a computer model of the distillation process will be required. Sufficient information exists within the ERDA laboratories to enable Sandia to construct such a computer code. After the design of the still is established, fabrication will be subcontracted to a firm with extensive cryogenic experience. To obtain budgetary estimates, preliminary discussions were held with personnel of Arthur D. Little, Inc., Cambridge, Massachusetts. We feel that this firm, and perhaps others, would be available and qualified to support Sandia on the cryogenic portion of the TSTF project.

Coolant Loop

Helium and water are candidate primary coolants in current EPR designs. For EPR applications (but possibly not for ITR or TNS), it will be necessary to limit the amount of tritium entering the power cycle. In anticipation of EPR requirements, the Sandia TSTF facility will include testing of both types of coolant systems. In the case of helium, a combination of permeation barriers and tritium removal will be used to limit tritium permeation losses through the heat exchanger tubes to acceptable levels. In the case of water, however, no economically feasible methods appear to exist for separating small amounts of tritium from water on the scale expected for the EPR.

Figure 8 is a simplified schematic of a possible EPR helium coolant loop. Preliminary calculations indicate that catalytic conversion of the entire helium coolant stream is economically impractical. In this proposal, it is assumed that permeation barriers will be used to reduce the tritium flux from the coolant to the power cycle to a sufficiently low level that side-stream processing is possible. Figure 8 thus shows a portion of the helium stream diverted through a catalytic reactor where the tritium is oxidized to form tritiated water which is adsorbed in a molecular sieve bed.

Figure 9 illustrates the layout of the TSTF tritium removal system for the helium coolant loop. We will build, test, and evaluate in the TSTF a system for removing tritium under the high temperature and pressure operating conditions of the EPR.

With water/steam as the EPR coolant, most of the tritium will be converted to HTO. In the absence of radiolysis, the permeation of tritium is expected to be negligible because HTO does not permeate through metals. However, the radiolytic decomposition of HTO is expected to increase the gaseous phase tritium partial pressure in the coolant, and thereby cause increased permeation of tritium into the power cycle. Thus, the amount of

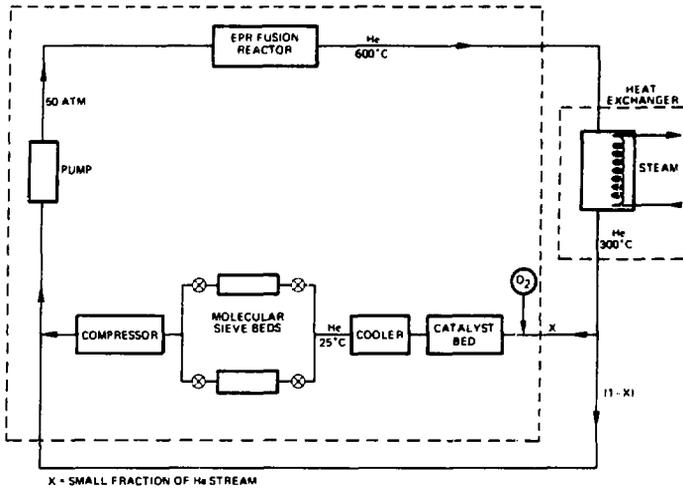


Figure 8. Schematic of EPR Helium Coolant Loop.
 (The components within the large dashed rectangle are simulated in the TSTF by the system shown in Figure 9.)

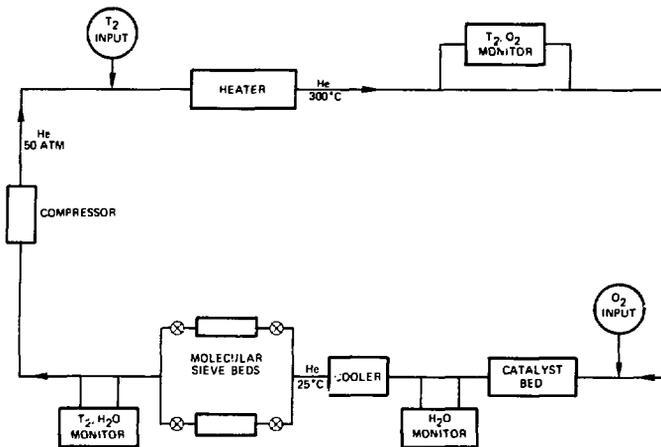


Figure 9. TSTF Tritium Removal System for Helium Coolant Loop

tritium retained in the water should be minimized to reduce permeation, to reduce tritium losses to the environment if leaks develop in the EPR coolant system, and to minimize tritium inventory.

The technology required for the design of either a steam or helium heat exchanger is well established. For TSTF, we conclude that it is neither necessary nor desirable to build a scaled-down heat exchanger. Figure 10 depicts a test apparatus for evaluating heat exchanger tube permeation barriers at EPR operating temperatures and pressures but without flow. These conditions will be adequate to simulate the tritium permeation through the heat exchanger surfaces and will scale directly with tube area.

