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APRIL 1971 J. SPACECRAFT VOL. 8, NO. 4

Development of a Fluidically Controlled Hydrazine Roll-Rate Control System

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A program was undertaken to design, develop, test and deliver three rocket engine modules (REM's) for flight feasibility testing on a re-entry test vehicle. These units, which provide positive/negative roll torques, consist of four hydrazine monopropellant engines, a propellant tank, pressurant tank, pressure regulator with pyrotechnic isolation, and a fluidically controlled propellant valve. Each REM, when coupled with a fluidic sensing and logic module, comprises a closed loop, fluidically controlled Roll-Rate Control System (RRCS) requiring no electrical power for operation. This paper describes the REM requirements, unique features and test results.

Introduction

IN April 1969 Sandia Laboratories contracted with Hamilton Standard, Division of United Aircraft Corporation, to design, test, fabricate and deliver three rocket engine modules (REM's) for flight feasibility testing. These REM's (Fig. 1), when coupled with fluidic sensing and logic modules developed by Sandia Laboraties, form self-contained, self-powered, closed-loop, roll-rate control systems (RRCS). These feasibility systems will be used to demonstrate, inflight, control of the resonant pitch-roll coupling phenomenon found in re-entry test vehicles. Roll-rate control torques are applied by two sets of hydrazine monopropellant rocket engines firing in pairs (Fig. 2). Except for the pyrotechnic system initiation, the RRCS is completely self-contained with sensing, logic and firing control of the engines accomplished fluidically without the use of electrical power. This approach provides system simplicity and reliability and reduces the system weight by eliminating the need for stored electrical power. Positive propellant expulsion is accomplished by the metallic diaphragm incorporated in the propellant tank. The over-all RRCS is packaged on a mounting frame and is designed to fit a limited envelope.

The program described in this paper was undertaken to provide flight feasibility hardware within a limited schedule. To minimize technical and schedule risks, conservative design margins where applicable, and proven components (by test or flight experience) were employed. An equally important consideration was the ability to ultimately incorporate, with minimum technical risk, the principal features of this system into a production unit.

The REM portion of the program was successfully concluded at Hamilton Standard with the completion of ground tests during which all major technical and performance objectives were met. The delivery of three flight REM's completed the program.

System Requirements

The system design requirements were based on the needs of the ultimate flight production units; they allow for the

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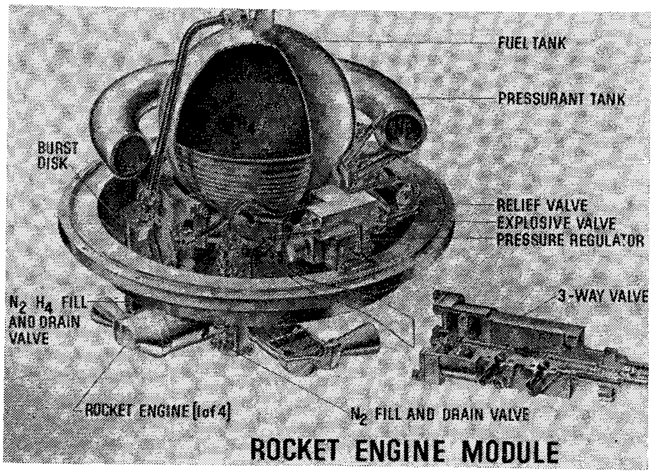

Fig. 1 Rocket Engine Module.

technological improvements and advances in state-of-the-art normally associated with long-range development and production programs. For the present hardware feasibility program, the requirements were modified as necessary to permit utilization of available technology and proven design concepts, while yet demonstrating the feasibility of concepts directly benefiting the longer range production design. The principal long-range requirements are:

1) A torque of $18.4_{-2.4}^{+5.6}$ ft-lb in either direction, on command.

2) A minimum of 225 ft-lb sec of total impulse.

3) A specific impulse of 196 lb_f sec/lb_m minimum at an ambient pressure of 2.0 psia with a 10:1 expansion nozzle.

4) The following REM response characteristics: Initial pulse: $T_{90} = 200$ msec; $T_{10} = 50$ msec. All others: $T_{90} =$ 50 msec; $T_{10} = 50$ msec. Here "response" is the time from the inception of the fluidic signal at the valve driver outlet until the specified P_c condition is achieved; T_{90} is the time to rise to 90% of achieved chamber pressure; and T_{10} is the time to decay to 10% of achieved chamber pressure.

5) Storage of the fully loaded and charged system for periods up to 10 yr.

6) Survival of mission environments.

7) No need for onboard electrical power.

8) Minimal all-up wet weight and envelope/volume of the REM.

9) Storage capability for fluidic power.

