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DESIGN CONSIDERATIONS FOR AN ORBITAL NONPROPULSIVE VENT SYSTEM

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ABSTRACT

Minimizing of attitude disturbances during critical maneuvers in space is extremely important to the success of present and future aerospace missions. Thus, a means is needed to ensure that definite attitude positions can be maintained during specific phases of a mission and in some cases indefinitely. To fulfill this requirement, excess or residual propellant vapors and waste gases must be removed with minimum impulse unbalances imparted to the vehicle. The obvious method of accomplishing this is to employ a vent system that dissipates the impulse generated by the various effluents in a nonpropulsive manner. Such nonpropulsive vent (NPV) systems have been designed, installed and flown on several S-IV and S-IVB stages of the Saturn Launch Vehicles. This system was the first of its kind to be tested in orbit, and the data from these flights clearly substantiates the design adequacy of the system. Design considerations and the overall approach in resolving the requirements of this system are discussed in detail.

INTRODUCTION

Minimizing of attitude disturbances during critical maneuvers in space is extremely important to the success of present and future aerospace missions. It is necessary that definite attitude positions be maintained during various phases of a mission and in some cases for an indefinite period. Docking maneuvers, orbital transfer, and stage passivation are examples of such mission phases. Payload constraints may also dictate stringent limits on attitude. To fulfill these requirements, an adequate method of removing excess or residual propellant vapors and waste gases with minimum impulse unbalances imparted to the vehicle is necessary. The simplest and most effective means of accomplishing this employs a vent system which dissipates the impulse generated by the various effluents in a nonpropulsive manner. Design considerations are:

A. Requirements for elimination of thrust unbalance.

B. The external impingement of the effluents on critical components such as solar cells, optical instruments, etc.

C. Tooling and alignment tolerances.

D. Plenum size.

E. A precise means to ensure that identical pressures exist at the two exhaust nozzles.

F. Mach numbers in the vent lines to ensure balanced flow.

G. Effect of temperature differences in the vent system on flowrate.

H. Flow control (choke point) in the system.

I. Continum or molecular flow regime of the exhaust products.

J. Design considerations to ensure that the Prandl-Meyer expansion of the vented products does not reimpinge on the stage.

K. Gas quality and heating rates.

Such nonpropulsive vent (NPV) systems have been designed, installed and flown on the S-IV and S-IVB stages of the Saturn launch vehicles. This system was the first of its kind to be tested in orbit and has met or exceeded the orbital attitude design specifications in all cases.

The purpose of this paper is to present the technical considerations that went into the design of these orbital vent systems and how the application of the information gained may be used in the design of subsequent vent systems. Also presented is a brief performance review of the flight data.

DESIGN CONSIDERATIONS

Requirements for Elimination of Thrust Unbalance

The mission constraints and vehicle attitude correction capability dictate the overall requirements for elimination of thrust unbalances. For instance, vehicles with large residuals of attitude control propellants may only require gross elimination of unbalanced forces, whereas critical docking maneuvers may dictate that absolutely no unbalanced forces react on the vehicles.

A gross elimination of unbalance moments in the pitch, yaw, and roll axis can be achieved by simply aligning the vent exits through the vehicle center of gravity. Although the overall accuracy of such a system is minimal the design can be extremely simple, and may prove adequate for short duration missions or those with large attitude control systems. The only significant attitude change would be in orbital location as a result of translation of the vehicle. A concept such as this was utilized on one of the early S-IV stages when time was not sufficient to allow significant vehicle changes. On this stage, the hydrogen umbilical vent was located in a horizontal plane close to the center of gravity during the time interval critical for nonpropulsive venting. Thus, all that was required was a device to assure flow discharge into the radial direction. This was accomplished by a gravity latching vent cover downstream of the relief valve (Figure 1). Since pitch, yaw, and roll tolerances were the only stipulated requirements, small translation movements of the stage were deemed acceptable. On this stage, a tangential flow unbalance was more critical than a normal or radial unbalance because the moment of inertia of the vehicle in the roll axis was an order of magnitude less than in the pitch yaw axis.

