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Feasibility Study of LITVC for Shuttle SRB

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TECHNICAL PAPER

FEASIBILITY STUDY OF LITVC FOR SHUTTLE SRB

SUMMARY

The feasibility of using a Liquid Injection Thrust Vector Control (LITVC) system to perform the required thrust vectoring that is presently provided by the SRB baseline (flexible seal/hydraulic actuator) is investigated. Vector angle duty cycles ranging from 270 deg-sec and maximum vector angle of 6 deg to no vectoring requirement are considered. LITVC and baseline configurations are compared through the use of parametric curves to determine where the performance of one system crosses the performance of the other. The practicality of implementing LITVC is also considered.

LITVC was determined to be attractive for low to moderate duty cycles (< 100 deg-sec and 3.5 deg maximum angle), but unattractive for high duty cycle requirements (270 deg-sec and 6 deg maximum angle). LITVC does not look promising at the present time because of this restriction and the effort and difficulties associated with implementing the system.

INTRODUCTION

Liquid Injection Thrust Vector Control (LITVC) has many inherent qualities which make it attractive for thrust vector control on the Shuttle SRB. It would allow the use of a fixed thermal shield for the aft skirt and a fixed SRM nozzle. Stable, low-toxicity injectants and TITAN electromechanical injector valves are available. A blowdown tank with injectant may be small enough to fit within the aft skirt. LITVC is operational on several launch and post boost systems. These recognized qualities along with the LITVC effect on motor performance and the practicality of implementing a LITVC system on the SRB are considered.

DESCRIPTION

Duty Cycle

The first problem to be addressed is that of defining the Shuttle SRM vectoring duty cycle requirements. LITVC performance capability can be analyzed by using duty cycle requirements presented in either of two ways. If the duty cycle time versus vector angle can be accurately defined, sizing of the LITVC system can proceed by calculating a time plot of injectant mass flow rate and using the area under this curve to determine the quantity of injectant required. Unfortunately, it is not possible to construct a duty cycle which includes all requirements and contingencies. A second approach, which uses the total degree seconds and maximum deflection angle, is also acceptable for a feasibility study. This approach is acceptable because of the shape of the injectant specific impulse versus vector angle performance curve in the required operating region (Figure 3c). The curve can be closely approximated with a straight line. Using this linear approximation, an average vector angle (total deg-sec divided by time of operation) determines an average injectant specific impulse which is used to calculate the quantity of injectant required. This second approach is the one selected for use in this analysis.

ED13 provided duty cycle requirements. The following requirements were provided after considering the operational characteristics of LITVC.

Duty cycle degree-seconds: 270

Duty cycle maximum angle: (1) 5° from 0 sec to 25 sec SRM operation time.
(2) 6° from 25 sec to 40 sec SRM operation time.
(3) 6.36° from 40 sec to burnout.

The quantity of injectant required is not a function of the vector angle alone, but it is a function of vector angle and mass flow rate of the propellant combustion products out the nozzle. The worst combination of vector angle and propellant combustion product flowrate was found to be 6° at 13,438 lbm/sec. This reflects a maximum performance motor conditioned to 90°F.

Configuration

Sketches of the LITVC aft end SRM and injectant system configurations are presented in Figures 1 and 2, respectively. Sizing of the components shown was based on the 270 deg-sec and 6 deg maximum angle duty cycle. Figure 1 shows the flexible joint removed and nozzle inlet section restructured. Because of the high reactivity of the nitrogen tetroxide injectant with a carbon ablative, the nozzle exit cone is shown as silica phenolic instead of the carbon phenolic used on the baseline. The present carbon phenolic nozzle with a method of characteristics contour experiences particle impingement near the exit plane. Because silica phenolic is more sensitive than carbon phenolic to particle impingement, a parabolic contour was designed which does not show an impingement problem when analyzed using the Solid Performance Program (SPP). The parabolic contour results in a 0.17 sec decrement in SRM specific impulse. A honeycomb stiffening structure is shown on the outside diameter of the exit cone. LITVC creates wall pressures in the expansion cone 100 to 600 percent above normal nozzle static pressure, and the pressures may be as high as 50 percent of chamber pressure. Twenty-four injector valves, a manifold, a feed duct, and a blowdown injectant tank are also shown in Figures 1 and 2. For the 270 deg-sec/6 deg maximum angle situation, the injectant tank would be approximately 3.5 ft in diameter and

