of the argument $Q\rho/\rho_{bo} > 3$, which will apply to nearly all values of the lower integral limit. Therefore, the integral in Eq. (10) may be written as $Ei(-Q\rho/\rho_{bo})$. For most purposes, the total history is not required, since only the burnout value is of interest. The special burnout value is simply

$$\xi_{bo}/\xi_{ss} = 1 + (K/V_{bo})e^{Q}Ei(-Q) \quad (11)$$

Equation (11) gives the burnout roll-rate lag, which is an important factor in specifying the required fin cant.

Results

The foregoing analytic expressions are somewhat unusual in that they are rigorously derived but are nevertheless of a simple form that is easy to use. The only assumption required in the integration was that the aerodynamic coefficients C_{l_δ} and C_{l_p} be constant. At high supersonic Mach numbers, the coefficient variation goes as $1/M$, which is indeed a slowly varying function. Since the largest part of the roll-rate lag occurs near burnout, it is suggested the burnout rather than a nominal value of C_{l_p} be used in the formula.

According to Eq. (11), the loss in roll rate is

$$\Delta\xi_{bo}/\xi_{ss} = (K/V_{bo})e^{Q}Ei(-Q) \quad (12)$$

Since $Q \ll 1$, Eq. (12) is approximated, for study purposes only, by

$$\xi_{bo}/\xi_{ss} = (-K/V_{bo})(1 + Q)\ln[1/1.781\,Q] \approx -(d\ln V/dh)_{bo}\ln(1/1.781\,Q) \quad (13)$$

This equation shows that the roll-rate lag varies directly as the logarithmic velocity change with altitude, whereas an increase in the damping coefficient Q will decrease the roll-rate lag.

Equation (12) was evaluated for the Aerobee 350, on which 6-D machine results[1] first uncovered the problem of roll-rate lag. For the case of a 150-lb payload with a two-caliber nose extension, these results[1, 2] apply:

M_{bo}	= 8.3	$1/\beta$	= 21,000 ft
V_{bo}	= 9080 fps	I	= 39 slug ft^2
ρ_{bo}	= 3.71×10^{-6} slug/ft^3	Q	= 0.174
h_{bo}	= 149,000 ft	$Ei(-Q)$	= −1.34
γ_{bo}	= 23 deg	$\Delta\xi/\xi_{ss}$	= −0.246, Eq. (15)
K	= 1400 fps		
C_{l_p}	= −0.317	$\Delta\xi/\xi_{ss})_{6\text{-D}}$	= −0.233 (Ref. 1, Run 74)
AB^2	= 505 ft^4		

This example clearly illustrates the close agreement between the analytic and 6-D machine runs.

When a specified burnout roll rate is required, the steady-state fin cant δ_{ss} should be given an increment of

$$\Delta\delta_{ss} = -\delta_{ss}(\Delta\xi_{bo}/\xi_{ss}) \quad (14)$$

to compensate for the roll-rate lag.

It could be argued that after burnout the roll rate will have time to accelerate back up to its steady-state value so that compensating fin cant will not be required. However, both the 6-D machine results and the analytic development[4] indicate that postburnout roll acceleration is negligible in the upper atmosphere.

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Application of Jet Pumping to Liquid Injection Thrust Vector Control

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SCHEMATICALLY, liquid injection thrust vector control (LITVC) system designs are simple. High-pressure gas (He, N_2, etc.) is regulated from a tank to the injectant tank; injectant is forced through, and is regulated by, the injector valves (Fig. 1). An electronic assembly provides command to the servo valves and the (hydraulically actuated) injectors. Nevertheless, a standard LITVC system may add appreciable weight (reactive-injectant, plus inert) to a stage; because high injection pressures are necessary, tanks, feed lines, and the injector constitute a large percentage of the total. In addition, valve actuation requires considerable power due to high line pressures; valve seating, chattering, and water hammer problems may be encountered. This note deals with decreasing weight by using jet-pumping for injection.

