

Spacecraft compartment venting

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ABSTRACT

At various times, concerns have been expressed that rapid decompressions of compartments of gas pockets and thermal blankets during spacecraft launches may have caused pressure differentials across their walls sufficient to cause minor structural failures, separations of adhesively-joined parts, ballooning, and flapping of blankets.

This paper presents a close form equation expressing the expected pressure differentials across the walls of a compartment as a function of the external to the volume pressure drops, the pressure at which the rates occur and the vent capability of the compartment. The pressure profiles measured inside the shrouds of several spacecraft propelled by several vehicles and some profiles obtained from ground vacuum systems have been included. The equation can be used to design the appropriate vent, which will preclude excessive pressure differentials. Precautions and needed approaches for the evaluations of the expected pressures have been indicated. Methods to make a rapid assessment of the response of the compartment to rapid external pressure drops have been discussed. These are based on the evaluation of the compartment vent flow conductance, the volume and the length of time during which the rapid pressure drop occurs.

Keywords: spacecraft launch, compartment venting, contamination control

1. INTRODUCTION

Concerns have been expressed at various times that rapid decompression of certain volumes or of gas pockets during spacecraft launch may have resulted in pressure differentials across walls sufficient to cause minor structural failures and loss of adhesion between parts.¹ It has often been speculated that honeycomb structures not properly vented, with their sealing faces improperly adhesively attached, may have caused damage of elements attached on those surfaces. For example, solar cells may have been damaged during the rapid change of spacecraft external pressure. Ballooning of multilayer blankets and foams are also expected to occur. The rapid environmental pressure changes occur during the transonic region of flight, which happens within a few seconds after launch. The time and the intensity of the rate of pressure change depend on the spacecraft weight and the propulsion employed to launch it. The purpose of this paper is to review the parameters characterizing the magnitude of the pressure gradients produced across the walls of a compartment during the rapid external changes of pressure. Those parameters expressed in a closed form equation, given the data on a semisealed volume, its venting conductance and the external pressure parameters, can provide estimates of the expected pressure differentials across the volume walls. It provides data to design a system which will be structurally safe during the expected launch rapid pressure drop. In this respect, data of pressure measurements obtained during launch in the shrouds of many spacecraft will be included in this paper. Pressure profiles obtained with certain ground vacuum facilities utilized for the testing of compartment and systems for rapid decompressions will be also included.

2. ANALYSIS

The pressure differential ΔP between the internal pressure of a volume V and the external pressure P_∞ decaying at a rate dp/dt can be obtained as follows:^{2,3}

The conservation of mass for the gas inside the volume at density ρ exiting the volume V via an orifice of area A with a coefficient C and discharging at velocity v is $d(\rho V)/dt = \rho v AC$. The density in terms of pressure and temperature from the gas law is $\rho = P/RT$ and its derivative is $dp/dt = 1/RT dp/dt$ for isothermal conditions and constant temperature. The flow velocity from the conservation of kinetic and potential energy is $v = \sqrt{2gh}$ which for $h = \Delta P/\rho = \Delta P RT/P$, can be written as $v = \sqrt{2gRT\Delta P/P}$. The substitution of these in the mass flow is then $dp/dt = AC\rho/V \sqrt{2gRT\Delta P/P}$ or solved for the pressure

differential, one gets $\Delta P = 1/2 gRT(V/AC)^2 (dp/dt)^2/P_o$. In these equations, $g = 9.81 \text{ m/s}^2$, is the acceleration of gravity, $R = 29.2 \text{ m/K}$ is the gas constant for air, $T(K)$ is the temperature, $C \sim 0.65$ is the orifice discharge coefficient and P_o is the pressure at which the rapid change of pressure occurs. This shows that the pressure created in the volume is higher than the external pressure and is a direct function of the square of the external pressure drop rate, of the square of the ratio of the volume to the venting area and it varies inversely with the pressure P_o at which the maximum drop rate occurs.

