WFPS-TME-034

JUNE 1976

MASTER

**Westinghouse Electric Corporation
Fusion Power Systems Department**

THE TFTR ULTRAHIGH-VACUUM PUMPING SYSTEM INCORPORATING MERCURY DIFFUSION PUMPS

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THE TFTR ULTRAHIGH-VACUUM PUMPING SYSTEM
INCORPORATING MERCURY DIFFUSION PUMPS

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ABSTRACT

The TFTR vacuum vessel will have a system of four 61 cm diameter mercury diffusion pumps to provide a base pressure in the 10^{-8} - 10^{-9} Torr range as well as a low impurity level within the vessel. The system, called the Torus Vacuum Pumping System (TVPS), will be employed with the aid of an occasional 250°C bakeout in situ as well as periodic applications of aggressive discharge cleaning. The total interior surface area of the vessel is 1200 m², and its volume is 63,300 liters. In addition to evacuating the main vessel volume, the twelve bellows guard regions of the toroidal vessel (total volume ~ 600 liters) will be exhausted to a pressure of $\sim 10^{-4}$ Torr.

The vacuum system backing the mercury diffusion pumps consists of four mechanical pumping units, a 1000 liter holding tank to contain the exhausted gases from the mechanical pumps, two zirconium aluminum getter pumping units, two residual gas analyzer units, and a Dry Gas supply. The TVPS is an ultrahigh-vacuum (UHV) system using no elastomers as well as being a closed system with respect to tritium or any tritiated gases. The backing system employing ~ 75 all-metal isolation valves is designed with the features of redundancy and flexibility employed in a variety of ways to meet the fundamental requirements and functions enumerated for the TVPS. Since the design, as presented in this report, is one which is a modification of the conceptual design of the TVPS, those features which have changed are discussed. Calculations are presented for the major performance parameters anticipated for the TVPS and include conductances, effective pumping speeds, base pressures, operating parameters, getter pump parameters, and calculations of time constants associated with leak checking.

The effective hydrogen pumping speed of the four two-trap diffusion pump stacks is $\sim 2 \times 10^4$ liter/sec at the vessel. Each stack is connected through similar ducts directly to the torus such that the neutral beam injector ducts are no longer utilized as pump ducts. The backing system is located in the basement of the TFTR facility and detailed descriptions of the main

units and the arrangement of valving and vacuum lines connecting them are given. The fore-line arrangement is in the form of a stack with the mechanical pumps arranged two-by-two on the floor, the zirconium aluminum getter units at an intermediate level above the floor, and the residual gas analyzers at an upper level. The configuration provides easy maintenance access for the vacuum lines and units. The effect on operating parameters of locating the backing system directly under the device in the basement pit area is also investigated.

Modifications in the vacuum pumping system for the guard regions on the twelve bellows sections are presented so that it is compatible with the main TVPS. The bellows pumping system consists of a mechanical pump unit, a zirconium aluminum getter pump unit and a residual gas analyzer.

The control and management of the TVPS is described with particular attention given to providing both manual and automatic control at a local station and at the TFTR Central Control. Such operations as testing, maintenance, leak checking, startup, bakeout, and various other operations are considered in some detail. Various aspects related to normal pulsing, discharge cleaning, non-tritium operations and tritium operations were also taken into consideration.

Finally, a cost estimate is presented. The cost of the TVPS hardware (without the bellows pumping units) is estimated to be \$811 k, and the hardware for the pumps and valving on the bellows sections at \$168 k. With controls and instrumentation estimated at \$100 k and spare parts at \$260 k, the total cost is \$1339 k for the TVPS.

ACKNOWLEDGEMENT

This work was performed for the Plasma Physics Laboratory, Princeton University, under U. S. Energy Research and Development Administration Contract E(11-1)-3073, Sub-contract 192. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States Government is permitted.

Several discussions with Drs. W. J. Lange, G. Gibson, and R. C. Svedberg conducted during the preparation of this report are greatly appreciated. The authors would like to express their appreciation to C. Sortino, C. M. Gaydos, P. B. Folmer, J. J. Selembo, and D. N. Turkall for their expert preparation of the many figures appearing in this report. We also wish to thank Y. A. Harlow who typed the main text and handled the final organization and editing of the report.

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1.0 INTRODUCTION

This report presents a detailed description of a modified conceptual design of the Torus Vacuum Pumping System for the TFTR (Tokamak Fusion Test Reactor). This description includes the basis for the design, calculated and required performance parameters, schematics and equipment drawings, and the control and operation of the Torus Vacuum Pumping System, hereafter referred to as the TVPS.

The background with which the reader should have some degree of familiarity includes a knowledge of basic vacuum techniques as contained within one of many standard texts on modern vacuum technology (for example see References 1 to 6), and the information contained in the numerous reports on the conceptual design⁽⁷⁻¹⁰⁾ of the TFTR vacuum system and the analyses⁽¹¹⁻¹⁴⁾ carried out subsequently to that design. This report is intended to be self-sufficient, but the reader familiar with TFTR will certainly be at a greater advantage. If information contained in previous reports is restated in this report it is to provide continuity so that the reader does not need to unnecessarily refer to information in other documents.

The system described within this report is the result of several studies carried out by many individuals. The first study was started in February, 1974. It has gone through many changes, developments, and updates, as well as through an increased attention to detail. This TVPS is still in the conceptual design stage, and will move through a preliminary design, a final design, and will be built, installed, tested, and operated. At the present time the TVPS utilizes four 61 cm diameter mercury diffusion pumps as the primary pumping units. Other units such as turbomolecular pumps, cryopumps, and getter pumps were considered as alternatives with mercury pumps being finally chosen^(8,10). The diffusion pumps are backed by a subsystem which is required to be closed with respect to any tritium or tritiated gases and which does

not incorporate any elastomeric materials. The TVPS is an ultrahigh-vacuum system and those surfaces exposed to the vacuum will be pre-conditioned prior to final assembly. The main toroidal vacuum vessel will be baked in situ after it has been at atmospheric pressure with additional conditioning being provided for in the form of discharge cleaning conducted on a regular basis.

The main purpose of the present design study is five-fold:

- 1) To incorporate changes in the TVPS which reflect changes in TFTR since the Final Conceptual Design Report⁽⁸⁾, e.g., accommodations for baking the device in situ⁽¹¹⁻¹⁴⁾ and considerations related to the leak checking the vacuum vessel^(12,13).
- 2) To provide additional details which, due to time limitations, were not provided in previous reports.
- 3) To include changes in the TVPS which will allow for increased flexibility in the operation of the system and for increased protection of components against gauge, valve, and pump failures or malfunctions.
- 4) To interface the TVPS with the device so that a standardization of the ducting to the mercury pump stacks, as well as, to the neutral beam injector arms can be accomplished.
- 5) To incorporate the bellows pumping system into the TVPS.

To complete the purpose of this study, the report is divided into the following sections:

1) introduction, 2) overview of modified system, 3) calculated performance parameters, 4) details of mercury pumps, 5) details of backing system 6) details of bellows pumping system, 7) some consequences of locating the backing system in the basement pit, 8) the control and operation of the TVPS, 9) cost considerations, and 10) a summary.

2.0 OVERVIEW OF THE MODIFIED SYSTEM

2.1 GENERAL DESCRIPTION OF THE TVPS

The primary concern throughout the development of the TVPS is to provide a practical system with the necessary reliability, redundancy, and flexibility so that TFTR will not be "down" due to a failure of the vacuum system. The features of reliability, redundancy, and flexibility are aspects of the TVPS which are compatible and complementary to the functions and requirements (as discussed in the next section) which must be incorporated to assure that the TVPS operates properly. Reliability is one of the primary reasons for the choice of mercury diffusion pumps. These pumps are off-the-shelf items having high pumping speeds for hydrogen and a history of operating on a continuous basis for years without any major maintenance problems. Two independent cold traps have been incorporated in the mercury diffusion pump stack to assure that there is an extremely small probability for the backstreaming of mercury into the primary vacuum vessel. If such backstreaming does occur, a cleanup is easier relative to systems employing oil. A two-trap diffusion pump stack is a standard feature on systems built to ultra-high vacuum standards in which a bakeout in situ is carried out periodically. More details on this stack, which is the primary pumping unit on TFTR, is given in Sections 3 and 4. At this time, the most important detail to keep in mind is that there is a total of four stacks on TFTR.

One of the main characteristics of the backing system is its redundancy feature. This is particularly apparent in the valving system. Each major unit, i.e., mechanical pump, holding tank, zirconium aluminum getter pump, residual gas analyzer unit, N_2 Gas supply has at least two valves on its associated vacuum lines which communicate to the mercury diffusion pumps. Thus, two valves must be opened (closed) to allow a pump to exhaust (to be isolated from) the foreline. The redundancy feature is also developed further by connecting two independent

zirconium aluminum getter pump units and two independent residual gas analyzer units to each of the diffusion pumps. These redundancy features are shown in Fig. 2-1 which is a simplified block diagram in which the details of each block (or main unit) will be discussed in Sections 4 and 5. As shown in Fig. 2-1, two gauges are placed in parallel at each location where there is a gauge. Thus, a backup gauge is immediately available and a means of cross checking pressure readings is also available. The pumping system on the bellows sections of the toroidal vessel is not shown in the figure, but is discussed in Section 6. For the meaning of the various acronyms used in Fig. 2-1 and throughout the remainder of this report, refer to Table 2-1.

The unit referred to in Fig. 2-1 as the T_2 Cleanup, is part of the TFTR Tritium Cleanup System and is described in great detail elsewhere⁽¹⁵⁾. Briefly, the unit detritiates the gases exhausted by the mechanical pumps by catalytically converting the gaseous tritium into tritiated water that is trapped with a desiccant which can be disposed of by off site burial. There are five units in all and one is specifically available to the various vacuum pumping systems, e.g., TVPS, Neutral Beam Vacuum Pumping Systems, and those systems associated with the various plasma diagnostic appendages. Each cleanup unit includes hopcalite oxidizers, catalytic oxidizers, catalytic crackers, desiccant cartridges, and monitoring devices.

Bellows couplings (BC1 and BC2) are shown in Fig. 2-1 and provide ease of assembling and disassembling of the forelines and roughing lines from the diffusion pumps during maintenance. Bellows will probably be needed in other sections of the backing lines, but such details will be determined during the final design of the TVPS. It is important to be aware that if a bellows is located in a branch of the foreline through which large amounts of tritium pass, the thin walls will allow the tritium gas to permeate through to the test cell. The rate may be high enough to violate ≤ 1 Ci/year of gaseous radioactivity expected⁽¹⁶⁾ to be released from the TFTR device.

Figure 2-1 Schematic of One of The Components of The Torus Vacuum Pumping System. The various units, e.g., ZA1, MP1, etc., have additional valves not shown in the figure. More detail is presented later in Fig. 5-5.

TABLE 2-1

ACRONYMS USED IN REPORT

Acronym	Meaning
BAG	Bayard-Alpert (Type) Gauge
BC	Bellows Coupling
BPS	Bellows Pumping System
CC	Cold Cathode (Ionization Gauge)
CT	Cold Trap
DP	(Mercury) Diffusion Pump (Stack)
HT	Holding Tank
MP	Mechanical Pump (Unit)
PM	Precision Manometer
RGA	Residual Gas Analyzer (Unit)
TC	Thermocouple (Gauge)
TM	Tritium Monitor
TVPS	Torus Vacuum Pumping System
V	Valve
ZA	Zirconium-Aluminum (Getter Pump Unit)

Therefore, it is recommended that dewars enclose the bellows and have the property that a liquid coolant such as water or freon can be circulated over the surfaces of the thin walls (see Section 3.8 for more details).

A block diagram of the four mercury pumps (DP1, DP2, DP3, and DP4) and the system backing them is shown in Fig. 2-2. This figure indicates the interfacing of the various backing pumps to each other and to the main mercury pumps. Since the main purpose of the figure is to show the valving between units, the details of the main backing units are not given. From the schematic, the following can be seen: 1) two valves separate units, 2) there is valving which allows each MP and ZA to communicate with each DP (see Table 2-1 for meaning of acronyms), and 3) there are redundancies in the ZA's and RGA's to provide a backup which is immediately and continuously available. An advantage of allowing communication between forelines is that during the period when one of the forelines is "down", another one can be used to service its associated mercury pump as well as the mercury pump with the "failed" foreline system. Thus, all mercury pumps can continue to be used. A second advantage is that all four mercury pumps can be backed by one (a single) zirconium aluminum getter canister. This is a real benefit (as will be discussed again) in the handling of the spent tritium during and following D-T operations. A third advantage in consolidating the foreline is that the number of isolation valves has remained fixed at roughly seventy-five representing no increase in cost for the added protection and flexibility.

In concluding this section on the general description of the TVPS, a short summary of points discussed in previous reports are worth restating. First, the system is constructed primarily of stainless steel, and other metals, with a minimum of non-metals. The materials making up the main toroidal vessel and the TVPS will be chosen to have low outgassing rates and to meet those requirements set for ultrahigh-vacuum systems. Secondly, no elastomeric materials can

Figure 2-2 Schematic Of Torus Vacuum Pumping System

be used and ConFlat⁽¹⁷⁾ copper seals are suggested⁽¹⁰⁾. Thirdly, the fabrication of all the components on the high vacuum side of the mercury pumps will be prebaked in the same manner as the main vacuum vessel to reduce the levels of dissolved hydrogen, water vapor, oxides, etc. Sections, 1 cm thick or less, will be baked in vacuum or dry argon at 450°C for ≥ 60 hours and thicker sections at 500°C for ≥ 60 hours.

2.2 REQUIREMENTS AND FUNCTIONS OF TVPS

In the general description of the TVPS given in the previous section, several of the requirements on the TVPS were indicated, e.g., no elastomer seals, but there was no attempt in that section to provide a listing of the general requirements. To summarize the most important requirements the following areas are noted: UHV standards for components, closed system with respect to tritium, "clean" pumps as far as contributing to plasma impurity levels, automatic and manual controls on the system, reliable and safe operation of system, utilization of off-the-shelf items and of standard sizes when possible, safe access for maintenance and provision for adequate gauging and gas analysis. See Table 2-2 for greater detail.