A grid pattern (Figure 2) vent device was utilized with the grid length to diameter ratio of the order of 1:5. The individual hole sizes were 1-1/3 inches by 2 inches. The grid was purposely made this large to assure nonplugging by solids that might result from freezing of the exhaust products that drop below the triple point. The purpose of the 2-inch length was to straighten the flow and ensure flow discharge in the radial direction. Flight data indicated that, although the upstream flow direction was roughly 45 degrees from the radial direction, the flow discharge angle was very close to radial, i.e., within 0.8 degrees or less as derived from attitude changes. This demonstrated the relative simplicity of directing the flow discharge under sonic exit conditions. Subsequent to the original design used on the S-IV stage, other systems on the S-IVB have also utilized the same concept of venting through the vehicle center of gravity; i.e., the LOX umbilical vent and the O_2/H_2 burner systems. It is emphasized, however, that the impulse generated from these two systems was considered negligible and the resultant imbalances could be tolerated.

For extended missions and critical maneuvering in space, high accuracy nonpropulsive vent systems are required, and numerous concepts have been proposed to achieve the goal of eliminating unbalanced forces. Opposing nozzles, which were first utilized on the S-IV stage and all S-IVB stages, appear to represent the highest accuracy and simplest system. The nozzles, mounting in diametrically opposite directions, can effectively eliminate overall thrust from exhaust gases. Experience to date has indicated that a thrust elimination as high as 99.8 percent can be achieved. The following sections of this paper will present the final S-IV and S-IVB nonpropulsive vent configurations and the various design factors that contributed to the evolvement of these systems.

Nozzle Alignment and Calibration

If possible, the nozzle fixtures should be designed to allow alignment changes after installation. The S-IV and S-IVB stages utilized several different types of special alignment tools and procedures.

The S-IV nonpropulsive vent fixtures were comprised of nozzle fixtures serving as alignment pieces and insert nozzles. Due to the peculiar design of the S-IV vent system with large straight through connecting plenum tubes, the alignment could be achieved by bore sighting. Probably this is more accurate than other methods described herein. The S-IVB-203 continuous vent nozzles, which were canted by 13.5 degrees from the horizontal to achieve a limited axial acceleration, were aligned with a special tool using gravity bubbles. This assumed that the stage was mounted perpendicularly. The S-IVB LH_2 NPV orifice plates are aligned with large bars having feelers at each end, using the forward skirt as reference plane. The alignment tolerances are usually quoted as ±1/4 degree in the vertical and horizontal planes.

The nozzle calibration of selected pairs of nozzles calls for effective flow areas within 2 percent of each other; i.e., $A_{eff_1} = A_{eff_2} \pm 2$ percent. This would result in a maximum of 1 percent unbalanced total thrust. Actually, a pair of converging/diverging nozzles has a much smaller variation in flow coefficient and the purpose of the nozzle calibrations was to eliminate gross errors in hardware selection.

Plenum Configuration

The plenum is the tubing upstream of the dual nozzles. Its main purpose is to minimize unequal pressure losses. Although the tubing leading to the two nozzles is usually identical, the presence of bends and bellows, as well as nonuniform heating (Raleigh effects), can cause unequal pressure losses. Thus, proper design of a plenum is critical to the overall NPV system configuration and must include the following considerations: (1) Mach number in the line and flow control point in the system, (2) Raleigh effects from unequal heating, and (3) effects of continuum versus molecular flow regimes.

Mach Number Considerations and Flow Control Point – In the continuum flow regime, the plenum should be such that relatively low Mach numbers exist. The earlier designed S-IV systems imposed a limit of Mach 0.02 in the plenum. This was partially due to the strict attitude tolerances dictated by the payload structural limits. However, flight data and the somewhat less stringent requirements of the S-IVB vehicle enabled a relaxation of this limit to values as high as Mach 0.15. Since the exit nozzles are always choked, this is achieved by simply applying the isentropic Mach number versus area ratio relationship. Upstream of the T section leading to the plenum area, high Mach numbers or choking conditions are permissible.