Figure 1 shows a plot of the differential pressures ΔP across a volume V with a venting orifice A obtained when the external pressure is P_o and is changing at a rate of dp/dt . The plot reflects a base pressure of $P_o = 6 \text{ psi}$, temperature of $T = 298K$ and an orifice discharge coefficient of $C = 0.65$. The other constants for the calculation are $g = 980\text{cm/s}^2$ and $R = 29.2 \text{ m/K}$. The reason for the indicated rates of pressure drop will be apparent by the experimental data to be discussed later. The values of ΔP can be easily obtained for any other dp/dt and orifice coefficient. The dependence of ΔP on the rate, on the pressure P_o , and on the effective discharge area (CA) can be seen by the plot and with reference to the above equation. For a system of volumes in parallel or in series, the pressure gradient evaluation for one of the volumes will require the evaluation of an equivalent orifice or conductance which reflects the other volumes and passages leading to the external pressure in the environment. The choice of the external pressure rate (dp/dt) and the base pressure (P_o) reflects the experimental data on those parameters as shown in figures 2 and 3.

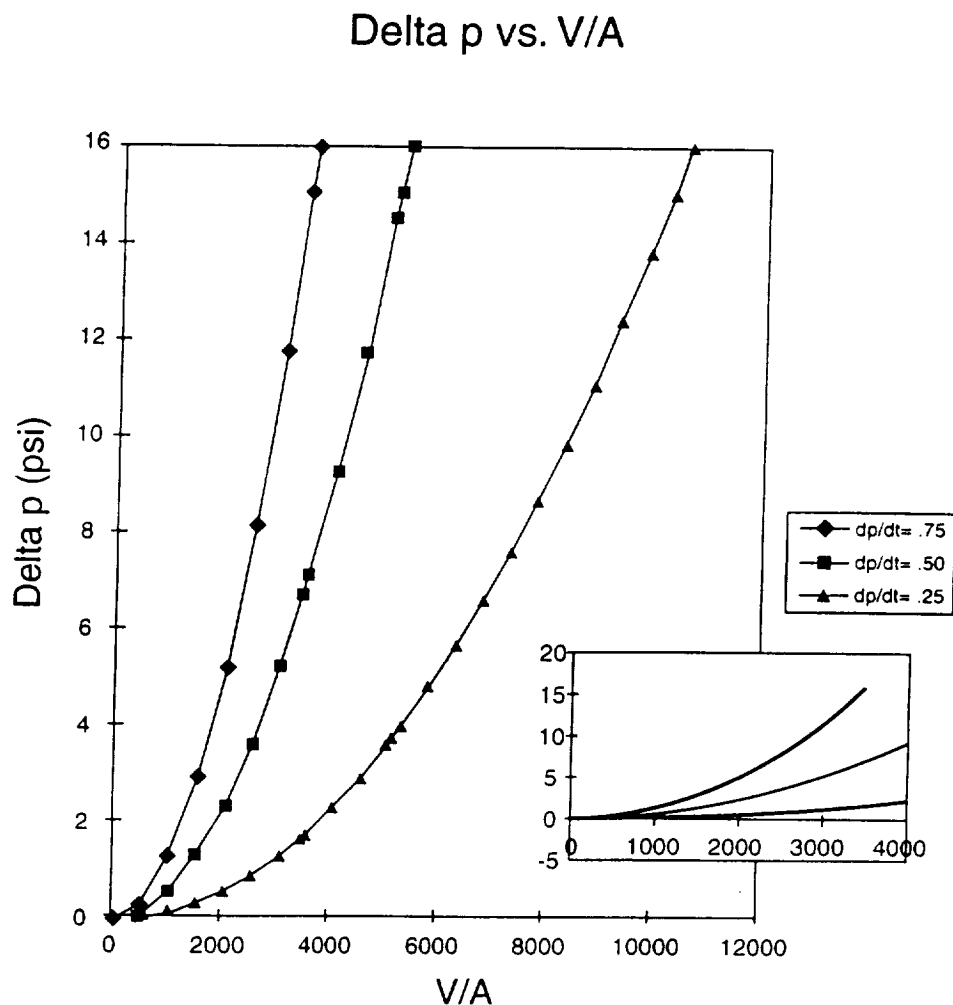


Figure 1. Differential pressure (delta p) between a volume V with a venting orifice A and external pressure, P_o (psi) changing at a rate of dp/dt (psi/s). The plot reflects a base pressure of $P_o = 6\text{psi}$, temperature $T = 298 \text{ K}$ and and orifice discharge coefficient $C_o = .65$.

