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SATURN S-IVB CONTINUOUS VENT SYSTEM FOR PROPELLANT CONTROL DURING PARKING ORBIT

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ABSTRACT

Cryogenic propellant tanks coasting in space must be vented periodically to prevent excessive pressure. This requires that the liquid be settled with auxiliary ullaging rockets prior to venting to ensure minimum propellant loss. Other problems associated with blowdown of saturated liquids, such as surface level rise and boilover, are severe. The S-IVB, third stage of the Saturn Launch Vehicle, eliminates these problems during the earth parking orbit by continuously venting the liquid hydrogen tank. The boiloff gas is vented in the aft direction providing a continuous settling thrust on the propellants. The philosophy behind the system design is explored and critical components in the design are examined. Evaluation of system performance on several flights is presented.

INTRODUCTION

The Saturn lunar mission requires two burns of the S-IVB stage, the third stage of the launch vehicle. Between burns, the vehicle coasts in an earth parking orbit for a period of up to 4.5 hours prior to the S-IVB stage final burn to translunar trajectory insertion. The orbiting vehicle consists of the command/service module, lunar excursion module, instrument unit and the S-IVB. Total orbital mass is approximately 300,000 pounds. Propellant mass in the S-IVB tanks is approximately 130,000 pounds liquid oxygen and 28,000 pounds liquid hydrogen. Solar heating in the low earth orbit requires that the hydrogen tank be vented to prevent overpressure caused by hydrogen boiloff. The oxygen tank does not require venting. Various methods of venting the hydrogen tank were considered before choosing the operational system known as the Continuous Vent System (CVS).

The CVS accomplishes two major functions: (1) it maintains structurally acceptable ullage pressure and (2) it provides a settling acceleration that keeps the propellant settled in the aft or bottom end of the tanks. A further function is to maintain the liquid hydrogen at a saturation pressure low enough so that engine turbopump net positive suction head (NPSH) requirements can be met after repressurization.

VENT SYSTEM DESCRIPTION

The S-IVB vent systems are shown schematically in Figure 1. Venting prior to liftoff is accomplished through a single umbilical vent directed by a diverter valve. Just prior to liftoff the diverter valve is cycled to the flight position so that all subsequent venting

is through either the nonpropulsive vent (NPV) or the CVS. The main vent valves perform the dual function of pressure relief and commanded venting. Commanded venting is utilized after liftoff only for stage safing after the second burn. Some pressure relief occurs through the NPV system during boost and S-IVB powered flight. However, the predominant vent mode during flight, and the only venting during orbital coast is through the continuous vent system. This system maintains settled propellants and required LH₂ tank pressures during orbital coast and is the subject of this paper.

ORBITAL PROPELLANT CONTROL

In addition to the CVS, orbital thrust is obtained for relatively short periods from two 70-lb hypergolic ullage engines located in the attitude control modules and from the O₂H₂ burner located on the main thrust structure. The O₂H₂ burner is used primarily to heat cold high pressure helium for repressurization of the propellant tanks just prior to second burn. Exhaust gas from the burner provides 15 to 30 lbs of settling thrust while operating.

At first-burn engine-cutoff (orbital insertion) the two 70-lb ullage engines are fired for 87 seconds to ensure that any propellant disturbance caused by the cutoff transient is resettled. The CVS is actuated 59 seconds after cutoff. The delay and overlap are timed to ensure that any slosh present during main engine burn is not amplified in the transition to the orbital thrust level. The CVS remains in operation for the duration of orbital coast until restart preparations begin. Average duration of coast has been approximately 2.5 hours on Apollo lunar flights although the original design conditions specified 4.5 hours. At 528 seconds prior to second engine start the CVS is deactivated and the O₂H₂ burner is started to pressurize the propellant tanks. The O₂H₂ burner provides settling thrust until the last 70 seconds when the ullage engines are again burned until main engine start.

The switch from O₂H₂ burner thrust to ullage engine thrust just prior to second main engine start is only to facilitate the automatic pressurization system failure correction. There is no physical requirement for the higher thrust level.

CONTINUOUS VENT SYSTEM DESCRIPTION

The vent system locations on the stage are shown in Figure 2. All valves and piping are located in the forward interstage. Significant components of the system are the pressure regulator module, the wrap-around ducts and the propulsive nozzles.