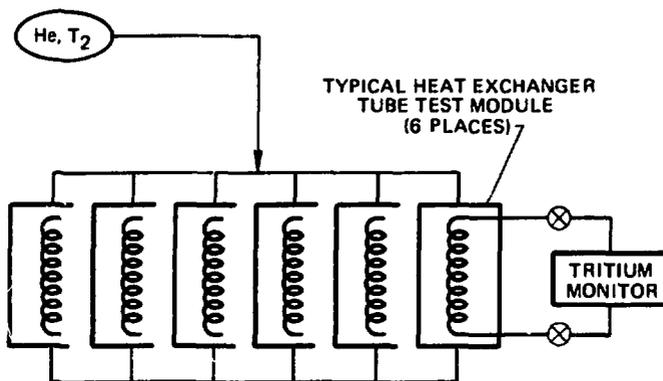


Figure 10. Barrier Material Test System

Fuel Injection, Heating, and Storage

Fuel Injection

The GA, ANL, and ORNL EPR proposals indicate that the primary supply of fuel for (pulsed) tokamak operation will be provided prior to initiation of plasma discharge and neutral beam heating. If a substantial fraction of the D-T fuel is consumed during burn (implying long burn times or high plasma density), it will be necessary to replenish the fuel supply by external injection. The refueling operation, if necessary for EPR, presumably will be accomplished by pellet injection, gas blanket flow, flowing plasma boundary, or neutral beam injection.

The SLL TSTF baseline design assumes that EPR fuel injection takes place after the plasma exhaust cycle, and is accomplished by the controlled flow of a predetermined gas mixture of deuterium, tritium, and impurities into the reactor in a period of a few (~5) seconds.

If the simulation of midburn fuel replenishment becomes necessary, an appropriate fuel injection device (pellet, blanket, neutral beam injector) will be installed at one of the pre-allocated positions on the reactor. We recognize that pellet fabrication and neutral tritium beam injection may substantially increase the load on the isotopic separation facility. Estimates of these increased demands have been included in the design of the cryogenic still. An upper limit on the magnitude of the increase in gas loading due to neutral beam injection can be estimated by computing the quantity of fuel introduced into the torus during one burn cycle of the ANL EPR. In this device, injection will occur in two stages--ignition and burn. The ignition injection will consist of a 40 megawatt, 3-second-long pulse of 180 keV neutral deuterium (D^0) atoms, while during the 50 second burn 23 megawatts of D^0 will be injected. The corresponding amounts of gas introduced will be ~60 torr- ℓ and ~500 torr- ℓ during each stage of injection. Thus the total amount of fuel injection (~0.6 x 10^3 torr- ℓ) is only ~25 percent of the gas load to be pumped at the end of burn in the absence of injection.

Although neutral beam injection into the torus would not significantly increase the reactor gas load, the quantity of gas to be pumped in the neutral beam devices themselves is large, primarily because of ionization and neutralization inefficiencies. For example, assuming 15 percent efficiencies in both the ionizer and neutralizer of the injector, the neutral gas input to the injector is a factor of $(0.15)^{-2} \approx 40$ times greater than the effective neutral gas load injected into the torus. However, assuming that the composition of the neutral beam is primarily deuterium, most of the neutral beam injection gas which does not reach the torus can be purified and returned to storage without isotopic separation; as indicated in Figure 3, a small side stream could be sent for distillation to maintain the required isotopic purity.

Similarly, refueling schemes such as a flowing plasma boundary may increase the load on the isotopic separation facility by a factor of ~20. In this instance, the SLL TSTF may operate at a further reduction in scale, although some spare capacity has been designed into the purification and isotopic separation facilities.

Fuel Heating

Gas dynamic complications arise during the torus injection and pump-down processes because the flow is unsteady and goes from the transition flow regime to the free-molecular flow regime. To simulate pumping speeds

and flow conditions, it is necessary to duplicate both gas pressure and temperature in the TSTF. Gas pressure will be regulated by the quantity of fuel injected prior to the simulated burn cycle, while the temperature will be attained by thermal heating of the gas. It has been shown (Appendix G) that a one-meter-long heater within the torus at the pump-out port can raise the gas to the desired temperature during the pump-out process. This technique (as opposed to heating the complete volume of gas for long, 60 second, periods of time) will conserve energy, reduce external heat dissipation, and minimize tritium permeation through the walls of the simulated torus.

