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ELECTRONICALLY VARIABLE PRESSURE REGULATOR (EVPR) *

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ABSTRACT

A new programmable electronically variable pressure regulator (EVPR) concept accurately controls the local outlet or remote system pressure. It uses an integral pulse width modulated rare earth permanent magnet motor operating in response to redundant pressure transducer feedback signals. The EVPR is a simple single stage device that does not use dynamic seals or pilot valving. Conversion of partial revolution motor torque to poppet lifting force is accomplished by pure flexure action to avoid using bearings. The flexure drive (called the ROTAX) has a variable lead to minimize motor weight and power consumption.

Breadboard tests have been completed successfully on two critical design elements of the EVPR: the ROTAX and the motor. The ROTAX cable system was tested for 250,000 cycles without failure. The breadboard motor met the basic design requirements including the design torque and power consumption. Prototype parts have been fabricated, and testing of the prototype EVPR has started. It is PC computer controlled to facilitate programming, data acquisition and analysis. A lightweight dedicated microprocessor is planned for the flightweight EVPR.

INTRODUCTION

The primary objective of the NASA JSC technology program being conducted by Eaton Corporation, Valve and Actuator

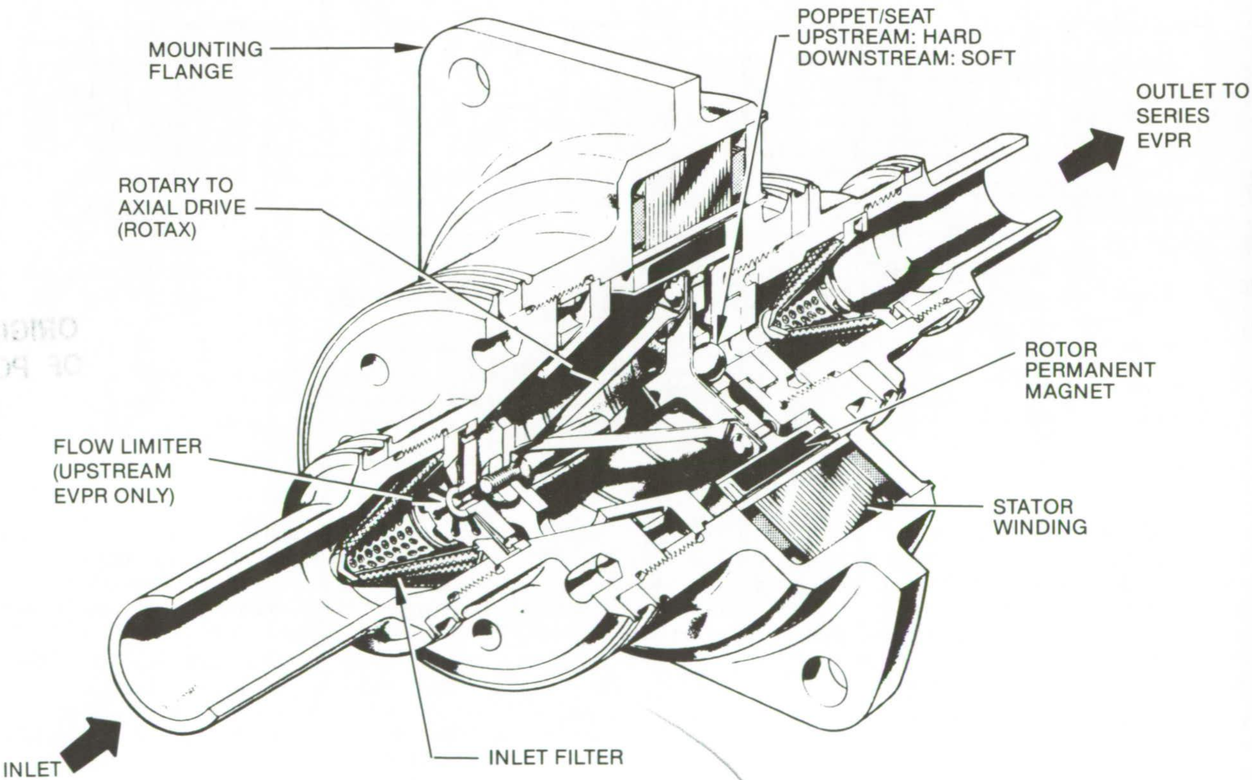

FIGURE 1. EATON ELECTRONICALLY VARIABLE PRESSURE REGULATOR (EVPR)

*This work was performed under NASA JSC contract No. NAS-9-17907 with Eaton Corporation, Valve & Actuator Division, El Segundo, California

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Division, is to develop a multifunction regulator with an electronically variable setpoint. The device has a simple configuration to overcome problems inherent in complex, pilot operated mechanical regulators. The regulator is designed to avoid contamination problems in bipropellant pressurization systems. A single stage, bellows-free EVPR concept was selected to eliminate the reliability problems of piloted regulators with their tight sliding fit clearances, tiny orifices and fine filters that are prone to jamming and plugging by contamination, including ice particles that often form during rapid blowdown of high pressure supply tanks.