The regulator module consists of two parallel flow paths. During the CVS operation, flow is continuous through a fixed small area orifice. Flow also occurs in the second or regulator leg when the fixed orifice area is insufficient to maintain tank pressure at a nominal 20 psia. The orifice is sized to maintain a pressure of 20 psia in the minimum predicted heating case with no flow through the regulator. The 20 psia value ensures that J-2 engine pressure and NPSH requirements will be met at restart. This minimum flow value also ensures that the minimum design settling acceleration is always obtained. The regulator maintains the nominal ullage pressure regardless of expected or unexpected variations in heat flux. The orbital heat flux varies with time in orbit due to boost aerodynamic heating thermal lag, and once per revolution solar heating. Variables such as launch time, surface radiation properties, surface condition, and insulation properties contribute to the vehicle-to-vehicle variable nature of the heat flux.

The wrap-around ducts obviously serve to convey vented gas to the nozzles. One design point considered essential is their large diameter compared with the nozzle throat diameter. The large area ratio provides for a low Mach number with resultant low pressure drop. The low absolute pressure drop ensures that any difference in pressure drop between the two legs is of second order importance. Differences in thrust generated between the two nozzles due to pressure differences will thus also be of second order importance. Area ratio of the lines/nozzles is approximately 7.5 giving a maximum mach number of 0.15. The ducts are of equal length and have the same bend and joint configuration.

The propulsive nozzles are located diametrically opposed on the forward skirt. This positioning is necessary to balance plume impingement force on the vehicle skin. The nozzles are the converging-diverging type with a throat area of 0.93 in.² and an expansion ratio of 8.6. Very close tolerances are held in the throat diameter. A ball joint attachment is used at the duct/skin/nozzle joint to permit adjustment of the nozzle angular attitude. Tolerances of $\pm 1/4$ degree are specified for alignment of the nozzle axis with the vehicle longitudinal axis. The nozzles must be positioned within $1/4$ degree of being diametrically opposed on the skirt, and within one inch of each other in the longitudinal direction. This one inch tolerance also corresponds to approximately $\pm 1/4$ degree when measured from the vehicle centerline. The special effort taken with the wrap-around ducts and nozzles to minimize thrust unbalances is necessary to minimize attitude control propellant consumption.

SELECTION CRITERIA

Prior to the selection of the continuous vent system, it was planned to use a cyclic vent system.⁽¹⁾ In the cyclic system the propellant tanks are locked up and the vehicle coasts without thrust. Periodically the hydrogen tank is vented or blown-down to maintain structurally acceptable pressure. Auxiliary thrusters are used to settle the liquid away from the vents before and during the blowdown.

Payload is a prime advantage of the CVS over the cyclic system. Table 1 gives an approximate weight breakdown. The system is simpler and more reliable due to the lack of dependence on

multiple actuations of pressure switches, vent valves, and settling thrusters. Furthermore, the settled propellant condition makes the task of predicting thermodynamic and heat transfer performance much easier since the amount of wetted wall is known.

Table 1

| S-IVB CONTINUOUS VENT SYSTEM VERSUS CYCLIC VENT SYSTEMS WEIGHT COMPARISON | |
|---|--------------------|
| Condition | Weight |
| APS Settling engine elimination | - 800 lbs |
| APS Propellant reduction | - 1,200 lbs |
| Solid Ullage rocket addition* | + 350 lbs |
| CVS Hardware addition | + 100 lbs |
| LH ₂ Boiloff Reduction** | - 40 lbs |
| Total Weight Change | - 1,510 lbs |

*Elimination of the hypergolic ullage engines requires that solid engines be added to provide positive thrust at S-II/S-IVB staging.

**The liquid is settled in the CVS case. Thus, less wetted wall is available for heat transfer to the liquid.

In the cyclic system during the locked up coast periods, the propellant will take some unsettled configuration. In the absence of body forces, this configuration will be that of a spherical ullage gas ball in the center of the tank with the walls completely wetted. At the 100 nmi Saturn orbit the drag produces a deceleration of approximately 2×10^{-6} g which would tend to settle propellants at the front of the tank. However, the attitude control system is intermittently thrusting in nearly random fashion normal to the drag. The resulting propellant/ullage configuration is then impossible to define as is the effective heat transfer area. However, the entire wall would probably be effectively wetted. Adding to the uncertainty is the degree of mixing taking place in the liquid. Pressure rise rate is very much greater in the stratified case than in the completely mixed case.

Venting of a tank two-thirds full of saturated liquid also presents problems. Thrust level during venting must be high enough or venting rate low enough to prevent boilover or excessive liquid entrainment. Both of these phenomena can cause severe liquid loss.

DESIGN CRITERIA

The following requirements are placed on the CVS (1) maintain 20 psia nominal ullage pressure, (2) flow between 0.1 and 0.6 lb/sec saturated GH₂, (3) maintain 6 lbs thrust minimum to meet 2×10^{-5} g acceleration requirement, and (4) induce less than 2 percent thrust unbalance.