Fuel Storage

Two technologies are sufficiently well developed for storage of large (> 10 g) quantities of tritium. The first, storage in the gas phase at pressures near 1 atm, requires no technical innovations, and is appropriate for both TSTF and EPR. However, for kilogram inventories, the required volume [3730 l(STP) kg⁻¹] becomes large. For this reason, storage of D and T as a metal tritide (10 l kg⁻¹ T at 25 percent theoretical density UT₃) may be more practical. At the SLL TSTF scale of 1:200, an EPR inventory of 8 kg scaled to 40 g would result in 150 l (STP) of gas phase storage, or a 1060 g U-bed occupying 0.4 l volume. Since both methods are practical with current technology, and neither technique requires an excessive amount of glove box space, the SLL TSTF baseline design will incorporate both gas-phase and uranium tritide storage as alternative methods of tritium, deuterium, and mixed isotope storage.

Environmental Control Systems and the Tritium Research Laboratory

The TSTF will occupy approximately 13% of the floor space of the Tritium Research Laboratory, as shown in Figure 11. The TRL incorporates containment and cleanup facilities in which tritium that is released is collected and held for proper disposal rather than vented to the atmosphere. This containment is achieved with hermetically sealed glove boxes that are connected by manifolds to two central decontamination systems, the Gas Purification System (GPS) and the Vacuum Effluent Recovery System (VERS).

Environmental control of the TSTF is provided by use of the identical secondary containment and decontamination approach that has been applied to the Tritium Research Laboratory

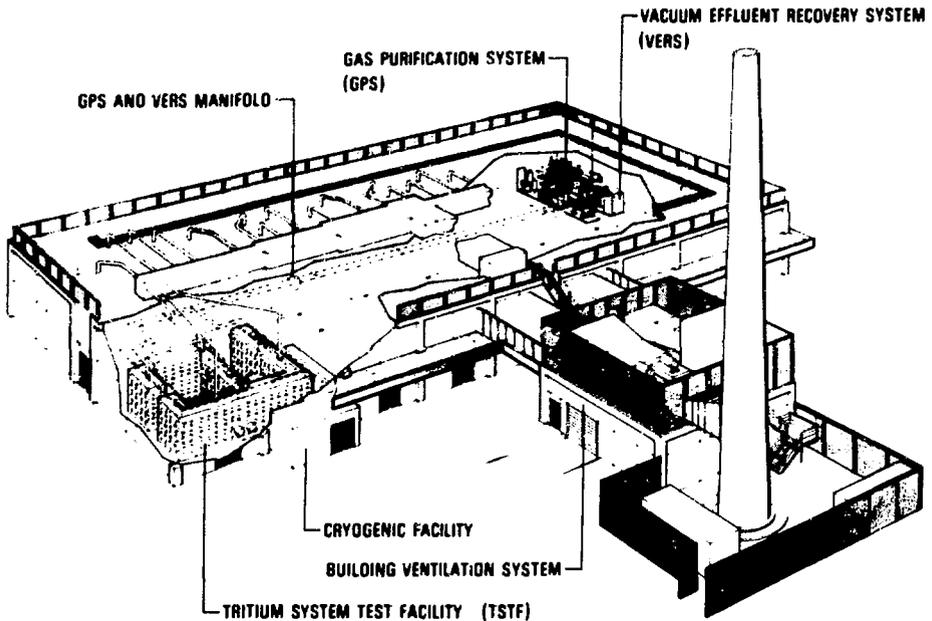


Figure 11. TSTF in Tritium Research Laboratory

Facility Containment

The TSTF will be secondarily contained in 1.2-m wide x 3-m high glove boxlines, depicted in Figure 12. The boxlines are compartmented into lengths ranging from 2.7 m to 4.9 m, depending upon the apparatus contained within. One compartment exceeds the 3-m height to accommodate the cryogenic still. The total glove box volume is approximately 100 m³. The boxlines are compartmented to keep a tritium release from contaminating the entire boxline and to maximize the speed with which the decontamination system can clean up a tritium release.

Boxline Description--The boxlines will be constructed from hydrogen compatible materials, for example, aluminum or austenitic stainless steel. A modular construction of approximately 0.9-m x 1.5-m gasketed panels attached to a structural framework will be used (see Figure 12). Each box compartment will contain glove ports and viewing windows to provide necessary manual and visual access to the interior. Glove ports will be covered and evacuated when not in use to reduce both tritium buildup inside the gloves and permeation into room air. Viewing windows will be gasket-sealed laminated safety glass. An air lock passthrough 0.5 m in diameter