The programmable EVPR can be used in many applications, including pressure regulation, flow control, temperature regulation, shut off, etc. It is anticipated that the application versatility of the multifunction EVPR will reduce both non-recurring and hardware costs in specific applications. Since the EVPR can be programmed for smooth, transient-free operation, including gradual pressurization and depressurization, it is well suited for use in oxygen and hydrazine systems where it is important to avoid adiabatic compressional heating.

The project presents difficult design constraints, such as wide outlet pressure controllability, 0-34 atm (0-500 psia); tight control accuracy (less than two percent of set point); high inlet pressure, 340 atm (5000 psia); large flow rate, 9 SCMM (320 SCFM) GHe; and high burst pressure, 850 atm (12,500 psia). It was determined that a high torque capability motor was required, but the EVPR would also contain a thick non-magnetic pressure-containing wall through which the motor windings must efficiently couple magnetically to the rotor assembly. Sophisticated structural, magnetic and thermal finite element computer analysis techniques were utilized to thoroughly optimize and size the device with adequate margins of safety.

DESCRIPTION

The EVPR concept is shown in a flightweight configuration in Figure 1.

Flow from inlet to outlet ports is coaxial. Integral inlet and outlet filters prevent particulate contamination of the device. An active flow limiter is used to minimize the size of the downstream system over-pressure protection relief valve.

The EVPR actuator is a fully integrated custom design brushless DC motor. A unique flexure device, called the ROTAX, converts the partial rotation of the motor to axial poppet lifting motion. The EVPR regulates the outlet pressure by pulse width modulation (PWM) of the motor windings using pressure transducer feedback. The EVPR uses hall effect devices (HEDs) for both open and closed position indication. Mechanical stops limit rotation of the motor and prevent over-stressing of the ROTAX and the poppet/seat assembly. Although the motor normally powers the EVPR in both the opening and closing directions, the rotor is biased magnetically to close the EVPR in the event of electrical power loss. The magnetic bias also provides sufficient force to keep the EVPR positively closed during launch vibration.

The EVPR is designed for use in the Orbital Spacecraft Consumables Resupply System (OSCRS), which will be used to transfer N_2H_4, MMH propellants and other fluids. Figure 2 shows the Gamma Ray Observatory (GRO), which is a possible resupply mission for the OSCRS.

Four EVPRs will be used as a quad-redundant pressure control system, but normally only one EVPR regulates GHe pressure during the N_2H_4 transfer operation. The quad-redundant arrangement allows system operation to continue even in the event of one EVPR failing open and another EVPR failing closed. The Space Shuttle Orbital Maneuvering System (OMS) presents another potential application for the EVPR. In this application quad-redundant EVPRs regulate MMH and N_2O_4 tank expulsion pressures.