The functions of the TVPS include those of any ultrahigh-vacuum system, as well as a unique function not encountered in most systems, i.e., that of removing and storing tritium and tritiated gases. The main functions for which the TVPS must be designed are listed in Table 2-3.

2.3 MODIFICATIONS IN THE CONCEPTUAL DESIGN OF TVPS

Before going into the details of the calculations and component descriptions, a listing of the important modifications incorporated in the TVPS conceptual design should be made. For this purpose, a simplified schematic, Fig. 2-3, is included which shows the conceptual TVPS. In

general, the details within each block are different than the corresponding block on the new modified system as shown in Fig. 2-2. The changes are the subject of the remainder of this report and Table 2-4 lists the modifications made to the conceptual design in order to arrive at the present design. Figure 2-4 is included to provide the details of the individual pumping units on the conceptual TVPS.

Figure 2-3 Schematic of the Conceptual TVPS as Described In References 8 and 10. The Valves are Indicated With a U (not a V) so that the Numbering is not Confused With That for the Modified Design. The Numbering of the Valves in this Figure is Consistent With that in Reference 8.

Mechanical Pumping Unit

Getter Pumping Unit

RGA Vacuum System

Tritium Holding and Cleanup Unit

Figure 2-4 The Subsystems of The TVPS For The Conceptual Design

TABLE 2-2

REQUIREMENTS ON THE TVPS

- All vacuum components are to be constructed according to ultrahigh vacuum standards, i.e., no elastomers, no vacuum greases, all parts will have low outgassing rates, and those parts at the high vacuum side of the primary pumps will be bakeable to 500°C.
- The system is to be closed with respect to tritium and tritiated gases and will be able to remove gases from the main chamber for at least eight hours without any need to halt the normal pulsing of TFTR during D-T operations.
- No pumping unit will contribute any impurities such as oils or hydrocarbons to the plasmas created in the TFTR device.
- Automatic and manual modes of control are to be provided for operating the TVPS both locally and at the TFTR Central Control. The controls will allow the system to operate according to several standard modes, e.g., startup, shutdown, normal hydrogen pulsing, normal D-T pulsing, discharge cleaning, bakeout, maintenance, and system checkout.
- Components will allow for the maintenance-free operation of the TVPS over long periods (several months) of normal operations by providing the necessary reliability, safety, flexibility, and redundancy to minimize any dependencies on a single pump or gauge. The only exception would be the removal of getter units on a weekly basis or as necessary to meet the environmental protection conditions for the on-site storage of tritium.
- Where possible, components are to be standard (off-the-shelf) items so as to reduce the dependence on "special" equipment.
- Safe access to all the major components requiring maintenance (e.g., hard-sealed valves, mechanical pumps, getter pumps, oil traps, and gauges) will be provided in the arrangement of the backing system in the basement area.
- Vacuum gauges and gas analyzers are to be provided so that the system and its components can be protected against likely failures, so that the operation of each pumping unit can be monitored, and so that the TVPS can be efficiently utilized during leak checking operations as well as other maintenance operations.

TABLE 2-3
FUNCTIONS OF TVPS

- To provide within the TFTR device a low base pressure (in the 10^{-8} Torr range) for all hydrogen isotopes (H_2 , D_2 , and T_2).
- To control the impurities which are outgassed and sputtered off the vessel walls by quickly removing them from the vessel volume during normal pulsing as well as during bakeout and discharge cleaning operations.
- To rapidly pumpout the main chamber between normal pulsing operations by removing spent fuel gases and by-products and returning the chamber to base pressure before the next pulse.
- To pumpout the device during discharge cleaning and to temporarily contain the gases which are removed until the Tritium Cleanup System can detritiate them.
- To remove by-products outgassed from the vessel walls during a bakeout in situ.
- To pumpout the bellows guard sections and maintain a low pressure ($\leq 10^{-3}$ Torr) in the sections during those periods when the main vessel is under vacuum and to fill the sections with a search gas during the leak checking of the bellows sections.
- To continuously monitor the gases removed from the main vessel during the various modes of TFTR operation.
- To remove and safely store all tritium and tritiated gases pumped from the main vessel.

TABLE 2-4

CHANGES IN CONCEPTUAL TVPS

CONCEPTUAL TVPS

- Mercury pump stack with one cold trap having a hydrogen pumping speed of 7500 liter/sec
- Two mercury pumps on torus, two mercury pumps on neutral beam ducts to torus
- The effective pumping speed at the torus for hydrogen is 28000 liter/sec for the four mercury pumping units (one cold trap each).
- One Bayard-Alpert type gauge on each mercury pump
- Backing systems arranged in pairs
- Mechanical pumps rated at 33.3 liters/sec were used to back mercury pumps.
- Two Zirconium-Aluminum canisters (four cartridges/canister) on each backing system, eight canisters total and 32 cartridges total. Four canisters must be used at one time. An additional four canisters (16 cartridges) in reserve.
- One residual gas analyzer per pair of backing systems for a total of two analyzers.

MODIFIED TVPS

- Mercury pump stack with two cold traps having a hydrogen pumping speed of 5200 liter/sec
- Four mercury pumps on torus
- The effective pumping speed at the torus for hydrogen is 20000 liter/sec for the four mercury pumping units (two cold traps each).
- Two Bayard-Alpert type gauges on each mercury pump
- Backing systems arranged to allow each to communicate with the other three systems
- Mechanical pumps rated at 46.7 liters/sec are used to back mercury pumps (and one 10 liter/sec pump to pumpout bellows sections). A single 46.7 liter/sec pump can back two mercury pumps if necessary.
- Two Zirconium-Aluminum units (each unit with four canisters having eight cartridges each) backing all four mercury pumps for a total of 64 cartridges (a third and smaller Zirconium-Aluminum unit is on the bellows pumping unit). Only one canister needs to be used at one time.
- Two residual gas analyzers shared by all four backing systems (a third analyzer is on bellows pumping system). Each residual gas analyzer unit includes a calibrated leak and two Bayard-Alpert type gauges.

- One 100-liter holding tank per pair of backing systems for a total of two tanks.
- One gauge at each location requiring a pressure reading, total number of locations is twenty-four.
- Generally there are two valves isolating each backing line component from the rest of the system.
- Approximately seventy-five ultrahigh-vacuum isolation valves required with no communication between forelines.
- Two penetrations through test cell floor per mercury pump required for vacuum lines to basement, ten penetrations total, including two leading directly to the tritium cleanup system.
- A dry nitrogen gas supply was provided for each foreline for a total of four supplies.
- Bellows couplings were not indicated on vacuum lines from mercury pumps to backing system
- Details not shown on the arrangement of vacuum lines connecting the mercury pumps with the backing system located in the basement.
- Many details not shown on the arrangement of the backing system in the basement area.
- One 1000-liter holding tank shared by all four backing systems (as well as by the bellows pumping system)
- Two gauges at each location requiring a pressure reading, total number of locations is twenty-one (as well as four on bellows pumping system)
- Everywhere there are two valves isolating each backing line component from the rest of the system.
- Seventy-five (plus twenty-five on bellows pumping system) ultrahigh-vacuum isolation valves required with communication between forelines.
- One penetration through test cell floor per mercury pump required for vacuum lines to basement, four penetrations total. (the bellows pumping system requires twelve penetrations).
- One Dry nitrogen gas supply for entire backing system (plus one dry gas supply for bellows section) is provided.
- Bellows couplings are indicated on roughing lines and forelines. The one near the mercury pump on each foreline is liquid-cooled to reduce tritium permeation.
- Details are provided on the arrangement of vacuum lines connecting the mercury pumps with the backing system located in the basement.
- Details were provided on the arrangement of the backing system (and bellows pumping system) in the basement area.

3.0 CALCULATED PERFORMANCE PARAMETERS

3.1 CONDUCTANCES OF DUCTS AND LINES

3.1.1 Ducts From Mercury Pumps To Torus

Since the vessel will be at pressures at or below 10^{-2} Torr when the mercury pumps are in use, the gases will be removed according to the characteristics of molecular flow. The conductances of the ducts will thus obey the following relation:

$$C_M(\text{liter/sec}) = \frac{D^3 (\text{cm}^3)}{L (\text{m})} \times \begin{cases} 0.121 & \text{for Air} \\ 0.416 & \text{for H}_2 \end{cases}$$

where D is the diameter of the duct and L is the duct length. For the TFTR pump ducts:

$$D = 63.5 \text{ cm (25")}$$

$$L = 1.22 \text{ m (4')} \quad \text{and}$$

$$C_{HV}^{(\text{air})} = 2.54 \times 10^4 \text{ liter/sec}$$

$$C_{HV}^{(\text{H}_2)} = 8.73 \times 10^4 \text{ liter/sec}$$

where the subscript HV indicates the high vacuum ducts to distinguish these conductances from those to be calculated elsewhere in the report. For the two ducts with 40 cm x 70 cm rectangular apertures (see Section 4.2.1), which require special adapters to allow the circular ducts to be connected, the conductance to the mercury pump is slightly reduced. To estimate the reduction, a comparison of the ratio of the square of the area of the opening to the circumference around the opening can be used, where:

$$\frac{(\text{Area})^2}{\text{Circumference}} = \begin{cases} 50,300 \text{ cm}^3 & (\text{circle}) \\ 35,600 \text{ cm}^3 & (\text{rectangle}) \\ 43,000 \text{ cm}^3 & (\text{average}) \end{cases}$$

Using the average value to calculate the reduction in conductance ($\frac{43,000}{50,300} = 0.85$), the special ducts can be characterized by:

$$C_{HV}^{(\text{air})} = 2.16 \times 10^4 \text{ liter/sec}$$

$$C_{HV}^{(\text{H}_2)} = 7.42 \times 10^4 \text{ liter/sec}$$

3.1.2 Forelines To Backing Pumps

For the pumpdown of the vessel, the gases will flow in the viscous regime where the conductance of a line for air is given by:

$$C_V^{(\text{air})} \text{ (liter/sec)} = 1.82 \frac{D^4 \text{ (cm}^4\text{)}}{L \text{ (m)}} \bar{P} \text{ (Torr)}$$

where $\bar{P}$ is the average pressure (in time and along the length of the line), and for the TVPS foreline:

$$D = 9.21 \text{ cm (3.625-in ID for "4 in" tubing)}$$

$$L \approx 27.5 \text{ m (90')}. \quad .$$

Thus,

$$C_{V,F}^{(\text{air})} \text{ (liter/sec)} \approx 480 \bar{P} \text{ (Torr)}$$

where the F indicates the foreline.

Near the base pressure in the foreline ($\sim 2 \times 10^{-4}$ Torr), the conductances of the lines can be calculated using the first equation in Section 3.1.1, and

$$C_{M,F}^{(\text{air})} \gtrsim 3.5 \text{ liter/sec}$$

$$C_{M,F}^{(\text{H}_2)} \gtrsim 13.1 \text{ liter/sec}$$

Thus, the conductances to the backing pumps are given by:

$$C_F = C_{V,F} + C_{M,F}$$

and

$$C_F^{(\text{air})} \geq 3.6 \text{ liter/sec}$$

$$C_F^{(\text{H}_2)} \geq 13.5 \text{ liter/sec}$$

3.2 EFFECTIVE PUMPING SPEEDS

3.2.1 Mercury Pumps

The hydrogen pumping speed of the Edwards 61 cm diameter mercury diffusion pump is 15,000 liter/sec (AVS). The effective pumping speed above the high vacuum valve is greatly reduced from this value since cold traps must be incorporated. For a two-trap stack this effective speed is given by:

$$\frac{1}{S_{\text{eff}}} = \frac{1}{S} + \frac{2}{C_{\text{trap}}} + \frac{1}{C_{\text{valve}}} - \frac{2}{C_{\text{end}}}$$

where the conductance of a connection flange, i.e.,

$$C_{\text{end}}^{(\text{H}_2)} \text{ (liter/sec)} = 44.4 A \text{ (cm}^2\text{)}$$

must be subtracted out for each cold trap when it is connected to another component. For the values of the various conductances on the 61 cm pump stack as given in Fig. 3-1, S_{eff} is calculated to be 5,200 liter/sec for hydrogen and 1800 liter/sec for air. The pumping speed curve for the 61 cm two-trap stack is shown in Fig. 3-2. Since, during the early stages of developing the TVPS, 41 cm diameter mercury pumps were considered, it is of some interest to include the values of S_{eff} for the 41 cm diameter pump. These results are shown in Fig. 3-3.

Conductances & Speeds (liter/sec)

	H ₂	Air
C (Valve) =	120 000	33 000
C (End) =	130 000	34 000
C (Trap) = at -125°C	15 000	4 000
C (End) =	130 000	34 000
C (Trap) = at -125°C	15 000	4 000
S (DP) =	15 000	12 000

$$\frac{1}{S_{\text{eff}}} = \frac{1}{S} + \frac{2}{C_{\text{Trap}}} + \frac{1}{C_{\text{Valve}}} - \frac{2}{C_{\text{End}}}$$

$$S_{\text{eff}} = \begin{cases} 5\,200 & (\text{H}_2) \\ 1\,800 & (\text{Air}) \end{cases}$$

$$S_{\text{eff}} \text{ (1-Trap Stack)} = 7\,500 \quad (\text{H}_2)$$

Figure 3-1 The Various Conductances and Speeds Associated With a 61-cm Diameter Mercury Diffusion Pump Stack.

Figure 3-2 Hydrogen Pumping Speed Curve for a 61-cm Mercury Diffusion Pump Stack Consisting of a High Vacuum Valve and Two Cold Traps.

Conductances & Speeds (liter/sec)

	H ₂	Air
C (Valve) =	56 000	15 000
C (End) =	58 000	15 000
C (Trap) = at -125°C	8 400	2 200
C (End) =	58 000	15 000
C (Trap) = at -125°C	8 400	2 200
S (DP) =	11 000	6 000

$$\frac{1}{S_{\text{eff}}} = \frac{1}{S} + \frac{2}{C_{\text{Trap}}} + \frac{1}{C_{\text{Valve}}} - \frac{2}{C_{\text{End}}}$$

$$S_{\text{eff}} = \begin{cases} 3\,200 & (\text{H}_2) \\ 990 & (\text{Air}) \end{cases}$$

$$S_{\text{eff}} \text{ (1 - Trap Stack)} = 4\,750 \quad (\text{H}_2)$$

Figure 3-3 The Various Conductances and Speeds Associated With a 41-cm Diameter Mercury Diffusion Pump Stack.