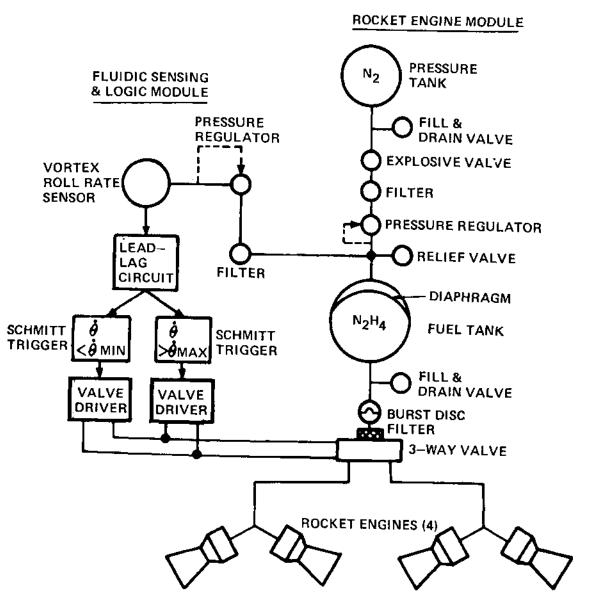

Fig. 2 Roll-rate control system (RRCS) schematic.

During the feasibility program, virtually all of these requirements, except the 10-yr storage and minimum weight and volume requirements, were specifically demonstrated. Since the flight test vehicle had ample capacity, a total volume of nearly 900 in.^{3} was made available. The REM dry weight was established at 13.1 lb. The schedule established for this program required that all three REM's be delivered in nine months.

System Description

The RRCS (Fig. 2) senses the instantaneous roll rate and compares it with a desired value; if it is beyond specified limits, fluidic signals are transmitted to the REM which provides positive or negative torque as required. The flight feasibility REM is a pressure-regulated, positive-expulsion system. The toroidal pressurant tank is sized to contain nitrogen for both propellant expulsion and fluidic module power. The spherical propellant tank incorporates a metallic diaphragm for positive propellant expulsion and for minimizing center-of-gravity shifts during both the operational spin mode and during the application of acceleration forces.

The pressurant is loaded into the toroidal tank through a fill and vent valve. The initial charging pressure of the nitrogen is 3500 psia at 70°F. Pressurizing the GN_2 tank pressurizes the system up to a normally closed pressurant isolation valve. The pressure regulating valve is protected from squib-generated and GN_2-entrained contaminants by a 40-μ absolute filter located between the squib and the regulating valve. The GN_2 relief valve is a spring-loaded poppet valve with a cracking pressure of 760 ± 38 psia and a reseat pressure of 684 psia minimum. It is sized to vent overboard the unregulated GN_2 in the event of a regulator-open failure, removing the possibility of rupturing the propellant tank. In this mode, it is possible to complete a portion of the mission using torque produced from the unregulated propellant supply.

A burst disk and filter, packaged in a common assembly, are located between the propellant tank and the pneumatically operated 3-way valve to insure positive separation of the unpressurized propellant and the thrust chambers prior to system actuation. The Inconel burst disc is cross-scored to prevent fragmentation at rupture, which occurs between 150 and 300 psid. The filter has a 20-μ nominal, 40-μ absolute capability.

The squib isolation valve, the nitrogen filter and the nitrogen pressure regulator are located in a pressurant module to facilitate packaging and to reduce system weight. The normally closed squib valve is activated by an electrical signal through a bridge wire circuit. Upon squib actuation, the piston ruptures a flow-blocking shear seal, allowing the high-pressure nitrogen to flow to the regulating valve, which is a single-staged, balanced-poppet, spring-loaded device adjusted for pressure regulation between 440 and 480 psia with inlet pressures ranging from 4140 to 600 psia. The

Table 1 REM weight summary

Component	Weight, lb
Thrust chamber assemblies (4)	2.45
Propellant tank	2.87
Pressurant tank	3.43
Fill & drain & vent valves	0.19
Pressurization module	0.54
3-way valve	0.73
Relief valve	0.11
Mounting structure and brackets	0.99
Miscellaneous hardware	1.80
Total dry weight	13.11
Propellant (N_2H_4) 98 in.^{3}	3.54
Pressurant (GN_2) 48 in.^{3}	0.52
Total net weight	17.17

Table 2 Thrust chamber performance (thrust chamber only)

Thrust	21.6	
Chamber pressure	200 psia	
Inlet pressure	376 psia	
Expansion ratio	10:1	
Specific impulse	203 sec min at 2.0 psia ambient	
Weight	0.61 lb	
Response	T_{90}	T_{10}
1st pulse	30 msec	32 msec
Other pulses	18 msec	33 msec

regulator is sized to flow 10 standard ft^3/min of GN_2 with an inlet pressure of 600 psia at 70°F. Provisions have been incorporated for repeated refurbishment of the module after firing of the squib. This involves replacement of the squib, shear seal and "O" rings.