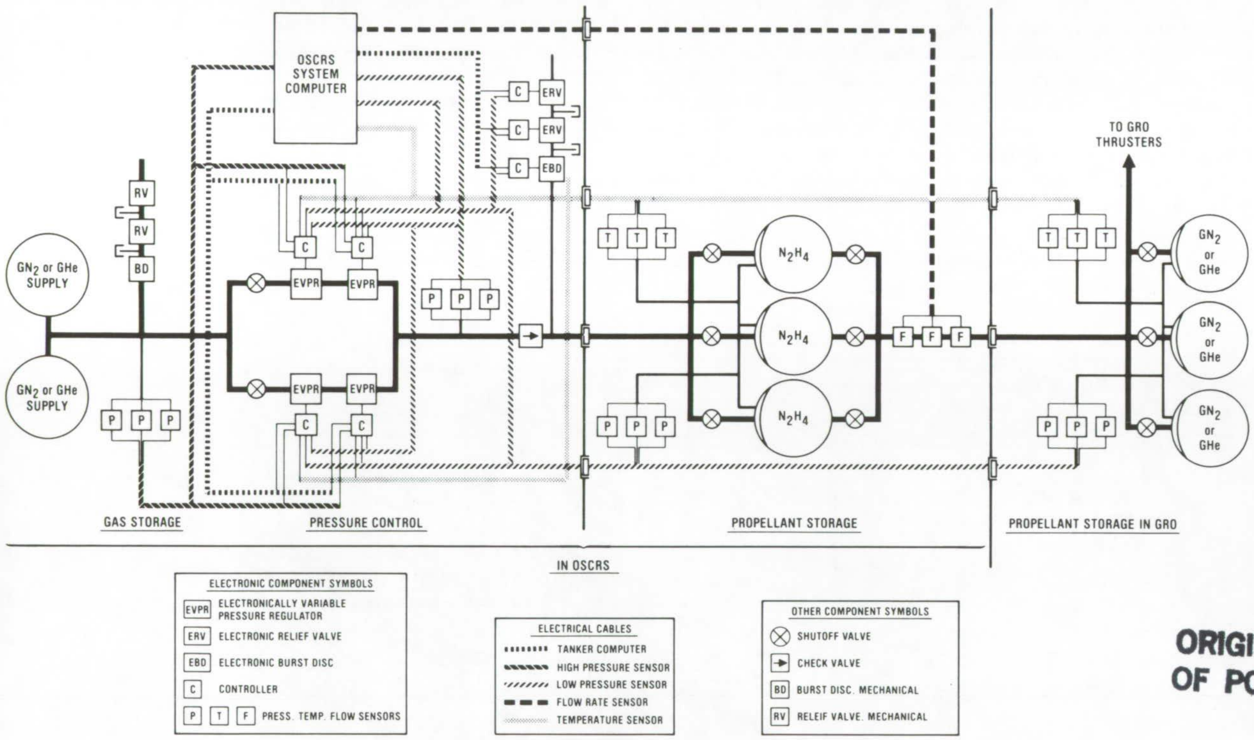

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FIGURE 2. OSCRS N_2H_4 TRANSFER TO GRO

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NASA TECHNOLOGY PROGRAM REQUIREMENTS

The basic EVPR technology demonstration objectives are summarized below:

- Pre-programmed or operator commanded set point
  - Electronically vary regulated pressure set point
  - Transient-free, controlled ramp up to pressurize and ramp down to depressurize
- Local or remote regulated pressure feedback control from triple-redundant pressure sensors
- Avoids all-mechanical regulator problems
- Reduces program and hardware costs

The NASA technology program prototype EVPR is designed to operate in accordance with the OMS system application and specifications, which are generally more severe than those anticipated in the OSCRS application. Critical performance parameters are listed in Table I.

TABLE I. CRITICAL NASA EVPR PROGRAM PERFORMANCE CRITERIA

INLET PRESSURE	13.6-340 ATM (200 TO 5000 PSIA) GHe
REGULATED PRESSURE	3.4-34 ATM (50 TO 500 PSIA), ELECTRONICALLY SELECTABLE
PROOF PRESSURE	510 ATM (7500 PSIA), INLET AND OUTLET
BURST PRESSURE	850 ATM (12,500 PSIA), INLET AND OUTLET
REGULATED PRESSURE ACCURACY	±2% OR BETTER OF SET POINT
FLOW RATE	0-9.0 SCMM (0-320 SCFM) GHe
INTERNAL LEAKAGE	< 10 SCCH GHe
EXTERNAL LEAKAGE	$< 10^{-6}$ SCCS GHe*
VOLTAGE	18-32 VOLTS
SERVICE LIFE	20 YEARS
EFFLUENT COMPATIBILITY	N_2O_4, MMH, H_2O AND N_2H_4 VAPORS
DOWNSTREAM VOLUME	$0.17M^3$ ($6FT^3$) MINIMUM FOR OMS
	$0.007M^3$ ($0.25FT^3$) MINIMUM FOR OSCRS
LIFE	20,000 CYCLES
ENVIRONMENTAL TEMPERATURE	4 °C TO 48 °C (40 °F TO 120 °F)
GAS TEMPERATURE	−128 °C TO 93 °C (−200 °F TO 200 °F)**
BOOST VIBRATION	$15G_{RMS}$ RANDOM

*Flightweight version only
**Allows a 44 °C (80 °F) gas temperature rise due to motor dissipated power

The prototype EVPR being built and tested in the NASA technology demonstration program is not required to meet external leakage and weight criteria of the flightweight unit.

CONCEPT SELECTION

Careful study of the EVPR performance criteria (Table I) with the objective of avoiding failure modes and problems associated with pilot operated devices led to the selection of a directly operated (no pilot valve) EVPR that does not employ dynamic seals (such as bellows) or bearings (such as ball screw drives). The following basic design concepts were studied and compared:

Candidate EVPR Concepts

No. 1 Two-stage, using a torque motor operated pilot valve
No. 2 Two-stage, using a proportional solenoid operated pilot valve
No. 3 Single-stage, operated by a bellows-isolated motor
No. 4 Single-stage, operated by an effluent contacting motor (no bellows)

Candidate Drive Methods for EVPR No. 4

No. 1 Ball screw drive
No. 2 ROTAX flexure

Table II summarizes the evaluation of four EVPR concepts and two rotary-to-axial drive methods. Ten points is the highest score, making 120 points the maximum possible total for the 12 evaluation parameters.