The effective pumping speeds of the four mercury pumps, after taking into account the conductances of the ducts connecting them to the torus, are given by:

$$S_{\text{total}}^{(\text{H}_2)} = 2.0 \times 10^4 \text{ liter/sec}$$

$$S_{\text{total}}^{(\text{air})} = 6.7 \times 10^3 \text{ liter/sec}$$

where the duct conductances are given in Section 3.1.1.

3.2.2 Mechanical Pumps

The pumping speed curve for the Sargent-Welch duo-seal, 1396 mechanical pump is shown in Fig. 3-4. At a pressure of 2×10^{-4} Torr (expected base pressure in foreline), the 1396 pump has a speed of ~ 25 liter/sec and the foreline has a conductance of ~ 3.5 liter/sec. Thus, the effective speed at the diffusion pump for the mechanical pumps is ~ 3 liter/sec at 2×10^{-4} Torr.

During pumpdown, the speed of the 1396 decreases from 47 liter/sec at 760 Torr to 32 liter/sec at 10^{-2} Torr. Assuming that over the time period of the pumpdown the pump has an average speed of 35 liter/sec and that the conductance of the foreline is

$$C_V^{(\text{air})} (\text{liter/sec}) = 480 \times \frac{760}{4}$$

$$= 9 \times 10^4$$

the air speed at the torus for the four mechanical pumps on the TVPS is 140 liter/sec.

3.2.3 Zirconium Aluminum Getters

The speed is limited by the conductance (molecular flow) of the forelines. For hydrogen, and at base pressure,

$$S_{\text{ZA}} \approx C_F^{(\text{H}_2)} = 13.5 \text{ liter/sec}$$

Figure 3-4 Pumping Speed Curve for the Large Mechanical Pumps Backing the Mercury Diffusion Pumps

per foreline, and for four forelines

$$S_{ZA}^{\text{total}} \approx 54 \text{ liter/sec.}$$

This can be compared to a hydrogen pumping speed of a C-500 cartridge of ~ 2500 liter/sec.

3.3 BASE PRESSURES

3.3.1 Base Pressure In Torus

The toroidal vacuum vessel has a large surface area exposed to the vacuum system. As a result, the base pressure is strongly dependent on the outgassing rates of the walls. This large surface area is $\sim 10^7 \text{ cm}^2$ for the main vessel walls consisting of twelve bellows sections and $\sim 1.6 \times 10^6 \text{ cm}^2$ for the various diagnostic extensions and ports⁽¹⁴⁾. The total surface area is $1.16 \times 10^7 \text{ cm}^2$. If the specific outgassing rate of the stainless steel surfaces is 10^{-10} Torr liter/cm² sec for hydrogen, the main gas evolved from stainless steel, then:

$$Q = 1.16 \times 10^{-3} \text{ Torr liter/sec}$$

$$P_B \approx 6 \times 10^{-8} \text{ Torr} \quad (\text{H}_2)$$

at a hydrogen pumping speed of 2×10^4 liter/sec. It can be anticipated that after a bakeout at 250°C for an extended period, the specific outgassing rate could be reduced to

$$q \sim 2 \times 10^{-12} \text{ Torr liter/sec cm}^2$$

so that a base pressure following an in situ bakeout of TFTR could be

$$P_B \approx 1 \times 10^{-9} \text{ Torr} \quad (\text{H}_2)$$

If, after D-T operation begins, the primary gas evolved from the walls is a mixture of D_2 and T_2 , the base pressure assuming a 10^{-10} Torr liter/sec cm^2 outgassing rate is

$$P_B \sim 9 \times 10^{-8} \text{ Torr (50\% } D_2 / 50\% T_2)$$

or assuming a rate of 2×10^{-12} Torr liter/sec cm^2 is

$$P_B \sim 2 \times 10^{-9} \text{ Torr (50\% } D_2 / 50\% T_2).$$

3.3.2 Base Pressure In Foreline

The foreline consists primarily of 10 cm (4 in) line and for four ~ 30 m lengths of the line the inside area is $4 \times 10^5 \text{ cm}^2$. So that there is $\sim 5 \times 10^5 \text{ cm}^2$ of total surface area and if that surface outgasses at a rate of $\sim 5 \times 10^{-9}$ Torr liter/sec cm^2 , $Q = 2.5 \times 10^{-3}$ Torr liter/sec.

The conductance of the four forelines in parallel is ≈ 15 liter/sec at base pressure, so that $\Delta p = \frac{Q}{C} = 1.7 \times 10^{-4}$ Torr. For a mechanical pump with a blanked off speed of 2×10^{-5} Torr, the base pressure at the DP is $\sim 2 \times 10^{-4}$ Torr.

3.4 STARTUP AND SHUTDOWN

3.4.1 Pumpdown Time

The equation for the pumpdown time is given by (e.g., see Reference 2)

$$t = K 2.3 \frac{V}{S_{\text{eff}}} \log \frac{P_i}{P_f}$$

where

$K = 1$	at	1000 to 100 Torr
$= 1.25$		100 to 10
$= 1.5$		10 to 1
$= 2$		1 to 0.1
$= 4$		0.1 to 0.01

For a pumpdown from 760 Torr to 0.01 Torr,

$$K \log \frac{P_i}{P_f} = 9.63$$

and

$$t = 22.1 \frac{V}{S_{\text{eff}}}.$$

Now $V = 63,300$ liter and $S_{\text{eff}} = 140$ liter/sec, so that

$$t = 2.8 \text{ hours.}$$

Below 10^{-2} Torr, the gases being pumped are, to a large extent, those gases being desorbed from the vessel walls. For this reason, the high vacuum portion of the pumpdown by the mercury pumps will depend greatly on the wall conditions and an estimate of the time to reach the base pressure cannot be reliably predicted.

3.4.2 Up-To-Atmospheric Pressure

To let the vessel, volume 63,300 liter, up to atmospheric pressure, a total quantity, Q , of gas required is:

$$\begin{aligned} Q &= 63,300 \text{ liter} \times 760 \text{ Torr} \\ &= 4.8 \times 10^7 \text{ Torr liter.} \end{aligned}$$

For a Dry Nitrogen cylinder at a pressure of 2500 PSI (1.3×10^5 Torr) having a volume of ≈ 40 liters, the number of containers required is:

$$\frac{4.8 \times 10^7 \text{ Torr liter}}{40 \text{ liter} \times 1.3 \times 10^5 \text{ Torr}} = 9.2.$$

Thus, 10 standard cylinders of gas per shutdown are required. It will take on the order of 10 minutes to fill the vessel, so that a flow of Dry Gas at a rate of 100 liter/sec will be required.

3.5 PULSED OPERATIONS

3.5.1 Gas Loads From Discharge Pulses

For a hydrogen (or deuterium or tritium) plasma having an average density $\bar{n}_i$ of ions, the total number of molecules (two ions per molecule) needed to initiate a plasma of volume V_p is given by:

$$N_m = \frac{1}{2} \bar{n}_i V_p$$

where the factor $\frac{1}{2}$ accounts for the diatomic nature of the gas. For a quantity N_m of molecules, the gas load can be calculated using the ideal gas law;

$$PV = \frac{N_m RT}{N_A}$$

where

PV = gas load in Torr liter

R = 62.36 Torr liter/mole K (universal gas constant)

N_A = 6.023×10^{23} mole⁻¹ (Avogadro's number)

T = gas temperature ≈ 300 K

N_m = number of gas molecules

and

$$PV \text{ (Torr liter)} = 3.106 \times 10^{-20} N_m$$

For a 2.5 MA plasma⁽⁸⁾

$$\begin{aligned}V_p &= 2\pi^2 a^2 R \\&= 2\pi^2 85^2 \times 248 \text{ cm}^3 \\&= 3.54 \times 10^7 \text{ cm}^3\end{aligned}$$

$$\bar{n}_i = 2.5 \times 10^{13} \text{ cm}^{-3}$$

$$N_m = 4.42 \times 10^{20}$$

$$PV = 13.7 \text{ Torr liter}$$

Assuming ~ 10% of the gas is not ionized,

$$PV \approx 15 \text{ Torr liter.}$$

A quantity of gas of 15 Torr liter corresponds to a filling pressure for the 63,300 liter volume of the TFTR of :

$$P_{\text{fill}} \sim 2.4 \times 10^{-4} \text{ Torr.}$$

For a 1.0 MA plasma⁽⁸⁾

$$V_p = 8.35 \times 10^6 \text{ cm}^3$$

$$\bar{n}_i = 5.5 \times 10^{13} \text{ cm}^{-3}$$

$$N_m = 2.3 \times 10^{20}$$

$$PV = 7.14 \text{ Torr liter}$$

and assuming ~ 10% of the gas is not ionized:

$$PV \approx 8 \text{ Torr liter}$$

and

$$P_{\text{fill}} \sim 1.3 \times 10^{-4} \text{ Torr.}$$

For the expected case for which 90% of the plasma pulses are of the 1.0 MA variety and 10% are of the 2.5 MA variety, the average pulse requires ~ 9 Torr liter of gas for initiation. If this gas is tritium, then in units of curies of T_2 (1 curie = 0.295 Torr liter), the quantities introduced into the torus are:

$$Q_{T_2} \approx 30 \text{ Ci/pulse} \approx 2.9 \text{ kCi/96 pulses} \approx 14.4 \text{ kCi/5 days}$$

where, for design purposes, a normal operating day consists of a pulse every five minutes for eight hours. It is unlikely that this rate of pulsing will be implemented in practice.

There is a limit⁽¹⁶⁾ of 24 kCi of tritium which can be held up on the TFTR site by the TVPS, and thus after 800 pulses, approximately 8 days of normal operation, the 24 kCi limit is reached. If only 2.5 MA pulses are initiated, then after 5 days this limit is reached, or if only 1.0 MA pulses are initiated, then the limit is reached after 9 days.

These results will be discussed again in Section 3.6 where the zirconium aluminum getter system is considered.

3.5.2 Gas Loads From Neutral Beam Injection

The TFTR Neutral Beam Injection System^(8,18,19) is characterized as follows:

167 A (Equivalent) of 120 keV D^0 (20 MW)

250 A (Equivalent) of 60 keV D^0 (15 MW) .

The number of particles (neutral ions) injected is thus:

$$\frac{(167 + 250) \text{ A}}{1.602 \times 10^{-19} \text{ A sec/particle}} = 2.6 \times 10^{21} \text{ particles/sec}$$

corresponding to 1.3×10^{21} molecules/sec. This represents a gas load of:

$$Q_{NB} = 41.4 \text{ Torr liter/sec}$$

where 1 Torr liter/sec due to the streaming of cold gas through the neutral beam ports and into the torus has been added. Thus:

$$PV_{NB} = \begin{cases} 21 \text{ Torr liter for a 0.5 sec injection} \\ 4 \text{ Torr liter for a 0.1 sec injection} \end{cases}$$

3.5.3 Total Gas Loads

For a 2.5 MA pulse and a 0.5 sec neutral beam injection, the gas load is 36 Torr liter (15 + 21), and for a 1.0 MA pulse and a 0.1 sec neutral beam injection, the gas load is 12 Torr liter (8 + 4). If these two types of operations are carried out on a 10% / 90% basis, then 15 Torr liter of gas will be introduced (on the average) into the torus. In addition, the outgassing of the vessel walls will contribute to the gas load. There is approximately $1.2 \times 10^7 \text{ cm}^2$ of internal surface area in the device where bellows convolutions and diagnostic extensions are taken into account. If an outgassing rate of $10^{-10} \text{ Torr liter/sec cm}^2$ is assumed then:

$$1.2 \times 10^7 \text{ cm}^2 \times 10^{-10} \text{ Torr liter/sec cm}^2 = 1.2 \times 10^{-3} \text{ Torr liter/sec}$$

of gases continuously evolve from the walls, or:

$$\approx 4.3 \text{ Torr liter/hour}$$

$$\approx 100 \text{ Torr liter/24 hours}$$

$$\approx 730 \text{ Torr liter/7 days.}$$

Thus, the total gas loads for various periods of operation are:

- ~ 200 Torr liter/hour (12 pulses)
- ~ 1600 Torr liter/24 hours (96 pulses)
- ~ 8000 Torr liter/7 day week (96 x 5 pulses)
- ~ 12,500 Torr liter/8 days of operation (768 pulses)

3.5.4 Gas Pressure in Backing System Following A Pulse

Assuming that on the average each of the four backing lines has a volume of ~200 liters (~28 m of "4 in" tubing), there is 800 liters of "ballast" volume in the forelines to receive the spent gases after a pulse. For a full power pulse in which a 2.5 MA plasma is injected with neutral beams for 0.5 second, 36 Torr liters of gas will be pumped by the mercury pumps into the foreline. If, for simplicity, this quantity of gas instantaneously fills the 800 liter volume, then the pressure rise (above the 2×10^{-4} Torr base pressure) is:

$$\Delta p = \frac{36 \text{ Torr liter}}{800 \text{ liter}} = 4.5 \times 10^{-2} \text{ Torr}$$

which is well below the critical backing pressure (~0.5 Torr) for the mercury diffusion pumps.

3.5.5 Time Constants And Pumpout Times Between Pulses

For the main vessel and mercury pumps, the time constant for hydrogen is:

$$\tau_{DP} = \frac{V}{S} = \frac{63,300 \text{ liter}}{20,000 \text{ liter/s}} = 3.2 \text{ sec.}$$

Thus, to reduce the pressure after a full power pulse to the base pressure, the pumpout time is:

$$\begin{aligned} t_{DP} &= 2.2 \tau \log \frac{2.4 \times 10^{-3} \text{ Torr}}{6 \times 10^{-8} \text{ Torr}} \\ &= 32 \text{ sec.} \end{aligned}$$

For a D-T pulse, $\tau \sim 5$ sec, and $t \sim 50$ sec.