Nonuniform Heating of the Plenum Ducts (Raleigh Effects) – In the continuum flow regime, the Raleigh effects are considered to be minimal and can generally be discounted. There are two reasons for this: (1) the differences in temperature are usually small (such that no unequal pressure losses occur) and, (2) the temperature differences at the nozzles do not affect the nozzle thrust except for possible changes in the flow medium's specific heat ratio, which are negligible; i.e.,

$$F = P_o \times A_{throat} \times C_F$$

where C_F is a function of nozzle expansion ratio and specific heat ratio *only*.

Continuum Versus Molecular Flow – The purpose of this paragraph is to point out that differences do exist and must be incorporated in the evolution of each system, but not to provide a detailed discussion of the design differences that must be considered when dealing with molecular type flow venting (as compared to the more general continuum flow). The main points to consider are concerned with Raleigh effects and the flow control point of the system. The Saturn V Orbital Workshop, for instance, utilizes the oxidizer tank for waste water and trash storage at pressures well below the triple point. Part of the water dumped into the tank freezes, and, during steady state operation, the only significant vented effluents from the tank are in the form of sublimated water vapor. The sublimation rate is such that it places the flow at the low side of the continuum regime. This introduces several new problems in the design of a NPV system. The Raleigh effects become significant now, due to higher temperature differences in the two exit lines. The use of converging/diverging nozzles was abandoned in this case since the boundary layer buildup in the diverging part was practically eliminating any control over the discharge flow angle. Also, in that section the molecular flow regime was becoming predominant which leaves some doubt as to the effectiveness of nozzle alignment. The final design provides open tubing with flow exit conditions in the continuum regime.

Plume Impingement

This is the most common cause for excessive unbalances and should not be underrated. Any vehicle hardware penetrating into the exhaust plume, regardless of the distance from the nozzles, will be exposed to the momentum of the gas particles and will react accordingly. This was experienced during passivation of the S-IV stage while the Pegasus panels were deployed. The magnitude of the impingement was roughly equivalent to that generated by a half spherical plume with the gas particles at their maximum velocity. This was verified when on a subsequent stage the plumbing was reversed and plume impingement occurred at a different thrust versus time rate. The vehicle roll rates verified these trends. Thus the use of converging/diverging nozzles becomes mandatory in systems such as these. Not only do nozzles offer the least error due to variation in flow coefficients, they also can be designed for a minimum flow impingement (due to narrowing of the plume) which outweighs the higher thrust coefficient. The effects of plume impingement have been demonstrated on various vehicles.

Gas Quality and External Heating Rates

The knowledge of external heating rates is essential for sizing nonpropulsive vent systems. A system that is too large could cause liquid entrainment problems by causing rapid boiling or flashing during venting, whereas an undersized system could cause constraints on the mission sequence as a result of the excessive times required to vent the tanks properly and could jeopardize the tank structure due to the inability to adequately relieve the pressure buildup.

The systems employed on the S-IV and S-IVB stages were complicated by variable heat input rates. The initial rates were extremely high due to the heat transfer stored in the tank walls and insulation during the ascent phase of the mission. The steady state rates were significantly lower than this initial rate.

Thus, it is necessary to provide for these possibilities by either design of a dual blowdown syste, each sized for different boiloff or gas heating rates, or to sequence the venting such that the problems are minimized. The S-IV vehicle incorporated the former method, whereas the S-IVB utilized the latter. This was made possible on the S-IVB due to the longer orbital control capability (battery life and the ability to send commands to the stage real time) that was inherent in the design of that stage.

Venting of liquids will also upset the thrust balance to some degree and should be avoided. The tumbling rate of the S-IV stage provided a centrifugal force sufficient for liquid orientation. The S-IVB has axially pointed auxiliary vents. Generally, a 1×10^{-5} g level on that stage is expected to maintain liquid settling.