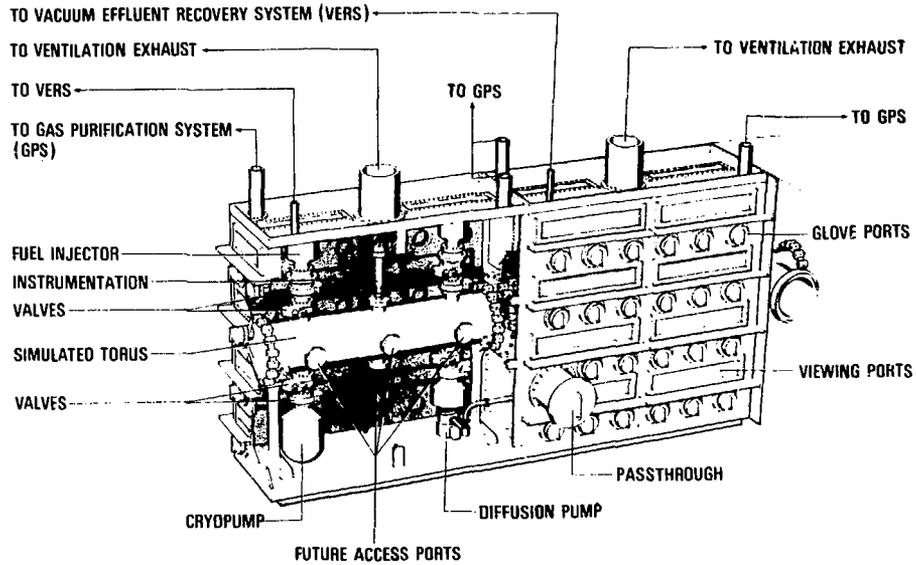


Figure 12. TSTF Glove Box Section

by 0.6 m long will be provided for routine movement of small items into and out of each glove box compartment. Large items can be put into or removed from the boxline through one of the removable modular panels.

Central pressure control and vacuum systems will be used to maintain total boxline pressure and to evacuate glove ports and passthroughs. Tritium monitors will be installed in each box compartment. A purification system will control oxygen, moisture, and nitrogen content of the argon boxline atmosphere. Both regular utility and emergency electrical power will be provided within the boxline. Feedthrough provision will be made for instrumentation, inert gas, and cryogenic services. A cooling system will be provided to remove heat load from each of the box compartments.

Each boxline compartment is connected to the two TRL central decontamination systems, the GPS and VERS. The boxline compartments will also be connected to, but manually valved off from, the stack exhaust system. Individual boxline compartments will be connected to the stack exhaust system when high velocity air hood operation is required for movement of large items into or out of the box.

Gas Purification System (GPS)--The GPS will decontaminate the boxline atmosphere in the event of an accidental release, an expected release resulting from maintenance, or a slow buildup of background contamination. The GPS, illustrated in Figure 13, consists of blowers for gas circulation, catalyst beds for conversion of hydrogen isotopes to water, dryers to collect oxidized hydrogen isotopes, and control and diagnostics systems to provide remote and manual control and assessment of operational status.

The GPS tritium collection capacity is limited by individual dryer holding capacity. The capacity of each dryer, while maintaining 1 ppm or less water effluent, is 37 gm moles of water, or 222 gm of tritium if all water is T_2O . Major system performance criteria are summarized in Appendix D. Acceptance testing at the manufacturer's plant and preoperational testing in progress at Sandia Laboratories have verified the capability of the GPS to meet all criteria so far evaluated with hydrogen. Catalyst performance tests using a prototype reactor were run with tritium, and concentration reduction factors of approximately 10^5 from an inlet concentration of 1 ppm were measured.

Two modes of operation, recirculating and stacking, are possible. The recirculation mode is the normal method of operation of the GPS. In this mode the glove box gases are pumped from the box through the GPS and returned to the box. The glove box atmosphere is recirculated until the tritium concentration has been reduced to an acceptable level, at which time the laboratory control computer sends a shut-down command to the GPS. Operation in the stacking mode is similar to the recirculation mode with

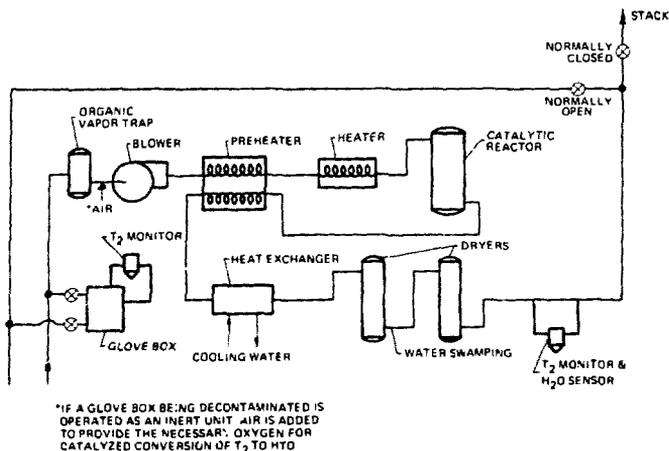


Figure 13. Gas Purification System (GPS) Schematic

the exception that the glove box atmosphere is not recirculated but stacked after passing through the GPS. This is accomplished by drawing clean box atmosphere gas into the manifold ahead of the glove box and venting the GPS effluent to the ventilation exhaust.

