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THE VACUUM SYSTEM TRANSIENT SIMULATOR AND ITS APPLICATION TO TFTR*

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Summary

The vacuum system transient simulator (VSTS) models transient gas transport throughout complex networks of ducts, valves, traps, vacuum pumps, and other related vacuum system components. VSTS is capable of treating gas models of up to 10 species, for all flow regimes from pure molecular to continuum. Viscous interactions between species are considered as well as non-uniform temperature of a system. Although this program was specifically developed for use on the Tokamak Fusion Test Reactor (TFTR) project at Princeton, it is a generalized tool capable of handling a broad range of vacuum system problems.[1] During the TFTR engineering design phase, VSTS has been used in many applications. Two applications selected for presentation are:

- Torus vacuum pumping system performance between 400 Ci tritium pulses
- Tritium backstreaming to neutral beams during pulses

Introduction

A vacuum system network is represented as a matrix of pressure nodes. The nodes are beginning and end points for system components, with the connection between two nodes represented by the characteristic performance of a type of component. Components (or connections) may be pumps, ducts, valves, baffles, specific gas load sources, etc. Each type of connection is modeled by a particular subroutine in VSTS. As nodes are established and connected from the data inputs, their volumes and surface areas are determined based upon connection geometry. Both the volume and surface area of each connection are split equally and concentrated at each of the two end-point nodes. The final result is a matrix model where each pressure node contains a summation of all the half-volumes and half-surface areas of the adjacent components. Figure 1 shows a sample system and its equivalent nodal representation.

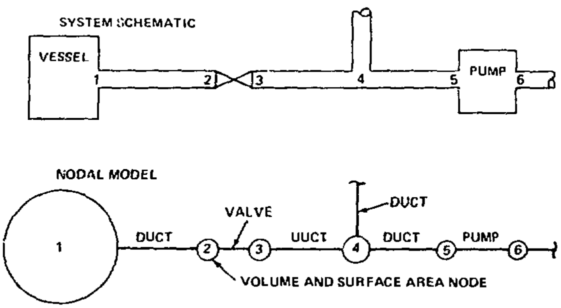

Fig. 1 Sample System with Nodal Representation

Over small time intervals the gas transport between nodes is assumed constant and determined from steady state conductance and pumping speed relationships. The applicable conductances or speeds of each connection are updated with the nodal pressures for finite time steps.

Analysis

Considering a simple system of two pressure nodes i and j, connected together by a device having a conductance C_{ij}, the throughput from i to j is

$$Q_{ij} = C_{ij}(P_i - P_j) \text{ torr}\cdot\text{l}\cdot\text{s}^{-1} \qquad (1)$$

where P is the nodal total pressure. Expansion of this relationship to the case of multiple nodes being connected to node i leads to a definition of net throughput out of node i as

$$Qnet_i = \sum_{j=1} C_{ij}(P_i - P_j), \text{ torr}\cdot\text{l}\cdot\text{s}^{-1} \qquad (2)$$

where the quantity $Qnet_i$ may be positive or negative. In a model system, the values of pressure for each of the nodes are continually changing, and therefore, $Qnet_i$ is also continually changing. However, considering a small enough interval Δt, and assuming that the net throughput does not change during Δt, the change in pressure of node i over Δt is approximated by

$$\Delta P_i = \frac{\left[q_o A_i + Qnet_i\right]\Delta t}{V_i} \text{ torr} \qquad (3)$$

where V_i is the volume of the node in liters, A_i is the internal surface area in cm^2, and q_o is the outgassing rate in torr·l·s^{-1} cm^{-2}.

For a single-specie, conductance is expressed as[2]

$$C = ZC_m + C_v \ \ \text{l}\cdot\text{s}^{-1} \qquad (4)$$

where C_v is the continuum flow contribution, C_m is the molecular flow contribution, and Z is an empirical correction factor which attempts to describe the slip region before transition flow. Z is found from

$$Z = \frac{1 + 2.507\ (r/La)}{1 + 3.095\ (r/La)} \qquad (5)$$

where r/La is the ratio of duct radius to the molecular mean free path.