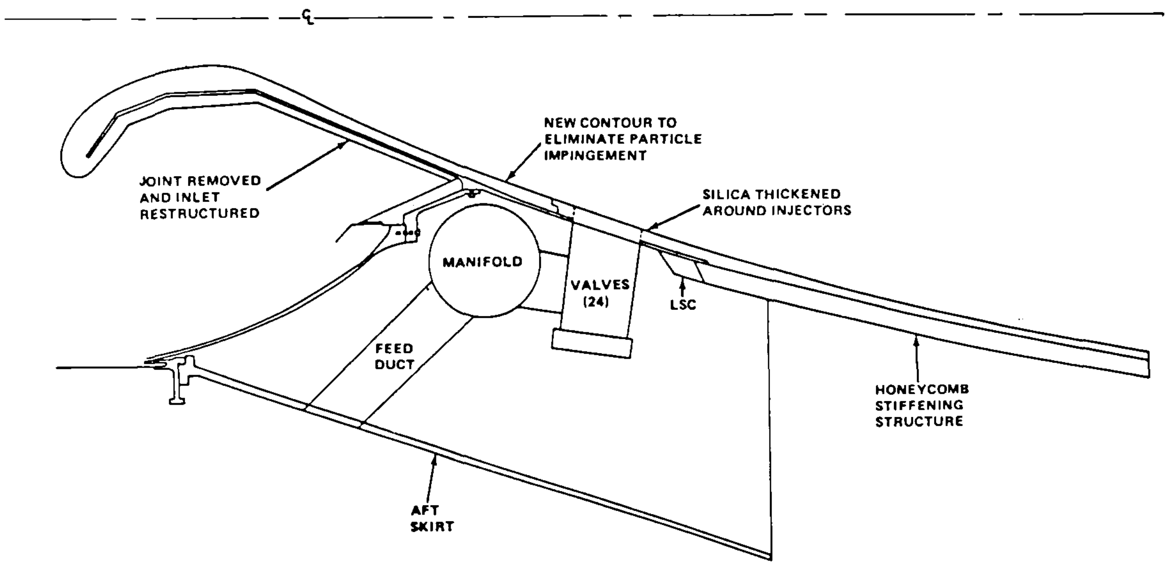


Figure 1. Aft end configuration.

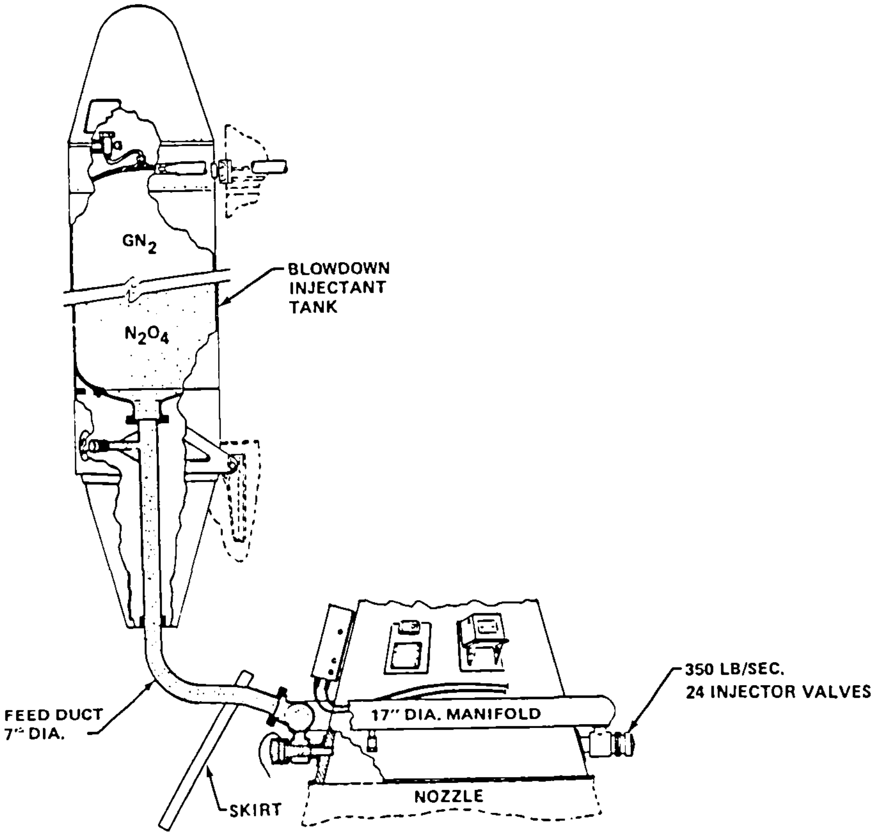


Figure 2. LITVC injectant system.