Vacuum Effluent Recovery System (VERS)--The VERS is used to decontaminate exhaust gases from the laboratory vacuum systems before venting these gases to the stack. The VERS is a system very similar to the GPS but with a much smaller throughput. All TSTF effluent, other than box compartment atmospheres, will be processed through the VERS. The GPS dryers are used for collection of the VERS water effluent. VERS processing capacity is limited by the holding tank volume of 11.4 m³ at 93 kPa.

The VERS, illustrated in Figure 14, consists of an effluent monitoring section for dividing effluent into two contamination levels, a storage section for collecting effluent, a decontamination section for oxidation and collection of the oxidized hydrogen isotopes, and control and diagnostics systems to provide automatic and manual operation and assessment of operational status. The catalytic reactor is maintained at an elevated temperature standby condition to assure combustion of tritiated hydrocarbons and to be ready to begin processing upon receipt of a start signal.

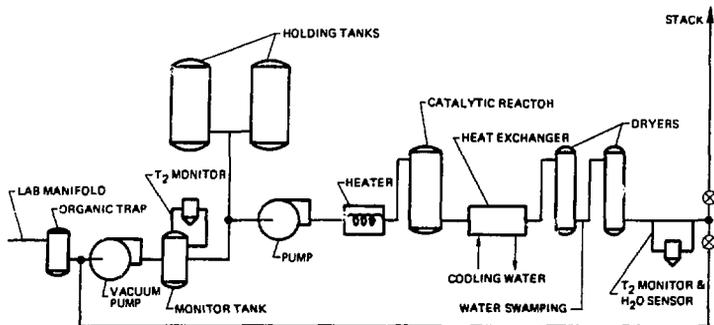


Figure 14. Vacuum Effluent Recovery System (VERS) Schematic

Expected TSTF Tritium Release

Expected tritium releases from the TSTF may occur as a result of maintenance operations such as component removal or replacement, and as a result of permeation. In all such events, released tritium is secondarily contained by the sealed boxline and subsequently removed from the boxline atmosphere by the TRL decontamination systems. The only tritium escaping to the laboratory room air and being vented to the stack is that small quantity permeating through window and glove port gaskets and through gloves in uncovered glove ports. Personnel and environmental protection is provided by a combination of the use of proven health physics techniques and the TRL decontamination systems as follows:

Permeation and Leakage--Permeation and leakage from apparatus result in a slow buildup of background tritium concentration in the boxline compartments. When the concentration reaches a predetermined level, the GPS is used to reduce the concentration to a lower level. This activity is performed as routine maintenance on a schedule which results in keeping boxline compartments below Maximum Permissible Concentration (MPC) levels associated with working full time in the gloves.

Planned Maintenance--Component removal or replacement which requires breaking a tritium containment boundary of the apparatus will result in the release of tritium and tritiated water vapor into the boxline compartment. Before a component is removed from a tritium contaminated system, it is isolated by valves from the rest of the apparatus, exposed to deuterium several times to reduce adsorbed tritium by exchange, then purged with an inert gas. When the residual contamination as measured by a tritium monitor is sufficiently low, the component is removed or replaced. If the component is too large for the passthrough, the boxline compartment is

cleaned up using the GPS in both recirculation and stacking modes. The boxline compartment is manually connected to the building ventilation exhaust, and one of the modular panels removed from the box. With the compartment being used as a high velocity air hood, the component is removed through the panel opening.

Accidental TSTF Tritium Release

Accidental tritium releases may result from human error or equipment malfunction. In all accidental releases, the tritium is contained within the boxline and subsequently removed from the boxline atmosphere by the TRL decontamination systems.

EPR Containment/Cleanup Simulation

The TRL decontamination systems, in conjunction with the TSTF boxline and simulated torus, will be used to demonstrate all aspects of EPR routine and accidental tritium containment/cleanup systems. Use of these systems allows flexibility in volume selection and cleanup mode.

Simulation of EPR Room Volumes--The TSTF compartmented boxline can be arranged to provide a range of volumes from approximately 2.7 m³ to 100 m³ by opening panels in the walls separating the compartments. Proper selection of boxline compartments can result in volumes which scale appropriately for the various room sizes of EPR. Similarly, combinations of rooms with various flow restrictions can be generated by appropriate selection of boxline compartments and adjustment of inter-connecting opening sizes.