Firing of the squib and subsequent pressurization of the propellant ruptures the burst disc, allowing the pressurized propellant to flow to the pneumatic 3-way valve. A fluidic signal, generated by the fluidic sensing and logic module, provides the intelligence to direct the valve to either remain in a neutral position or to distribute propellant to either pair of thrust chambers which provide positive or negative roll control torques.

The REM weight summary is shown in Table 1.

Key Features

The hydrazine rocket engines (Table 2) are slight modifications of engines developed by Hamilton Standard and used on an earlier application.

Each thrust chamber incorporates an injector, thermal stand-off, a catalyst bed and an exhaust nozzle. An in-line orifice is used to match the chamber pressures of the engines to achieve the necessary thrust matching. Capillary tubes fabricated from Inconel 600 transport propellant from the inlet manifold into the Shell 405 ABSG catalyst, providing very short response times while minimizing the entry velocity of the propellant into the reactor bed and preventing hydraulic milling of the catalyst and subsequent channeling of the bed. Spacing of the injector elements provides uniform distribution of the propellant in a manner that wets the maximum amount of catalyst. A thermal stand-off is located between the reaction chamber and the propellant inlet manifold to reduce heat soakback to the injector to an acceptable level. A right-angle, 10:1 area ratio conical nozzle is used to facilitate mounting of the engines into the REM. The thrust chamber is fabricated from Inconel 600, which offers good high temperature characteristics and is resistant to nitriding in the ammonia rich environment.

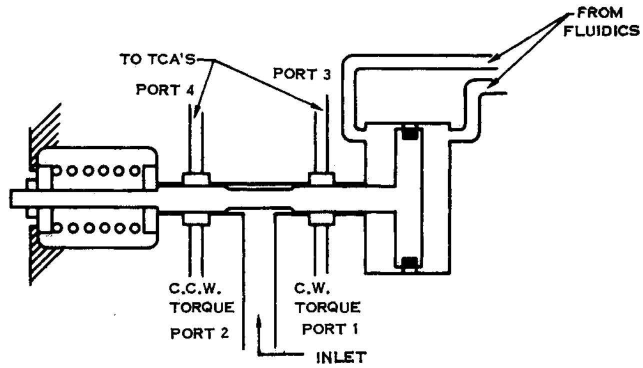

Fig. 3 3-Way valve.

A fluidically actuated pneumatic 3-way propellant control valve (Fig. 3) is utilized to distribute the hydrazine, on command, to two pairs of thrusters. In its neutral position, with no signal, it shuts off propellant flow to the engines. It directs flow to either pair of thrusters to provide positive or negative roll control torque, as commanded, by the fluidic sensing and logic module. It comprises an actuator, a spool valve, a centering device, and a fluidic interface. The actuator employs a flat plate piston using an "O" ring with a teflon outer slipper seal to minimize actuator friction. The actuator piston slides in a valve housing bore and is attached to the spool valve. Right or left valve actuation is obtained through