FINAL S-IV AND S-IVB NONPROPULSIVE VENT SYSTEM CONFIGURATION

The final designs utilized on both the S-IV and S-IVB stages are shown in Figures 3 and 4. Basically, the concept is to vent both tanks into tubular plenum chambers with diametrically opposed exit nozzles.

The S-IV stage (Figure 3) used 3-inch diameter plenum tubes mounted horizontally in the forward interstage intersecting the centerline of the vehicle. This configuration of straight through tubing provides a rigid support for the exit nozzle assemblies. The tubes are connected at their midpoint by a flexible metal shock mount which allows independent movement of the tube in the horizontal direction while preventing common impact in the vertical direction. The exit nozzle assembly consists of 10-inch long alignment pieces drilled to a 3/4-inch ID and of 4-inch long conical nozzle inserts with throat diameters of 0.332-inch ID and 0.465-inch ID, respectively, for the oxygen and hydrogen systems. The valves, mounted in the tubing upstream of the dual plenums, are pneumatically activated fail-in-last-position valves.

A supplement hydrogen blowdown system which is actuated for a total of three minutes prior to payload shroud separation at high vehicle inertia uses simple pneumatic valves. The configuration of this latter system is similar to the LH_2 NPV described above, only with a much larger capacity.

The auxiliary NPV system provides for a large initial pressure decrease in the LH_2 tank to ensure that the propulsive LH_2 relief valves are not actuated. Data obtained from previous S-IV flights indicates that without the high flowrate from the auxiliary NPV system, the extremely high initial heat inputs to the LH_2 residual, when the liquid is dispersed in the tank at engine cutoff command, would increase the ullage pressure to the vent setting and result in actuation of the LH_2 relief valve, thereby causing excessive stage angular motion. The LH_2 NPV system remains open permanently and, after the initial pressure decay caused by the auxiliary NPV system, satisfactorily vents the hydrogen boiloff overboard.

The heat transfer into the LOX tank is relatively small, therefore, only a single pair of diametrically opposed nozzles were used for the LOX NPV system. These nozzles (nominal diameter 0.332-inch) are also opened at engine cutoff command and remain open during orbit.

The S-IVB hydrogen and oxygen nonpropulsive vent systems consist of wrap-around plenum ducts (Figure 4). The requirement to use wrap-around ducts instead of straight through tubing was dictated by the presence of the forward and aft domes in the respective interstages. The hydrogen NPV uses an identical pair of 4-inch pipe assemblies mounted horizontally around the forward dome and leading to the diametrically opposed exit orifice plates. The single tubing leading to the dual plenums incorporates redundant vent-relief valves, one of which has latching capability. The oxygen NPV is of similar configuration, however, the exit nozzles are of the converging/diverging type due to more stringent impingement considerations. The dual plenums wrap-around the thrust structure of the aft interstage.

FLIGHT DATA

Of the ten to twenty S-IV and S-IVB vehicles which have been flight tested with various configurations of nonpropulsive vent systems, the S-IV-9 flight data has been particularly selected for discussion due to some unusual effects that were discovered during that mission. The NPV systems on the remaining S-IV and S-IVB flights exhibited excellent performance and operated within the expected design limits.

Satisfactory performance of the S-IV-9 nonpropulsive vent system was extremely critical because of the payload structural limitations. The purpose of the earlier vehicle flight tests of the NPV systems was to prove that nonpropulsive venting with extremely low thrust unbalances was possible. The Saturn SA-9 mission was to place the Pegasus meteoroid detection satellite into orbit (Figure 5). The S-IV-9 stage was to remain permanently attached to the payload. Structural integrity of the payload limited the permissible angular rates to 10 deg/sec in roll and yaw and 4 deg/sec in tumble. The S-IV-9 stage was inserted into orbit with 255 lbs of LH_2 residual and 800 lbs of LOX residual. By the time the tanks were vented to depletion, the LH_2 tank had expelled a total impulse of 40,111 lbs-sec of which 13,000 lbs-sec were vented through the auxiliary blowdown system, and the LOX tank had expelled a total impulse of 37,600 lbs-sec. Unexpectedly, the S-IV-9 vehicle showed a considerable roll angular velocity (Figures 6 and 7). The maximum angular rates detected were 0.25 deg/sec in pitch-yaw and 9.8 deg/sec in roll direction. (These rates, due to precession, stabilized out later to a value of 2 deg/sec rotation in tumble.) These rates would correspond to an overall thrust unbalance of 0.164 percent in pitch yaw and 2.5 percent in roll direction. The expected thrust unbalances based on the system's maximum tolerances were 2.46 percent in pitch-yaw and 0.28 percent in roll direction. Thus, while the pitch-yaw unbalance was smaller by an order of magnitude, the unbalance in roll direction was nine times higher than expected. The percentage of unbalance in roll was calculated to be even worse when its origin was detected.

