However if current heating constraints are satisfied the trajectory will skip out of the atmosphere for re-entry speeds in excess of approximately 9200 m/sec. Figure 1 shows the speed loss during a single re-entry pass for various aerodynamic configurations of the Orbiter. For re-entry speeds higher than 9200 m/sec, two options are available: a) propulsive deboost prior to re-entry to reduce re-entry speed, or b) multiple skips through the atmosphere. The second procedure is highly desirable from the logistical refueling viewpoint; however, the navigational and targeting requirements for this procedure need to be investigated.

In addition to aerobraking re-entry profiles, the Shuttle lift capability could be utilized to perform plane change maneuvers, i.e., to go from a nominal EPO to a sun-synchronous orbit ($i = 103°$). However, the net plane change achievable, even if the lift vector orientation is completely free to optimize the plane change, is small compared with the total required. The so-called synergetic maneuvers, combining atmospheric thrusting with aerodynamic maneuvering has not been investigated.

For specific payload requirements, the Orbiter main propellant requirements as a function of aerobraking capability may be defined. Figure 2 shows the propellant required for the geo-synchronous and lunar missions as a function of the fraction of the final deboost that may be accomplished aerodynamically. The required propellant weight may, in turn, be related to a specific number of Shuttle flights as is shown in Fig. 3.

Assuming a 50% average payload factor (average load factor = payload delivered/maximum payload capability) to low Earth orbit, approximately 18–25 nominal Shuttle missions would be required, in order to deliver sufficient propellant to perform the Orbiter geo-synchronous missions.

To illustrate the potential capability of performing advanced missions, a typical mission model was constructed for synchronous missions. Using a total baseline list of potential future NASA payloads, a list of 131 payloads was extracted. This data was used to determine how many Shuttle flights would be required, per year, to deliver all of these payloads over a 12-year span. Initial results of the analysis indicate that two Orbiter missions per year would be required.

Based on the payload characteristics approximately 20 nominal low Earth orbit Shuttle missions (to the same orbit area) would be required annually, to deliver propellant (in addition to their payload) for each Orbiter mission. Current Shuttle traffic models project an eventual frequency of 25–30 flights, annually, to low Earth orbit. However, as a large number of these are to polar inclinations an increase in the annual projected number of flights to lower inclinations is required to achieve two Orbiter missions/year to synchronous orbit without additional refueling missions.

### II. Study Results and Conclusions

As a result of this study, it is concluded that the use of the Space Shuttle for manned advanced missions from low Earth orbit is feasible and may be competitive with other proposed concepts. It is recognized that the cost effectiveness of this concept is sensitive to any system modifications required, the frequency of nominal low Earth orbit Shuttle flights, the actual Shuttle payload load factor to low Earth orbit, and the characteristics of the orbit itself.

The potential advantages of this concept are 1) significant reduction in over-all transportation costs; 2) the capability to deliver several payloads or payload clusters on a single mission to synchronous orbit; 3) manned capability to synchronous orbit (and to the moon); 4) potential reduction in synchronous orbit payload RDT & E costs; and 5) potential savings in new, upper stage RDT & E costs.

In addition the following is also noted: 1) the concept takes advantage of uniquely developed Shuttle technology (i.e., aero/thermo system, main propellant tank, etc.); 2) the main propellant tank, with modifications, could form the nucleus of an orbital propellant depot; 3) the concept is compatible with the Shuttle Booster; and 4) the cost effectiveness of the concept increases with increasing Shuttle utilization.

# Prediction of Pressure Fluctuation in Sounding Rockets and Manifolded Recovery Systems

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### Background

BAROMETRIC sensors are used to determine altitude in sounding rocket applications. In addition, some scientific payloads are sensitive to rapid pressure fluctuation and must be specially packaged to prevent large pressure differentials from developing. Consequently, a method for predicting such pressure fluctuations would be of considerable practical utility.

This paper presents a method for predicting the pressure-time response of a volume subjected to airflow through from one to four tubes or orifices using simplified energy equations. Nonetheless, these equations have been successfully used for prediction in a variety of analyses. The following assumptions are made in developing the equations used in this analysis.

1) The pressure, density, and temperature are distributed evenly and instantaneously throughout the manifold.

