Table 1 **Propellant residuals using helium pressurant**

Temperature differential fuel-ox., °F	RCS usage, %	RCS mixture ratio shift	Propellant residuals, % of total load
0	0	0	0.8
+20	0	0	1.5
−20	0	0	0.3
0	50	0	0.4
0	50	−0.2	1.6

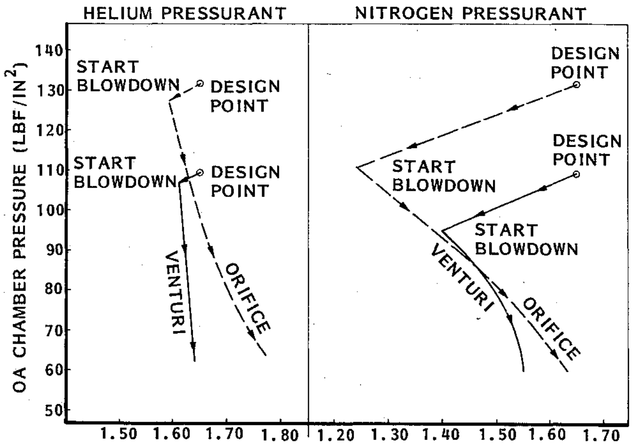

Fig. 3 **Orbit adjust thruster performance requirements.**

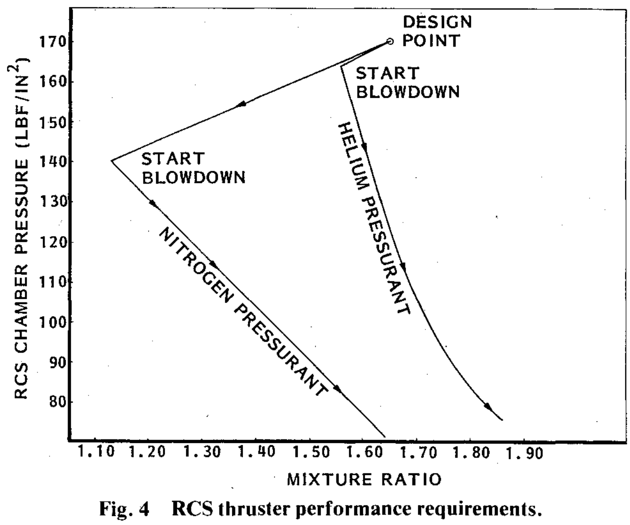

Fig. 4 **RCS thruster performance requirements.**

helium as the pressurant greatly reduces the total variation. Use of a venturi minimizes the required operating range for both thrust and mixture ratio. Figure 4 shows the corresponding RCS thruster performance map for a case where the RCS uses 50% of the total propellant. Of course, the required operating range can be shifted somewhat from that shown on these plots by varying the initial propellant loads or pressures, but the helium system still exhibits less variability and less sensitivity to changes in the operating environment. Table 1 summarizes the propellant residuals which resulted from various runs involving tank temperature differentials, RCS usage, and RCS mixture ratio shifts due to pulsing; use of helium appears to offer acceptable values. The blowdown system is also self-regulating to some extent in that a higher flow from one tank will cause a more rapid pressure decay which will bring the system back toward its design point mixture ratio. This feature minimizes the residuals in one tank when propellant depletion and gas ingestion occur in the other.

Conclusions

The feasibility of a bipropellant blowdown system depends on the ability of the engines to run stably and with proper thermal control over a range of feed pressures and mixture ratios. Detailed system studies or development would consider the question of combustion and feed system stability, especially at the low pressures in the latter portion of the blowdown. Performance evaluation would also include the efect of off-design conditions on combustion efficiency. However, a simple system using passive surface tension propellant management appears to be feasible in terms of propellant residuals and compatibility with demonstrated or expected engine capabilities. Helium as the pressurant is probably mandatory, and venturi flow control for large orbit adjust thrusters is suggested.