For the backing system volume (~ 800 liter) and the mechanical pumps, the time constant (assuming all gases such as hydrogen are pumped at the same rate as air) is:

$$\tau_{MP} = \frac{800 \text{ liter}}{62 \text{ liter/sec}} = 12.9 \text{ sec.}$$

The pumping speed, 62 liter/sec, is that for four pumps working between 4.5×10^{-2} Torr and 2×10^{-4} Torr, each at the end of the 27.5 m of foreline, and the conductances of the line is that midway between the mercury pump and the mechanical pump (i.e., $L = 14$ m in the formula for the conductance of hydrogen).

The pumpout time is:

$$\begin{aligned} t_{MP} &= 2.2 \times 12.9 \text{ sec} \times \log \frac{4.5 \times 10^{-2} \text{ Torr}}{2 \times 10^{-4} \text{ Torr}} \\ &= 67 \text{ sec} \end{aligned}$$

which is short compared to the 300 seconds between pulses. If the zirconium aluminum pumps are being used, then:

$$\tau_{ZA} = \frac{800 \text{ liter}}{140 \text{ liter/sec}} = 5.7 \text{ sec}$$

and

$$t_{ZA} = 30 \text{ sec}$$

which is approximately equal to t_{DP} .

3.5.6 Holding Tank Capacity

During discharge cleaning of the TFTR device, working gas fills the vessel to a pressure of approximately 4×10^{-4} Torr. The plasma pulses are then initiated in this gas which is continuously pumped by the mercury pumps while being replenished by the gas supply. Thus, a constant throughput of 4×10^{-4} Torr $\times$ 20,000 liter/sec = 8 Torr liter/sec is being removed by the pumping system. For a 12 hour discharge cleaning operation a total of $\sim 3.5 \times 10^5$ Torr liter of gas is involved. If the gas is hydrogen and if the zirconium aluminum getters are employed, ~ 150 C-500 cartridges would be required. This would be impractical and since non-getterable gases, such as helium, may be used the mechanical pumps will be required to back the mercury pumps. The exhaust of the MP's will contain tritium after D-T pulsing operations so that the ballast tank on the exhaust side of the MP's will be required to temporarily store gases until they can be passed through the Tritium Cleanup System.

The holding tank (HT) on the exhaust lines from the MP's has a volume of 1000 liter. The size of the HT was chosen to handle the 3.5×10^5 Torr liter of gas required for a 12 hour discharge cleaning operation, i.e.,

$$\frac{3.5 \times 10^5 \text{ Torr liter}}{\frac{760}{2} \text{ Torr}} = 920 \text{ liter} \approx 1000 \text{ liter}$$

where the HT will have an initial pressure of 1.0 atmosphere and a final pressure of 1.5 atmosphere.

During discharge cleaning each MP will remove a throughput of 2 Torr liter/sec of gas. If the MP has an effective speed of 20 liter/sec at the mercury pump, then the pressure in the foreline will be at a constant value of 10^{-1} Torr. To check for consistency, at 10^{-1} Torr, the conductance of the foreline is ~ 50 liter/sec, the pump has a speed of ~ 33 liter/sec, and the effective speed at the DP is 20 liter/sec as assumed. The pressure 10^{-1} Torr is well below the critical backing pressure of an Edwards pump (0.5 Torr).

3.6 ZIRCONIUM ALUMINUM GETTER PUMP PARAMETERS

3.6.1 Sorption Capacities

The SAES ST-101 zirconium (16%) aluminum alloy⁽²⁰⁾ used in the C-500 cartridges on the getter pumping units of the TVPS has a rated capacity for the sorption of hydrogen of 6 Torr liter per gm of getter material and a maximum permissible capacity (to avoid the flaking of the getter material) for the sorption of hydrogen of 15 Torr liter per gm. The C-500 has 385 gm of getter material, and thus a rated capacity of 2310 Torr liter and a maximum permissible capacity of 5775 Torr liter. In Section 3.5.1 calculations indicate that after ~ 8 days (800 pulses) of normal operation, the 24 kCi limit imposed on TFTR is reached and those getter pumps backing the mercury pumps should be removed for regeneration. At that time $\sim 1.25 \times 10^4$ Torr liter of gas will have been pumped (sorbed) as was shown in Section 3.5.3. For this quantity of gas,

$$\frac{1.25 \times 10^4 \text{ Torr liter}}{2310 \text{ Torr liter/cartridge}} \approx 6 \text{ cartridges}$$

are required. If a canister of eight (8) cartridges, as shown in Fig. 3-5, is employed as the basic component of the getter pumping system, then this canister has a reserve capacity which is at least a factor of two larger than the needed capacity for the 8×96 pulses. The factor of two between the reserve and required capacity takes into account the results of recent experiments⁽²¹⁾ which show that the getters can be operated to 150% of their rated capacity without any serious consequences.

3.6.2 Equilibrium Partial Pressure of Hydrogen

As the zirconium aluminum (ZA) getters pump hydrogen, the partial pressure, P_{H_2} , for hydrogen does not remain constant. The value of P_{H_2} is a function of the getter temperature T (in K) and the specific quantity, q , of hydrogen sorbed (in Torr liter per gm of getter material) given by⁽²²⁾:

Figure 3-5 Arrangement of C-500 Cartridges in a Canister

$$\log P_{H_2} = 4.4 + \log q^2 - \frac{7000}{T}$$

$$T \leq 573 \text{ K}$$

$$q < 15 \text{ Torr liter/gm}$$

and shown in Fig. 3-6 at an operating temperature of 325°C for the getter pump. This temperature is recommended since values greater than 300°C allow the pumps to remove hydrogen even in the presence of chemically active, impurity gases such as carbon monoxide⁽²¹⁾. It is also recommended that the operating temperature not be unnecessarily high since the hydrogen partial pressures increase rather quickly with temperature. For example, P_{H_2} is up by an order of magnitude from that at 325°C if the getters are operated at 380°C.

3.6.3 Partial Pressures Of Non-Getterables

There will be gases, particularly helium, which will be produced in the TFTR device and will not be pumped by the getter units. As a result, the pressure in the foreline will increase during those periods in which the MP's are not used. Since it is important that the pressure not reach 0.5 Torr, the critical backing pressure for the DP's, it is necessary to estimate the pressure rise after a day of operation. If 20 MW of D-T power is generated for each TFTR pulse, then:

$$\frac{20 \text{ MW}}{17.5 \text{ MeV} \times 1.6 \times 10^{-19} \text{ A s/particle}} = 7 \times 10^{18} \text{ particle/sec}$$

is the production rate of helium. After 96 0.5-sec pulses, 3.4×10^{20} helium particles, or ~11 Torr liter of helium, is produced. In addition, let us assume that for each pulse 0.15 Torr liter of non-getterable impurities are produced (~1% of the total amount of working gas removed after an average pulse). Thus, a total of ~25 Torr liter of gases are not pumped by the ZA unit and remain in the 800 liter foreline, and the final backing pressure is:

$$\frac{25 \text{ Torr liter}}{800 \text{ liter}} = 3 \times 10^{-2} \text{ Torr.}$$

Thus, the foreline has an adequate ballast volume to handle gases not pumped by the ZA's.

Figure 3-6 Equilibrium Hydrogen Pressure in Foreline During Which Time the Zirconium-Aluminum Getters are in Operation and Operating at $T = 325^{\circ}\text{C}$.

3.6.4 The Replacement Of A Canister

In this section the venting and pumpdown of the foreline to remove and replace a canister is discussed. The portion of the foreline to be vented is ~2.5 m of 10.2 cm line having a volume of ~17 liter.

Prior to the venting of the ZA unit, the cartridge heaters will be turned off and the getters allowed to cool to room temperature. At room temperature, the hydrogen partial pressure in the foreline will be very low, $\leq 10^{-7}$ Torr. If this pressure is due to the tritium isotope of hydrogen, approximately 6 μ Ci of tritium will be trapped in the vented volume and will pass into the atmosphere of the test cell. Since this quantity is very small, its release poses no health problems and no special venting system other than a standard vent valve is required.

At the time the system needs to be re-evacuated, a total of 63 liter x 760 Torr $\approx 4.8 \times 10^4$ Torr liter of gas must be pumped out by the MP's. The 63 liter volume is a sum of the 17 liter volume of the foreline portion and 46 liter volume of the getter canister (see next section). If this were allowed to fill the 800 liter foreline, then the pressure would rise to 60 Torr which is above the critical backing pressure of the DP's. Thus, it is recommended that MP 4 with an extra valve V3 (see Fig. 2-2) be used to evacuate the ZA. During this time, ~ 40 seconds, V3 is closed and DP4 is not backed. Since there is a large 200 liter ballast volume into which DP4's exhaust can fill, the backing pressure for DP 4 should increase only slightly.

3.6.5 Volume Of ZA Canister

In the event of fire, all of the gases sorbed in a canister may be desorbed and the pressure in the canister will rise as a result. To prevent the canister from exploding under the pressure, its volume should be sized such that the pressure within is no greater than 2×760 Torr during a fire burning at a temperature of $\sim 1400^\circ\text{C}$. Assuming that no more than 1.25×10^4 Torr liter of gas are sorbed (see Section 3.4.3), the volume can be calculated by noting that the pressure of a given quantity of gas in a specific volume is proportional to the absolute temperature of

the gas. Thus:

$$\frac{P_{\text{fire}}}{P_{\text{room}}} = \frac{T_{\text{fire}}}{T_{\text{room}}}$$

$$\frac{P_{\text{fire}} V}{P_{\text{room}} V} = \frac{T_{\text{fire}}}{T_{\text{room}}}$$

$$V = \frac{(P_{\text{room}} V)}{P_{\text{fire}}} \times \frac{T_{\text{fire}}}{T_{\text{room}}}$$

$$V = \frac{1.25 \times 10^4 \text{ Torr liter}}{2 \times 760 \text{ Torr}} \times \frac{1673 \text{ K}}{300 \text{ K}}$$

$$V = 46 \text{ liter.}$$

After taking the size, number, and arrangement of C-500 cartridges into account (see Fig. 3-5), a canister having a volume of 46 liter can be 36 cm diameter by 46 cm high.

3.7 LEAK CHECKING AND LEAK RATES

3.7.1 Leak Rate of 61 cm Diameter HV Valve

The total length of seal for four 61 cm diameter HV valves is $\sim 8 \times 10^2$ cm. When the HV valves are closed, the throughput to the DP's due to leaks should be no larger than that due to outgassing at base pressure after a bakeout (see Section 3.3.1), i.e., $Q = 2 \times 10^{-12}$ Torr liter/cm² sec $\times 1.16 \times 10^7$ cm² = 2.3×10^{-5} Torr liter/sec. Thus, the specific leak rate of the seal should be $< 3 \times 10^{-8}$ Torr liter/sec per cm of seal which can be compared to 10^{-12} Torr liter/cm sec for a "good" seal.

3.7.2 Minimum Detectable Leakage In A Bellows Section

The twelve bellows sections in the main vessel are made of 1 mm thick stainless steel and have a guard vacuum provided by the BPS at a pressure P_G of 1.3×10^{-4} Torr (see Section 6). If a leak develops, it will only be detected if the leakage is greater than $Q_o = 1.16 \times 10^{-3}$ Torr liter/sec, the outgassing rate. Such a leak can be characterized by a conductance C_L where:

$$C_L = \frac{Q_o}{P_G} \approx 10 \text{ liter/sec.}$$

Using the conductance for the molecular flow regime

$$\begin{aligned} C_L \text{ (liter/sec)} &= 12.1 \frac{D^3 \text{ (cm}^3\text{)}}{L \text{ (cm)}} \\ &= 121 D^3 \text{ (cm}^3\text{)} \end{aligned}$$

the diameter of the leaking "duct" in the bellows where $L = 0.1$ cm is:

$$D \sim 0.4 \text{ cm}$$

3.7.3 Time Constants For Various Search Gases

Assuming that during leak checking only two DP's in conjunction with an RGA in the backing system is employed, the following time constants (volume/pumping speed) can be calculated. Similar calculations were presented in a previous report⁽¹³⁾, but some of the parameters have changed.

The speeds of 2 DP's can be deduced from the discussions in Section 3.2.1, i.e.,

$$S_{HV}^{(\text{air})} \approx 3.4 \times 10^3 \text{ liter/sec}$$

$$S_{HV}^{(\text{H}_2)} \approx 1.0 \times 10^4 \text{ liter/sec.}$$

Taking the ratio of the square root of the masses into account, the corresponding speeds for the search gases, argon and helium, are:

$$S_{HV}^{(Ar)} \approx 2.9 \times 10^3 \text{ liter/sec}$$

$$S_{HV}^{(He)} \approx 7.0 \times 10^3 \text{ liter/sec}$$

Since the vessel has a volume of 63,300 liter, the respective time constants are:

$$\tau_{HV}^{(Ar)} \sim 22 \text{ sec}$$

$$\tau_{HV}^{(He)} \sim 9 \text{ sec} .$$

In addition to the time constants τ_{HV} on the high vacuum side, the corresponding time constants τ_F on the foreline side of the DP's must be considered. Now the speeds in the foreline at base pressure are conductance limited and are:

$$S_F^{(air)} = 3 \text{ liter/sec}$$

$$S_F^{(H_2)} = 13 \text{ liter/sec}$$

for a foreline volume of ~ 200 liter. Thus, after similar calculations which were carried out for the HV side,

$$\tau_F^{(Ar)} = 78 \text{ sec}$$

$$\tau_F^{(He)} = 22 \text{ sec} .$$

The time constants calculated above are important factors in determining the shapes of pressure vs time curves⁽²³⁾. The larger time constants result in greater indicated pressure changes during the probing time, while a smaller constant allows a more rapid removal of the search gas from the system. Thus, there is an optimum value of τ . On the high vacuum side, $\tau_{HV} \sim 10$ sec provides the best leak-hunting conditions, while $\tau_F \sim 20$ sec is found to be best⁽²³⁾. These values are similar to those for helium usage on TFTR, so that the TVPS should lend itself quite efficiently to helium leak checking.