TABLE II. EVPR AND DRIVE METHOD EVALUATION

PARAMETER	TWO STAGE		SINGLE STAGE		DRIVE METHOD FOR REG NO. 4	
DESIGN CONCEPT	1. TORQUE MOTOR PILOT	2. PROPORTIONAL SOLENOID PILOT	3. BELLOWS ISOLATION	4. NO BELLOWS	1. BALL SCREW	2. ROTAX FLEXURE
1. COMPLEXITY (RELIABILITY, COST)	2	4	8	10	6	10
2. FAILURE MODE (PREDICTABILITY)	5	5	6	8	5	10
3. PRESSURE RESISTANCE (UPSTREAM REG OPEN)	6	10	3	10	10	10
4. INTERNAL LEAKAGE	5	5	10	10	10	10
5. VIBRATION	5	7	8	10	10	8
6. FAILURE DETERRENT	6	8	6	8	8	8
7. ABSENCE OF SMALL FLOW PASSAGES OR CREVICES	6	6	10	10	8	10
8. SERVICE AND CYCLE LIFE	8	8	8	10	8	10
9. ABSENCE OF SLIDING SEALS AND FITS	10	8	10	10	8	10
10. RESPONSE AND STABILITY	10	10	8	9	10	10
11. PROPELLANT VAPOR COMPATIBILITY	8	8	10	10	8	10
12. PROGRAM AND TECHNICAL RISK	6	9	5	10	7	9
TOTAL SCORE	77	87	92	115	98	115
RANKING	4	3	2	1	2	1

Concepts Nos. 1 and 3 utilize the bellows (or possibly flexure tubes) to isolate non-propellant-compatible pilot torque motor and direct motor drives. These bellows are normally subject to only regulated pressure when the upstream regulator is controlling, but must withstand without damage full supply pressure up to 340 atm (5000 psia) when the downstream regulator is called upon to regulate in series and quad redundant installations. The high pressure bellows used in concepts Nos. 1 and 3 present considerable technical risk, and the No. 3 concept high pressure bellows may be impossible because of its much larger size and stroke requirement. Regulator concepts Nos. 2 and 4 don't use bellows, and therefore don't share this significant concern.

Another major design concept driver is the need to avoid small flow passages that might clog. This criteria eliminates pilot-operated concepts Nos. 1 and 2 from further consideration. Based on the gross deficiencies of concepts Nos. 1, 2 and 3 due to inadequate supply pressure resistance for this system application and the ground rule to avoid small passages, only the No. 4 single-stage concept survives. The overall scoring totals in Table II confirm this selection based on all parameters considered. The drive method comparison in the last two columns of Table II shows the ROTAX flexure to be the best choice for the selected EVPR concept.

A single phase torquer was first examined to actuate the EVPR due to its very simple non-commutated, single winding design. However the OMS specifications (pressure drop, flow rate) indicated a very large torquer would be required. Typically, a torque motor has much higher weight and power consumption when compared to a three phase motor, especially above a 0.115 NM (1 in-lb) continuous torque rating. Following considerable study the NASA EVPR was designed with a three phase brushless DC permanent magnet motor because of weight and size criteria, and also because a two pole single phase torquer could not develop enough magnetic bias anti-rattle force to satisfy launch vibration criteria. Also, the higher power torquer could not meet the specified thermal heat transfer requirement that the gas temperature rise be less than 44 °C (80 °F) due to motor winding heating.

The permanent magnet brushless three phase motor uses a trapezoidal drive to electronically energize coil windings in the stator. Three HEDs provide rotor magnetic field position information to commutate the motor coils. Also, a brushless sinusoidal drive is being investigated which yields near zero ripple motor torque and does not commutate the motor coils for enhanced EVPR control and response characteristics. Since the brushless DC motor does not use mechanical brushes, it has a higher reliability and longer life than a conventional DC brush type commutated motor used in servo control. An eight pole motor was selected because it minimizes the armature and stator back iron while keeping the design as simple as possible. The permanent magnet material, Neodymium-Iron-Boron, possesses a high magnetic energy product (35 MGOe) and low density to reduce the rotor weight, thus providing high non-operational resistance to vibration and shock.

The EVPR is a normally-closed device (and as such serves as a shutoff valve in addition to its regulation duty) and exhibits a fail-closed mode with loss of electrical power. This is provided by two permanent magnet generated closing bias forces: (1) the permanent magnet rotor is offset axially from the stator lamination stack, which creates a closing direction bias on the rotor, and (2) additional permanent magnets are embedded in the seat end of the EVPR housing, which attracts rotor iron in the closing direction. Since the ROTAX exhibits very little mechanical spring rate, its contribution to the closing bias force is quite small.

The unique frictionless ROTAX flexure drive does not require lubrication, operates at near 100 percent efficiency, and is not affected by contamination. The ROTAX is advantageous in the EVPR GHe/GN_2 and propellant vapor environment where material selection is limited by compatibility considerations and lubricants can not be used. The ROTAX has an intrinsically advantageous variable lead characteristic which minimizes the worst-case motor torque requirement when the poppet initially lifts off the seat at maximum inlet pressure. Since a ball screw drive has a constant pitch, its usage requires a larger motor. Also, a ball screw would not operate at optimum performance, life and reliability because no lubrication is permitted and optimum bearing materials cannot be used in propellant vapor environments.

DESIGN DESCRIPTION

EVPR fluid contacting materials are 300 series corrosion resistant steel, titanium alloy, synthetic sapphire and TFE Teflon. These materials are compatible with GHe, GN_2, N_2H_4, MMH, N_2O_4, and H_2O. The permanent magnets are sheathed with welded 300 series stainless steel to prevent contact with effluent gases and propellant vapors. Motor stator laminations, windings, and HEDs are also hermetically sealed from effluent contact (and, in the flightweight design, will be hermetically sealed from ambient atmosphere contact).