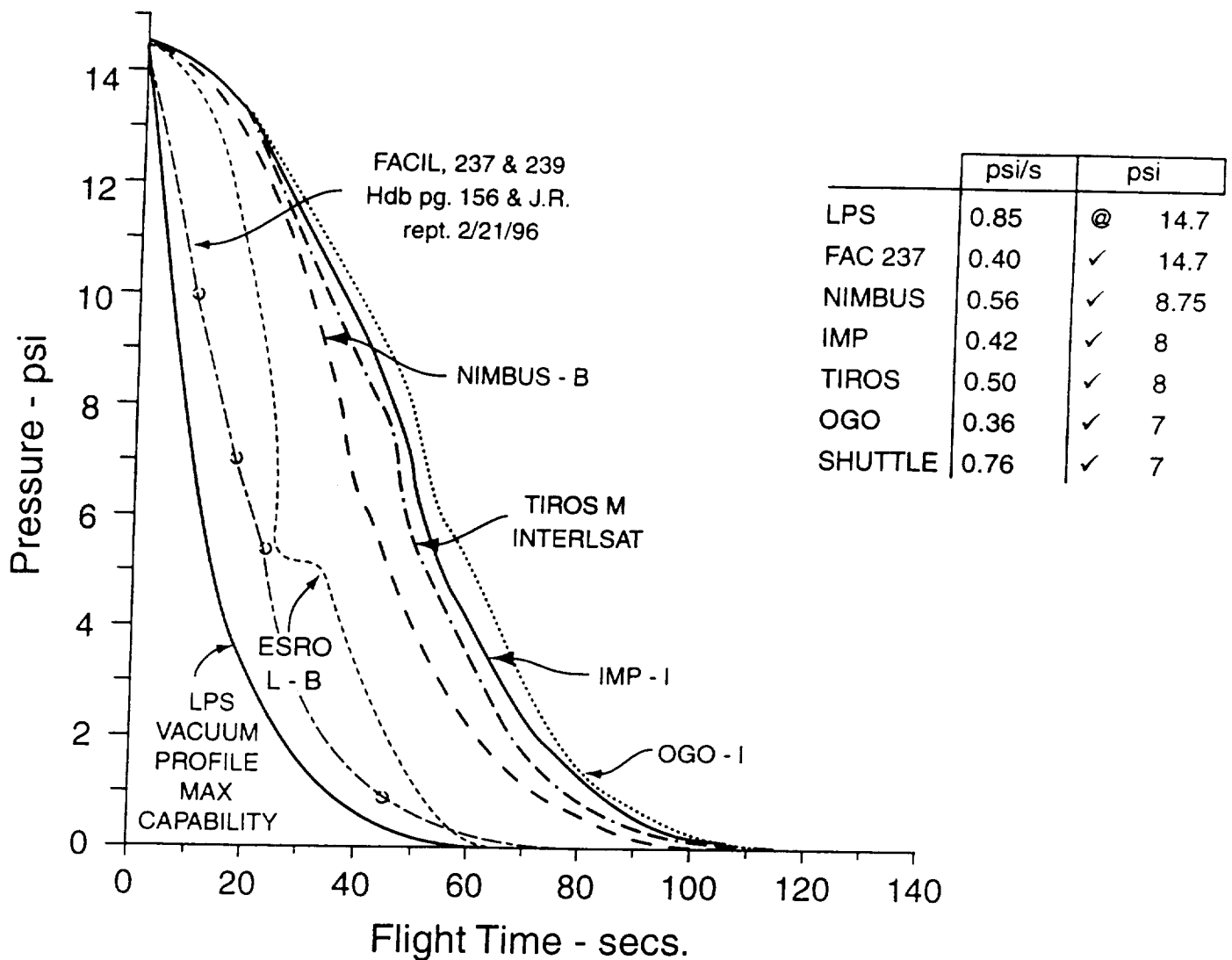


Figure 2. Payload fairing internal pressure history and LPS maximum pressure profile capability.

Figure 2 shows the pressures and their rates measured inside the fairing of several spacecraft during their launch. The measurements made by members of the Dynamic Branch of the then Test and Evaluation Division of GSFC during the 1960-75 period, show that the maximum rates occurred at different times into the launch and they were different for different spacecraft and by inference different launch vehicle. The maximum rate occurs when the base pressure P_0 is between 8 and 6 psi. It is also known that the maximum rate occurs during the transonic region of the flight. For convenience, the maximum rates as estimated from the profiles have been listed in the plot. The maximum pressure profile of the no longer available facility, the launch phase simulator (LPS) is indicated for completeness and reference. The profiles of two Goddard facilities employed for the rapid venting are shown. Figures 3 and 4 show the expected orbiter internal pressure history during ascent as a function of lift-off time and cargo bay design pressure.⁴ The maximum rate dp/dt in the orbiter cargo bay is indicated to be 0.75 psi/s and to occur 40 seconds after lift off. Those values are suggested for the design of orbiter payloads venting.