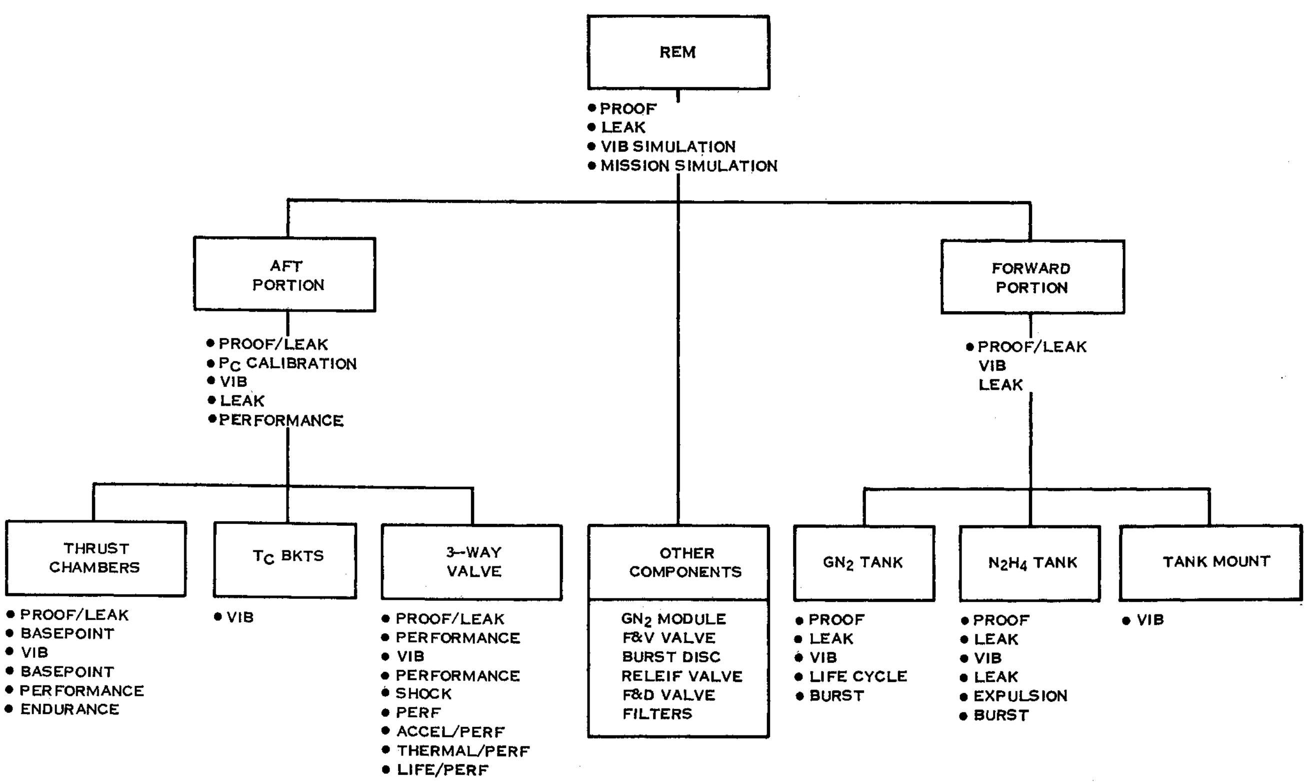

Fig. 4 Design verification test summary.

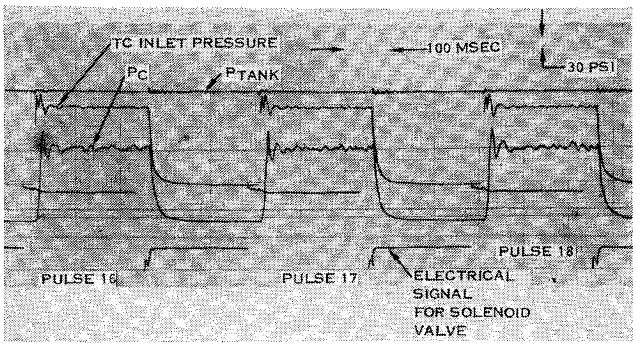

Fig. 5 Pulse mode operation.

the application of a pneumatic pressure supplied by the fluidic valve driver. The valve is designed for operation with a 10-psid actuating force across the piston. With the spool in the null position, there is a 0.125-in. overlap between the propellant inlet and outlet ports. This, coupled with a 0.0003- to 0.0005-in. diametral clearance between the spool and the bore, reduces leakage to an acceptable level. A bleed port located between the propellant outlet port and the actuator bore prevents hydrazine leakage into the actuator. The spool is chrome-plated to prevent galling. A preload spring serves as the valve centering device returning the valve to null upon termination of the valve driver signal.

The 7.5-in.-ID, toroidal GN_2 tank is fabricated from Inconel 718 sheet stock and hot-formed into two transverse halves by spinning. This technique provides relatively uniform wall thickness with good surface characteristics. Butt welding of the two halves is closely controlled, with a 0.005-in. maximum allowable surface mismatch to insure proper weld penetration and to reduce stress concentrations in the weld joint. Wall thickness, based on a 2:1 safety factor at a burst pressure of 8700 psid, varies from 0.062 in. at the inside of the toroid to 0.056 in. at the outer diameter. Radial slots are provided in the three mounting lugs to allow for pressure expansion.

The hydrazine propellant tank produced by Arde, Inc., is a 6.125-in.-diam sphere incorporating a metallic expulsion diaphragm. The philosophy of reducing risks resulted in selecting a tank/diaphragm combination of 108-in.^{3} swept volume as compared to the 85.5 in.^{3} required. The hemispherical diaphragm is 0.010 in. thick and is fabricated from AISI 304L (as is the tank) and is reinforced by concentric circular wire rings to ensure a proper rolling action. Initial diaphragm actuation pressure is 40 psid. The tank mounting lugs and ports are welded to the tank halves before the final girth weld is made. Both tank halves and the diaphragm are welded with a specially developed girth weld in a single pass.

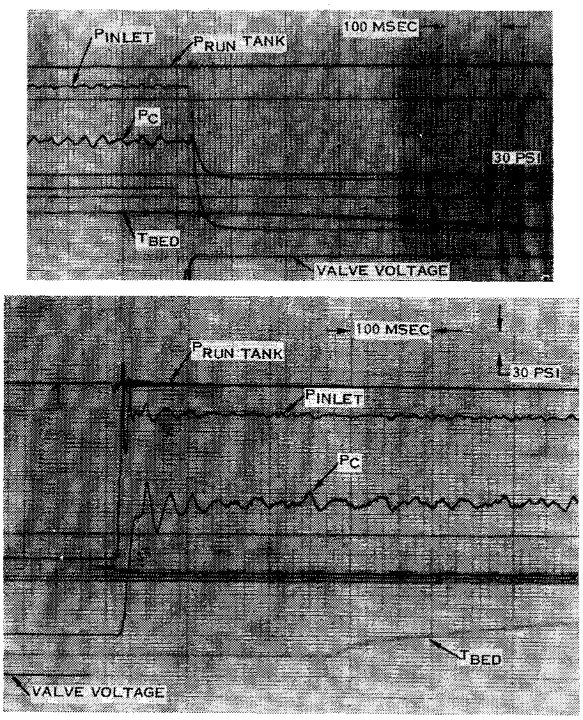

Fig. 6 Steady-state operation.