The prototype evaluation EVPR uses bolt together construction with external O-ring seals and MS fluid ports with O-rings to facilitate assembly and disassembly in the development program. The flightweight version will employ all-welded external sealing, and will use ports suitable for welding or brazing to system tubing. The EVPR prototype is microcomputer controlled as shown in Figure 3.

Triple redundant pressure transducers use signal conditioning electronics to provide digital feedback signals to the EVPR driver electronics through the input/output (I/O) expansion card. The expansion card is plugged into the computer PC bus. The expansion card is a buffer for input and output signals sent to the 80386 IBM PC compatible computer which controls the EVPR. LT Control Software provides full PID control and automated test

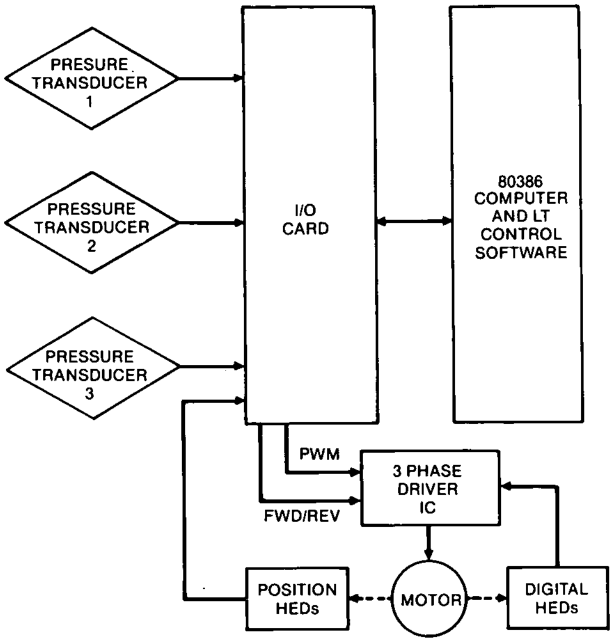

FIGURE 3. PROTOTYPE EVPR CONTROLLER DIAGRAM

data acquisition. The PC controls the EVPR by two output signals, one for forward or reverse direction, and the other for the pulse width modulation (PWM) duty cycle, into the three phase driver electronics. Three digital HEDs provide rotor position signals input to the EVPR driver electronics and commutate the coils independently of the PWM duty cycle. Motor coils are energized with the PWM duty cycle needed to zero-out any error between the commanded set point and the pressure sensor feedback signals.

The flightweight electronic controller could utilize a dedicated microcontroller such as the Motorola MC68HC11 shown in the Figure 4 flightweight EVPR electrical schematic.

The microcontroller contains a self test to verify that the EVPR is functioning properly, a pressure transducing voting mode program, and a PID control loop program to null the pressure error. Flight electronic controller weight will be minimized by utilizing microprocessor or ASIC technology.

A "smart pressure transducer", developed by the Pressure Sensor Division of Eaton Corporation, operates from −128 °C to 93 °C (−200 °F to 200 °F) with a steady state accuracy of 0.2 percent of the full scale, 34 atm (500 psia). Three of these pressure transducers, along with their signal conditioning electronics, are used to provide "majority vote" feedback control signals to the EVPR electronics. If desired, any one pressure sensor can be excluded.

The analog pressure and temperature output from each pressure transducer is converted to a digital signal within a dedicated electronic signal conditioning package used with each pressure sensor. A microprocessor determines the pressure value from a lookup table of calibration data using an integral temperature sensor. Each pressure sensor transmits pressure signals to the EVPR electronic controller as a digital serial output signal that is RS232 compatible.

DESIGN PROCEDURE AND ANALYSES

EVPR flow rate sizing was determined from the worst case flow requirements: two EVPRs in series, 40.8 atm (600 psia) inlet pressure, 18 atm (265 psia) outlet pressure, and 9 SCMM (320 SCFM) GHe minimum flow rate. Figure 5 illustrates the pressure drop allocation for two EVPRs in series.