The oxygen and hydrogen orbital vents differed greatly in total blowdown time which amounted to 2 to 3 hours for the hydrogen NPV and approximately 24 hours for the oxygen NPV. The roll rate curve followed closely the total impulse curve of the oxygen orbital vent. This left little doubt that the unbalance was originated by the oxygen orbital vent. The thrust unbalance of the oxygen vent would then amount to 5.3 percent which would be 19 times larger than expected.

A post flight investigation showed that the installation and alignment of the nonpropulsive vent system had been performed properly and under close inspection. A bending of the 3-inch tubular plenum chamber under possible flight stresses seemed unlikely, especially since only a S-shaped deformation could create roll misalignment without creating pitch or yaw misalignment simultaneously. Finally, it was established that plume impingement of the oxygen exhaust flow could have caused the roll disturbance. As shown in Figure 8, the oxygen nozzles are 26 degrees off from the Pegasus wing plane while both hydrogen NPV's are almost perpendicular to the wing plane. This puts the oxygen vent into a somewhat unfavorable position with respect to plume impingement. The possibility had been considered earlier, but the effect was expected to be negligible because of the large distances involved.

The vertical distance between the LOX vent and the lower edge of the Pegasus wing is 13.8 feet, and by the time the flow has reached the lower edge of the wing, its plume expansion (area) ratio is of the order of a million to one. Subsequent extensive investigations, however, have yielded that assuming a uniform isentropic expansion until the maximal velocity is reached, the flow that impinges on the two wings could indeed produce a load high enough to cause the experienced rotation.

CONCLUSIONS

A review of the flight data and experience acquired in the design of S-IV and S-IVB nonpropulsive vent systems has resulted in the following conclusions:

A. Nonpropulsive venting is feasible.

B. Nonpropulsive vent systems can be built and aligned to extremely small tolerances and these tolerances can be maintained during flight.

C. Diametrically opposed nozzles appear to provide the best means to effectively cancel thrust in a balanced manner. Equal and opposite nozzles placed on the same side of a vehicle will cause severe imbalances due to plume impingement. In addition, it is extremely difficult to balance the flow out of a system of this type. This will result in a significant increase in roll rates.

D. Plume impingement of opposing nozzles on the vehicle skin is symmetrical and balanced. However, any vehicle hardware penetrating into the exhaust plume of the venting exhaust products will be exposed to the momentum of the flow and react accordingly.

E. The system plenum should be sized to maintain relatively low Mach numbers upstream of the control point.

F. Temperature differences in the system appear to have little effect on thrust unbalance.

G. Liquid venting should be avoided and special means employed to ensure that this goal is accomplished, i.e., liquid orientation controls must be taken into account.

H. Mission and system design constraints may dictate or strongly influence the final system selection. The constraints may include such items as mission lifetime, attitude limits, type of exhaust products, flow regimes, etc.