Simulation of Cleanup Systems--The TRL decontamination systems, the VERS and GPS, have been designed to provide a range of processing capacity (though not continuous) for the two systems from 2.5 to 430 m³/hr; catalyst operating temperatures from nearly room temperature to 800 K (room temperature cannot be achieved because of the PV work added to the gas stream by the blowers); recirculation, once-through and (for limited volumes) evacuate-and-backfill modes of operation; the use of argon, nitrogen or air as the process gas; and the ability to remove and replace catalyst and sieve material safely while using built-in redundancies to maintain an operational system. These design features provide flexibility not only to detritiate simulated room volumes using two operational modes, but also to generate flow rate scaling, catalyst efficiency, and other data to provide the basis for extrapolation to larger reactor-size future systems.

Reactor Room Cleanup Simulation--The GPS will be used for simulation of reactor room cleanup by connecting it to the total volume (~100 m³) of the

TSTF glove boxline. The boxline atmosphere may be decontaminated by operating the GPS in either the recirculation or stacking mode. The processing time required depends upon the amount of tritium released and by its form. If we assume⁽⁶⁾ that the reactor room volume is 18,000 m³ and that 1 kg of tritium is released, the resulting tritium concentration is 560 Ci/m³. The desired concentration after cleanup will depend upon the HTO/HT ratio in the reactor room atmosphere and whether or not reentry will be made using protective clothing and self-contained breathing apparatus. Assuming that the reactor room tritium concentration will be reduced to Maximum Permissible Concentration levels for reentry without protective clothing, and assuming exponential dilution, the maximum and minimum GPS cleanup times for the simulated reactor room can be estimated.

If all of the tritium is in HT molecules, so that a Maximum Permissible Concentration of 2 mCi/m³ is applicable, and if the maximum GPS flow rate of 430 m³/hr is used, the cleanup time would be 3 hours. At the other extreme, using an MPC of 5 μ Ci/m³ applicable to 100 percent HTO conversion, and a flow rate of 215 m³/hr, the cleanup time would be 9 hours. These times are similar to those required for cleanup of a full scale reactor hall.

Tritiated Water Recycle/Disposal--Tritiated water at an EPR or TSTF will be created during gas purification system operations and within a helium coolant loop as the permeated tritium is oxidized on the catalyst. Small additional amounts may be generated within the torus and pumping system. In any case, the water will eventually be accumulated on molecular sieves at some stage in the tritium handling. In an EPR, this batch of water on the molecular sieves will be isolated by valves, driven off, and captured on a trap for subsequent recovery of the tritium.

We propose to send the small amounts of tritiated water generated at the TSTF to Monsanto Research Corp., Mound Laboratory for tritium extraction. This will provide an adequate simulation of waste water processing and avoid duplication of an expensive facility. TSTF operations will not be compromised, since the water is collected in a batch during sieve regeneration; subsequent isolation for shipment to Mound will not affect the continuous functioning of the TSTF.

Tritium Control, Monitoring, and Assay

The baseline SLL TSTF design requires extensive instrumentation for safe control, maintenance, and operation of the simulated fuel processing loop. The TSTF will be tested in several phases of H-D operation prior to actual tritium operation. Initially, most flow control will be carried out manually. However, it is clear that fully automatic control of the entire

fuel stream will be necessary for a meaningful scale demonstration of an EPR. As H-D phase operations continue, data from the simulated fuel cycle will be coupled with analytical calculations to parameterize loop behavior. In the final phases of operation, models of loop behavior will be coupled with a computer-controlled data acquisition system for fully computerized control of the flow loop.

At the critical points in the process stream (see Appendix F for detailed description), mass spectrometers (both quadrupole for in-process and magnetic for bench sampling), ion chambers, and calorimeters will be used to monitor H, D, and T and impurity content of the fuel. These data, along with pressure, temperature, flow rate, and other information will be used to evaluate performance of individual components, and to provide input for analytical models of loop behavior.

Loop Analysis and Modeling

An analysis of the TSTF fuel loop begins with a design of the flow paths and time sequence for mass flow through the system during startup, shutdown, and steady-state operation. Flow paths for the TSTF are depicted in Figure 15, along with the measurements that are necessary for adequate management and control of the system during all phases of its operation. A time sequence for startup and the resulting buildup of tritium within various components of the loop is given in Figure 16.

Separate U-bed storage of D_2 , T_2 , and D-T allows preservation of any accomplished isotopic separation in the event of a shutdown. Surge tanks are required to couple the cyclic operation of the pumps with the continuous operation of the traps, the Pd/Ag diffuser, and the cryogenic still. They also provide damping for perturbations in process conditions.

Since Pd/Ag diffusers require an appreciable pressure drop for efficient operation, the feed pressure to the diffuser is controlled to a predetermined design value and flow through the diffuser is controlled by the diffuser temperature. The distillation column is sensitive to mass flow and is a low pressure drop device. Therefore, flow controllers maintain the feed and product flow rates at design conditions, while the quality of isotopic separation is determined with analytical instrumentation. Startup and shutdown procedures are outlined in Appendix H.