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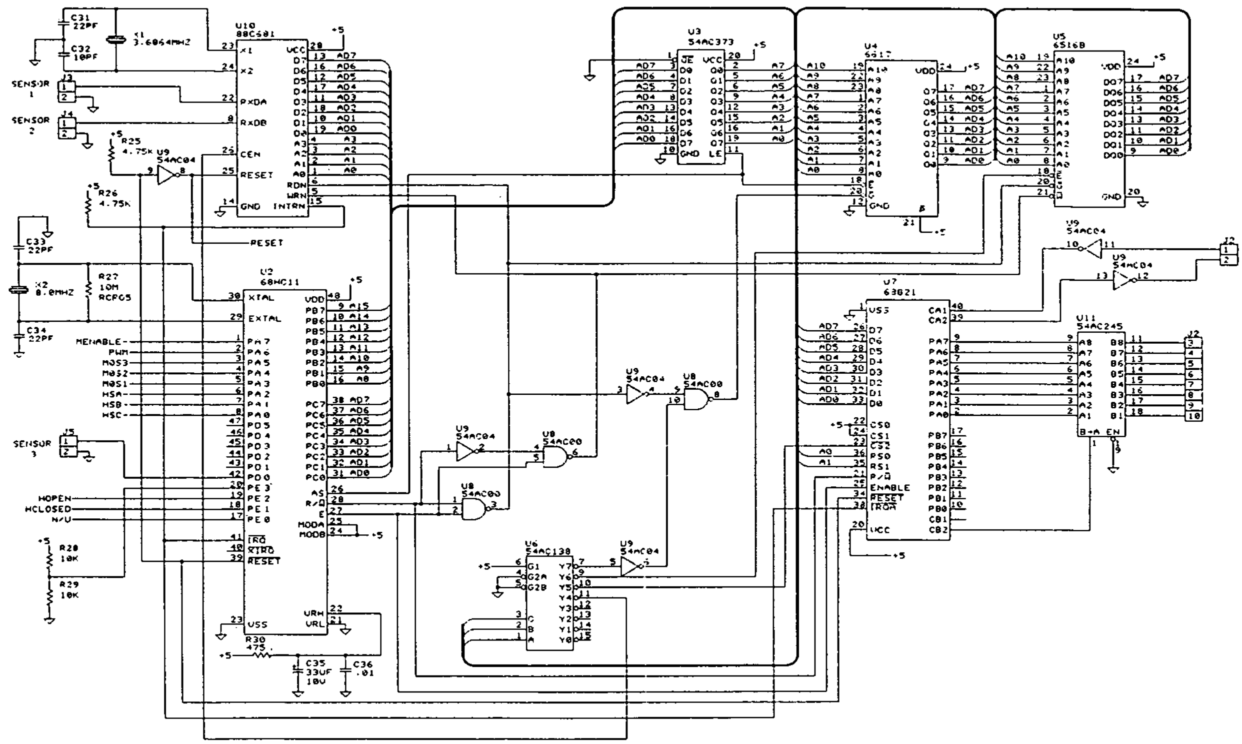

FIGURE 4. FLIGHTWEIGHT EVPR MICROCONTROLLER

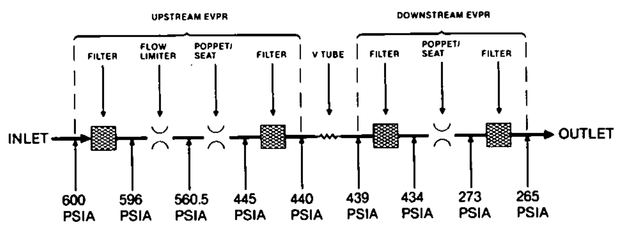

FIGURE 5. PRESSURE DROP BUDGET, 9.0 SCMM GHe, 21°C

After sizing the internal flow passage and valve poppet/seats to these criteria, the total actuation force was determined by summing the pressure unbalance and magnetic bias forces as shown in Figure 6.

As is shown in Figure 6, both of these forces decrease in a nonlinear manner as the poppet lift increases. The motor and ROTAX drive system must be designed to exceed this force profile with sufficient force margin to meet dynamic performance and reliability criteria.

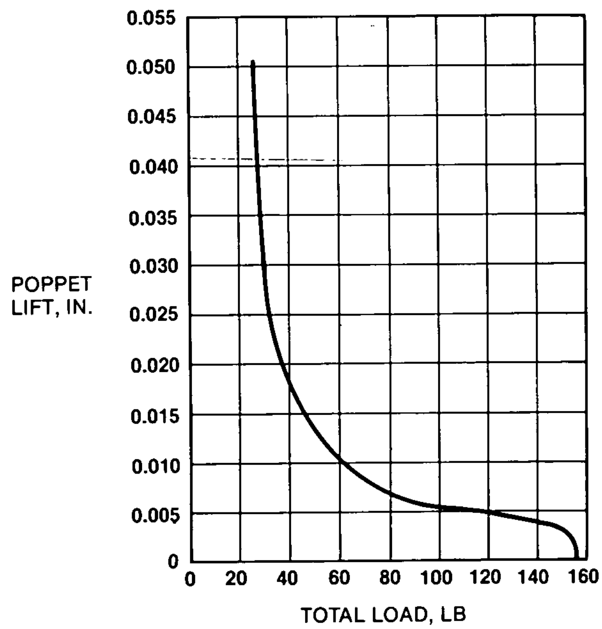

FIGURE 6. PRESSURE AND MAGNETC BIAS FORCES

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A spider-like insert was added to the center of the ROTAX to increase the rate of poppet lift towards the end of the valve opening action. The ROTAX was analyzed using a computer program to model its nonlinear behavior. Figure 7 shows the calculated ROTAX lift versus rotation.