NOMENCLATURE

F - Thrust

A_{throat} - Nozzle throat area

P_o - Total pressure at throat

$$C_F = \frac{A}{A^*} \quad (1 + KM^2) \left(1 + \frac{K-1}{2} M^2\right)^{\frac{K}{K-1}}$$

$$\text{with } M = f\left(\frac{A}{A^*}, K\right)$$

ACKNOWLEDGEMENT

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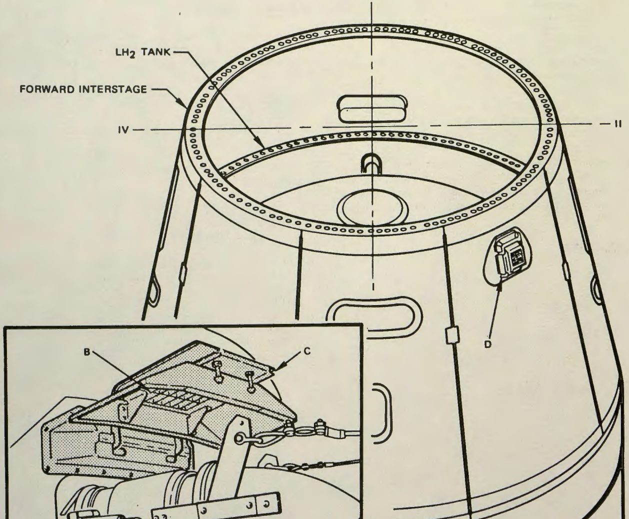