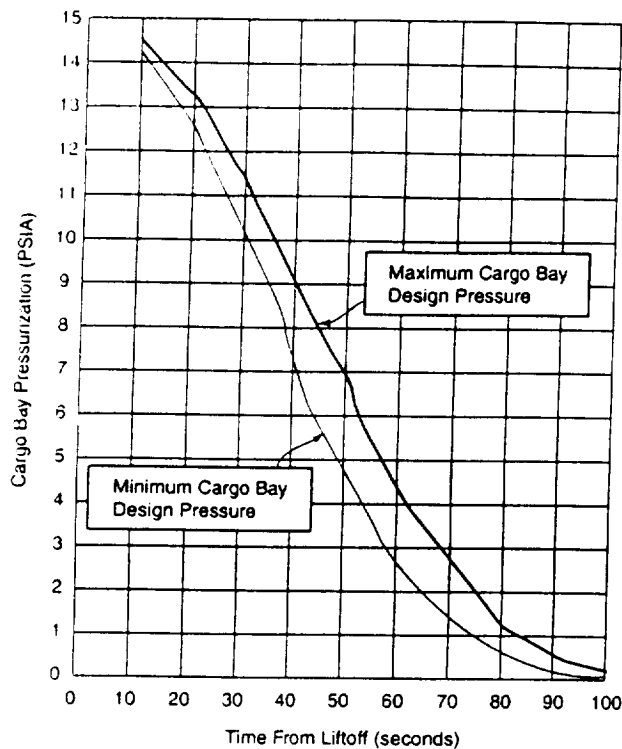


Figure 3. Orbiter cargo element internal pressure history during ascent.

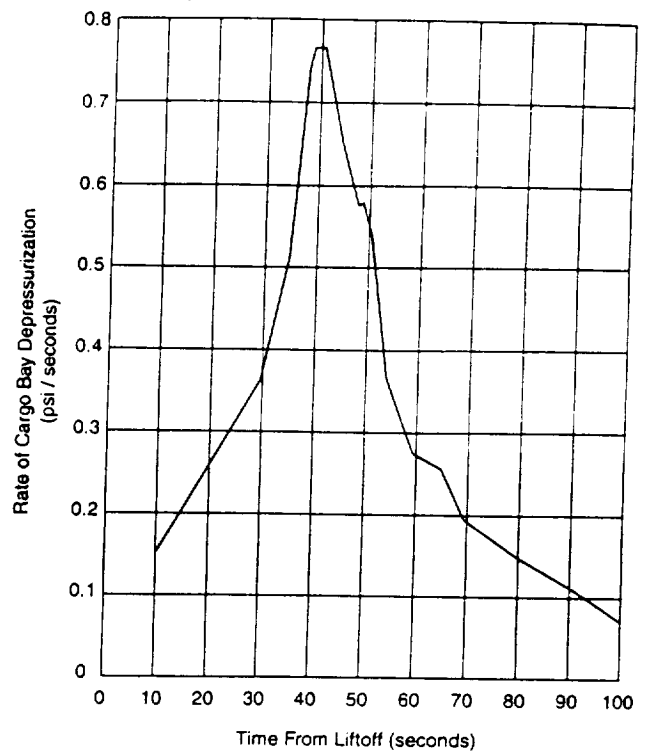


Figure 4. Maximum cargo bay pressure decay rate during ascent.

3. DISCUSSION

The close form equation for ΔP can be used to verify the pressure differentials created across the walls of a volume of a spacecraft when the volume, the vent passage and the rate of external pressure produced by the launch vehicle are known. Or, the equation indicates the venting (product of the vent area and the discharge coefficient or the equivalent orifice) required to limit the pressure differentials. A large volume with a small vent may experience a large pressure differential which could cause structural damages to systems mounted in or above the volume in question. On the other end, the pressure in a volume with a large venting area will follow the rapidly decaying external pressure without the creation of an over pressure with respect to the outside. This implies that the volume-vent system must have a response time (the time to drop to $1/e$ of initial pressure) comparable to the time during which the rapid pressure change occurs. As shown by figures 2 and 3, the duration of the rapid pressure change is of the order of 5 seconds. The response time of the volume system should be of this length or shorter.