Using component characteristics of the design described above, a detailed mass flow loop analysis will be done to allow eventual computer control of the process and to facilitate scaling to an EPR design. A computer model will be constructed which will proceed from a simple loop,

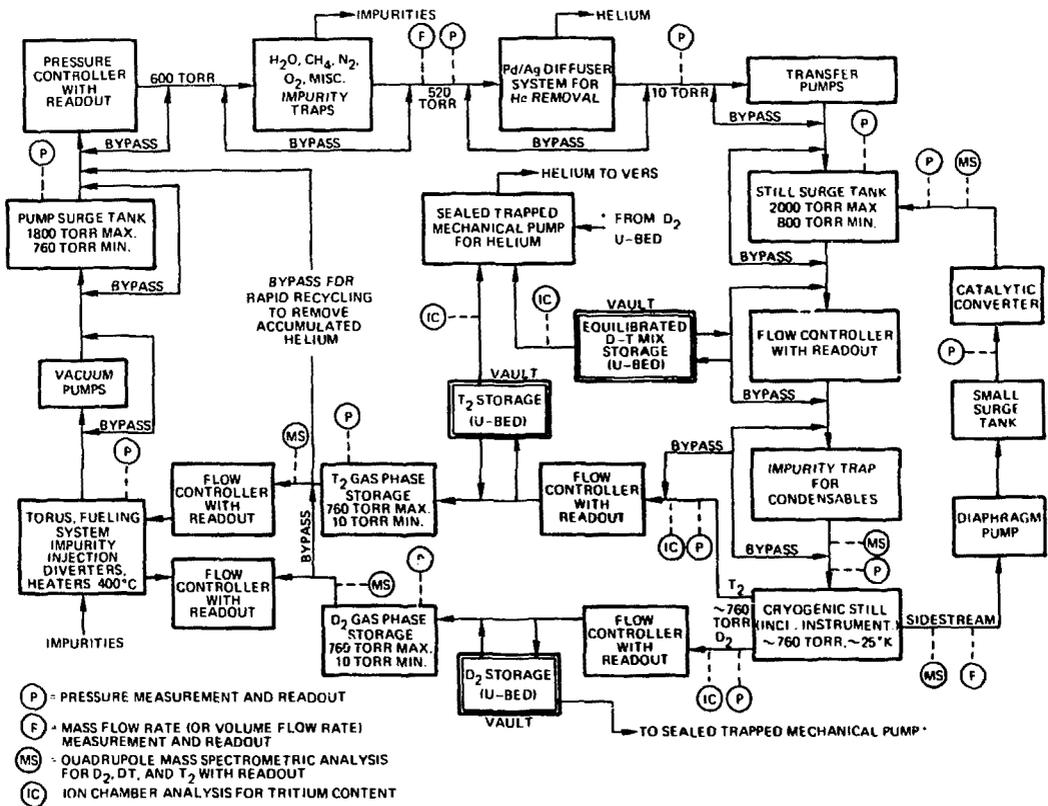
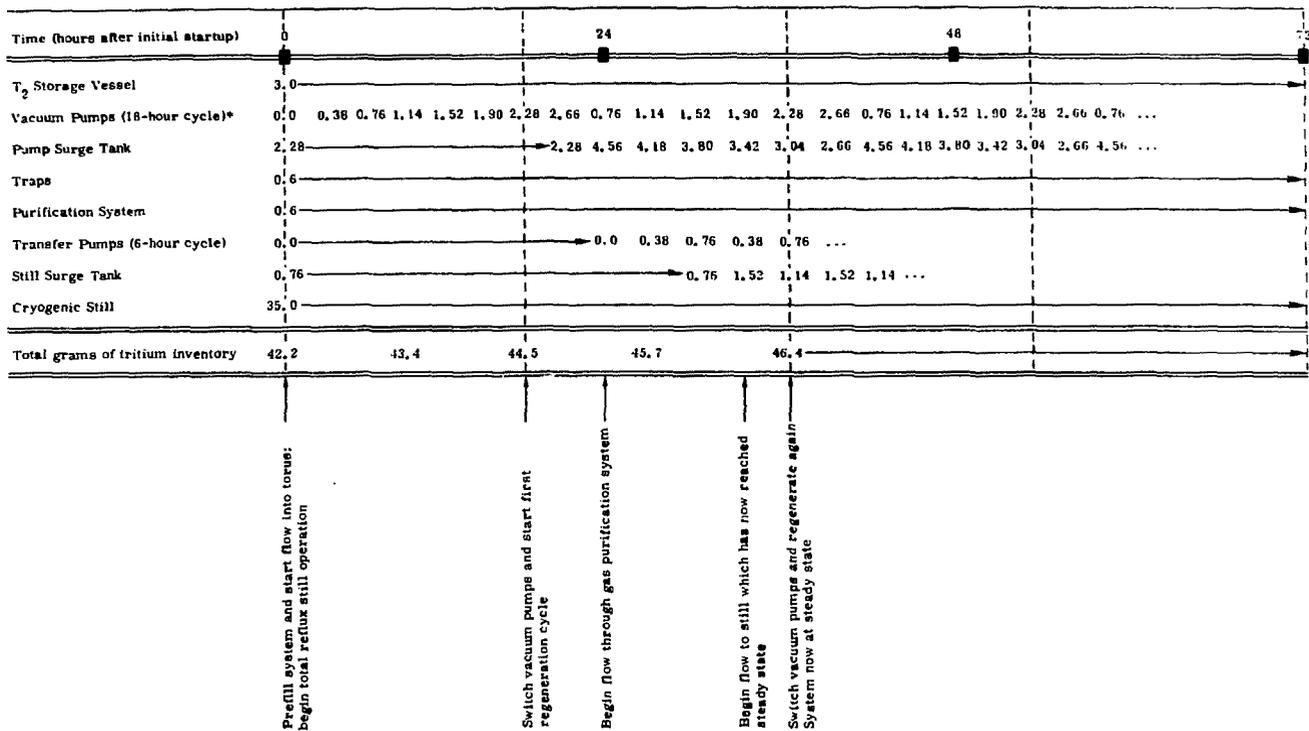