Figure 1. S-IV-7 Stage LH$_2$ Vent Deflector Assembly

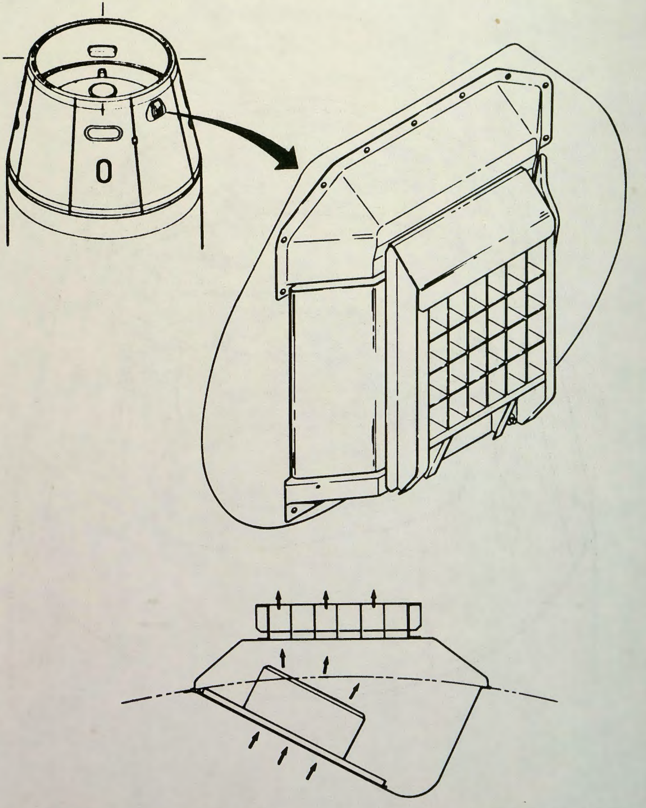

Figure 2. S-IV-7 Stage Grid Pattern Vent Device

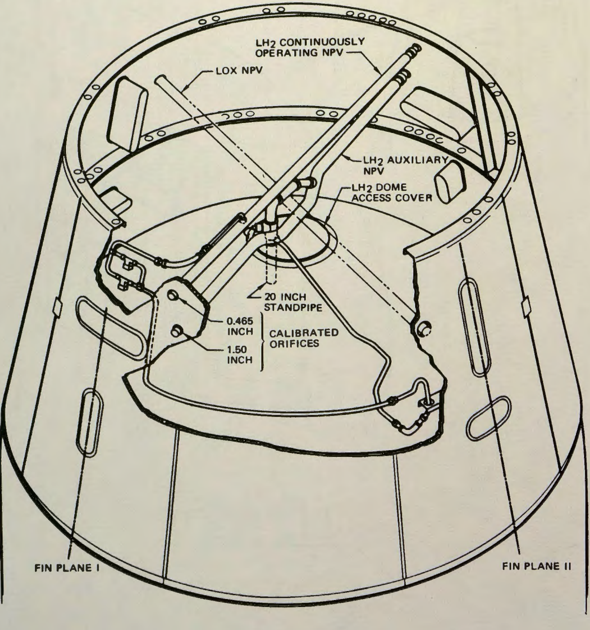

Figure 3. Final S-IV Nonpropulsive Vent System

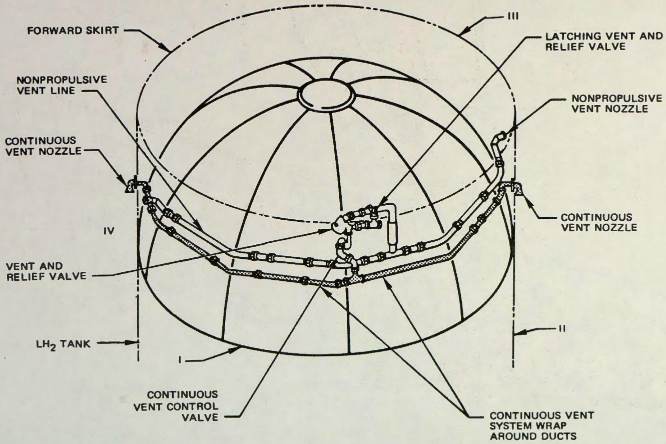

Figure 4. Final S-IVB Nonpropulsive Vent System

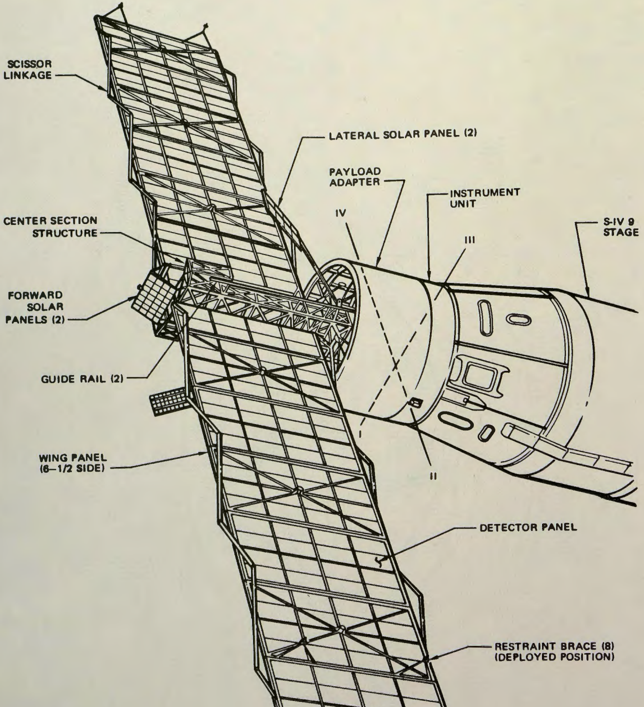

Figure 5. Pegasus (Meteoroid Technology Satellite)