Jet-Pump Injection System

A specially designed jet-pump injector is shown in Fig. 2. Primary fluid expands through the nozzle at 1. Because of the low static pressure induced at 2, secondary fluid flows into the mixing chamber at 3. With the exchange of momentum and energy, the fluid mixture can be ejected with appreciable velocity and at a higher total pressure than either the primary or secondary injectant. From the conservation equations it can be shown that the mass-rate ratio of secondary to primary injectants is about 15, depending upon fluid property values.[1,2]

Figure 3 illustrates the principle of a monopropellant jet-pump system. Gas is regulated at high pressure to the small primary injectant tank and at low pressure to the large secondary tank. The valve allows 1) primary injectant to flow through the rocket section of the jet pump, and 2) secondary injectant to enter the mixing chamber. Primary advantages of the jet-pump system over the standard system are as follows:

1) The large secondary injectant tank (containing approximately 95% of the injectant weight) and the large diameter piping are maintained at a low pressure and are, therefore, light weight.

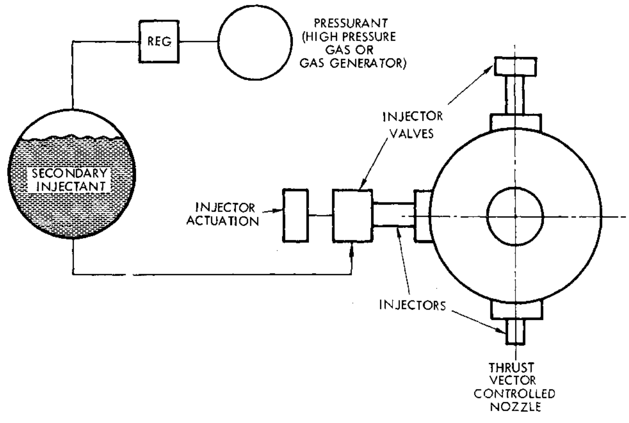

Fig. 1 Schematic: standard gas-pressurized LITVC system.

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Table 1 Materials and operating characteristics: standard vs jet-pump systems

Characteristic	Standard system ($NaClO_4$)	Jet-pump system (peroxide/$NaClO_4$)
Injectants		
Primary	Not applicable	H_2O_2
Secondary	$NaClO_4$ solution	$NaClO_4$ solution
Tank Pressure		
Primary, psia	Not applicable	500
Secondary, psia[a]	750	75
Pressurant		
Material	N_2	N_2
Initial pressure, psia	4000	4000
Final pressure, psia	800	550

[a] Note difference in pressure levels in large, secondary-injectant tanks.

2) Because of the low pressure in the secondary injectant tank and the small volume of the primary tank, only a small amount of pressurant (gas) is required.

3) The heterogeneous mixture of primary and secondary injectant passes through the nozzle wall at high velocity and may be partially gas. (The presence of a gaseous oxidizer may improve I_{sps}.[3,4])

Injectant Selection

Hydrogen peroxide was selected as the jet-pump energy source (primary injectant) because it has such desirable characteristics as thermal, impact, and chemical stability; high density; low cost and ready availability; and low corrosivity. An 87% gravimetric solution of H_2O_2 decomposes to oxidizer-rich gas at approximately 1200°F, a temperature readily accommodated by modern rocket chamber materials. A high-density (90 lb/ft^3) water solution of sodium perchlorate was selected as the secondary injectant because of its oxidizer-richness, high density and specific heat, low cost and ready availability, low viscosity, ease of storage, low vapor pressure (to avoid jet-pump cavitation), and high latent heat of vaporization.

As a basis for comparing the standard and the jet-pump systems, a solid rocket was chosen which produced a nominal 1×10^6 lb thrust for 110 sec. A typical lateral-thrust/time duty cycle was assumed. Pertinent operating characteristics of each system are shown in Table 1.

Table 2 Weight comparison between LITVC systems: standard vs jet-pump

Item	Standard system ($NaClO_4$)	Jet-pump system (peroxide/$NaClO_4$)
Injectant: reactant		
Primary (H_2O_2)	Not applicable	785/39[a]
Secondary ($NaClO_4$) solution	12,550/628[a]	11,765/589
Hardware and inert tanks, injectant		
Primary	Not applicable	25/25
Secondary	1500/1500	200/200
Plumbing and valves	395/395	150/150
Supports, misc.	150/150	100/100
Hydraulics	135/85	100/75
Electric	30/30	30/30
Pressurant		
Tanks	1000/1000	100/100
Gas	1184/1184	100/100
Plumbing and valves	175/175	50/50
Supports	100/100	25/25
Subtotal reactant		
Primary	Not applicable	785/39
Secondary	12,550/628	11,765/589
Inert	4669/4619	880/855
Total	17,219/5247	13,430/1483

[a] Liftoff wt/burnout wt.