100 ft long. The feed duct and manifold would be approximately 7 in. and 17 in. in diameter, respectively. Each of the 24 injector valves must have the capability of flowing approximately 350 lbm/sec.

Performance Curves

Three performance curves (Fig. 3) were used in this analysis. All three curves were generated from Titan 5-segment data and represent the best data available at the time of

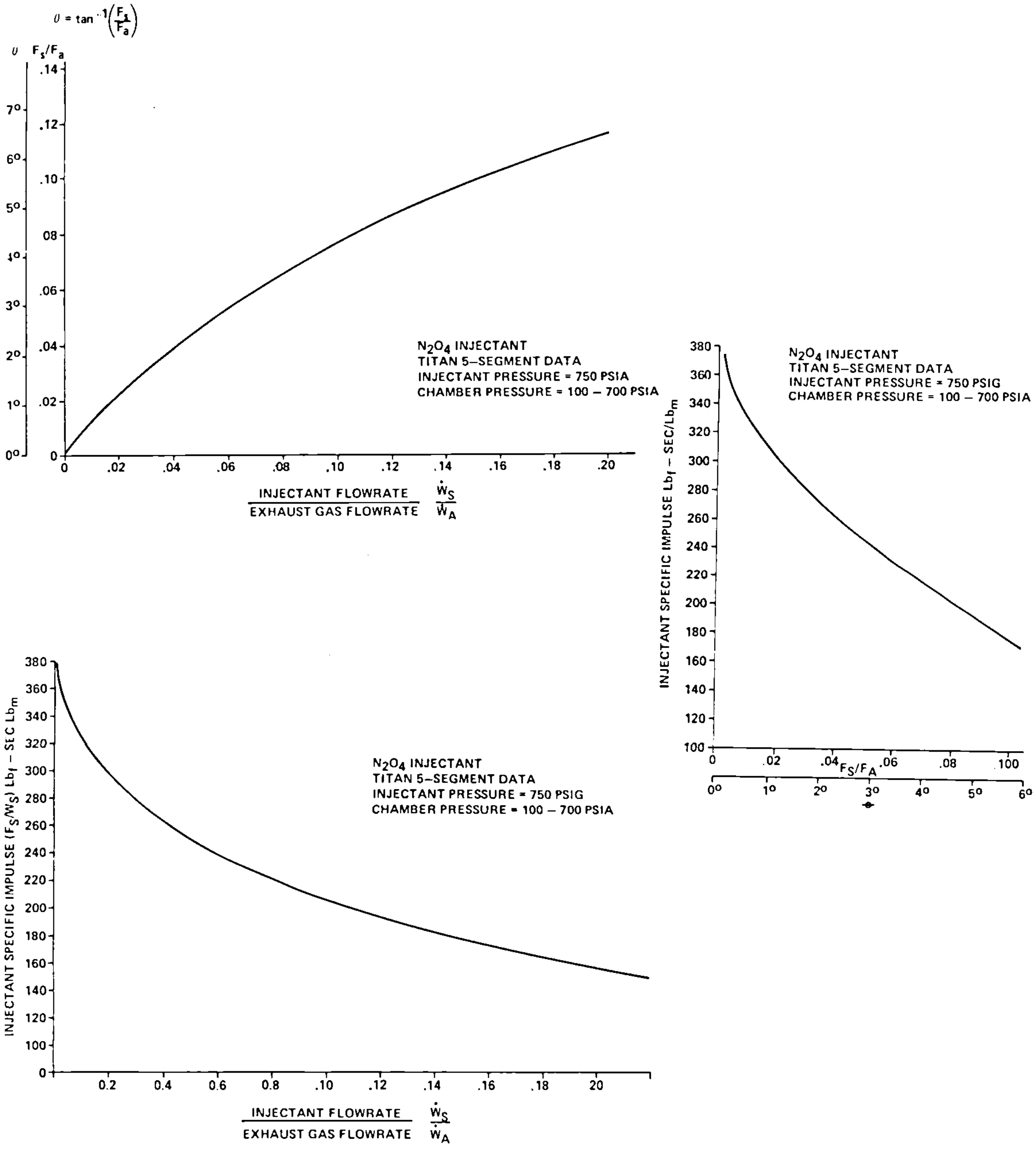


Figure 3. Performance curves.