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Evacuation of a Spacelab Experiment Chamber Through the Venting Line

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Introduction

An onboard spacelab vacuum facility is required to support the many needs of experiments. The current engineering requirements related to the operating vent pressure ranges from about 1 to 10^{-6} mbar. For experiment evacuation the standard venting line (inner diameter 55 mm, stretched length up to 8 m) has to be used, which connects the experiment chamber with the outlet butterfly valve.[1] The ultimate pressure achievable is determined by the tube dimension and the outgassing of the inner tube wall. For lower pressures, an auxiliary pump will be required, operating with the venting line as a "forepump" tube.[2] Because power

Presented as Paper 78-1605 at the AIAA/IES/ASTM 10th Space Simulation Conference, Bethesda, Md., Oct. 16-18, 1978; submitted Jan. 3, 1979; revision received Nov. 19, 1979.

Index categories: Nozzle and Channel Flow; Rarefield Flows; Space Processing.

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is a critical resource, the operating time of such a pump has to be minimized. To attain a suitable application of the vacuum system, the properties of the venting line must be known. In this paper, analytical and experimental results for a long tube are presented for both the viscous and molecular flow.

Viscous Flow Range

For a first approach, the venting line is assumed to be a straight cylindrical tube of length L. The appropriate equations for steady, adiabatic one-dimensional flow in a tube of constant diameter d are[3]:

Energy:

$$\frac{dT}{T}+\frac{\gamma-1}{2}M^2\frac{dc^2}{c^2}=0 \tag{1}$$

Continuity:

$$\frac{d\rho}{\rho}+\frac{1}{2}\frac{dc^2}{c^2}=0 \tag{2}$$

Momentum:

$$\Delta p+(4/d)\tau_w\Delta x+c\rho\Delta c=0 \tag{3}$$

It can be seen that the Mach number M tends to unity along the flow direction. For the venting line, $p_s\sim 0$; therefore, $M_L=1$. With the friction factor λ assumed to be constant, it follows from Eqs. (1-3) that

$$\lambda\frac{L}{d}=g_1(M_0)=\frac{1-M_0^2}{\gamma M_0^2}+\frac{\gamma+1}{2\gamma}\ln\frac{(\gamma+1)M_0^2}{2(1+[(\gamma-1)/2]M_0^2)} \tag{4}$$

The subscripts 0, L, and c denote the state at $x=0$, $x=L$, and inside the chamber, respectively. For isentropic flow between the chamber and the tube entrance $x=0$, the following relation is found:

$$\frac{\dot{m}\sqrt{RT_c}}{d^2(\pi/4)p_c}=g_2(M_0)=\sqrt{\gamma}M_0\left[\left(1+\frac{\gamma-1}{2}M_0^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}\right]^{-1} \tag{5}$$

The relations for $\lambda(Re)$ are then introduced.

For laminar flow:

$$\lambda=64/Re \qquad Re<2300 \tag{6}$$

For turbulent flow (Blasius formula for smooth pipes)[4]:

$$\lambda=0.316Re^{-1/4} \qquad 10^4>Re>4.10^3 \tag{7}$$

For $(p_c\dot{V})$-flux and pumping speed S_c, the following relations can be obtained.

Laminar flow:

$$\frac{p_c\dot{V}}{d}=16\pi\nu RT_c\frac{L}{d}\frac{1}{g_1(M_0)} \tag{8a}$$

$$\frac{S_c}{d^2\pi/4}=\sqrt{RT_c}g_2(M_0) \tag{8b}$$

$$dp_c=\frac{\nu\sqrt{RT_c}}{d/L}\cdot\frac{64}{g_1(M_0)g_2(M_0)} \tag{8c}$$

Turbulent flow:

$$\frac{p_c\dot{V}}{d}=\frac{\pi}{4}\nu RT_c\left(\frac{0.316}{g_1(M_0)}\frac{L}{d}\right)^4 \tag{9a}$$