3.8 TRITIUM PERMEATION RATES FOR THIN WALLED BELLOWS COUPLINGS

As indicated in Section 2, any bellows coupling in a vacuum line through which large amounts of tritium pass will act as a source of that gas to the test cell. The quantity released depends on the wall thickness of the coupling and on the wall temperature of that coupling. Thus, if a bellows is required to be thin walled, as in the case of small diameter flexible vacuum lines, an obvious solution to containing tritium is to cool that section of the line. A water cooled or a freon cooled jacket is not a standard item, but no serious problems in developing one are envisioned. As a guide to determining the required temperature to limit tritium permeation, calculations (by H. J. Garber) at a number of temperatures and as a function of wall thickness were performed. The results are shown in Fig. 3-7 in terms of $\mu\text{Ci/day}$ per square meter of bellows surface.

Figure 3-7 Tritium Permeation Rates for Thin Bellows Coupling Walls at a Number of Wall Temperatures. T_2 Pressure was Assumed to be 3×10^{-3} Torr. (H. J. Garber)

4.0 DETAILED DESCRIPTION OF MERCURY PUMPS

4.1 THE TWO-TRAP STACK

As indicated in a previous report⁽¹¹⁾ the two-trap mercury diffusion pump stack is highly desirable in order to provide for the in situ bakeout of the main vessel. The traps are operated independently so that during bakeout the upper trap, CT2 as shown in Fig. 4-1, is degassed while CT1 remains cooled. During high vacuum operations, when both traps are cooled, any accidental release of vapors from CT1 will not enter the main vessel. So as not to accumulate large amounts of condensed vapors on CT1, it will need to be degassed periodically.

The cold surfaces of the traps are at a temperature of 150 K (-123°C) at which the vapor pressure of mercury is $\sim 10^{-14}$ Torr as shown in Fig. 4-2. These temperatures can be maintained using liquid nitrogen or using a closed-circuit coolant loop of a chiller system supplying the 150 K coolant⁽²⁴⁾. Since any mercury vapor arriving at the cold trap surface will condense and freeze, a baffle at 243 K (-30°C) between the trap and the mercury pump is required to condense any backstreaming mercury and allow it to return to the pump. This feature is indicated in Fig. 4-1 as the HG Reflux Baffle at $235\text{ K} < \text{Temp.} < 245\text{ K}$.

In addition to adding a second trap to the mercury stack, a second BAG has been added. The second gauge provides an important redundancy allowing a backup gauge to be present and a means to cross check a vacuum reading. Note that in Section 3, various calculated parameters relevant to the mercury stacks have been presented.

Figure 4-1 Schematic Of The Mercury Diffusion Pump Stack Consisting Of Two Independent Cold Traps.

Figure 4-2 Vapor Pressure Data For Hg

4.2 THE INTERFACING OF THE MERCURY PUMP WITH OTHER SYSTEMS

4.2.1 The Interface With The Vacuum Vessel

Figure 4-3 is a plan view of the TFTR device and the TVPS mercury diffusion pumps. In addition, the test cell floor is cut away to show the basement area where the backing system is located. Refer to Section 5 for the discussion of the backing system. Shown in Fig. 4-4 is Section BB of Fig. 4-3. The pumping stack depicted is composed of an Edwards 24M4 pump, two Edwards NTM24A traps and a 61 cm all-metal gate valve. The gate valve is a non-standard item.

The duct connecting a stack to the toroidal vessel is a cylindrical section with an inside diameter of 63.5 cm and can mate with any of the existing fourteen 63.5 cm diameter vacuum vessel ports. Both ends of the cylindrical duct are compatible with the vessel ports. A new special adapter as shown in Fig. 4-3 allows the pump duct to be connected to a "spare" neutral beam injector port. These ports (there are two and DP2 and DP3 are connected to them) are 40 cm x 70 cm rectangular ports. The special adapter converts these ports to 63.5 cm cylindrical ports. As shown in Fig. 4-3, the center line of all four DP's are at the same distance (1.22 m) from the vacuum vessel and the conductances to each DP is approximately the same in each case (see Section 3). The pump ducts are designed so that there is no obstruction of the "view" for any diagnostic equipment located on these ducts.

4.2.2 The Interface With The Facility

As indicated in Fig. 4-4, the mercury diffusion pump stack is too long to remain above the device substructure and still allow a clear "view" for diagnostic equipment without the use of 90° elbows to attach the DP. The arrangement shown in Fig. 4-4 permits the duct of 63.5 cm diameter to have maximum conductance. In order to have this arrangement, a cut out in the substructure is necessary and shield blocks of high density material can be used to fill the area around the pump if necessary.

Figure 4-3 Plan View of TFTR Device Showing The Mercury Diffusion Pumps And Ducts. Also Shown is a Cut Away View of Basement Area Where The Backing System is Located. The Forelines Are Shown Only to Indicate Their Presence and the Actual Arrangement Will Require Attention to Other Systems. The Vacuum Lines of the Backing System Are Not Shown so as to Simplify The Figure.

Figure 4-4 Mercury Diffusion Pump On The TFTR Vacuum Vessel
See Section BB of Fig. 4-3

Another interface of the mercury pumps and the facility is in the provision for passing vacuum lines from the pumps, through the test cell floor and into the basement where the backing system is located. As shown in Fig. 4-4, this can be accomplished by allowing the roughing line from the duct to the torus to pass straight through to the basement. The foreline from the back of the DP can then be connected through a tee just below valve V2. After the vacuum line (only one per DP) enters the basement, it can pass along the ceiling until it is finally in the vicinity of the backing system and in such a way they do not interfere with the various diagnostic penetrations. The forelines are shown schematically in Fig. 4-3.

Another aspect of the interface of the DP's with the torus vacuum vessel is on the coupling and uncoupling of the pumps to the vessel. As shown in Fig. 4-4, such an operation requires the disconnecting of the 10 cm lines at valves V1 and V4 and then the unbolting of the 63.5 cm flange nearest the torus. After shielding blocks are appropriately removed, the diffusion pump stack and pump duct can be moved away from the torus

4.2.3 The Interface With The Backing System

Of course, the mercury pumps interface with the backing system. In the conceptual design, the roughing lines penetrated the test cell floor as did the backing lines and communicated with the MP's independently. This arrangement is unnecessary and a single line can serve as a roughing line and as a foreline so that the number of penetrations are reduced to one per DP.

4.2.4 Standardization Of Device Interfacing

In the conceptual design of the TFTR, two of the four DP's were attached to the ducts of the neutral beam injectors and two to the torus directly. Thus, two designs for the adapter ducts to the neutral beam injectors were required as well as a third duct design to interface the

device with the two DP's directly attached to the vessel. The two types of neutral beam injector ducts are a type with a diffusion pump and a second type without the pump. In an attempt to provide components of a standard design, the two DP's on neutral beam ports were moved to other locations so that the four ducts between the neutral beam injectors and the device are the same (standard). With these changes, all four pump ducts are now of identical design and can be located at any 63.5 cm port if space is available.

5.0 DETAILED DESCRIPTION OF BACKING SYSTEM

5.1 MECHANICAL PUMPING UNIT AND HOLDING TANK

A mechanical pumping unit on the TVPS consists of a 47 liter/sec mechanical pump (Welch 1396) with appropriate devices on the inlet and outlet sides so that no oil vapors backstream or pass into the 1000 liter holding tank (HT). The inlet device is envisioned as a high conductance zeolite trap (molecular sieve) similar to those available from Varian. The outlet device, an oil demister, is an element which causes the oil vapors to condense and to be collected in a small reserve volume. Leybold-Heraeus has a large variety of mechanical pump accessories which can be appropriately utilized. An alternative unit to the one just described could be a "dry" mechanical pump (needing no filters or traps) utilizing teflon bearings (however, these are not off-the-shelf components and must be special ordered).

To complete the MP, two TC gauges, a valve (V27), and a bellows coupling (BC3) are added. A schematic of an MP is shown in Fig. 5-1 along with the HT to be described later in this section. The valving in the line connecting the MP and the HT is shown in Figs 2-1 and 2-2. To allow for ease of handling, the large MP's could be placed on a mobile cart.

The four MP's backing the mercury pumps are as described above. The MP (MP5) associated with the bellows pumping system which evacuate the twelve bellows guard regions has a smaller pump, e.g., a Welch 1374 rated at 10.8 liter/sec. The size of this pump is the only difference between MP5 and the other four MP's.

The 1000 liter holding tank shown schematically in Fig. 5-1 services all five MP's. In fact, the HT is the only component utilized by both the backing system for the DP's and the bellows

Figure 5-1 Mechanical Pumping Unit And The Holding Tank On The Exhaust Of Pump. 5-2

pumping units. This feature of maintaining the independence of the two sets of pumping units is very important and allows the DP backing pumps to act solely on the DP's.

Since the function of the HT is to temporarily contain the exhausts from the MP's during any tritium operation, it has two tritium monitors (TM1 and TM2) to detect the level of radioactivity in the exhausted gases. These monitors are devices having ionization chambers and measure low level beta activity. Tritium monitors of the type available from Johnston Laboratories, Inc. or from Overhoff and Associates are suggested.

Additional monitoring of the HT is provided by pressure gauges (PM's). The gauges are precision manometers which operate in the range from 0 to 1500 Torr. This pressure range is anticipated during operations such as discharge cleaning, where the initial pressure in the tank is atmospheric pressure and the final pressure is one and a half atmospheres. If additional capacity is required, the HT may be initially evacuated to one-half atmosphere by an auxiliary pump properly trapped. In all cases, the gas pressure in the tank should not go below one-half an atmosphere or above 1.5 atmospheres for efficient mechanical pump operation.

The holding tank is constructed of 1.3 cm thick stainless steel and has inside dimensions of 90 cm diameter x 160 cm high with the top and bottom of the tank having domed coverings to eliminate any possible failure of the tank while under pressures different from atmospheric pressure.

5.2 ZIRCONIUM ALUMINUM GETTER UNIT

During TFTR operations involving hydrogen, the MP's described in the previous section can adequately back the mercury pumps. In fact, there is no need to use the HT during such operations.

Once tritium is introduced into the TFTR device, any gases removed must be carefully monitored and cannot be released to the atmosphere. The ZA's are incorporated to remove and store gases following the introduction of tritium.

The experimental studies⁽²¹⁾ of the zirconium aluminum getter pumps showed that when run at temperatures $> 300^{\circ}\text{C}$ and in parallel with hot tungsten filaments acting as crackers, the getters have the necessary capacity and speed and can be reactivated numerous times. For the TFTR, C-500 cartridges are recommended and various operating parameters have been discussed in Section 3.

The cartridges are housed in 0.3 cm thick stainless steel canisters with inside dimensions of 36 cm diameter x 46 cm high. The canister walls must be cooled so that they are maintained at a low temperature ($\sim 0-10^{\circ}\text{C}$) during operation of the getters. Water lines constructed of copper are suggested. The cartridges will be attached to the top and bottom of the canister as indicated in Fig. 3-5. The cartridges should be bolted to the canister without any of the bolts penetrating the top or bottom and thus eliminating possible vacuum leaks. The top of the canister should be removable with metal seals to provide a vacuum tight fitting. An additional vacuum fitting is required to flange the 10 cm vacuum line to the canister. It should be noted that since the C-500 cartridges can be regenerated by removing gases through the 10 cm line, there is no need to open the canisters by removing the top cover.

In addition to the 10 cm vacuum line there will be other penetrations required to supply electrical power to the tungsten filaments to be used as crackers and to the heaters associated with the C-500 cartridges.

Each of the ZA's backing the DP's consist of four canisters with each canister having eight

cartridges, two vacuum gauges (CC's), a vent, a valve (V23) above each canister, and a central valve (V7) which can isolate the entire unit. A schematic of this unit is shown in Fig. 5-2. The gauges on the ZA's should have a larger pressure range than that of TC gauges, and cold cathode (CC) ionization gauges, e.g., Varians NRC 524, are utilized.

The number of C-500 cartridges has been increased from 48 (including spares not valved into the system) to 80. As designed in the conceptual studies of TFTR, as many as four individual canisters would require handling during a given regeneration period. The present system requires that only one canister be removed during the regeneration period. Also, there is no need to have "spare" canisters in a storage area, since there are enough locations (eight) on the backing system to connect all of the canisters including "spares". After a canister has been removed for regeneration, the valve (V23) associated with the canister can be closed (and a blank-off cover provided if necessary) and the system operated without the canister in place. The removed canister should have a "cap" placed over the 10 cm opening and then it can be sent for regeneration.

There are three ZA's associated with the TVPS. Two (ZA1 and ZA2) are located on the backing system for the DP's and are identical. The third (ZA3) is associated with the BPS and is a smaller unit having only two canisters instead of four as on ZA1 and ZA2. The number of C-500 cartridges in each canister is always eight and each canister (ten total) is identical to the others on all three getter pumping units.

5.3 RESIDUAL GAS ANALYZER UNIT

For the applications in TFTR, the RGA will be required to identify the gas species present as well as to indicate to some accuracy the pressure levels of each gas. In order to provide

Figure 5-2 Zirconium-Aluminum Getter Pump Unit. ZA1 And ZA2 Have Four Canisters As Shown, But ZA3 Has Only Two Canisters (Eight C-500 Cartridges Each). The Flange Joints Indicated Above The Valves Could Also Be Located Below The Valves As Discussed In The Text.

these capabilities, the primary characteristics of the RGA -- absolute sensitivity to a reference gas such as argon or nitrogen, relative sensitivity to the other gases, and the cracking pattern of the gases present in the system -- must be known. The RGA tube of the quadrupole-type such as the Varian Gas Analyzer is recommended while instruments having omegatrons or monoples may also be appropriate. In any case, the performance characteristics of the RGA should include:

- 1) Mass Range 1-50 u
- 2) Sensitivity 5×10^{-12} Torr (N_2)
- 3) Pressure Range 10^{-4} to 5×10^{-11} Torr
- 4) Dynamic Range ≥ 10 ppm
- 5) Resolution ($M/\Delta M$) ≥ 50 at $M = 50$
- 6) Variable (or multiple) Scan Rates
- 7) A Leak Detection Mode (with a minimum detectable leak rate of 10^{-10} Torr liter/sec for helium)

The RGA has its own vacuum pumping system which is shown in Fig. 5-3. The sorption pump is used as a roughing pump to rough down to 10^{-3} Torr and is of the type available from Ultek or Varian. The sorption pump must be surrounded by liquid nitrogen while roughing out the RGA system. The ion pump is then used to reduce the pressure down to the 10^{-11} to 10^{-12} Torr range. An ion pump such as that available from Veeco having a speed of 20 liter/sec is envisioned. Two BAG's are also associated with the RGA's pumping system.