Table 3 Engine characteristic performance

	T_{90}, msec	T_{10}, msec	Roughness, % P_c	I_{sp},[a] sec
a) Before vibration	15	28	±7	211
After vibration	16	31	±7	209
b) Before	18	32	6	209
Midpoint	18	35	8	207
After	19	35	9	209

[a] At 2.0 psia ambient and 10:1 expansion ratio.

The fluidic sensing and logic module developed at Sandia currently has a control band of $\pm\frac{1}{2}$ rps about the nominal roll rate. The fluidic vortex sensor, which is 1.7 in. in diameter, contains a 1-in.-diam coupling ring and an airfoil pickoff. Dynamic compensation is provided by a lead-lag network, and the maximum and minimum roll rate set points are detected by Schmitt triggers. The valve driver consists of two bistable power amplifiers working in parallel to provide neutral, command-clockwise and command-counterclockwise signals to the 3-way valve. All of the fluidic elements except the rate sensor, are manufactured by etching using a photochemical process.

Table 4 Performance test duty cycle

Mode	T_{on}, sec	T_{off}, sec	Number of pulses
Pulse	1.0	3.0	1
	0.5	0.5	4
	0.5	3.0	1
	0.25	0.25	9
	0.25	3.0	1
Steady-state	15.0	...	...

Test Results

Figure 4 identifies the design verification tests (DVT) conducted during the REM feasibility program. The REM was divided into forward portions to facilitate system assembly and test by providing parallel path operation. The forward portions consisted of the two tanks, the small components and the associated plumbing. The aft section consisted of the thrust chambers with inlet tubes and the 3-way valve. It was necessary to fire each aft portion individually to allow P_c calibration of all thrusters to insure the required torque balance on the system level.

Thrust chamber design verification tests

The DVT series for the thrust chamber, which was an existing engine modified by altering the mounting configuration

Table 5 Three-way valve performance summary

		Flow at 25 psid, lb/sec	Response T_{on}, msec	Response T_{off}, msec
Previbration	Ports 2 and 4	0.318	16	22
	Ports 1 and 3	0.297	16	18
Postvibration	Ports 2 and 4	0.338	16	21
	Ports 1 and 3	0.306	17	18

Table 6 REM performance values

	T_{90}, msec	T_{10}, msec	P_c, psia
1 TC	29	38	212
3 TC	30	38	216

and converting the axial nozzle to a 90° exit nozzle (with no measurable performance change) included the basepoint tests before and after exposure to the vibration environment and the performance/endurance test sequence. An electrical solenoid valve was used because the pneumatically actuated 3-way valve was still in the component development stage. Use of the solenoid valve resulted in a 150% increase in the propellant hold-up volume between the valve seat and the thrust chamber injector manifold, and it increased the total response times, both on and off, by 50%. Therefore, the response data in this section are for the thrust chamber only and do not include the valve response time.

Exposure to the vibration environment involved mounting two thrust chambers on the thruster flight mounting bracket, hard-mounting the bracket to the vibration fixture and inputting the vibration environment to the base of the fixture. The sinusoidal input vibrational environment, common for all component vibration tests, is: 10–31 Hz (±2%): 0.2 ± 0.02 in. double amplitude; 31–2000 Hz (±2%): 10 g.

The thruster principal resonant frequency occurred near 600 Hz where peak amplification factors were observed. Other minor resonances were observed between 1400 Hz and 1600 Hz, but the transmissibility factors in this range

Table 7 REM response times (msec) at *g*-levels

		1*g*	60*g*	110*g*
Ports 2 and 4	On	30	31	41
	Off	29	30	40
Ports 1 and 3	On	31	33	53
	Off	31	30	32

were greatly reduced limiting the possibility for significant structural damage. As shown in Table 3a, a small, but predictable shift in thrust chamber response was noted due to the exposure to the vibration environment for the specified 45 min. A summary of the thrust chamber performance acquired from basepoints taken before, during and after the endurance test is shown in Table 3b.

After the post vibration basepoint was recorded, the thruster was subjected to an endurance/performance evaluation consisting of ten cycles of the performance test shown in Table 4. Thrust chamber test traces, taken after exposure to vibration, are shown in Figs. 5 and 6.