In a multi-specie model, the throughput between nodes is determined separately for each specie. The methodology employed for multi-specie transport is an expansion of the single-gas conductance relationship for continuum and molecular contributions. The throughput

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equation contains two terms, the first for molecular contribution and the second is a weighted fraction of the total continuum flow contribution. Throughput is found for the k^{th} specie from

$$\left[Q_{ij}\right]_k = \left[ZC_m (p_i - p_j)\right]_k + f_k C_v (P_i - P_j) \ \text{torr}\cdot\text{l}\cdot\text{s}^{-1} \quad (6)$$

where p_i and p_j are the partial pressures for the specie, and P_i and P_j are the nodal total pressures. The continuum term weighting factor "f", is the ratio of specie average partial pressure to average total pressure. An important point is that while molecular contributions to throughput are independent for each specie between two common nodes, the continuum contributions are interdependent and in the same direction. For cases of non-uniform temperature, the room temperature pressure of a node is modified by a flux correction factor and equation 6 is expanded to consider nodes of different temperature as:

$$\left[Q_{ij}\right]_k = \left[ZC_m (p_i (T_i/293)^{1/2} - p_j (T_j/293)^{1/2}\right]_k + f_k C_v \left[P_i (T_i/293)^{1/2} - P_j (T_j/293)^{1/2}\right] \ \text{torr}\cdot\text{l}\cdot\text{s}^{-1} \quad (7)$$

Equation 7 is used to express the throughput of all non-pumping devices in VSTS. Pump throughput however, is considered to be independent of outlet pressure. If the conditions at the inlet of a pump are such that flow is completely molecular in nature, the pumping speed of each gas specie is determined separately from a pump performance table as a function of specie inlet partial pressure. The throughput for a pump is then [3]

$$\left[Q_{ij}\right]_k = \left[S_{ij}\ p_i\right]_k \sqrt{T_i/293} \ \text{torr}\cdot\text{l}\cdot\text{s}^{-1} \quad (8)$$

with T_i the pump inlet temperature, and S the pure specie pumping speed.

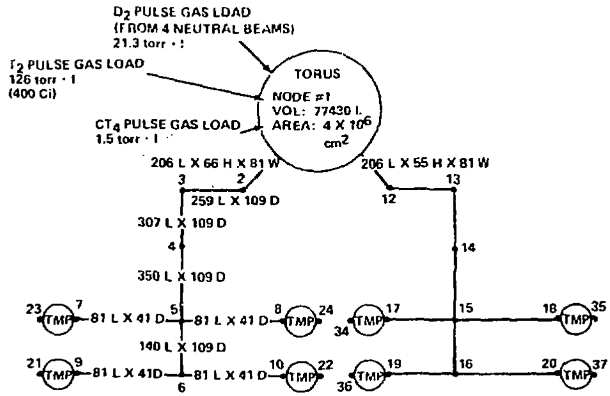
When the mean free path of any one specie at the pump inlet is less than the aperture dimension of the pump, the gas mixture is considered to have interdependent viscous effects. The pumping speed of the mixture is found from the pump performance table based upon an average bulk molecular weight and the individual specie speeds are determined by prorating the mixture speed as a function of specie mass fraction.

Applications to TFTR

Torus Vacuum Pumping System Performance Between 400 Ci Tritium Pulses

Figure 2 shows the schematic of the torus high vacuum pumping system model which uses eight turbomolecular pumps, each having a nitrogen pumping speed of 3500 l/sec. The discharges of the TMP's are manifolded together into two groups of four which are in turn connected to the main backing system duct. The backing system as shown schematically in Fig. 3, uses getter pumping during plasma discharges with tritium and mechanical/roots pumping during non-tritium discharges. The entire system as modeled in VSTS required 56 connections and 44 pressure nodes.