On the inlet to the RGA tube is a calibrated leak module (e.g., as provided by Hasting-Raydis)

Figure 5-3 Residual Gas Analyzer Unit. All Three Units - RGA1, RGA2, And RGA3 - Are Identical.

and valve V10 (not shown in Fig. 5-3, see Figs. 2-1 and 2-2). This valve is a high precision gas flow valve of the type available from Veeco. The Veeco unit is a piezoelectric valve employing a viton disc. Since elastomers are not to be employed on the TVPS, a similar valve not utilizing the viton disc is envisioned.

There are three RGA's associated with the TVPS. Two (RGA 1 and RGA 2) are located on the backing system for the DP's, and the third unit (RGA 3) is on the BPS. All three are identical.

5.4 GAS SUPPLY UNITS

5.4.1 Dry Nitrogen Supply Unit

There are two gas supply units -- one for the backing system of the DP's and another one on the BPS. The dry nitrogen supply unit, referred to as the N_2 Gas in the various figures, is a set of twelve pressurized cylinders of research purity nitrogen at 2490 p.s.i.g. as supplied, for example, by Matheson Gas Products. The unit is arranged in sets of six cylinders on a standard manifold (e.g., Matheson's Double Row Type Manifold). Since 10 cylinders of gas are required to let the torus up to atmospheric pressure, there will need to be a number of reserve cylinders. Each manifold will have a regulator to control the gas. The N_2 Gas unit is shown in Fig. 5-4. (See Section 3.4.2 for calculations.)

5.4.2 The Dry Gas Supply Unit On The DPS

The Dry Gas on the BPS will supply research purity nitrogen as well as research purity argon and helium. The unit is arranged with a cylinder having its own regulator for each of the three different gases. The Dry Gas unit will be used to let the bellows guard regions up to atmospheric pressure and to aid in the leak checking of the bellows surfaces of the toroidal

Figure 5-4 Dry Nitrogen Supply Unit

vessel. During such leak checking procedures, helium or argon will fill the guard volumes and the RGA's on the backing system to the DP's will be used as leak detectors.

5.5 ARRANGEMENT OF THE TVPS UNITS LOCATED IN THE BASEMENT

In Section 2, a discussion of the TVPS was presented without any indication of the details of the many primary units. In Section 4 and in this section, these details were presented. At this point the overall arrangement of the TVPS will be discussed. In particular, the interfacing of the primary units with each other and the arrangement of the system in the basement area are given. A schematic representation of the TVPS is shown in Fig. 5-5. This figure is a reminder of the arrangement of the vacuum lines and valves between main units as shown in Fig. 2-1 and shows the details of these units as presented in Sections 4 and 5.

A set of equipment drawings (drawing no. 343763D) have been made for an arrangement consistent with the plan view as shown in Fig. 4-3 and the schematics, Figs. 2-1, 2-2, and 5-5, with particular attention to the backing system for the DP's. The following assumptions were made in developing these drawings. First, the equipment drawings do not show the BPS since an arrangement of the BPS components is anticipated to be very similar to the corresponding components on the backing system for the DP's. Secondly, these drawings have not indicated the details of the support structure which may be necessary to maintain the system in the arrangement shown. Thirdly, the positioning of valves and lines are not exactly as anticipated for the final system, i.e., lines were raised or lowered so that components which would have been hidden can be easily viewed. Fourthly, even though RGA1 and RGA2 are not located in close proximity to each other, (see Fig. 4-3), with a few relatively simple changes they could be located very near to each other. The same comment can be made concerning

Figure 5-5 Schematic of One of The Components of The Torus Vacuum Pumping System. Details of Subsystems Are Shown.

ZA1 and ZA2. This point is mentioned because it is likely that for maintenance purposes such a change is appropriate. The reason that such an arrangement was not made in this present study was that it is believed that the somewhat symmetrical arrangement shown in Fig. 4-3 is more easily described and understood. And finally, the positioning of components and lines was made with a constant awareness that the system needed to be available for the maintenance of almost all of the components. The maintenance consideration was a major factor when deciding to show all connections as flanged rather than welded ones. The area (6.4 m x 8.2 m) where the backing system is located in the basement has space for storage and for access of each main unit.

Shown in Fig. 5-6 is an elevated view of the backing system. This view corresponds to View AA of Fig. 4-3. Certain details such as components in the background of the figure and support structures have been omitted. As can be seen, the forelines to the DP's are located along the ceiling. The lines leading from the HT to the ceiling and then over to the main forelines allow the Tritium Cleanup System located out of view (see Fig. 4-3 for direction) to communicate directly with the torus vacuum vessel. These lines form a circuit between the Tritium Cleanup System and the torus vacuum vessel and are used when the TVPS is not utilized to detritiate the gases enclosed in the vessel.

The arrangement of pumps, lines, RGA's, and valves of the backing system is in the form of a stack. At the lowest level are the MP's and the HT. At this level, the exhaust lines of the MP's are manifolded together and are valved into the HT. A plan view (View CC) of this level is shown in Fig. 5-7. The various exhaust filters (the oil demisters) and an oil vapor trap at the HT are shown. The valving, i.e., V11, V12, and V13 allow the exhausted gas to be either vented or pumped into the HT for temporary storage (after the introduction of tritium into the TFTR device). Details are also shown for the connections between the HT and the Tritium Cleanup System which is located in another area of the basement.

Figure 5-6 Elevated View of the Backing System in the Basement (View AA of Fig. 4-3). Components and Units (e.g., ZA2, N₂ Gas, MPI, BPS, etc.) to be located in the Background of the Figure are not shown since such details would add considerable complication. The support structure needed to maintain the various units in their proper location is not shown.

Above the lowest level (Fig. 5-7) of the backing system as shown in Fig. 5-6, is the level at which the ZA's are manifolded into the foreline and the level at which there are lines allowing the four MP's to cross communicate with the four DP's. This intermediate level is shown in Fig. 5-8. As can be seen from Fig. 5-8, each of the four MP's can communicate with ZA1 through its respective valve V5 (there are four) and valve V7 (there is one on ZA1 and another on ZA2). Similarly, V6 allows the various pumps to communicate with ZA 2 via its main valve V7. While in operation, the MP's will actually be valved off through valve V3 (Fig. 5-6) at the time the ZA's are pumping on the forelines, and thus the valves V5 and V6 really allow a ZA to back a DP rather than to communicate with an MP. In addition to the valving of a ZA into a particular foreline, the manifolding also allows communication between MP's either to augment the pumping speed in a foreline or to temporarily replace a failed MP. If desired, the complete set of vacuum lines shown in Fig. 5-8 could be assembled at a single height. As shown in Fig. 5-6, two heights are indicated, but only for the purpose of revealing hidden lines and valves. Also, it is likely that both ZA1 and ZA2 can be located on the same side of the MP's without too many changes.

At the upper level of Fig. 5-6 is the manifolding to two RGA's. A plan view of this manifold is shown in Fig. 5-9 as well as a front view (View FF) of the RGA unit. The lines to the N₂ Gas Supply are also indicated. Again, as mentioned before, the several different heights of the lines could be reduced and both RGA's could be on the same side (the side RGA1 is located) without any difficulty.

As shown in Fig. 5-6 (and the three plan views) the lines, valves, 90° elbows, tees, crosses, and nipples are of standard 5 cm (2") or 10 cm (4") stock used in UHV assemblies with ConFlat seals. Except for valve V10 (there are two and they are variable leak valves) valves are all-metal (ConFlat) pneumatically-operated gate valves or possibly solenoid-operated valves to be used at the vent locations. It is anticipated that in the final design additional bellows coupling sections will be added to allow ease of coupling and uncoupling components. All gauges (BAG's, CC's, and TC's) require all-metal UHV (ConFlat) flanges.

Figure 5-8 Plan View DD Showing the Details of the Manifolding of the Zirconium Aluminum Units to the Forelines. The Vacuum Lines From the Mechanical Pump Exhausts are Indicated Only in the Area of MP4. See Fig. 5-6 for the Elevated View.

Figure 5-9 Plan View EE Showing the Details of the Manifolding of the RGA's to the Forelines. Details Shown in Figs. 5-7 and 5-8 which would appear "under" the Vacuum Valves and Lines Appearing here are Omitted for Clarity. The Valving to the N_2 Gas Unit is also shown. -View FF shows an RGA as seen by the Man in Fig. 5-6.

6.0 BELLOWS PUMPING SYSTEM

6.1 PERFORMANCE PARAMETERS OF THE BPS

The twelve bellows sections of the TFTR toroidal vacuum vessel have outer covers. The region between the cover and the bellows, called the guard region, will be evacuated. The two main reasons for this evacuation are that due to the high temperatures experienced during operations (normal pulsing, discharge cleaning, and bakeout) the bellows can allow ~ 3 Ci/year of tritium to permeate through the thin (1 mm) surfaces⁽¹⁴⁾, and that the bellows convolutions will be under less stress if the guard region is evacuated. A previous report⁽¹²⁾ on the BPS presented the relevant aspects of the pumping system required to service the bellows guard regions. In this section, an up-date of that report will be given. The following is a set of calculated results similar to those given in Section 3 for the main TVPS.

The vacuum lines connecting the various bellows sections to the main line leading to the pumps are 7.5 cm tubing. This tubing has an inside diameter of ~ 7 cm and is ≤ 18 m long for a given bellows section, and the various conductances are as follows:

$$\begin{aligned} C_M^{(\text{air})} &= 2.3 \text{ liter/sec} \\ C_M^{(\text{H}_2)} &= 7.9 \text{ liter/sec} \\ C_V^{(\text{air})} &= 243 \bar{P} \text{ (Torr) liter/sec} \end{aligned}$$

The base pressure of the system assuming there is a total of 10^7 cm^2 of surface outgassing at 10^{-10} Torr liter/sec cm^2 (mostly hydrogen) is

$$P_G \approx \frac{Q}{C_M^{(\text{H}_2)}} = \frac{10^{-3} \text{ Torr liter/sec}}{8 \text{ liter/sec}} = 1.3 \times 10^{-4} \text{ Torr}$$

For $Q = 10^{-3}$ Torr liter/sec (mostly hydrogen), 3.2×10^4 Torr liter/year of hydrogen will be evolved. At a rated capacity of 2310 Torr liter for a C-500 cartridge, a total of ~14 cartridges are required to handle the gases for a year without any regenerations. At 150% of the rated capacity⁽²¹⁾ only nine C-500's are required. Thus, a ZA (ZA3) of two 8-cartridge canisters should sufficiently service the BPS with each canister being regenerated every six months or more.

Using the pumpdown formula given in Section 3.4.1, the time to rough down the bellows sections is

$$\begin{aligned} t &= 22.1 \frac{V}{S_{\text{eff}}} \\ &= 22.1 \frac{1000 \text{ liters}}{7 \text{ liter/sec}} \\ &\approx 1 \text{ hr} \end{aligned}$$

where the 1000 liter volume takes the bellows guard regions and the foreline volume into account and $S_{\text{eff}} \sim 7$ liter/sec is appropriate for a Welch 1374 at pumpdown pressures. To shutdown the system and let the bellows guard regions up to atmospheric pressure, $1000 \text{ liter} \times 760 \text{ Torr} \approx 8 \times 10^5$ Torr liter of dry nitrogen is required. The fraction of a container needed is thus

$$\frac{8 \times 10^5 \text{ Torr liter}}{40 \text{ liter} \times 1.3 \times 10^5 \text{ Torr}} = 0.15 \approx \frac{1}{6}$$

and a cylinder of nitrogen can last for six "up-to-air" operations.

6.2 DESCRIPTION OF THE BPS AND ITS INTERFACING WITH OTHER SYSTEMS

The various units (MP5, ZA3, RGA3, and Dry Gas) have been described in some detail in Section 5. Briefly, MP5 has a 10 liter/sec mechanical pump and otherwise is the same as the

other MP's. The ZA3 has only two canisters compared with four on ZA1 and ZA2. The RGA is exactly the same as on the backing system for the DP's and the Dry Gas unit has a cylinder each of N₂, Ar, and He (additional gases such as H₂ may also be included).

A schematic diagram of the BPS is shown in Fig. 6-1 and the floor plan of the BPS is shown in Fig. 4-3. The stacked arrangement of the units similar to that for the main backing system is suggested. In that arrangement MP5 is on the basement floor and ZA3 is at an intermediate level with the RGA at the upper level as shown in Fig. 5-6 for the main backing system. Note that the exhaust to MP5 is connected to the HT.

The forelines connecting the BPS to the bellows sections are connected on the underneath side of the device (see Drawing 347462J where Section VV shows the "3 in" diameter line to the vacuum pumps). These lines will pass through the test cell floor into the basement. The lines should be similar to the many diagnostic lines penetrating the test cell floor. After entering the basement each line will have a valve, V33, and then be connected into the main manifold through which the BPS evacuates the guard regions. The details of this manifold (just below the basement ceiling) should be determined in coordination with the details of the other penetrations through the test cell floor.

Figure 6-1 Pumping Unit For The Bellows Sections

7.0 FORE VACUUM SYSTEM OF THE TVPS IN THE PIT

In the basement below the device there is an area referred to as the pit. The pit has a floor level which is 1.83 m below that of the basement. The following is a set of calculations based on the assumption that the TVPS (the backing system only) is located in the pit. If the TVPS would indeed be located in the pit then the floor plan (Fig. 4-3) would not necessarily remain as depicted. There has been no attempt to provide any details for a pit-located backing system, but the following should prove useful when making such considerations.