this study. The methods of plotting and correlating LITVC data generally involve converting the data and parameters to dimensionless ratios that eliminate factors of secondary importance for LITVC (e.g., the parameters of the SRM). Thus, thrust vector capability is expressed as side-force specific impulse, the thrust vector deflection is the ratio of side thrust to axial thrust, and the injectant rate becomes the ratio of injectant flowrate to nozzle exhaust flowrate. Figure 3a presents the ratio of side force to axial force or deflection angle versus the ratio of injectant flowrate to exhaust gas flowrate. It reduces the scatter in data from motors that have varying chamber pressures and weight flowrates. Figure 3b is side specific impulse versus the ratio of side force or deflection angle. The data are shown in a form that is ready for use in estimating the fluid required and the maximum flowrates. Figure 3c is a convenient combination of the information already available in the first and second curves. Other useful and interesting plots are available and examples may be found in Reference 1. One such plot for strontium perchlorate is shown in Figure 4. An interesting observation of this plot is the increase in specific impulse the Minuteman contoured nozzle has when compared to the Polaris conical nozzle. Many other factors are involved (e.g., injection pressure, injector location,expansion ratio, expansion ratio at injection, SRM chamber pressure, and thrust), but the predominant factor in the increase in specific impulse appears to be the contoured nozzle. Strontium perchlorate has a side specific impulse range of 150 to 260 sec (Figure 4). An extrapolation of the Minuteman plot would yield a value of about 260 sec near zero deflection. Nitrogen tetroxide has a side specific impulse range from 180 to 400 sec. Observation of the Titan performance curves, generated with a conical nozzle, used in this study indicate a side specific impulse near zero deflection angle of about 380 sec. The possibility exists that performance generated with the Shuttle contoured nozzle may be significantly better than indicated in Figure 3. However, this is mere speculation.

LITVC Performance Analysis

Table 1 presents some of the results of the LITVC analysis. All parameters of the flexible seal and LITVC systems are reduced to a common denominator, equivalent weight on one SRB. Weights are divided into two categories, weight savings on the SRB baseline and weight additions to the SRB baseline. When the weight savings equal the weight additions, the LITVC system performance becomes attractive relative to the flexible seal performance. The greater the weight savings relative to the weight additions, the greater is the attractiveness of the performance of LITVC.

Weight savings on the baseline consist of the average axial thrust provided by the LITVC system and the elimination of the nozzle flexible seal, boot, auxiliary power units, and associated TVC equipment. The LITVC system provides axial thrust in conjunction with the side thrust. To take complete advantage of this axial thrust, a monitoring system is assumed which constantly compares injectant quantity remaining with projected needs. Any excess quantity would be periodically dumped equally through all injectors to reduce weight and provide additional axial thrust.

Weight additions to the baseline consist of LITVC tankage, distribution system, miscellaneous structure, pressurant, usable injectant, residual injectant, nozzle phenolic, a weight equivalent for the decrement caused by the nozzle contour change, and the nozzle honeycomb used to strengthen the nozzle extension.