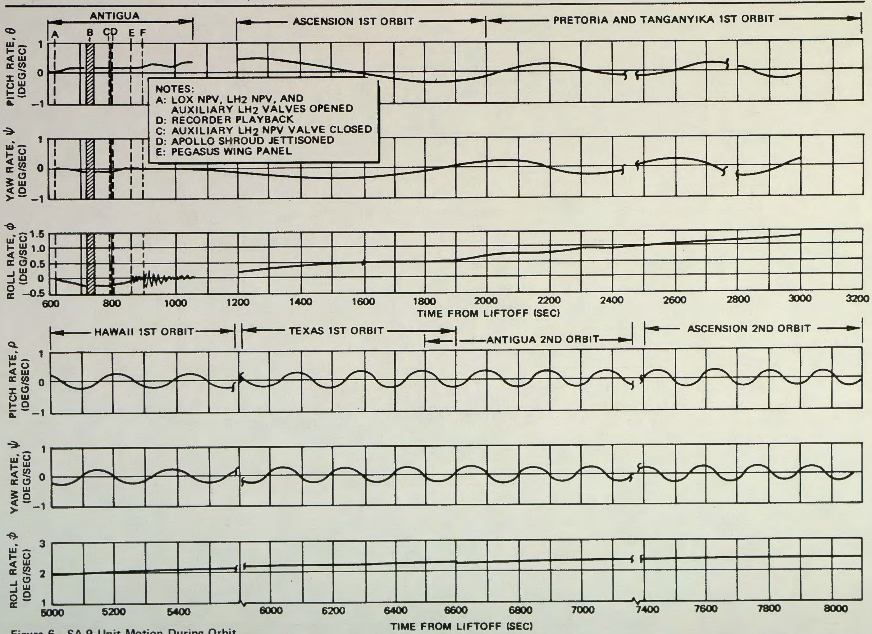

Figure 6. SA-9 Unit Motion During Orbit

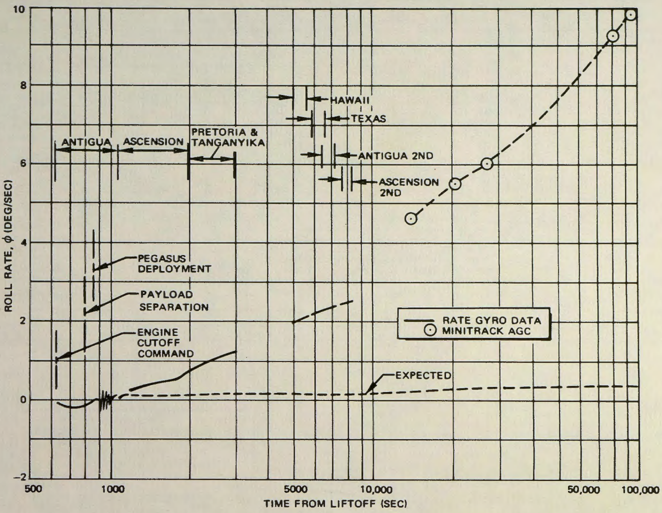

Figure 7. SA-9 Orbital Unit Roll Rate History

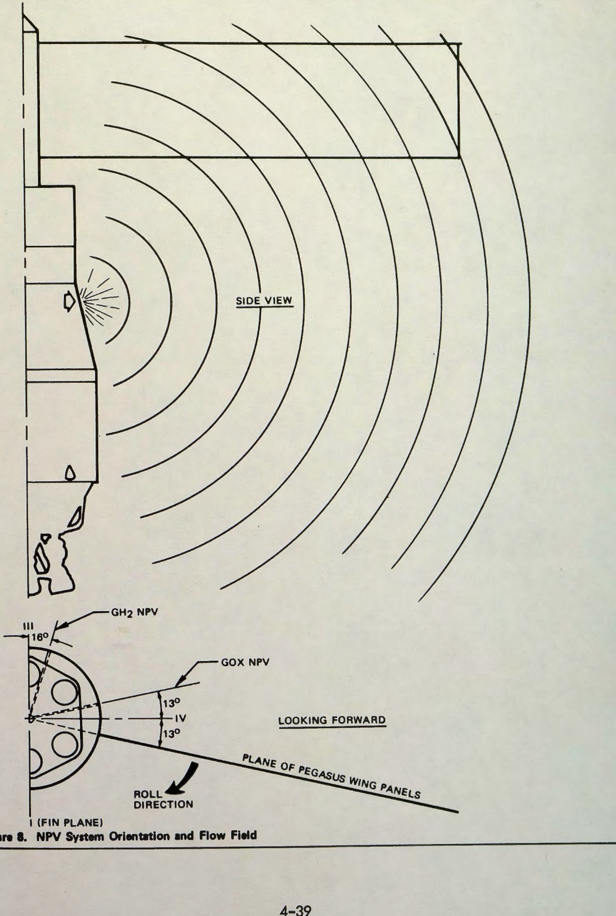

Figure 8. NPV System Orientation and Flow Field