This model was used to estimate pumpdown time and getter backing system performance between tritium pulses. The present TFTR scenario calls for a full



BOTH PUMPING LEGS ARE IDENTICAL EXCEPT FOR THE RECTANGULAR CONNECTING DUCTS AT THE TORUS. TMP DISCHARGES ARE MANIFOLDED INTO THE BACKING SYSTEM OF FIGURE 3. DIMENSIONS ARE IN CM. VALVES ARE NOT SHOWN FOR CLARITY.

Fig. 2 Schematic of Torus High Vacuum Pumping System

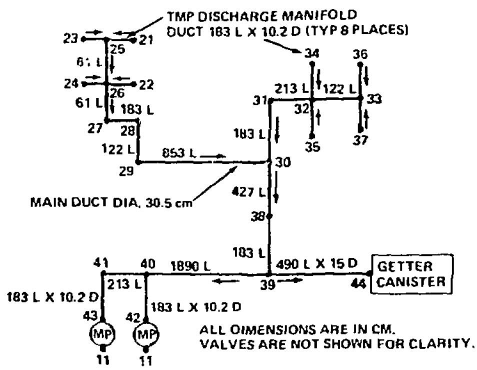


Fig. 3 Schematic of Backing System for 8 Torus TMPS

power D-T pulse every 300 seconds. The time between pulses is needed for torus gas evacuation and for clean-out of the backing system ducts. The manufacturer recommends that TMP backing pressures be kept below 0.08 torr at all times to minimize effects upon rotational speed and/or backstreaming to the torus.

The gas model for this simulation consisted of T_2, D_2, and CT_4, the latter representing hydrocarbon impurities. The pulse gas injection loads to the torus were 126 torr liters of tritium (400 Ci) and 21.3 torr liters of deuterium from 4 neutral beams, and the CT_4 load was scaled from PLT experience as 1% of all hydrogen isotopes (1.5 torr liters). Outgassing rates of T_2 and D_2 were conservatively estimated as 2×10^{-10} $\text{torr}\cdot\text{l}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ from experience with PLT and outgassing of CT_4 was estimated as 2×10^{-14} $\text{torr}\cdot\text{l}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$. The getter canister in the computer model contained 12 Westinghouse C500 (Zirconium-Aluminum) cartridges rated at 1400 l/s each, pure hydrogen pumping speed. The speed was mass corrected to estimate the pure pumping speeds of other species including CT_4. These speeds were then reduced to 1/3 to account for the assumed effect of the combined presence of other gases. The final values of getter pumping speed for the

12 cartridges are shown in the table below as used in the simulation.

Specie	Getter Pumping Speed $l \cdot s^{-1}$
D_2	3660
T_2	3200
CT_4	1620

Figure 4 presents the partial pressure profiles at three points within the vacuum system model from the simulation of the torus pumpout. These pressure points are the torus (node 1), the outlet of the TMP having the highest backing pressure of the eight TMP's (node 23), and the getter canister (node 44). Equilibrium pressures for T_2 and D_2 are re-achieved at the TMP outlets after about 260 and 180 seconds respectively. Equilibrium pressure is not achieved for CT_4, however, better than 99% of this specie is removed from the backing system between pulses. If the assumed getter pumping speeds for CT_4 are actually achieved, this residual will washout in successive pumpdowns between pulses and will not lead to a background pressure buildup. A peak total TMP pressure of 0.022 torr is attained about 3 seconds after the pulse. The torus reaches equilibrium about 120 seconds after the pulse, resulting in a total pressure of 1.6×10^{-7} torr.

Unless a reliable cracking process for CT_4 is achieved, the getters will not pump this specie. In view of this possibility, analysis of the backing system performance was considered using zero getter pumping speed for CT_4 to determine peak TMP backing pressure. At the start of this transient, it was assumed that an evenly distributed background partial pressure of 4.4×10^{-2} torr for CT_4 existed throughout the backing system. This partial pressure would be achieved after the planned cycle of 100 tritium pulses using a residual gas buildup for CT_4 of 1.5 torr liters per pulse. Figure 5 shows the first 6 seconds of this transient, the period within which the peak total TMP backing pressure of 5.5×10^{-2} torr is achieved. This pressure is less than one might expect due to the viscous sweeping effect the surge of T_2 and D_2 in the backing system has upon the CT_4. This effect is illustrated in the figure by a local decrease in CT_4 pressure at the TMP outlets and a corresponding increase in CT_4 pressure in the getter canister.