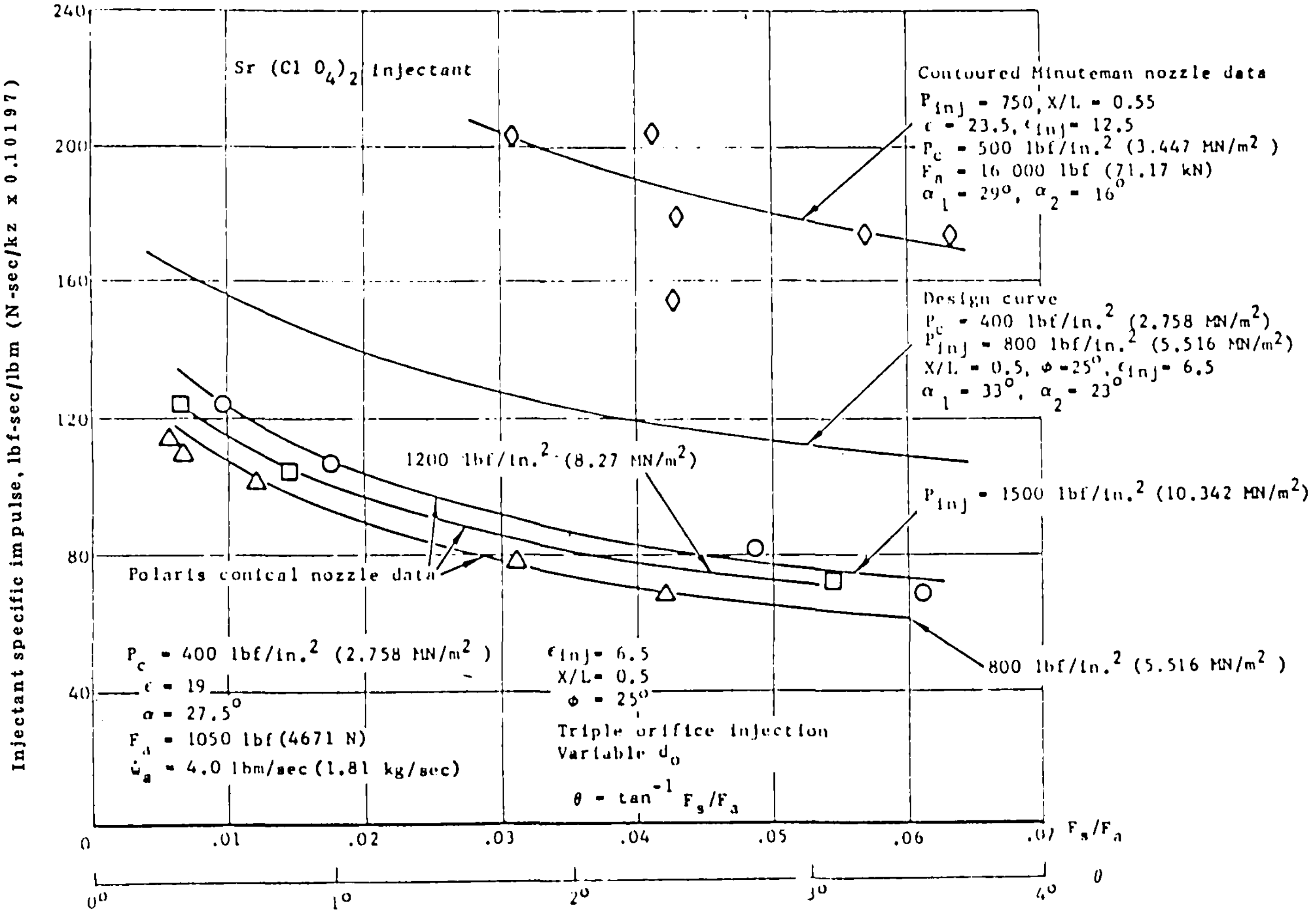


Figure 4. Contoured nozzle effects on injectant side specific impulse.

TABLE 1. LITVC PERFORMANCE ANALYSIS (ONE MOTOR)