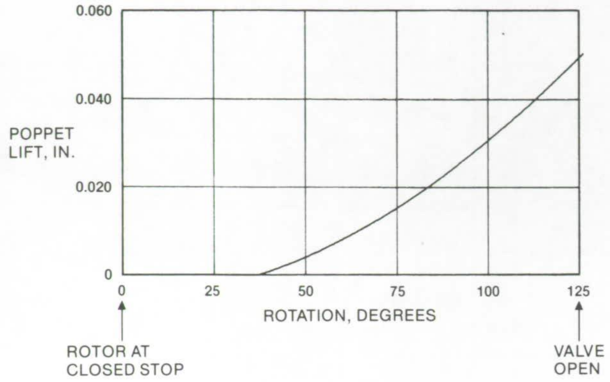


FIGURE 7. ROTAX LIFT CHARACTERISTIC

No poppet lift occurs while the motor rotates through the first 35 degrees during the 0.127 mm (0.005 inches) overtravel used to accommodate assembly tolerances and to allow for differential temperature contraction of the ROTAX cables. The torque profile that resists valve opening is shown in Figure 8 for rated flow throughout the inlet pressure range of 40.8 to 340 atm (600 to 5000 PSIA). A peak torque of 0.357 NM (3.1 in-lbs) occurs at 48 degrees rotation.

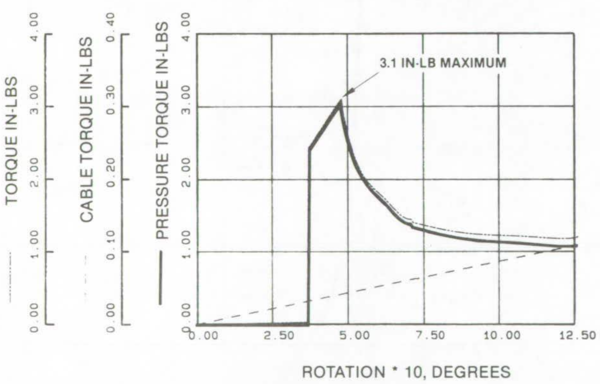


FIGURE 8. MOTOR TORQUE REQUIREMENT

The ROTAX flexure cable, made of multi-strand 304 stainless steel, has a peak combined (tensile plus torsional) stress of 358 MPA (52 ksi) as shown in Figure 9. SN curve analysis shows that the ROTAX cable will have infinite life because the 358 MPA (52 ksi) peak stress is sufficiently below its ultimate tensile strength, 1087 MPA (158 ksi).

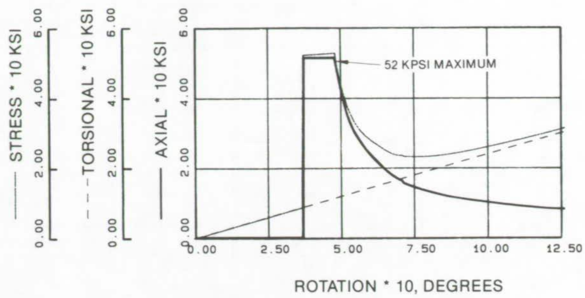


FIGURE 9. ROTAX CABLE STRESS

The motor was designed to actuate the valve at worst case conditions of 18 volts, 340 atm (5000 psia) GHe inlet presure, 9 SCMM (320 SCFM) GHe flow at 93 °C (200 °F). The motor was sized for 0.576 NM (5 in-lbs) peak torque, which provides a 61% steady state torque margin. The large "air" gap caused by the EVPR housing wall thickness and magnetic shielding required the design of a special stator and eight pole Neodymium-Iron-Boron permanent magnet motor. Infolytica PC magnet software proved invaluable to expedite the design optimization of this custom motor, an otherwise tedious task if done by hand computation. Figure 10 pictures the maximum motor flux plot taken from the computer CRT. Only one magnet pole was analyzed due to symmetry.

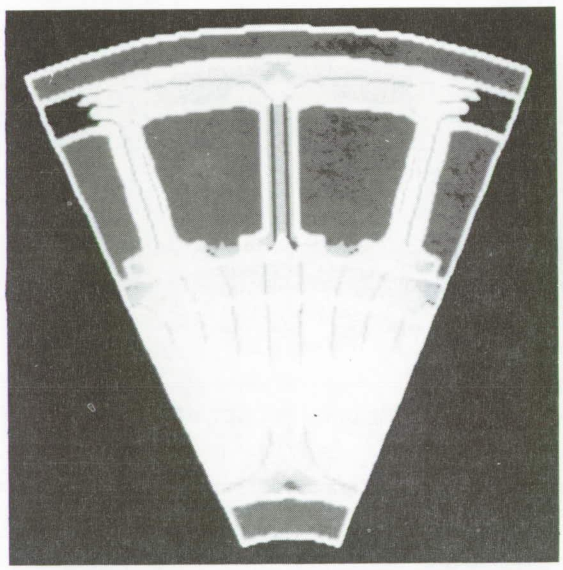
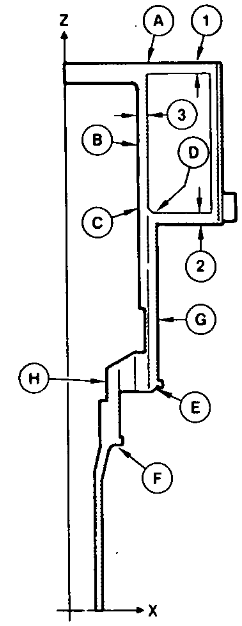