Results of This Application:

1. If the getter pumping speeds equivalent to 1/3 the Westinghouse C500 cartridge are obtained in a mixed gas environment, TMP backing pressures and line evacuation between pulses will surpass requirements. Peak TMP backing pressure is 2.2×10^{-2} torr.
2. If getter pumping for CT_4 is zero, the volume of the backing system ducts is large enough to contain a background partial pressure buildup of CT_4 from 100 successive pulses. The peak TMP backing pressure will increase to 5.5×10^{-2} torr but is still below the recommended value of 8×10^{-2} torr.
3. About 260 seconds between pulses is needed to evacuate the hydrogen isotopes from the backing system ducts while the torus is easily evacuated in about 120 seconds. The total time of 300 seconds between pulses is therefore reasonable.

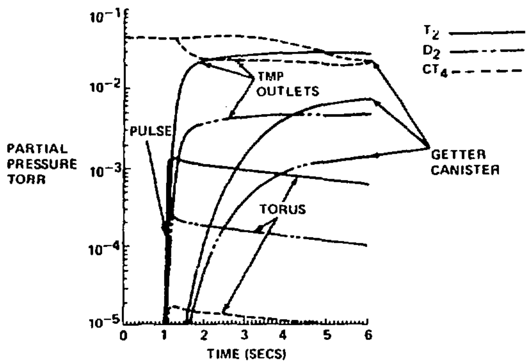


Fig. 5 Initial TVPS Transient with CT_4 Background from 100 Preceding Pulses

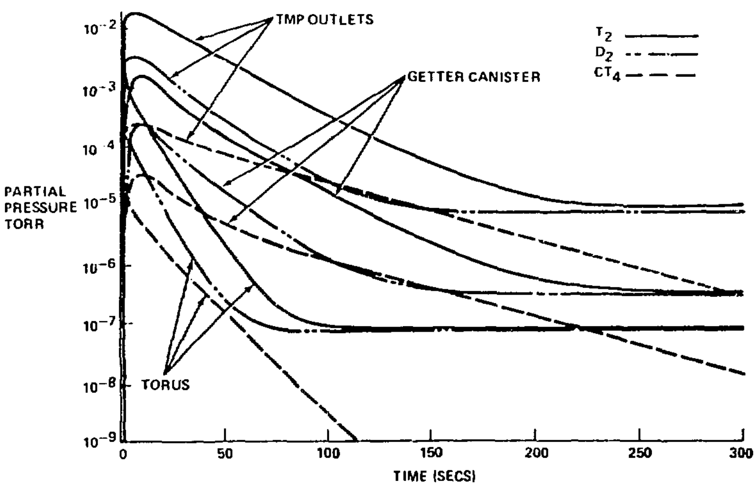


Fig. 4 Torus Vacuum Pumping System Performance Between 400 Ci Tritium Pulses

Tritium Backstreaming to Neutral Beams During Pulsed Operation

VSTS was used to evaluate vacuum system performance of a three chamber neutral beam model (Fig. 6) during pulsed operation to determine the amount of tritium backstreaming. Backstreamed tritium is pumped on the beam chamber cyropanels and is of concern due to the buildup of radioactive inventory after numerous beam pulses. The amount of backstreaming is related to the rate at which the fast shutter valve can open or close, and the ability to contain the plasma for a period after the beam pulse. This study considered fast shutter valve open/close rates from 50 ms to 200 ms. These valve rates were used for each of three plasma containment scenarios. The first scenario assumed the plasma would be contained for a period after the beam pulse long enough for the shutter valve to close. The second scenario assumed that the plasma could not be contained beyond the end of the neutral beam injection pulse, while the third assumed a plasma disruption occurred at the end of the beam injection pulse. The total quantity of tritium backstreamed into a single neutral beam for the three scenarios is shown in Table I for different fast shutter valve rates.