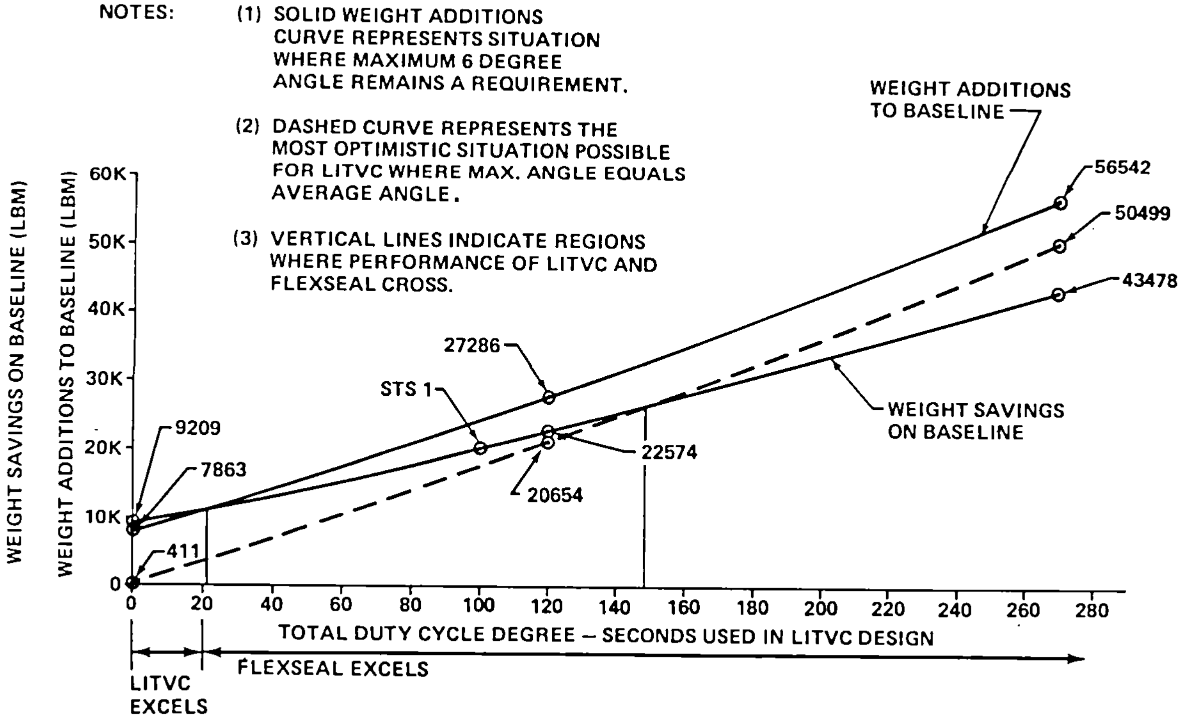
	$Sr(ClO_4)_2$	N_2O_4		
DUTY CYCLE	270 DEG-SEC 6 DEG MAX ANG	270 DEG-SEC 6 DEG MAX ANG	120 DEG-SEC 6 DEG MAX ANG	100 DEG-SEC 3.4 DEG MAX ANG (WORST CASE SEEN ON STS-1 FOR EACH PARAMETER)
WEIGHT SAVINGS ON BASELINE				
FLEXSEAL AND BOOT	7,500	7,500	7,500	7,500
TVC SYSTEM	1,709	1,709	1,709	1,709
INJECTOR AXIAL THRUST(3)	35,636	34,269	13,365	10,620
TOTAL	44,845	43,478	22,574	19,829
WEIGHT ADDITIONS TO BASELINE				
TANKAGE(3)	20,810	18,346	7,164	5,837
DISTRIBUTION SYSTEM(5)	13,566	6,632	6,632	3,099
MISCELLANEOUS STRUCTURE(3)(4)	6,308	3,263	1,708	1,391
PRESSURANT(3)	3,294	2,904	1,134	924
USABLE INJECTANT(1)(3)	30,835	19,395	7,558	6,159
RESIDUAL INJECTANT(3)	7,598	4,771	1,859	1,515
NOZZLE PHENOLIC	350	350	350	350
CONTOUR Isp DECREMENT(2)	411	411	411	411
NOZZLE HONEYCOMB	470	470	470	470
TOTAL	83,642	56,542	27,286	20,156

NOTES:
(1) AVERAGE VALUE FOR FLIGHT (USABLE INJECTANT AT LIFTOFF/2).
(2) CONTOUR WAS CHANGED TO ELIMINATE IMPINGEMENT ON SILICA EXPANSION CONE. WEIGHT PENALTY FOR Isp MUST BE DIVIDED BY 2 FOR ONE MOTOR.
(3) QUANTITIES WOULD CHANGE IF FEWER DEG-SEC WERE REQUIRED.
(4) WEIGHT SCALED USING RATIO OF TITAN AND SHUTTLE TOTAL FLUID WEIGHT PLUS TANKAGE WEIGHT.
(5) QUANTITY WOULD CHANGE IF MAXIMUM VECTOR ANGLE CHANGED. SCALED USING RATIO OF MAXIMUM FLOWRATES OF SHUTTLE AND TITAN INJECTANTS.
(6) NO DESTRUCT SYSTEM USED FOR TVC TANK.

Weight savings and additions are shown in the first column of Table 1 for strontium perchlorate and the 270 deg-sec, 6 deg maximum angle requirement. The performance decrement relative to the baseline is quite large. This was expected because of the low (relative to nitrogen tetroxide) specific impulse of strontium perchlorate. However, the results are shown because the compound has many desirable characteristics. It is stable in sealed storage, non-corrosive to stainless steels and aluminum, and low in toxicity. It has also been used extensively in other systems.

Results of the analysis using nitrogen tetroxide are shown in the remaining columns. Weight or weight equivalent deltas were calculated for 270 deg-sec/6 deg maximum angle, 120 deg-sec/6 deg maximum angle, and the actual STS-1 duty cycle. LITVC does not compare favorably with the baseline for either of the 6 deg maximum angle situations. However, it appears that LITVC would have performed on a par with the baseline for the duty cycle experienced on STS-1.