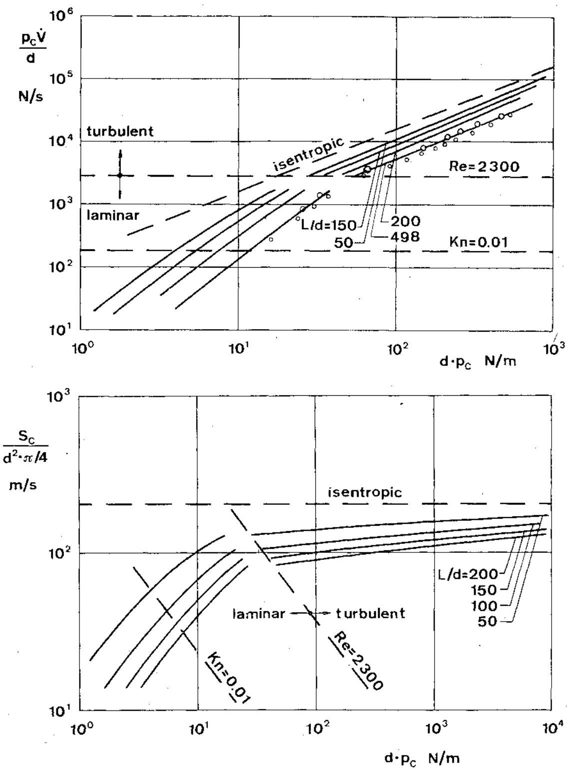

Fig. 1 Throughput and pumping speed according to Eqs. (8) and (9) for nitrogen at $T_c=298$ K and in comparison with experimental results for $L/d=498$.

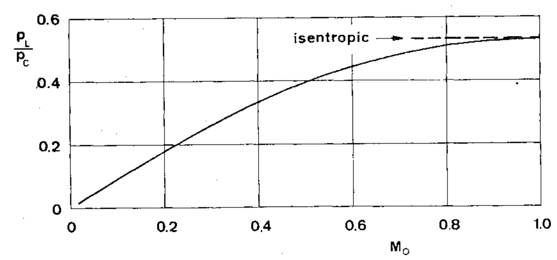

Fig. 2 Pressure ratio p_L/p_c vs M_0 required to achieve $M_L=1$.

$$\frac{S_c}{d^2\pi/4}=\sqrt{RT_c}g_2(M_0) \tag{9b}$$

$$dp_c=\nu\sqrt{RT_c}\frac{1}{g_2(M_0)}\left(\frac{0.316}{g_1(M_0)}\frac{L}{d}\right)^4 \tag{9c}$$

The pressure ratio p_L/p_c is given by

$$p_L/p_c=\sqrt{2/\gamma(\gamma+1)}g_2(M_0) \tag{10}$$

The upper limit of the laminar flow range follows from $g_1(M_0)=64\,L/2300\,d$. There is also a lower limit, determined by the slip flow condition, which becomes important for Knudsen numbers $>10^{-2}$.[5,6]

Figure 1 shows solutions of Eqs. (8) and (9) for nitrogen at $T_c=298$ K and various L/d-ratios. With increasing pressure p_c, the deviation from the isentropic flow curves diminishes. The pressure ratio p_L/p_c required to achieve $M_L=1$ is depicted in Fig. 2. For $M_0=1$, p_L/p_c is equal to the value for isentropic flow. For small values of M_0 a considerable p_L/p_c ratio is required to achieve $M_L=1$. Experimental investigations have been performed for a tube with 6.06 mm inner diameter, 3.019 m length, smooth inner tube surface and well-rounded entrance. Figure 1 shows the results in comparison with the theoretical curve. There is a good agreement in both the turbulent and laminar range.