3-Way valve design verification tests

Since this application is a new one for this type valve, special attention was directed toward identifying performance on the component level, in all anticipated environments. The test sequence conducted is shown in Fig. 7, and all valve tests used the fluidic valve driver for actuation. Results of performance checks before and after exposure to the input vibrational environment are shown in Table 5. The valve

Table 8 Tank test results

	N_2H_2 tank	GN_2 tank[a]
Leakage, scc/sec (He)	2×10^{-10}	1×10^{-6}
Expulsion, %	91.6 at 40 psid 95.2 at 500 psid	
Burst pressure, psia	2830	12,700 S/N 3 12,000 S/N 5 9,200 S/N 7

[a] Design burst pressure = 8696 psia min.

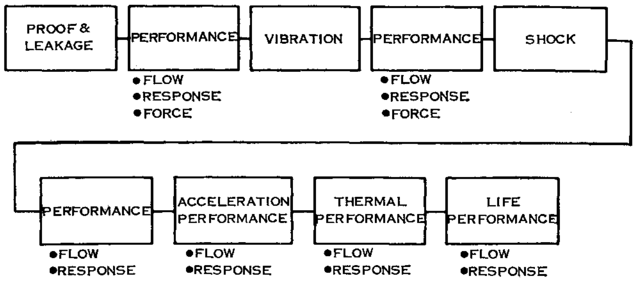

Fig. 7 3-Way valve DVT sequence.

(Fig. 3) was initially designed for a balanced ON/OFF response with 10 psid across the actuating piston. Improvements in the fluidic module during the program resulted in 14 psid being made available. This additional power resulted in improving opening response from the balanced condition, as noted in Table 5. No change was observed in closing response due to the additional power available since T_{off} is dependent primarily upon the closing spring force.

Table 9 Performance of REM in design verification tests[a]

Item		Requirement	Demonstrated
Torque, ft-lb		$18.4^{+5.6}_{-2.4}$	18.24 @ 2 psia amb
Total impulse, ft-lb-sec		225 (min)	316
Specific impulse, sec		196 @ 2.0 psia	210, 211, 211 & 214 on four TC's in REM
Response, msec			
1st start:	T_{on}	200	134
	T_{off}	50	43
Other starts:	T_{on}	50	25
	T_{off}	50	42
P_c roughness, %		±10	±7

[a] These tests were conducted using the original 3-way valve return spring. The modified spring increased the force margin and biased valve in the off direction to improve performance at 110 *g*'s and to equalize on/off response.

Figure 8 shows the 3-way valve/thrust chamber response. The trace shows the third pulse in a ten-pulse train obtained firing the aft portion of REM S/N 02 during P_c calibration. The two P_c traces are of the 1 and 3 TC's, producing clockwise torque. The data indicates the performance values shown in Table 6 and include the response contributions of both the valve and the thrusters.

Since the RRCS must function in the deceleration flight environment, the entire test setup and valve were mounted

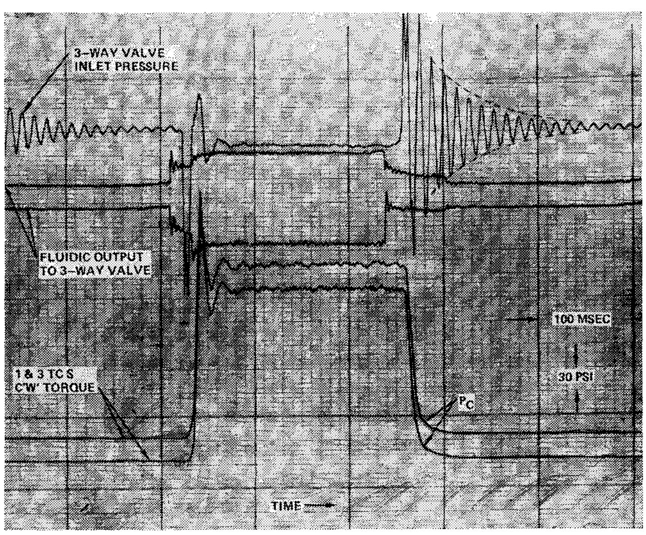

Fig. 8 Response trace-TC/3-way valve.

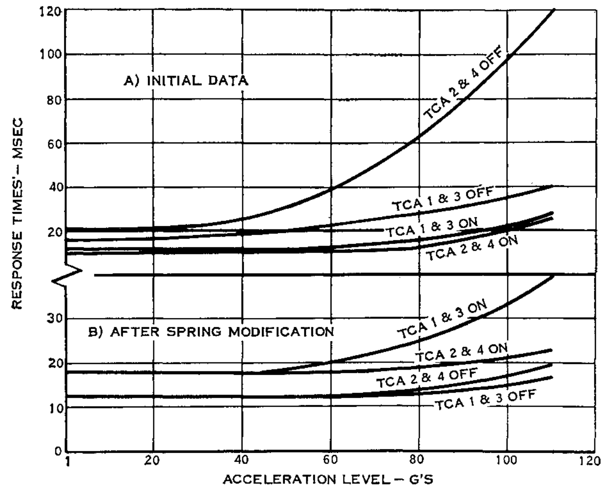

Fig. 9 Acceleration performance data.