Figure 15. Flow Schematic



*The ultimate source of the tritium that accumulates in the pumps on startup is the U-bed in the vault which keeps the storage vessel at constant pressure.

Figure 16. Startup and Steady-State Flow Conditions for TSTF
 (T_2 flow rate: 2.3 g/18 hr = 0.13 g/hr)

useful for component definition and specifications, to an appropriately sophisticated set of loops capable of optimizing operating parameters.

Loop analysis can be broken into three phases. Phase 1 is a simple loop model which consists of a set of differential equations that represent gross flow patterns in the main fuel loop. Simple conductances will be used, temperature stability assumed, and pressure determinations made. Even this simple model will aid in generating initial component definition and specifications. Temperature and coolant requirements will be calculated and conductance limitations examined. Phase 2 is an advanced loop model adding detailed flow patterns of side loops. Complex conductances will be considered, temperature instabilities allowed, and transient analysis will be possible. A preliminary optimization mode will be included. The system designer will be able to employ this model to determine detailed component capabilities and possible inventory analysis techniques. The transient analysis will yield vital information on startup and shutdown in addition to propagation of temperature deviations and their system consequences. Phase 3 combines a sophisticated flow model with computer access to system diagnostics to yield computer control and dynamic feedback stabilization for the TSTF. The detailed component capabilities generated by Phase 2 and confirmed experimentally will be incorporated into a full optimization and computer control mode. The result will be complete computer control of the tritium handling processes and the detailed engineering data necessary for scale-up to EPR.

Research and Development

As a normal outgrowth of the study required to define the TSTF proposed in this report, a number of development activities have been identified. The principal areas requiring effort are vacuum pumping, isotopic separation, decontamination systems, and assay instrumentation. The specific tasks identified have been divided into three categories: those required for TSTF operations, those required for EPR operation, and studies with potential long term payoff.

Activities Required for TSTF

- Develop a reactor to supply an equilibrium isotopic mixture of D_2 , DT, and T_2 at the appropriate feed rate to the distillation column.
- Develop a suitable control system to allow continuous operation of the cryogenic still.

- Evaluate the effects of repeated thermal cycling, decay-produced ^3He , and impurity gas pumping on the mechanical stability of the active material of getter pumps.

Activities Required for EPR

- Develop high conductance water cooled baffles for torus pumps.
- Develop optimum cryopump shield geometry and placement for high throughputs in the mtorr pressure range.
- Study sieve/pump optimization and sieve icing by high gas throughputs.
- Investigate alternative methods of removing tritium from a helium stream. Would include evaluation of oxygen-containing catalysts and hydride-forming metals at low inlet concentrations.
- Demonstrate validity of isotopic swamping concepts under expected EPR conditions.
- Investigate the sensitivity of candidate catalysts to poisons.
- Study water radiolysis processes in closed systems with tritium concentrations in the range of 1-50 Ci/l.
- Develop instrumentation for discriminating radioactive sources such as ^{41}Ar from T.

Activities With Potential Long-Term Payoff

- Investigate aerodynamics as an alternate isotope separation scheme.
- Develop new gas pumping concepts for mtorr pressures.
- Investigate the feasibility of producing large tritium compatible pumps from existing designs.
- Develop more accurate ($< \pm 0.5\%$) calorimetry techniques.

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