Maintaining 20 psia ensures that the LH₂ is properly conditioned so that engine restart can be accomplished at any time. The high flow capability is required right after orbital insertion to adequately vent gas generated as a result of thermal soak through of the high boost phase heating. The low value ensures that the minimum design thrust level will be maintained. Required minimum settling acceleration was chosen conservatively at 2×10^{-5} g's. Corresponding thrust for the 300,000 lb vehicle is 6 lbs. The effectiveness of the settling force can be estimated from the magnitude of the Bond Number. Bond number is the ratio of body forces to surface tension forces and is expressed:

$$Bo = \frac{\rho g d^2}{\sigma} \quad (1)$$

In order for the body forces to dominate, it is necessary that the bond number be much greater than unity. For the 260 inch diameter fuel tank $Bo = 350$. Thus, the chosen minimum design acceleration causes the body force to dominate over the surface tension force by two orders of magnitude.

The total heat input into the fuel tank required to give this thrust may be greater than that indicated by state-of-the-art insulation systems. Thus, hydrogen boiloff may be greater than that obtained from a system optimized on the basis of insulation/boiloff only. However, the overall weight favors the CVS. The results would, of course, change for longer coast times. Long coast times justify high performance insulation systems and advanced propellant acquisition and retention systems such as the MDAC-West integrated start tank.⁽²⁾

Thrust produced by the CVS is a function of system geometry, heat flux to both liquid and gaseous hydrogen, and hydrogen properties. The subsequent simplified analysis is based on the following assumptions: (1) fuel tank is at thermal equilibrium, (2) perfect gas equations are applicable, and (3) frozen equilibrium exists in propulsive nozzles.

Heat fluxes to the liquid and ullage are given by:

$$\dot{Q}_l = \dot{w} h_{fg} \quad (2)$$

$$\dot{Q}_u = \dot{w}(h_v - h_s) = \dot{w} C_p (T_v - T_s) \quad (3)$$

Specific impulse can be expressed as:

$$I_{sp} = \sqrt{\frac{RT_v}{g_c \gamma} \frac{1}{M_c} \frac{1 + \gamma M_e^2}{(1 + \frac{\gamma-1}{2} M_e^2)^{\frac{1}{2}}}} \quad (4)$$

And the thrust:

$$F = \dot{w} I_{sp} \quad (5)$$

Combining Equations 2 through 5:

$$F = \frac{\dot{Q}_l}{h_{fg}} \sqrt{\frac{R}{g_c \gamma} \left(\frac{\dot{Q}_u}{\dot{Q}_l} \frac{h_{fg}}{C_p} + T_s \right) \frac{1}{M_e} \frac{1 + \gamma M_e^2}{1 + \frac{\gamma-1}{2} M_e^2}} \quad (6)$$

This result is plotted in Figure 3 for the S-IVB configuration. The shaded region represents the approximate orbital heat fluxes experienced for quasi-steady state CVS operation.

The predicted heat flux into the liquid hydrogen is shown in Figure 4. The heat flux curves reach quasi-steady conditions after about 4,000 seconds. It takes this long for the tank shell and insulation to cool down to orbital conditions. The external skin temperature drops from the area of 400° to 500°R at orbital insertion down to an average 200°R. Most of the sensible heat represented by this temperature decline is transmitted to the liquid hydrogen.

PERFORMANCE PREDICTIONS

Predicted thrust profiles are shown in Figure 5. A computer program is utilized to perform the tedious energy balances required on the ullage and liquid constituents. Real liquid and gas behavior is considered as opposed to the simplified ideal gas analysis utilized in the previous section. Tabulated fluid properties enthalpy, compressibility, density, etc., are employed. Inputs include ullage and liquid heating profiles, initial conditions, and system configuration. The very wide band between maximum and minimum performance near the start of orbit is due to the following factors:

- A. Variations in ground vent back pressure cause corresponding variations in the pressure at which the liquid is saturated at orbital insertion. A high vent back pressure causes the liquid to be saturated at a pressure higher than the regulator setting. Thus, some propellant must flash off to lower the saturation pressure to the regulated pressure. This extra mass flow causes the higher thrust. Similarly, a low back pressure allows the liquid to absorb additional orbital heating reducing boiloff.
- B. Variations in regulator settings have a similar effect on boiloff in that the relationship between saturation pressure and regulator pressure is shifted.

The effect of possible variations in heat flux due to variations in surface radiation properties, insulation conductivity, and launch time are reflected in the predicted thrust spread after quasi-steady conditions are attained.