in a centrifuge at Hamilton Standard, and tests were conducted at acceleration levels up to 100 g's in a plane perpendicular to the spool axis and at 20 g's parallel to the valve axis. The initial test results for the valve are shown in Fig. 9. The increase in off-response at g-levels above 60 g's was excessive when compared to the total REM requirement of 50 msec. The valve is notably affected by the acceleration environment in the off direction, when driven solely by the spring. Further, ports 2 and 4 in the off direction require 120 msec to close. This latter condition is encountered when the valve is stroked to a position which increases the effect, on the valve, of the overhung mass of the spring and spring seats. At high g-levels, this cantilevered mass results in a significant contribution to frictional forces tending to overpower the available spring return force. The spool return spring was redesigned to increase the return spring force and to provide a bias force in the closing direction, and the acceleration/performance test was rerun (Fig. 9). In general, the return spring modification improved and reversed the response characteristics to bias the valve toward the closing direction. The net effect was that at only one point was valve response a concern. As shown in Table 7, the expected REM torque response for TC's 1 and 3 (clockwise torque) from fluidic signal on to rated torque at 110 g's is 53 msec. A reduction in this value is readily achieved by reshimming the valve return spring.

To conclude the DVT portion of the 3-way valve test program, thermal performance and cycle life tests were conducted. Operation at the two temperature extremes of 40°F and 160°F resulted in no measurable performance shift. A cycle life test, 1000 complete cycles of right-null-left-null, was conducted with the on time varying between 18 and 22 msec and off time at 11-12 msec.

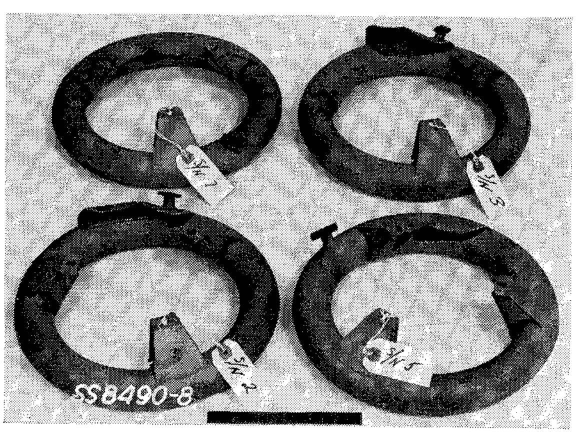

Fig. 10 GN_2 tanks.

Table 10 Production acceptance test results

Parameter	Requirement	Measured
Thrust chamber I_{sp}, sec	196 at 2.0 psia amb	203–214
P_c oscillation, %	±10	±7
3-way valve:		
Flow at 25 psid, lb/sec	0.209 (min)	0.283–0.342
Response, μsec	20	16–18

Tanks

The GN_2 tank was subjected to a 5-tank development program in which vibration, life cycle and burst pressures were evaluated. For the vibration test, the GN_2 and the N_2H_4 tanks were both mounted on the cylindrical flight mount to more closely simulate actual conditions. The GN_2 tank was then pressurized to 4140 psia and the N_2H_4 tank was loaded and pressurized to 440 psia. The vibrational environment was input to the base of the cylindrical tank mount. This configuration encountered its predominant resonances between 240 Hz and 650 Hz. The strain, as analyzed from the acceleration and frequency relationship, remained relatively constant in this range and indicated no structural difficulties as later verified in tank tests. At the completion of vibration testing, the results of Table 8 were obtained. Figure 10 shows the four GN_2 tanks after burst testing.

REM

At the completion of component development testing, fabrication of the DVT REM was undertaken. Each section (fore and aft) of the DVT REM was mounted on a vibration fixture, and the vibration levels were input to the base of the fixtures. The resonances and loadings observed during the component and subassembly level vibration tests were again generally observed in the REM tests. No structural damage resulted from these tests. Post-vibration leakage tests on each portion of the DVT REM were successful, and the REM assembly was completed and leak checked. The fluidic valve driver was then assembled to the REM, which was then loaded, charged and subjected to the REM mission simulation sequence. The results are summarized in Table 9. The response data for individual pulses during the DVT REM mission simulation test showed a first pulse on response of 134 msec and on/off responses of $25^{+1}_{-2}/41^{+2}_{-3}$ msec recorded for all other pulses in the test sequence. These data were obtained using the original 3-way valve spring.

At the conclusion of the REM DVT test cycle, the REM was refurbished by replacing the ruptured burst disc, reworking the pressurization module to replace the squib, seals and shear pin, and cleaning REM components and plumbing as required. In keeping with the philosophy of reducing technical risk, the N_2H_4 tank was replaced, since the diaphragm had been cycled and the tank had been exposed to the vibration environment on the DVT REM. The refurbished REM was then acceptance-tested and delivered as the third delivery unit.