Figure 5 presents plots of the results shown in the second through the fourth columns of Table 1 along with the results of additional calculations. The solid "Weight Additions to Baseline" curve on Figure 5 shows the weight additions for LITVC systems designed to perform maximum deg-sec from 0 to 270 with a 6 deg maximum vector angle. The solid "Weight Savings on Baseline" curve shows the weight savings for LITVC systems designed to perform maximum deg-sec from 0 to 270. The maximum angle is not a factor in this curve. LITVC performance increasingly excels the baseline design for a 6 deg maximum


NOTES: (1) SOLID WEIGHT ADDITIONS CURVE REPRESENTS SITUATION WHERE MAXIMUM 6 DEGREE ANGLE REMAINS A REQUIREMENT.

(2) DASHED CURVE REPRESENTS THE MOST OPTIMISTIC SITUATION POSSIBLE FOR LITVC WHERE MAX. ANGLE EQUALS AVERAGE ANGLE.

(3) VERTICAL LINES INDICATE REGIONS WHERE PERFORMANCE OF LITVC AND FLEXSEAL CROSS.

Figure 5. Flexseal/LITVC performance crossover diagram.

angle as deg-sec decreases below the point of intersection (approximately 20 deg-sec) of the weight savings and solid weight additions lines. The baseline configuration increasingly excels as deg-sec increase above the intersection.

The dashed curve in Figure 5 represents the most optimistic situation possible for LITVC, i.e., where the maximum vector angle equals the average vector angle. This is, of course, unattainable because the maximum angle could never realistically be as low as the average angle. The intersection of the weight savings line and the dashed line (approximately 150 deg-sec) is the point above which LITVC could never be expected to perform better than the baseline flexible seal.

Sample calculations of values used in Table 1 and Figure 5 are included in the Appendix.

LITVC Advantages and Disadvantages

LITVC advantages and disadvantages are presented in Table 2.

TABLE 2. LITVC ADVANTAGES AND DISADVANTAGES

ADVANTAGES

- A simplified SRB aft end design with a fixed nozzle and fixed heat shield.
- LITVC components are probably reusable.
- System is easily serviced and checked out.
- LITVC provides a rapid vectoring response time.
- Long term storage of the injectant is possible.
- LITVC performance is good for low duty cycle requirements.

DISADVANTAGES

- LITVC performance efficiency is degraded by large vector angle requirements.
- Design requirements must be well defined prior to hardware freeze.
- Initial design must be performed using performance data from previous programs.
- Nitrogen tetroxide is a highly toxic substance which requires special handling procedures.
- Nozzle chemical recession is increased adjacent to LITVC ports.
- External tank and fuel line required for large duty cycle.
- Long storage periods require replenishment of injectant and pressurant.
- Lacks flexibility for accommodation of changes in control requirements. Usually systems are overdesigned and later revision downward is inefficient.

CONCLUSIONS AND RECOMMENDATIONS

LITVC does not look promising with duty cycle requirements above 20 deg-sec if a 6 deg maximum angle is required. However, the performance does look promising for moderate to low duty cycle requirement (e.g., < 100 deg-sec and 3½ deg maximum angle).

Appreciably higher side force specific impulse may be achieved with a contoured nozzle as compared to the Titan conical nozzle. Nitrogen tetroxide performance curves for large motors with contoured nozzles are needed to facilitate design.

A small fixed cant angle or greater use of SSME TVC could potentially reduce SRB duty cycle requirements.

LITVC for Shuttle is not attractive at this time because: (1) long implementation lead time would be required because of the long lead hardware involved, (2) additional component and system tests to support Qualifcation Motors would be required, and (3) advantages do not presently outweigh disadvantages.

REFERENCES

1. Solid Rocket Thrust Vector Control, NASA SP-8114, dated December 1974.

APPENDIX

SAMPLE CALCULATIONS

Sample Calculations (N_2O_4)
270 Deg-Sec, 6 Deg. Max. Angle at 13,438 Lbm/Sec. Exhaust Flow)

Weight of Injectant

Assume:
(1) Injectant Pressure $\simeq$ 2 x SRM Chamber Pressure
(2) Average Deflection Angle = 2.25 Deg.
(3) Burn Time = 120 Sec.
(4) Side Injectant Specific Impulse = 270 Sec. (from Performance Curves)
(5) Average Axial Thrust = 2.223 x 10^6 Lbf
(6) Linear Performance Curve in Region of Operation
(7) Duty Cycle = 270 Deg-Sec.