FLIGHT PERFORMANCE

The CVS has performed perfectly on all ten Saturn flights where it was installed. It was first flown on AS-203, a special Saturn IB simulated restart flight to verify Saturn V orbital systems.⁽³⁾ The S-IVB on this flight was very well instrumented including TV cameras in the hydrogen tank. No indication of settling was observed in the TV pictures even at acceleration levels deliberately set below the 2×10^{-5} g minimum design level. All subsequent flights have verified the results of this early experiment.

Thrust data points of the five most recent flights are shown in Figure 5 superimposed on the preflight predictions. Virtually all data points fall within the prediction band. However, if the profile of any particular flight were drawn it would show that it does not follow the prediction lines. In general, the cyclic peaks are out of phase. This is due to launch times different from that assumed in the prediction.

POSSIBLE SYSTEM IMPROVEMENTS

The variable thrust of the CVS causes some minor problems in the area of guidance. The variable thrust results in a velocity increase that is not known with precision due to the relative insensitivity of the guidance accelerometers to the low thrust level. This problem could be alleviated by splitting the system so that the constant orificed flow is used to provide thrust while the variable regulator flow is routed into the nonpropulsive vent system. Constant minimum required thrust is then obtained when the tank pressure is at the regulated level. Originally, it was believed that the operational system was the more desirable since it maximized available settling force. However, all flight data indicated that the minimum design thrust is more than adequate to maintain settled propellants.

NOMENCLATURE

| | |
|----------|--|
| B_o | — Bond number, dimensionless |
| C_p | — Specific heat at constant pressure, Btu/lb °R |
| d | — Tank diameter, ft |
| F | — Thrust, lbs |
| g | — Acceleration, dimensionless |
| g_c | — Gravitational constant, 32.2 ft/sec ² |
| h_{fg} | — Heat of vaporization, Btu/lb |
| h_g | — Enthalpy of saturated gas, Btu/lb |
| h_v | — Enthalpy of vented gas, Btu/lb |
| I_{sp} | — Specific impulse, sec |
| M_e | — Mach number at nozzle exit, dimensionless |

| | |
|-------------|--|
| \dot{Q}_R | — Heat input rate to liquid, Btu/hr |
| \dot{Q}_U | — Heat input rate to ullage, Btu/hr |
| R | — Gas constant, ft ² /R |
| T_s | — Temperature of saturated gas, °R |
| T_v | — Temperature of vented gas, °R |
| \dot{w} | — Mass flowrate of vented gas, lb/sec |
| γ | — Ratio of specific heats, dimensionless |
| ρ | — Liquid density, lb/ft ³ |
| σ | — Surface tension, lb/ft |

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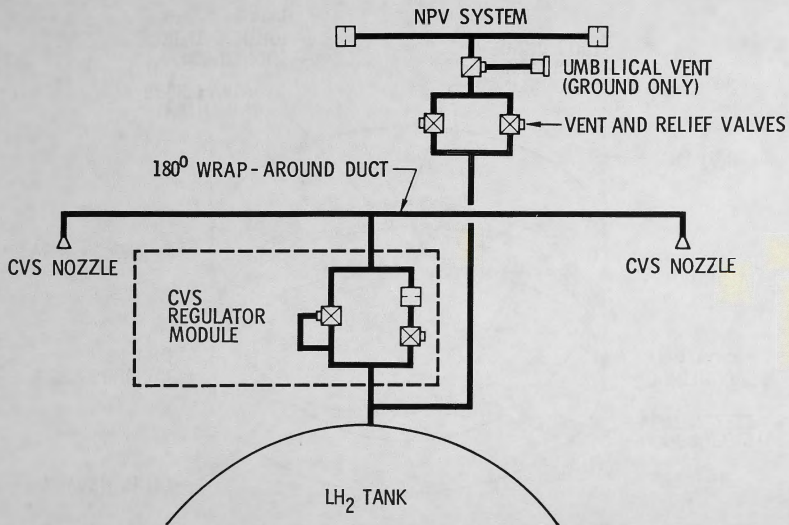