Table 11 REM P_c matching

	P_{inlet},[a] psia	TC P_c, psia 1	3	2	4
S/N 01 (DVT)	480			222	223
	480	227	224		
S/N 02	470			220	217
	475	216	212		
S/N 03	465	217	217		
	468			226	226

[a] P_{inlet} = static inlet pressure to the 3-way valve.

Production acceptance tests (PAT)

All components were subjected to an acceptance test sequence prior to use. Thrust chambers and 3-way valves were individually tested. Summary results are shown in Table 10. Each REM underwent P_c calibration to limit torque unbalance to <6 by changing thruster trim orifices at the inlet to the thrust chambers, as required. The average P_c's of opposing coupled thrusters were matched to within 10 psia (Table 11). Thrust chamber hot response in REM S/N 02 and S/N 03 from fluidic signal to 90% of P_c fell between 24 and 31 msec for all thrusters during all pulsing operations. When corrected for use of the modified 3-way valve spring these response times become 27 and 34 msec. Corrected off response times of 27 to 39 msec were observed.

Conclusions

1) A closed-loop roll-rate control system was designed and fabricated using fluidic sensing and logic to command monopropellant hydrazine REMs. 2) The REM, as designed, fabricated and tested successfully demonstrated compliance with the performance specification. 3) A common pneumatic power supply is feasible for sensing and logic power, control valve actuation, and propellant expulsion. 4) The conventional electrical solenoid valve can be replaced with a pneumatically actuted 3-way control value to eliminate electrical interfaces. Pneumatic valve responses of less than 20 msec are practical. 5) Response times of less than 50 msec were demonstrated with REM using the 3-way valve. 6) Steady-state specific impulse values greater than 200 sec were demonstrated at 2.0 psia amb pressure with a nozzle area ratio of 10. 7) Proven components in the REM reduced technical risk for the flight feasibility program, but significant reductions in size and weight can still be achieved by integrating functions and optimizing components.

APRIL 1971 J. SPACECRAFT VOL. 8, NO. 4

Lunar Flying Vehicle Propulsion System

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The optimization of a propulsion system for a Lunar Exploration Flying Vehicle (LFV) is discussed in order to report a special approach to extended system life, reliability, and flight safety. Pressure-fed engine and system design parameters are simultaneously optimized for minimum weight delivered to the moon and maximum LFV operational range on the moon. The resulting optimum engine chamber pressure and nozzle expansion ratio are 80 psia and 40:1, respectively. Refractory metal engine life is assessed in terms of time/temperature history on the basis of test data, concluding that a 3.5 hr burn time requirement can be met with a maximum operating temperature of 2250°F. Redundant engines are compared with derated (low operating temperature) engines for equivalent flight safety and reliability. Propulsion system design for derated engines with preflight check capability is proposed to reduce operational risks to the level of light aircraft operation on Earth.

Introduction

THE Lunar Flying Vehicle (LFV) is a one-man rocket propelled flight system for lunar exploration away from the Lunar Module (LM) landing site. Operations analysis and vehicle studies (Ref. 1) produced the optimized LFV configuration shown in Fig. 1. This configuration incorporates a pressure-fed propulsion system sized for 300 lb of useable N_2O_4-0.5 N_2H_4/0.5 UDMH propellants and two 150-lb throttleable engines to lift a payload of 520 lb (including the astronaut). The outboard engine arrangement incorporates articulated single-axis gimballing for pitch and yaw control. Roll control is provided by differential throttling of the engines. The LFV is flown, in flight attitudes similar to a helicopter, by continuous thrusting. High thrust is used to lift off, climb to altitude, and pitch over to accelerate along the flight path. The LFV then cruises inertially by rotating to vertical and reducing thrust to the level required to balance lunar gravity. High thrust is again required (in a rotated attitude) for deceleration followed by continuously lower thrust for descent and soft landing. To provide for 60 to 150 such flights, a total engine service life of 3.5 operating hr is required.

Similar one-man jet and rocket powered vehicles have successfully demonstrated free flight on Earth. Bell Aerospace has developed the rocket belt and jet belt (Ref. 2); North American Rockwell has experimented with a one-man flying vehicle tethered to simulate Lunar gravity (Ref. 3); and flight simulator investigations at NASA Manned Space Flight Center and Langley Research Center have demonstrated the feasibility of a rocket powered one-man flying vehicle in the lunar environment.

The design of an optimum propulsion system for this LFV configuration demanded identification of the design features for the best combination of weight, performance, extended system life, reliability, flight safety, and operational techniques. This paper reports the results of this portion of a one-man lunar flying vehicle study conducted for the NASA Manned Spacecraft Center under Contract NAS9-9044.

Basic System Model

The basic propulsion system under study is shown schematically in Fig. 2. The arrangement of components corre-

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