2) The pressure, density, and temperature at the port(s) is/are known for all time.

3) The specific heats, $C_v$ and $C_p$, are constant.

4) The volume of the manifold is much greater than the volume of any tube leading into it.

5) Continuum flow exists through the system.

6) Entrance effects have a negligible effect upon the tube flow.

7) An approximate equation for compressible adiabatic flow with friction can be used to calculate a mean value for velocity, given the mean density.

8) Mass continuity is satisfied, i.e., no mass addition in the manifold other than from the tubes.

9) Steady flow exists over the integration interval.

10) The behavior of air can be closely approximated by treating it as a perfect gas.

### Development of Equations

Consider the flow case shown in Fig. 1a. Where: $T$ = temperature, $t$ = time, $P_m$ = pressure in the manifold, $\dot{m}_{i,e}$ = mass flow rate, $i$ = inlet, $e$ = exit, and $m$ = manifold.

Using the first law of thermodynamics for an open system

$$\dot{m}_i\left(h_i + \frac{\bar{V}_i^2}{2g}\right) = \dot{m}_e\left(h_e + \frac{\bar{V}_e^2}{2g}\right) + \frac{d}{dt}\left(U_m + m_m\frac{\bar{V}_m^2}{2g}\right)$$

plus the equations for internal energy, $U_m = M_m C_v T_m$, and specific enthalpy, $h_m = C_p T_m$, we may arrive at Eq. (1).

$$\dot{T}_m = (C_p \Sigma_n \dot{m}_n T_n - C_p T_m \dot{m}_m)/C_v m_m \quad (1)$$

where $\dot{m}_m = \Sigma \dot{m}_n$, i.e., there are no mass changes in the manifold other than those introduced by the flow.

The mass flow rate in the tubes is determined using an approximate equation for compressible adiabatic flow with friction where $\rho_a$ and $\bar{V}_a$ are mean values and $i$ may be replaced by $e$ where applicable.

$\rho_a$ is determined by taking the average of the densities of air

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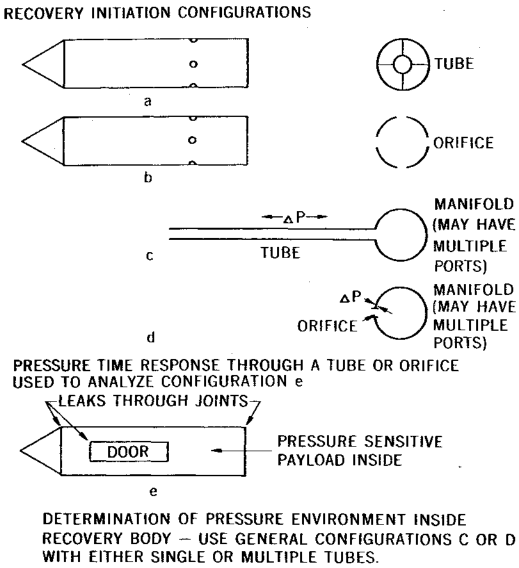


**Fig. 1 General manifold analysis configurations.**

at the end of the tube being analyzed and the air in the manifold. $\bar{V}_a$ is then found by iteration using Eq. (2).

$$\bar{V} = \left[ \frac{P_i - P_m}{f\rho_a\left(\frac{L}{R}\right) + \rho_a^2\left(\frac{1}{\rho_m} - \frac{1}{\rho_i}\right)} \right]^{1/2} \tag{2}$$

The $\rho_a$ and $\bar{V}_a$ so found constitute a $\rho_a \bar{V}_a$ couple which is used to compute the mass flow rate through the tube being analyzed.

$$\dot{m}_a = \rho_a \bar{V}_a A \tag{3}$$

$$\frac{d\rho}{dt} = \frac{\dot{m}_{\text{manifold}}}{\text{Vol}_{\text{manifold}}} = \frac{\Sigma \dot{m}_{\text{tubes}}}{\text{Vol}_{\text{manifold}}} \tag{4}$$

Equation (3) is used to compute the mass flow rate, $m$, for each tube. Since $d\rho/dt$ and $dT/dt$ of the manifold are now known, we may integrate numerically Eqs. (1) and (4).