Figure 1. S-IVB LH₂ Vent Systems Schematic

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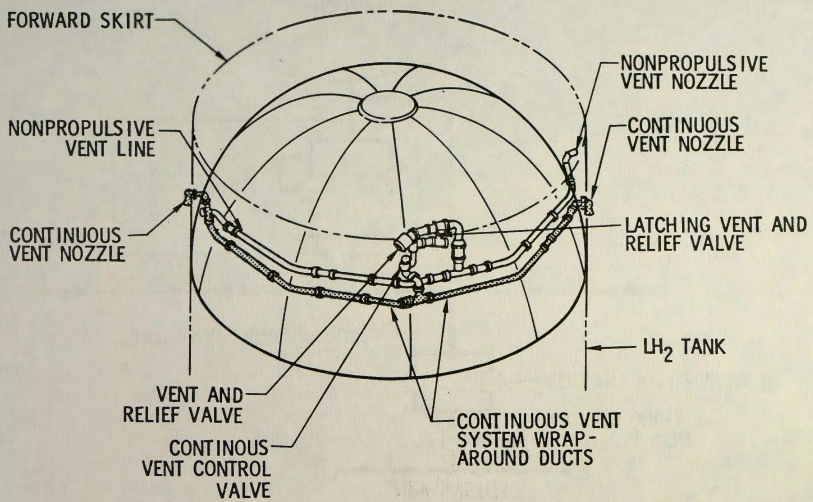


Figure 2. S-IVB LH₂ Vent System Components

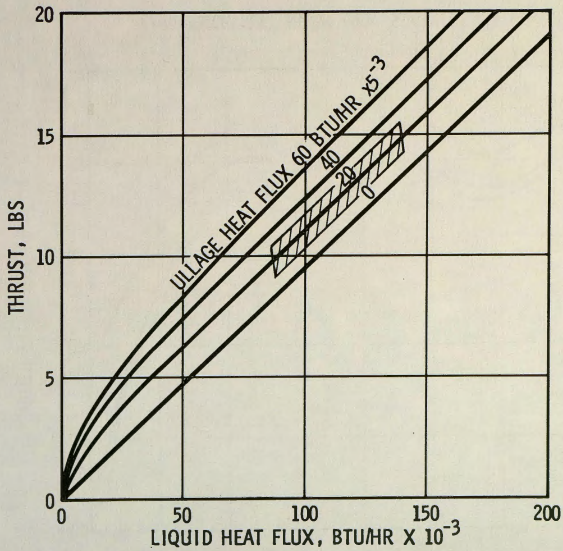
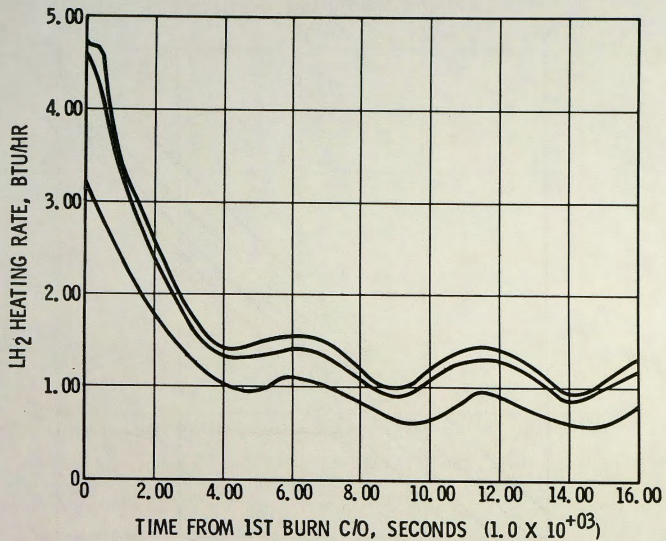


Figure 3. Continuous Vent Thrust — Steady State Conditions

Figure 4. S-IVB LH₂ Orbital Heating

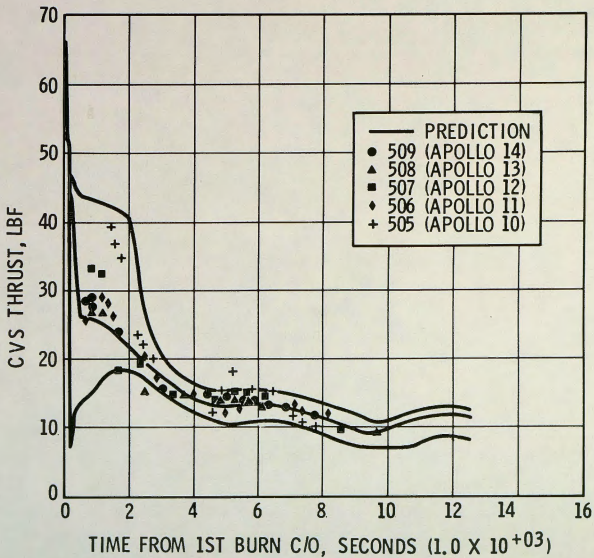


Figure 5. S-IVB CVS Thrust - Prediction and Data