As indicated in the derivation of the venting equation, the flow exit velocity for small differential pressures is a square root function of the pressure differential across the exit passage. It is not a constant sonic velocity as occurs at an orifice operating under choked flow pressure conditions. Choked condition occurs when the downstream pressure is less than 0.53 of the upstream pressure. A derivation of the time constant for the nonchoked condition must include several factors which would make the comparison between the system and external response time complicated. One approach may be to estimate the sonic flow time constant of the system and then modify it for the continuum nonlinear time response of the system. The venting time constant of a volume V , (ℓ) with the conductance S (ℓ/s) in the molecular flow region is $\tau = V/S$ (s). The venting of a volume from a pressure P_i to a pressure $P < P_i$ as a function of time is $P = P_i \exp(-S/Vt)$. The conductance $S \sim C \sqrt{A}$ (ℓ/s) includes the geometrical form of the vent passage, the velocity of the molecule and the effective vent area. The conductance can be easily found from kinetic theory and is available in books on vacuum technology. For example, for air at normal temperature exiting an orifice of area A (cm^2), the conductance in the sonic flow region is $S = 20 A \ell/s$. Conductance for

short, long pipes of different shapes are also indicated. It is then possible to obtain readily a system time constant $\tau_s = V/S$. The time constant with $S = 20A$ is for a sonic flow velocity which is $v = \sqrt{2gRT/\gamma + 1} = 18.3 \sqrt{T} = 313.2 \text{ m/s}$ for air at normal temperature. For the conditions being considered, with a pressure differential of about 2 psi at a pressure of about 6 psi, the flow velocity $v = \sqrt{2gRT\Delta P/P} = 409.7 \sqrt{\Delta P/P} = 253 \text{ m/s}$. The time constant for the system under consideration is then $\tau = 313.2/253$ ($\tau_s = 1.34 \tau_s$). This is the time to be compared to the time $t \approx 5 \text{ s}$ corresponding to the rapid ambient pressure drop and used to evaluate the system response. If $\tau > t$, the venting A should be increased. With regard to the testing of a system in a rapid evacuating chamber, the pressure profile provided in the chamber with the system under test should produce not only the proper pressure drop rate but the maximum rate must occur at about the proper base pressure. Some of the vacuum chamber's profiles plotted in figure 3 provide the proper pressure rates, but those maximum rates occur at base pressures P_0 generally higher than the normal 8 to 6 psi experienced during launch. This should be noted in the evaluation of ΔP and accounted for its effect.

4. CONCLUSIONS

The pressure differentials created across the wall of a compartment can be minimized by the proper venting. The flow conductance of the compartment vent in conjunction with the compartment size must have a pressure response time comparable to the compartment rapid drop of pressure. The compartment internal pressure must respond almost simultaneously to external pressure change.

The developed closed form equation provides a direct method to design the vent size to reduce the magnitude of the differential pressure. It can be used to verify the performance of an existing compartment-vent system. A simple rule for the evaluation of the compartment response has been indicated. It suggests to evaluate the time constant for a volume orifice system in the sonic flow region, increase that time by about 1.5–2.0 times and compare that time to the 5–6 seconds duration of the external pressure change. The two should be nearly the same. Experimental data on several pressure profiles produced by ground vacuum systems and measured during launch flight in the shroud of several spacecraft have been included to provide data on pressure rates and times of pressure excursion's. Those profiles provide data for a numerical step-by-step evaluation of the pressure in a compartment venting in an ambient changing according to that pressure profile.

In all these analyses, certain constraints may exist which must be considered.

- The location of the compartment with respect to other nearby volumes and obstacles to the venting flow.
- Venting requirements to avoid high voltage breakdowns in the volume.
- Outgassing of materials in the compartment.
- The ground flow purge requirements, air conditioning, etc.
- Limitations on the rate of pressure drops in the compartment to prevent diaphragms or other sensible device failure.
- The possibility of gaseous reflow in the compartment from other vent paths.

5. REFERENCES

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