### Orifice Flow

For orifice flow there is one significant difference in the preceding calculations—the mass flow rate through each orifice is calculated using

$$\dot{m}_a = C_q A(\Delta P/\rho)^{1/2} \tag{5}$$

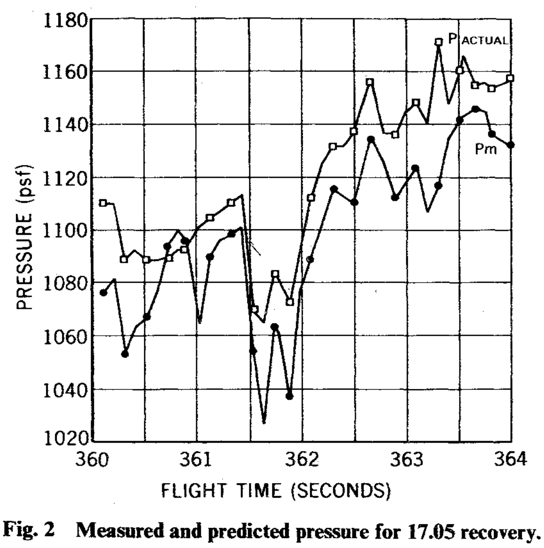


**Fig. 2 Measured and predicted pressure for 17.05 recovery.**

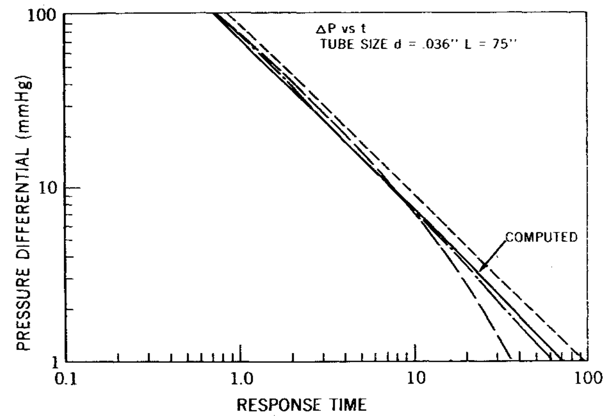


**Fig. 3 Pressure response through a tube.**

where $C_q$ may be input as a variable and $\rho$ is the density at the higher pressure.

The preceding analysis takes into account those variables which are felt to be significant for the problem analyzed. A solution to these equations has been programed for the 360/91 and is available from the author (Ref. 1).

These simplified equations provide a practical method of solving many otherwise insoluble problems met in sounding rocket applications. Originally this method was developed to help design the Aerobee 350 recovery initiation system. However, during final checkout of the computer program, wider application was successfully tried. In particular, this method was successfully used to bracket drogue deployment altitudes for the Aerobee 350 drop test at White Sands Missile Range (WSMR). Figure 2 shows a comparison of the measured manifold pressure from Flight 17.05 with the predicted manifold pressure for the same flight. As shown, the computed pressure follows the actual very closely. Then Fig. 3 shows the measured and computed response time through a long tube for the pressure at the low pressure end of the tube to reach 99% of the reservoir pressure. The measured response times according to the test report[2] have a ±15% tolerance. Therefore, the computed response time as shown in Fig. 3 compares favorably with the measured values.

Finally a discussion of the general type of problems that this method may be used to solve. In particular, Fig. 1 shows some of the possible configurations that might be analyzed using this method. The types shown have already been proven through successful predictions. Figures 1a and 1b depict a general re-entry body with tubes connected to a manifold or orifice openings using the body cavity as a manifold. Either type of system will work since both are currently in use on sounding rocket recovery systems. The orifice system is currently used on the Apache while the tube system in used on the Aerobee 350. Figures 1c and 1d show the general cases of a volume either exhausting or filling through a tube(s) or orifice(s). Then Fig. 1e shows one possible use for such a general approach. The body cavity may contain an experiment with a restriction on the pressure differential allowed across some of its components and yet be packaged so as to create such a pressure differential.

In general, if the problem can be resolved to one in which there is air flow through tubes or orifices from one volume to another, the analysis may be attempted with some expectation of success.

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