Total Side Impulse Required = Motor Axial Thrust x Burn Time x Tan of Average Vector Angle.
= $(2.223 \times 10^6)(120)(\text{Tan } 2.25)$
= 10,472,948 Lbf-Sec.

Weight of Injectant Required = 10,472,948/270
= 38,789 Lbm

Total Injectant Required = Weight of Injectant Required + 0.123 x Weight of Injectant Required.
= 38,789 + (38,789) (.123) = 43,560 Lbm

Total Volume of Injectant $= \frac{43{,}560}{90} = 484 \text{ Ft}^3$

Weight of Pressurant

Assume:
(1) 1200 Psi Initial Pressure, 600 Psi Final Pressure
(2) Perfect Gas
(3) Nitrogen Gas

Total Volume of TVC Tank = Volume of Injectant + Volume of Nitrogen
= 484 + 484
= 968 Ft^3

$$\text{Density of Nitrogen at 600 Psi} = \frac{\text{Constant x Pressure x Molecular Weight}}{\text{Universal Gas Constant x Temperature } (\text{R}^\circ)}$$

$$= \frac{(144)\,(600)\,(28.08)}{(1545.3)\,(520)}$$

$$= 3.0 \text{ Lbm}/\text{Ft}^3$$

$$\begin{aligned}\text{Weight of Nitrogen} &= \text{Density x Volume}\\ &= (3.0)\,(968)\\ &= 2904 \text{ Lbm}\end{aligned}$$

Tankage Weight

Assume: Titan Tank Diameter Lengthened to Accommodate Shuttle Injectant and Pressurant.

$$\text{Tankage Weight} = \frac{\text{Total Volume of Shuttle Tank} \quad (\text{Titan Tank Weight})}{\text{Total Volume of Titan Tank}}$$

$$= \left(\frac{968}{201.4}\right)(3817)$$

$$= 18{,}346$$

Miscellaneous Structure Weight

Assume: Scale-Up of Titan Using Ratio of Injectant + Pressurant + Tankage Weight of Shuttle to Titan.

$$\text{Miscellaneous Structure Weight} = \left(\frac{43{,}560 + 2{,}904 + 18{,}346}{8{,}424 + 636 + 3{,}817}\right)(870)$$

$$= 3{,}263 \text{ Lbm}$$

Distribution System Weight

Assume: Scale-Up of Titan Using Ratio of Maximum Flowrates of Shuttle and Titan Injectants.

$$\text{Maximum Injectant Mass Flowrate} = \left(\frac{\text{Injectant Flowrate}}{\text{Exhaust Gas Flowrate}}\right)(\text{Exhaust Gas Flowrate})$$

$$\begin{aligned}&= (.157)\,(13{,}438)\\ &= 2{,}110 \text{ Lbm/Sec}\end{aligned}$$

$$\text{Maximum System Weight} = \frac{\text{Maximum Injectant Flowrate of Shuttle}}{\text{Maximum Injectant Flowrate of Titan}} \times \text{(Titan Distribution System Weight)}$$

$$= \left(\frac{2{,}110}{600}\right)(1{,}886)$$

$$= 6{,}632$$

Average Axial Thrust from LITVC

Assume: $\alpha_{inj} = 16$ Deg.

$I_{sp(s)(0=0°)} = 370$ Sec. (from Performance Curves)

$W_s = \frac{38{,}789}{120} = 323$ Lbm/Sec.

$$\Delta F_a = I_{sp(s)(0=0°)}\, W_s \operatorname{Tan} \alpha_{inj}$$

$$= (370)\,(323)\,(\operatorname{Tan} 16°)$$

$$= 34{,}269$$

where

F_a = Axial Thrust Added by Injectant, Lb_f

$I_{sp(s)(0=0°)}$ = Specific Impulse of the Liquid Injectant in the Side Direction at 0 Deg Deflection, Lb_f - Sec/Lbm

W_s = Flowrate of Liquid Injectant, Lbm/Sec

α_{inj} = The Equivalent Half Angle of the Nozzle from the Injection Point to the exit, Deg.

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16. ABSTRACT

This report presents an analysis of a Liquid Injection Thrust Vector Control (LITVC) system for the Shuttle Solid Rocket Booster (SRB). A performance analysis which compares LITVC with the SRB baseline flexible seal is followed by a table of LITVC advantages and disadvantages.

The analysis concludes that LITVC does not look attractive for use on the SRBs at the present time because of the high duty cycle requirements and the cost and effort associated with implementing a major complex system.

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