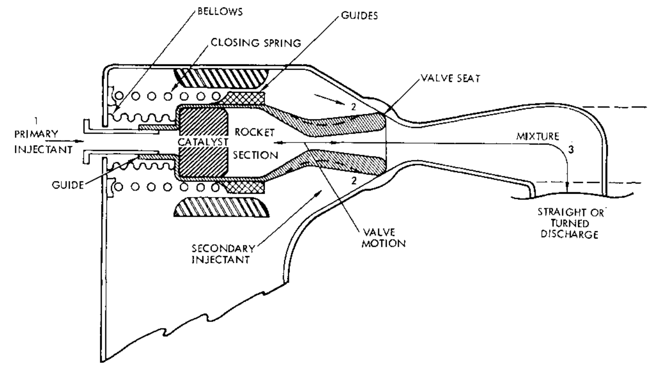

Fig. 2 Rocket-actuated, jet-pump valve schematic.

Weight Advantage of Jet-Pump System

A thorough design study was made of a standard LITVC system. Spherical pressurant tanks were located at the fore end of the rocket. Five percent of the total volume was allowed for ullage in the secondary tank, and 5% of total injectant weight was trapped in the lines at burnout. Maximum flow rate per nozzle quadrant was 786 lb/sec at an injector pressure drop of 550 psi. A total of 36 hydraulically actuated injector pintles were employed, 9/quadrant.

Hardware for the jet-pump system is not grossly unlike that of the standard system; major differences lie in the injector details. A spherical tank was used for the pressurant and a cylindrical tank for the secondary injectant. A small power source is required to operate the primary-injectant (H_2O_2) inlet valve for the rocket portion of the jet-pump. The jet-pump valve is self-actuating, eliminating the need for hydraulic actuation of a (nonexistent) secondary-injectant valve. The "pump" chamber pressure is assumed to be 450 psia, whereas the mixing chamber inlet pressure is roughly 15 psia (point 2 of Fig. 2). To achieve satisfactory penetration into the rocket jet, an injection velocity of 300 fps was used in the conservation equations; 300 fps is equivalent to about 600 psi pressure head. (This corresponds to the 590 psia in the standard injector plenum.) Calculations showed a 60°F temperature rise on the secondary injectant for a secondary-to-primary injectant weight ratio of 15 to 1. This correlates well with the experimental and analytical data.[1, 2]

The weight summaries for the two systems are compared in Table 2. At liftoff, there are 880 lb of inert weight for the jet-pump system (vs 4669 lb for the standard system) and, at burnout, 855 lb for the jet-pump system (vs 4619 lb for the standard). Thus, by using the jet-pump principle, a reduction of approximately 80% of the inert weight can be achieved for the particular engine and duty cycle studied. A total inert weight saving at liftoff of nearly 3800 lb/rocket is achieved.

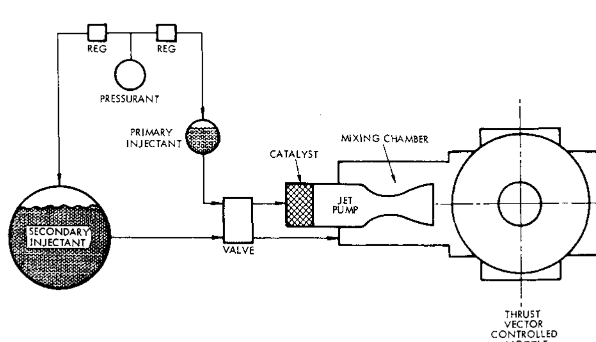

Fig. 3 Schematic: jet-pump LITVC system.

Conclusions

Calculated weights for the systems studied show an inert weight advantage of approximately 80% in favor of a jet-pump system. Translated into benefits applicable to a particular missile and orbit, the total savings would increase the payload of a two-solid-engine Titan III type missile system by approximately 300 lb at a 100-naut-mile orbit. Although the jet-pump principle is applicable to solid boosters or sustainers of virtually any size, it is likely that, below some particular size, the weight savings that accrue from low pressure would be nullified by minimum gage effects.