The primary effect of moving the TVPS to the pit is that the length of foreline between the MP's and the DP's is reduced from ~28 m to ~7 m, a factor of four. Thus, those quantities, e.g., conductances, foreline volume, foreline base pressure, which depends on this length, will change roughly by a factor of four. The quantities and parameters obtained in Section 3 were recalculated by taking into account the change in the length of foreline. Those numbers which are different as a result of the change are presented below along with those results (in parentheses) presented in Section 3. If a parameter is not affected, it is omitted from the present considerations.

By shortening the forelines, the conductances increase, and

$$\begin{aligned} C_F^{(\text{air})} &= 14 \text{ liter/sec (3.6 liter/sec)} \\ C_F^{(\text{H}_2)} &= 52 \text{ liter/sec (13.5 liter/sec)} . \end{aligned}$$

The effective pumping speeds of the various pumps also increase where:

$$S_{MP}^{(air)} \text{ (1 pump)} \approx 9 \text{ liter/sec (3 liter/sec)}$$

$$S_{ZA}^{(H_2)} \text{ (1 foreline)} \approx 52 \text{ liter/sec (13.5 liter/sec)}$$

Since the wall area of the 10 cm line has changed, the base pressure in the foreline should change, and

$$P_{BASE} \sim 3 \times 10^{-5} \text{ Torr (} 2 \times 10^{-4} \text{ Torr)}$$

Of course, the volume will be reduced by a factor of four to 50 liters which means that the foreline pressure immediately following a pulse will be higher than before, i.e., $\Delta P \sim 0.2 \text{ Torr (0.045 Torr)}$. In addition, the time constant associated with the pumpout of the foreline after the pulse will change where:

$$\tau_{MP} = 2.7 \text{ sec (13 sec) and } \tau_{ZA} = 1.1 \text{ sec (5.7 sec).}$$

Thus, the times required to return to the base pressure are greatly reduced, and $t_{MP} = 23 \text{ sec (67 sec)}$ and $t_{ZA} = 9 \text{ sec (30 sec)}$. In a similar way, the time constants associated with leak checking will decrease and the results are as follows:

$$\tau_F^{(Ar)} = 6.5 \text{ sec (78 sec) and } \tau_F^{(He)} = 1.4 \text{ sec (22 sec).}$$

One more parameter which is affected is the rise in pressure in the foreline due to non-getterable gases. The rise after an 8 hour day is 0.13 Torr (0.03 Torr).

For the fore vacuum system located in the pit there will be no appreciable change in cost of the system since only a reduction in the length of 10 cm vacuum line will result. The saving is approximately \$5 k for the four vacuum lines on the four diffusion pumps.

8.0 CONTROL AND MANAGEMENT OF THE TVPS

8.1 CONTROL SYSTEMS

To operate and control the TVPS requires a complex network of indicators, actuators, a compressed air system, a water cooling system, a cooling system for a variety of cryogenically cooled units, a variety of electrical controls and cables, and a large number of power supplies. Provisions are necessary for the remote control of valves and pumps and for the display of gauge outputs. It is expected that the local control system in the basement (see Fig. 4-3) will comprise a half-dozen six foot racks of hardware with the equivalent of one rack being utilized to control each of the six major groups of units, i.e., DP's, MP's, ZA's, RGA's, HT and the BPS. The local control panel should provide for both automatic and manual operations with protective interlocks to guard against the overheating of various elements, water-cooling failures, and power failures.

Along with the local control station there must be a system at the TFTR Central Control⁽²⁵⁾ permitting the following set of operations on the vacuum system to be initiated and to automatically proceed to completion: 1) system checkout, 2) startup and shutdown, 3) standby, 4) normal pulsing, 5) discharge cleaning, 6) bakeout, and 7) emergency. The RGA's associated with the TVPS will be interfaced with the central control computer to provide a continuous time history of the residual gases analyzed during all phases of TFTR operation. The computer should be programmed to process the raw data, RGA sensitivities and cracking patterns into partial pressures of the various gas components. A portion of the control panel in the TFTR central control room is envisioned as having sets of indicator lights placed in a schematic arrangement on a panel in such a manner that valve positions (open/closed), and gauge readings (good/poor/bad) can easily be read. Two important guide lines being stressed in the design of

the TVPS and its control system are: 1) the TVPS should be as independent of the other vacuum pumping systems (on the neutral beam injectors and on the many diagnostic systems) as possible communicating only through the ports and associated valves on the device, and not communicating directly through the sharing of pumps; 2) the TVPS should be interfaced with the TFTR emergency power supply to assure that no radioactive gases enclosed in the TFTR device and forelines of the TVPS are released to the atmosphere.

8.2 TESTING AND MAINTENANCE

Prior to the actual start of operations the TVPS must be completely checked out to assure that all individual components as well as the assembled units have, in fact, been built properly and are operating satisfactorily. All inspections and testing runs must be performed in accordance with ultrahigh-vacuum (UHV) standards. Each individual mercury diffusion pump stack must be leak tested to assure that the helium leak rate is less than 10^{-10} Torr liter/sec.

Since the initial operating period (~1 to 2 years) will not involve the use of tritium, hands-on maintenance can be used to service and repair the vacuum system. Once the system is working satisfactorily it will be advisable to confirm the adequacy of performing specific remote maintenance operations necessary after D-T pulsing begins such as DP replacement. After the introduction of tritium into the device, the basement area will not be accessible for periods up to several hours per day due to activation of the air.

Aside from limitations resulting from nuclear radiation hazards and the handling of activated components, the TVPS will have limited maintenance periods since it must be maintenance free over long periods of normal pulsing (Table 2-2). Even though reliability, safety, flexibility and redundancy are requirements on the system, components and parts do have limited lifetimes. The following is a list of some of the anticipated maintenance operations:

- 1) Replacement of all-metal valves (~100 total on the TVPS) after a number (on the order of 100) of operating cycles.
- 2) The regeneration or replacement of foreline traps (zeolite traps, oil vapor traps, and oil demisters).
- 3) The regeneration or replacement of sorption pumps and ion pumps.
- 4) The replacement of vacuum gauges (BAG's, CC's and TC's).
- 5) The checking and changing of pump fluids in the MP's and the DP's.
- 6) The replacement of pressurized gas cylinders.
- 7) The regeneration of zirconium aluminum canisters.

There will be many other maintenance operations, but the above type of operations are the most predictable.

During an operation in which a component such as a zirconium aluminum canister is to be removed, a section of the foreline must be vented. If tritium has been introduced, the vented section can contain radioactive gases and an RGA reading must be taken before the vent valve is opened. After an assessment of the quantity of tritiated gases has shown that the activity to be released is below an acceptable limit, the valve can then be opened (see Section 3.6.4).

8.3 LEAK CHECKING

Since leak checking a vacuum system is one of the most time consuming and difficult tasks associated with vacuum work, it is best to assure a minimum need for it. For the TFTR, with its

64 m³ vessel, its neutral beam arms, many diagnostic ports and appendages, and several pumping systems, it is clear that even with extreme care leak checking is more than likely to be required. To aid in the leak checking of such a large system, several important points should be observed while carrying out such operations:

- 1) Record outputs from gauges and leak detectors.
- 2) Look for POSITIVE evidence
- 3) Go from the gross but positive evidence to finely located leaks
- 4) Know the vacuum system well

It is also clear that a set of standards and accompanying procedures must be developed. For example, a "leak" could be a virtual leak, a pump or gauge malfunction, a foreline leak, or an unusually high outgassing rate. Such abnormalities are just as likely to occur as actual leaks and a set of procedures should start with the checkout of the system for such conditions. Procedures would include: double checking, looking for all leaks, repair operations, and the subsequent leak checking following all repairs. Since TFTR will require remote and semi-remote leak checking, special flanges and welds as well as numerous tubes (supplying a search gas) will be required. Reference 13 addresses the points raised in the above discussion and includes a logic chart for the leak checking of TFTR.

The role of the TVPS is vital in the leak checking of TFTR. The RGA's associated with the backing system can be utilized as leak detectors. Calculations carried out in Section 3 indicate that the TVPS is very compatible with the use of helium as the search gas. After deuterium has been introduced, a loss in detection sensitivity is probable since the ratio of the mass to the charge, M/q , of helium is the same, namely 4 u/e, as that for singly charged deuterium.

Since the bellows guard regions on the torus are sealed to hold a vacuum at $\leq 2 \times 10^{-4}$ Torr,

they will be very effectively utilized in leak checking the bellows walls. The procedure will involve the introduction of a search gas into each individual guard region and the detection, either by the RGA's or by a sniffer moving over the interior surfaces of the vessel, of the gas as it finds its way through an imperfection in the thin walled bellows (see Reference 13).

8.4 STARTUP, SHUTDOWN AND STANDBY

The startup, shutdown, and standby of the TVPS will occur on a relatively frequent basis since the pulsing of the device will occur only eight hours per day, five days a week. Startup, shutdown and standby operations will involve the opening or closing of valves and it will be necessary to develop procedures to minimize such valving operations. An all-metal valve can be operated for only a few hundred cycles between a gasket change.

A full shutdown and startup will only be necessary during an up-to-atmospheric-pressure period which is expected once every three months⁽¹⁴⁾. A partial shutdown or a standby will occur on a weekly basis at the end of the week. During the full startup, the MP's will rough down the vacuum vessel. The BPS will also rough down the bellows guard regions such that the pressure on either side of the bellows is equalized. Since the time constant (V/S_{eff}) for pumping down the twelve bellows regions (~ 143 sec) is approximately one-third that of the MP's roughing down the torus (~ 452 sec) the valve, V35 in Fig. 6-1, to the BPS main manifold should be one with a variable conductance to allow this equalized pumpdown to occur.

The startup or shutdown of the TVPS will require the employment of tritium monitors (e.g., TM1 and TM2 in Fig. 5-1 as well as others on the tritium cleanup unit and elsewhere) to check tritium levels as D-T operations commence. If the levels are too high, the Tritium Cleanup System will be utilized to reduce these levels. To carry out such a cleanup when the vessel is at or near atmospheric pressure the pumps on the TVPS can be isolated, and the torus and Tritium Cleanup System can be valved in a closed loop through valves V19, V20, V24, V25, and V26 shown in Fig. 2-2 which will cycle the gases in the torus through the cleanup system until the tritium levels are acceptable.

8.5 PULSING OPERATIONS

8.5.1 Non-Tritium Operations

There are two basic pulsing operations -- normal pulsing in which a 1.0 MA or a 2.5 MA plasma is initiated every five minutes for eight hours per day, and discharge cleaning in which a 300 kA plasma is initiated every 1.5 seconds for up to 12 hours. During these operations the four diffusion pumps, each backed by a mechanical pump unit exhausted to the atmosphere will evacuate the main vacuum vessel. The 10 liter/sec mechanical pump on the BPS will evacuate the bellows guard regions.

During normal pulsing the vessel will be returned following the pulse to base pressure $\leq 6 \times 10^{-8}$ Torr (H_2) in approximately 30 seconds. The gas load to the mechanical pumps as the result of the plasma pulse will be such that the foreline will return to its normal backing pressure in approximately 70 seconds (see Section 3.5.5).

During discharge cleaning the pressure in the vessel will be maintained dynamically by a continuous flow of the working gas (He , H_2 , etc.) into the vessel and out through the TVPS. The pressure in the vessel will remain at $\sim 4 \times 10^{-4}$ Torr and the pressure in the backing line will remain at $\sim 10^{-1}$ Torr. Discharge cleaning is expected ⁽¹⁴⁾ to occur on a weekly basis and to take approximately two hours to complete. On a less frequent basis, a 12 hour discharge cleaning will occur following a maintenance period or a 4 hour cleaning following a change in working gases, e.g., in going from hydrogen to deuterium.

8.5.2 Tritium Operations

Tritium will begin to be adsorbed by the vessel walls as soon as it is introduced into the device, and it will continuously desorb from the walls after the initial introduction. As a result, tritium levels and levels of tritiated gases must be continuously determined and recorded (a log of the time history). The RGA's and the TM's will be used to measure these levels. For those times

when the radiation levels are too high to exhaust the gases to the atmosphere the 1000 liter holding tank and the zirconium aluminum getters will be utilized to contain the gases in a closed system.

After the introduction of tritium, and during normal pulsing, the ZA's will back the DP's. The gas loads (see Sections 3.5 and 3.6) will require that a getter canister be removed for regeneration every eight days (on the average).

During discharge cleaning the MP's exhausting to the holding tank will back the DP's. The gas loads are too large for utilizing the getters requiring the canisters to be regenerated too frequently to be practical (see Section 3.5.6).

8.6 BAKEOUT IN SITU

The 250°C bakeout in situ of the TFTR vacuum vessel will occur on an infrequent basis. It is expected⁽¹⁴⁾ that a two-day bakeout will occur following a maintenance period in which the vessel is up to atmospheric pressure and that a one-day bakeout will occur following a change in working gas. During a bakeout the four diffusion pumps will evacuate the vessel and the mechanical pumps will remove the gases from the foreline.

If the tritium levels are low enough the MP's will be vented to the atmosphere or, if the tritium levels do not allow this, the exhausted gases will be held up in the holding tank until they can be passed through the Tritium Cleanup System. The holding tank is large enough to contain the exhausts for at least 2 days of baking in situ.

During a bakeout the bellows guard sections will receive large amounts of tritium which will permeate through the thin walls due to the high temperatures of those walls. As a result, MP5 (Fig. 6-1) will also need to be exhausted to the holding tank.

8.7 OPERATIONS DURING FAULTED CONDITIONS

Emergency operations will be required if a serious leak occurs in the toroidal vessel or in the foreline, or if a power, water or cryogenic failure occurs. Following the start of a leak in the main vessel the high-vacuum valves should be closed as quickly as possible. These valves are 61 cm in diameter and will require on the order of 10 seconds to close. During this time the MP's should back the diffusion pumps. If tritium operation has begun, the getter units should be isolated immediately after a vessel leak and the MP's should exhaust into the holding tank. The most important aspect of the emergency operation is to minimize the possibility of mercury backstreaming into the vessel and to protect any components which could be damaged.