If more than one neutral beam were actively employed, the backstreaming values per beam will be lower than those shown in the table for the disruption and short containment cases. This is due to a more rapid decrease in the torus particle density with more than one beam.

Table I T_2 Backstreamed for a Single Beam (Ci/Pulse)

VALVE RATE (ms)	LONG CONTAINMENT	SHORT CONTAINMENT	DISRUPTION
50	1.68	9.4	92.6
100	2.06	42.5	168
150	2.14	64.7	186
200	2.25	67.0	190

The study was conducted by setting up an operational scenario in the computer model spanning a total elapsed time of 1.1 sec. The scenario was keyed to the torus/neutral beam interface performance as shown in Fig. 7. This interface is the area outside the plasma as seen by the vacuum system. A model of this interface is required to predict vacuum system performance during the compression, containment, and expansion phases of the plasma. The scenario consists of a torus prefill phase where tritium pressure is increased from the base value to a maximum of 10^{-4} torr over a 50 ms period. Following the prefill, the gas is compressed and a plasma is initiated resulting in a density decrease and temperature increase at the interface. An advantage of this simulator over previous approaches is that

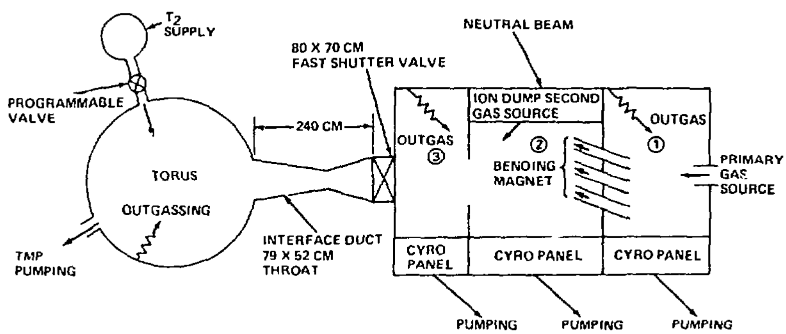


Fig. 6 Torus/Neutral Beam Computer Model

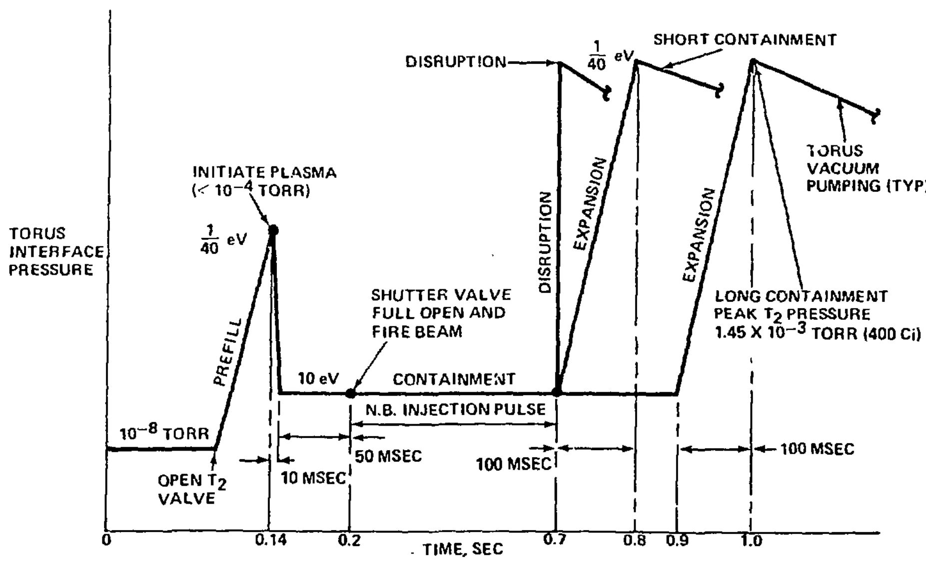


Fig. 7 Torus/Neutral Beam Operational Scenario

it can account for non-uniform temperature in a system as well as specie interactions.[4] The compression is assumed to take 10 ms and is followed by the containment phase where the temperature and pressure are held constant at 113,000°K (10eV) and 2×10^{-6} torr, respectively. The final phase of the scenario is the expansion of the plasma to fill the torus volume. During the expansion, the gas particles return to a temperature of 293°K. The expansion phase for the long and short containment scenarios is assumed to take about 100 ms, after which the interface tritium pressure reaches its peak value. For the case of the plasma disruption, the expansion phase is modified as follows: temperature decreases over a 100 ms period while pressure increases abruptly in 1 ms.[5]