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Deployment of Parawings for Use as Recovery Systems

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RECENTLY the NASA Langley Research Center has conducted a series of investigations to study some of the problems of deploying parawings for the recovery of boosters and nonlifting spacecraft. These investigations were conducted by means of radio-controlled drop tests of free-flying dynamic models. All of the deployment tests were conducted at low subsonic speeds. The prime considerations of the investigations were the mechanics and sequencing of events for deployment and the dynamic stability and control characteristics of the configurations during the deployment.

Models

Four different configurations were investigated and are presented in Figs. 1–4. The models were not exact scale reproductions of any particular vehicle-parawing combinations. The first one (Fig. 1) consisted of a model of a rocket booster with a foldable rigid parawing. Its structural members (the leading edges, the keel, and the spreader bars) were fabricated from aluminum-alloy tubing and were so constructed that the leading edges could be retracted until they were parallel to the keel, and then the leading edges and the keel could be folded back on themselves to make the over-all packaged length approximately one-half of the keel length. The second (Fig. 2) comprised a blunted-cone, nonlifting spacecraft with a telescoping rigid parawing. Again, the structural members were made from aluminum-alloy tubing. After the leading edges were retracted against the keel, they could be telescoped three times, so that the over-all packaged length was approximately one-third of the keel length. The third configuration (Fig. 3) was similar to the second, except that the structural members of the parawing were inflatable fabric tubes. The fourth (Fig. 4) was a Gemini-type spacecraft with an inflatable parawing; its deployment sequence and the suspension line geometry were similar to that proposed for the Gemini vehicle.

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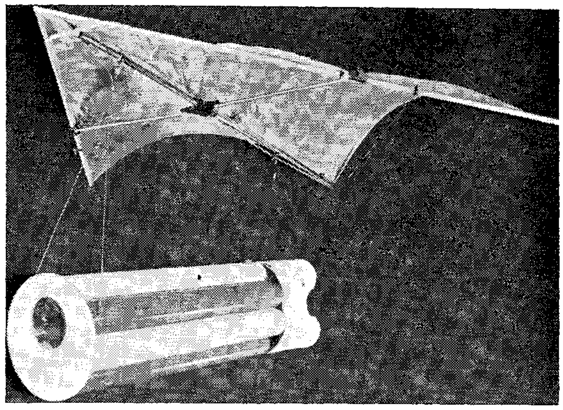

Fig. 1 Model booster and foldable parawing.

Results and Discussion

A separate investigation was conducted with each of the four parawing-vehicle combinations; detailed results of two of them are given in Refs. 1 and 2. These investigations were conducted somewhat in the manner of development projects, that is, they were intended to devise a successful method of deployment for each particular case, rather than to provide an exhaustive study of all possible deployment processes. Successful methods for deploying the parawings were developed in each case, but the development process involved trying a number of deployment steps, or features, that were not always successful. From these successes and failures, some general understanding of the problems and the importance of various features of the deployment process has been obtained. All of the deployment systems developed followed

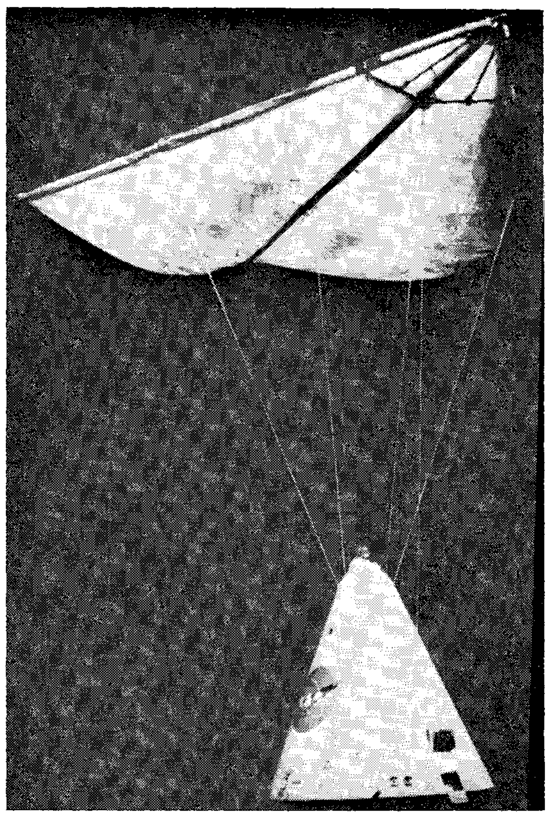

Fig. 2 Model spacecraft and telescoping parawing.