As for failures in the water or cryogenic systems or in the power supply to a component, interlocks will be incorporated and a set of automatic operations developed for such failures. If the failure is in the electrical power to the TVPS, the emergency power supply for the TFTR facility must provide power to all safety-related components to assure that radioactive gases are not released to the atmosphere.

Faulted conditions involving the failure of a gauge or pump in the foreline will be handled by relying on the redundancy feature of the fore system to provide an immediate backup component to replace the failed component. If a valve fails in an open position there will be a second valve in the line to be utilized. If the valve is closed, the flexibility of the backing system will, in general, allow the component isolated by the failed valve to be temporarily substituted for by a similar component elsewhere in the system.

9.0 COST CONSIDERATIONS

With information supplied by a number of manufacturers and obtained through catalogues on vacuum components and products the following cost estimate was obtained. This estimate was based on the system depicted in the many equipment drawings appearing in this report. For example, lengths of tubing, numbers of 90° elbows, numbers of crosses, etc., were determined and were costed out using the latest price lists. Several items, e.g., a 61 cm diameter HV gate valve or an enclosed bellows coupling, are not standard components so that the estimates on such equipment are more speculative, but when considered item-by-item, most errors will average out when the total cost is obtained. One more point which should be mentioned is that the present cost estimate was checked for consistency with those estimates obtained during the conceptual design study. The estimates were found to be consistent with each other.

A listing of estimates by major units, e.g., DP, MP, etc., is given in Table 9-1 for the TVPS without the bellows pumping system. A similar listing for the BPS is given in Table 9-2. Not included in either of these two lists is an estimate of the costs of controls and instrumentation or of the cost associated with spare hardware.

Since the controls and instrumentation of the TVPS including the BPS will have both a local (in basement) and a central (at main control room) component, there will be a great deal of overlap with other control systems. The details of the many automatic subsystems for remotely controlling valves, gauges, and pumps strongly depends on the final arrangement of components. The degree of remote controllability is also important. Since the backing system is located in the basement limited access during pulsing operations is possible. For the above reasons, an estimate on the controls cannot be as accurate as hardware estimates, but is assumed to be approximately \$100 k.

TABLE 9-1

COST ESTIMATE OF TVPS (WITHOUT BPS)

Unit	Number of Units	Cost/Unit (thousand \$)	Subtotal (thousand \$)
DP	4	75	300
MP	4	8	32
ZA	2	121	242
RGA	2	20	40
HT	1	18	18
N ₂ GAS	1	4	4
FORELINE (not part of main units)	4	40	160
OTHER (supports, etc.)	1	15	15
Total			<u>\$ 811</u>

TABLE 9-2
COST ESTIMATE OF BPS

Unit	Number of Units	Cost/Unit (thousand \$)	Subtotal (thousand \$)
MP5	1	7	7
RGA3	1	20	20
ZA2	1	62	62
DRY GAS	1	1	1
FORELINE & VALVING	1	78	78
Total			<u>\$ 168</u>

As for spare components, the assumption is made that to be adequately prepared, the equivalent of a DP with a full backing system is needed. With the inclusion of additional components needed for the maintenance of the BPS and for routine repairs and upkeep, an estimate of \$260 k was obtained. This includes a spare diffusion pump stack, mechanical pump unit, RGA unit, several getter canisters, several cylinders of various gases, a large number of all-metal valves, ~100 spare ConFlat seals, a number of stainless steel vacuum fittings, a number of replacement gauges, and lengths of vacuum lines. This spare parts estimate is considerably higher than that provided in the conceptual design study. Since the TVPS is a vital service system on TFTR, the costs are justified if the realization of a reliable vacuum pumping system is to be met. Table 9-3 is a summary of the present cost estimate.

In comparing this estimate to the previous one, the costs of the hardware and of the control of the TVPS (without the BPS) are essentially unchanged (within 12% of each other). An estimate for these two items of \$1020 k total during the conceptual design can be compared to \$911k total for the present system. The grand total cost of the TVPS now includes the BPS and an expanded spare parts inventory and is listed in Table 9-3 as \$1339 k

TABLE 9-3
SUMMARY COST ESTIMATE OF TVPS

Unit	Cost (thousand \$)
TVPS (without BPS)	811
BPS	168
CONTROL & INSTRUMENTATION	100
SPARE PARTS	260
<hr/>	
Grand Total \$ 1339	

10.0 SUMMARY

In this report, the ultrahigh-vacuum pumping system on the TFTR toroidal vacuum vessel is described in detail. This system, the TVPS (Torus Vacuum Pumping System), employs four 61 cm mercury diffusion pumps each of which communicates with the vacuum vessel through two cold traps, a high-vacuum gate valve, and a pump duct attached directly to the torus vessel. The diffusion pumps have an effective pumping speed at the torus of 2×10^4 liter/sec and will evacuate the vessel to a base pressure in the 10^{-8} - 10^{-9} Torr range. To accommodate these base pressures, the vacuum vessel walls are conditioned in situ by a combination of baking out the walls at 250°C and of aggressively discharge cleaning the vessel surfaces⁽¹⁴⁾. The TVPS will not contribute any impurities to the vessel volume or to the plasmas formed in that volume.

A general description of the pumping system is given in Section 2. The system backing the four diffusion pumps is a consolidated arrangement of four mechanical pumping units, a 1000 liter holding tank, two zirconium aluminum getter pumping units, and two residual gas analyzer units. The vacuum lines and the valving between the various units allows a great deal of flexibility and, in addition, requires that two valves be operated before a unit can communicate with the other units. The double valving provides both safety in operating the backing system and allows alternate operations for a valve which has failed in the open position. The flexibility of the foreline enables cross communication between the various diffusion pumps and mechanical pumps, and permits a single zirconium aluminum canister to back all four mercury diffusion pumps. The valving also permits each of two RGA's to communicate with each of the four forelines.

The most important requirements and functions related to the TVPS are given in Tables 2-2 and 2-3, respectively. The requirements of no elastomeric materials, of the system being closed with respect to tritium and of the system contributing no impurities to the plasma pulse are the most important. Listed in Table 2-4 are the various modifications which went into the con-

ceptual design^(8,10) of the TVPS in order to arrive at the present modified conceptual design. The more important modifications include the incorporation of an in situ bakeout, the addition of a second trap to each diffusion pump stack, the addition of redundancy features, a modified valving arrangement between the various forelines, the incorporation of a bellows pumping system (BPS), and the replacement of the two small holding tanks by a large single tank.

The basis for the present design of the TVPS includes a number of calculated performance parameters and the engineering of a set of conventional and ultrahigh vacuum components into a practical system with excellent maintenance features. The calculations are presented in Sections 3 and 4 and are summarized in Table 10-1. The engineering of the system is detailed in Sections 4 and 5.

In Section 4, the mercury diffusion pump stacks and their interface with the other systems on TFTR are described. For the present modified design, all four pumping ducts are attached directly to the torus vessel and thus the neutral beam injection arm ducts are not used as pump ducts. With the pumps in this arrangement, a standardized set of ducts is possible. Details of the arrangement of vacuum lines from the diffusion pumps to the backing system in the basement are also given.

Detailed description of the major units making up the backing system are given in Section 5. The mechanical pumping units (MP's) incorporate a large 47 liter/sec oil mechanical pump properly trapped on both the inlet and exhaust sides. The exhausts of the MP's can be either vented to the atmosphere or valved into the 1000 liter holding tank (HT) which has been sized to be utilized during discharge cleaning operations. Each of two zirconium aluminum getter units (ZA's) have four getter canisters with each canister containing eight SAES C-500 Zr/16% Al getter cartridges. The eight cartridges have the capacity to remove gases pumped during normal pulsing for up to the time the 24 kCi limit⁽¹⁶⁾ on tritium storage is reached. They will be reused after being regenerated. The performance characteristics and the vacuum pumps

TABLE 10-1
CALCULATE PERFORMANCE PARAMETERS FOR THE TVPS

Parameter	Subsystem	Parameter Value
Conductance	Duct to Each Diffusion Pump	$\sim 8 \times 10^4$ liter/sec (H_2)
	Each Foreline (at base pressure)	≥ 3.6 liter/sec (air) ≥ 13.5 liter/sec (H_2)
	Bellows Pumping System	~ 8 liter/sec (H_2)
Effective Pumping Speed	Each Diffusion Pump Stack	5200 liter/sec (H_2)
	At Torus for all Four Pumps	2×10^4 liter/sec (H_2)
	Four MP's During Pumpdown (Roughing)	140 liter/sec (air)
	Zirconium-Aluminum Getter Canister Pumping on the four Backing Lines	54 liter/sec (H_2)
Base Pressure	In Toroidal Vacuum Vessel for: $q = 10^{-10}$ Torr liter/sec cm^2	$\sim 6 \times 10^{-8}$ Torr (H_2) $\sim 9 \times 10^{-8}$ Torr (D_2/T_2)
	$q = 2 \times 10^{-12}$ Torr liter/sec cm^2	$\sim 1 \times 10^{-9}$ Torr (H_2) $\sim 2 \times 10^{-9}$ Torr (D_2/T_2)
	In Foreline	$\sim 2 \times 10^{-4}$ Torr
	In BPS	$\sim 1.3 \times 10^{-4}$ Torr
Gas Loads	From Plasma Initiation	~ 15 Torr liter/2.5 MA pulse ~ 9 Torr liter/1.0 MA pulse
	From Neutral Beam Injection	41.4 Torr liter/sec
	Total Gas Load (on the average)	~ 15 Torr liter/pulse

Pumpout Times and Time Constants	Pumpdown From Atmospheric Pressure Foreline BPS Time Constant for Vacuum Vessel and the four DP's Time Constant for Foreline and MP's (at low pressure) Time Constant for Foreline and ZA's Time Constants for Leak Checking $\tau_{HV}^{(He)}$ $\tau_{Foreline}^{(He)}$ $\tau_{HV}^{(Ar)}$ $\tau_{Foreline}^{(Ar)}$	 ~3 hours ~1 hour 3.2 sec 12.9 sec 5.7 sec 9 sec 22 sec 22 sec 78 sec
Ballast Volume	Each Foreline Twelve Bellows Guard Regions Zirconium-Aluminum Canister Holding Tank (HT)	~200 liter ~1000 liter 46 liter ~1000 liter
Getters	Cartridges per Canister Time Between Regenerations Gas Content per regeneration	8 8 days 1.3×10^4 Torr liter

Acceptable Leak Rates	<p>At a Bellows Section (due to a 0.4-cm diameter hole)</p> <p>Seal on the High Vacuum Gate Valve Above Mercury Pump</p>	<p>1.2×10^{-3} Torr liter/sec</p> <p>3×10^{-8} Torr liter/sec per cm of seal</p>
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for the residual gas analyzer units (RGA's) and a description of the Dry Gas supplies are also presented. In the last part of Section 5, a set of equipment drawings (Figs. 5-6 thru 5-9) showing the arrangement of the backing system are discussed. This arrangement is essentially in the form of a stack in which the MP's and the HT are located on the basement floor while the ZA's are manifolded into the foreline at an elevated level and the RGA's are similarly manifolded at a higher vertical level above the basement floor. The design provides excellent access for maintenance.

The bellows pumping system (BPS) which was incorporated⁽¹²⁾ after the completion of the conceptual design is updated in Section 6. This system provides a vacuum at $\sim 10^{-4}$ Torr in the twelve bellows guard regions of the torus vessel and is also instrumental in the leak testing of the bellows walls of the main vessel. The BPS is located with the TVPS backing system in the basement and shares the 1000 liter holding tank with that backing system. It has a 10 liter/sec mechanical pump, two zirconium aluminum canisters and an RGA unit, and the BPS is independent of the backing units for the diffusion pumps except for the valving to the HT.

Section 7 is a brief consideration of the changes in performance parameters which would result if the TVPS backing system was relocated from that location indicated in Fig. 4-3 to one directly under the TFTR device. The relocated system would be in the basement pit area associated with the plasma diagnostic equipment. Since the details of the diagnostic equipment were not available there was no attempt at providing an arrangement at this location as was done in Section 5.

To operate, control, service and maintain the TVPS requires a complex system of operating procedures which are discussed in detail in Section 8. The control system must provide both local and central control which allows for automatic and manual operations of a variety of procedures. Descriptions of the most important operations are provided. Included are details on the following: testing and maintenance, leak checking, startup and shutdown, non-tritium pulsing, tritium pulsing, bakeout in situ, and operations using faulted equipment. The main distinction, which must be made when considering these operations, is whether or not the TFTR

device has been exposed to tritium pulsing. A tritiated TFTR will limit various operations of the pumping system and will require the utilization of the zirconium aluminum getter units, the 1000 liter holding tank, and the tritium monitors. Any maintenance, even in the basement area, will be done only during very limited time periods. Since the TVPS is a large complex system providing a number of different services, a set of documents providing details and schedules on the operation and maintenance will be necessary for the TVPS before it is installed and put into operation.

Finally, Section 9 provides information on the estimated cost of the TVPS. The estimate of the cost of each major unit is given as well as on the valving and vacuum lines connecting these components. For the TVPS, without a bellows pumping system, the cost is estimated at \$811 k which is roughly the same as the estimated cost of the hardware on the conceptual TVPS. After adding the costs of the BPS (\$168 k), the control and instrumentation system (\$100 k), and spare parts (\$260 k), the total cost is \$1339 k. The major change in this estimate over that provided during the conceptual design is in the added costs of the BPS and of a larger inventory of spare parts.

In conclusion, the TFTR vacuum vessel will be evacuated and maintained at a base pressure in the 10^{-8} - 10^{-9} Torr range by the TVPS. This system is composed of four 61 cm diameter mercury diffusion pumps each with a two-trap stack and of a consolidated backing system located in the basement of the TFTR facility. None of the diffusion pumps are located on the neutral beam injection arms. The four high vacuum pumps have a total effective pumping speed for hydrogen of 20,000 liters/sec at the vacuum vessel. The TVPS is designed in detail based on a set of calculated performance parameters and on the features of flexibility and redundancy to accommodate both the maintenance and reliability of the system. The backing system is located apart from the plasma diagnostic area, but considerations were made on the assumption that this system could be located in the pit area below the device. The bellows guard regions on the main vessel are also evacuated and the units providing the pumping are described.

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