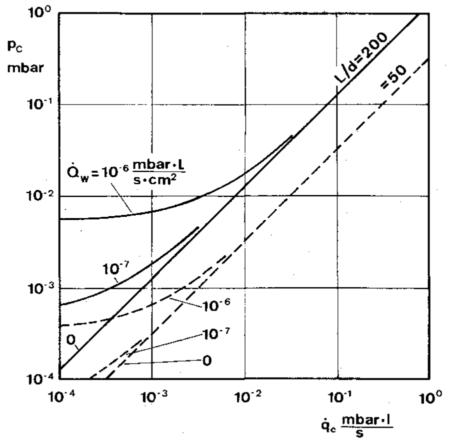

Fig. 3 Pressure p_c for air ($T_c = 298$ K) and $d = 38$ mm.

Molecular Flow Range

To calculate the pumping speed, throughput, and ultimate pressure in the range of molecular flow, an analysis has to be performed regarding the outgassing of the tube wall. For this purpose, the outgassing quantity, as well as its composition normally differing from the gas inside the vacuum chamber, must be known. For steady state, the mass balance gives for each gas component

$$\frac{\mathrm{d}^2 p}{\mathrm{d}x^2} = -\frac{4\dot{Q}_W}{d\bar{\alpha}G_0} \tag{11}$$

The boundary conditions are

$x=0$:

$$\frac{\mathrm{d}p}{\mathrm{d}x} = -\frac{\dot{q}_c}{d^2(\pi/4)G_0\bar{\alpha}} \qquad \dot{q}_c = \dot{q}(x=0) \tag{12}$$

$x=L$:

$$\frac{\mathrm{d}p}{\mathrm{d}x} = -\frac{1}{\bar{\alpha}}(p-p_s) \tag{13}$$

Here, p is the partial pressure, G_0 the orifice conductance per unit area, $\dot{Q}_W$ the outgassing rate per unit area, and $\bar{\alpha}$ the transmission probability per unit length. Equation (13) is based on the simplification of a Maxwell distribution at $x=L$. The beaming effet has been neglected.[7]

Further, it is assumed that there are two different gases—the chamber gas (index C) and the product of tube wall outgassing (index W). It follows from Eqs. (11-13) for the overall transmission probability $\alpha = G/G_{0c}d^2(\pi/4)$ when $\bar{\alpha} = (4/3)d$, that

$$\alpha = \left[1 + \frac{3}{4}\frac{L}{d} + 4\frac{\dot{Q}_W}{\dot{q}_c/d^2(\pi/4)}\sqrt{\frac{M_W}{M_c}}\frac{L}{d}\left(1 + \frac{3}{8}\frac{L}{d}\right)\right]^{-1} \tag{14}$$

Due to the fact that $\dot{Q}_W$ can vary over a wide range when changing tube wall conditions, only rough estimations of α for practical applications can be obtained.

The relations for pumping speed S_c and pressure p_c achievable inside the chamber are

$$S_c = \alpha G_{0c} d^2 (\pi/4)(1 - p_s/p_c) \tag{15}$$

$$p_c = \frac{\dot{q}_c}{\alpha G_{0c} d^2 \pi/4} \tag{16}$$

Because $p_s/p_c \ll 1$, the pumping speed is proportional to the transmission probability. In Fig. 3, p_c is plotted vs $\dot{q}_c$ for various lengths and outgassing rates and the diameter $d = 38$ mm. This case, close to that expected for the venting line, gives an overview of working pressures achievable in the vacuum chamber.

Conclusions

From these studies, the flow parameters of the Spacelab venting line in the viscous and free molecular flow ranges can be calculated for each line configuration. For the transition flow range (Knudsen numbers between 0.01 and 3) an extrapolation of these results can be made. In addition to the parameters for steady state discussed here, the evacuation time must be known in order to estimate the total experiment duration. In contrast to normal vacuum applications, the tube volume is of the same order of magnitude as the chamber volume; therefore, the analysis leads to a boundary value problem. A relation for the time constant applicable for free molecular flow is given by S.A. Schaaf and R.R. Cyr.[8]

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