In this paper only one sample simulation is shown, for a 100 ms fast valve rate with the short plasma containment scenario. Figure 8 presents the partial pressure responses of the torus plasma interface and the neutral beam chambers. During the period from 0.2 to 0.7 seconds chamber pressures are relatively constant during beam injection and plasma containment. After beam injection and while the plasma is expanding a surge in tritium pressure is experienced in all chambers. Figure 9 shows that about 94% of the backstreaming occurs during the plasma expansion phase, and furthermore if it can be contained sufficiently long, the entire throughput spike disappears.

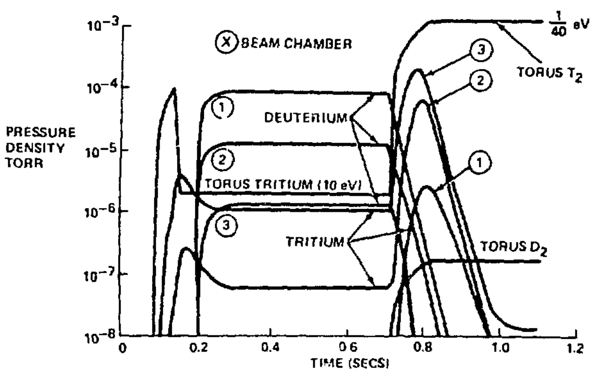


Fig. 8 Partial Pressures During Neutral Beam Pulse, Short Plasma Containment and 100 ms Valve

Results of This Application:

1. Based upon expected plasma performance, a fast valve rate as slow as 200 ms would be permissible. However, in view of the uncertainty of plasma containment times, a faster valve rate is desirable. On the other hand, practical design considerations indicate that 100 ms may be difficult to achieve.

2. With short plasma containment times a 100 ms valve rate, and 4 neutral beams, tritium operation would be limited to about 1 hour by the need to shutdown and regenerate the beam cryopanels. This estimate is based upon the use of 42.5 Ci/Beam/Pulse from Table 1.

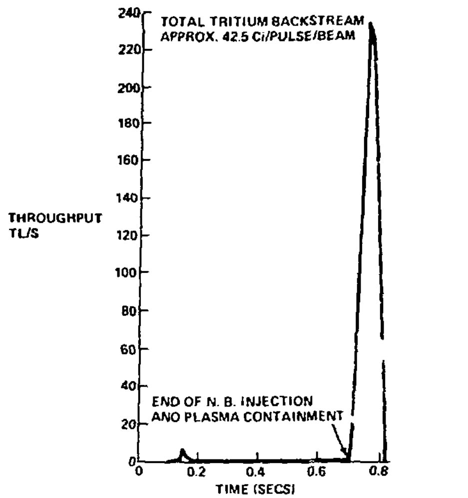


Fig. 9 Tritium Backstreaming Profile for Neutral Beam Pulse of Figure 8

3. Virtually all the tritium in the torus would be pumped by the beam cryopanels in a fraction of a second if a disruption occurred.

Conclusion

A generalized vacuum system transient simulator has been developed which can handle gas models with up to 10 species and systems with as many as 500 connections. This capability is required to analyze the complex transients that occur in TFTR neutral beam internal and external vacuum systems, torus high vacuum and backing systems, and diagnostics, both during and between plasma discharges. For the purpose of demonstrating simulator capability, two practical applications to TFTR have been presented and discussed.

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