FIGURE 10. MOTOR MAGNETIC FLUX AT MAXIMUM TORQUE, 0.576 NM (5 IN-LB)

Housing wall stresses were analyzed during 510 atm (7500 psia) proof pressure and 850 atm (12,500 psi) burst pressure with ANSYS finite element analysis program as shown in figure 11. The Ti-6AL-4V titanium alloy housing material has a tensile strength margin of safety of 1.09 at the burst pressure condition.



	DIMENSIONS (IN.)						STRESS (KSI)				
	①	②	③	Ⓐ	Ⓑ*	Ⓒ	Ⓓ	Ⓔ	Ⓕ	Ⓖ	Ⓗ
	0.103	0.105	0.067	32.6	17.1	132.9	87.5	31.8	25.3	—	—
			M.S.	3.91	—	0.2	0.83	4.03	5.32	—	—
	0.105	0.105	0.072	30.5	158.4	126.7	86.7	31.8	25.3	—	—
			M.S.	4.25	0.01	0.26	0.85	4.03	5.32	—	—
	0.105	0.105	0.077	28.7	147.2	120.7	85.6	31.7	25.3	—	—
			M.S.	5.57	0.09	0.33	0.87	4.05	5.32	—	—
AT PROOF PRESSURE:											
	0.105	0.105	0.0875	17.2	88.3 *	71.6	51.4	19.0	15.2	71.4	79.7
			M.S. =	7.72	0.70	1.09	1.92	6.89	8.87	1.10	0.88
			*DEFLECTION = 0.0044								
AT BURST PRESSURE:											
				28.7	147.2 *	120.7	85.6	31.7	25.3	119.0	132.8
			M.S. =	4.57	0.09	0.33	0.87	4.05	5.32	0.34	0.20

*MAXIMUM DEFLECTION @ B = 0.0072 IN. RADIAL.

FIGURE 11. BODY FINITE ELEMENT STRESS ANALYSIS

The rotor is biased magnetically to maintain the EVPR closed during launch vibration and to close the valve during loss of electrical power. The magnetic bias force is 6.6 N (30 lbs) when the valve is fully closed. During non-operational launch vibration, 15 g_{rms}, this magnetic bias keeps the 0.238 Kg (0.525 lb) rotor assembly in the fully closed position.

The bias force is generated by neodymium-iron-boron permanent magnets located in a housing that attract a ferromagnetic plate attached to the poppet-end of the rotor assembly. Additional closing bias is provided by an axial offset of the rotor relative to the stator lamination stack. A small helical spring keeps the ball poppet seated during non-operation vibration.

A thermal analysis of the EVPR was conducted under the following worst case conditions: valve barely open, near zero flow rate, 340 atm (5000 psia) inlet pressure, 48 °C (120 °F) mounting structure, vacuum environment, no radiation and 25 watts power.

The basic mode of heat transfer is by conduction from the motor coil end turns, through the stator laminates, through the aluminum alloy spacer and titanium cover, and finally out to the EVPR mounting surface. Some convective heat transfer takes place from the stator housing to internal gas. The purpose of the worst case thermal analysis was to verify that the internal gas temperature does not exceed 93 °C (200 °F). Figure 12 illustrates the thermal model of the EVPR and shows the temperature profile. The maximum temperature of the internal gas is 86 °C (187 °F), well below the requirement of 93 °C (200 °F).

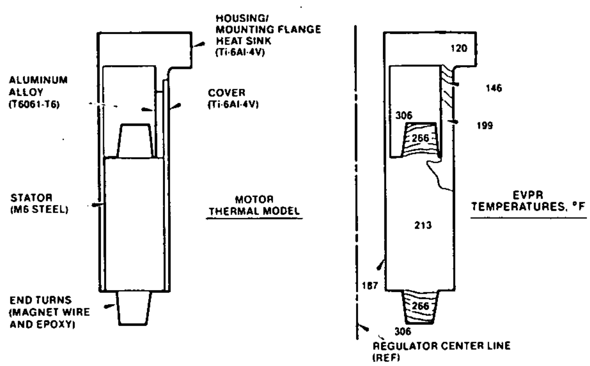


FIGURE 12. MOTOR HEATING THERMAL ANALYSIS

Dynamic computer simulation of the EVPR operating in the OMS showed that the regulated pressure was held to the ±2% allowable error band and that the system was stable under all steady-state and transient operating conditions. The OMS system, using a quad EVPR arrangement, was analyzed using the equivalent circuit shown in Figure 13. One downstream regulator is powered to the full open position and one upstream regulator is modulated to regulate the pressure output. The other series regulator leg of the quad is not active.

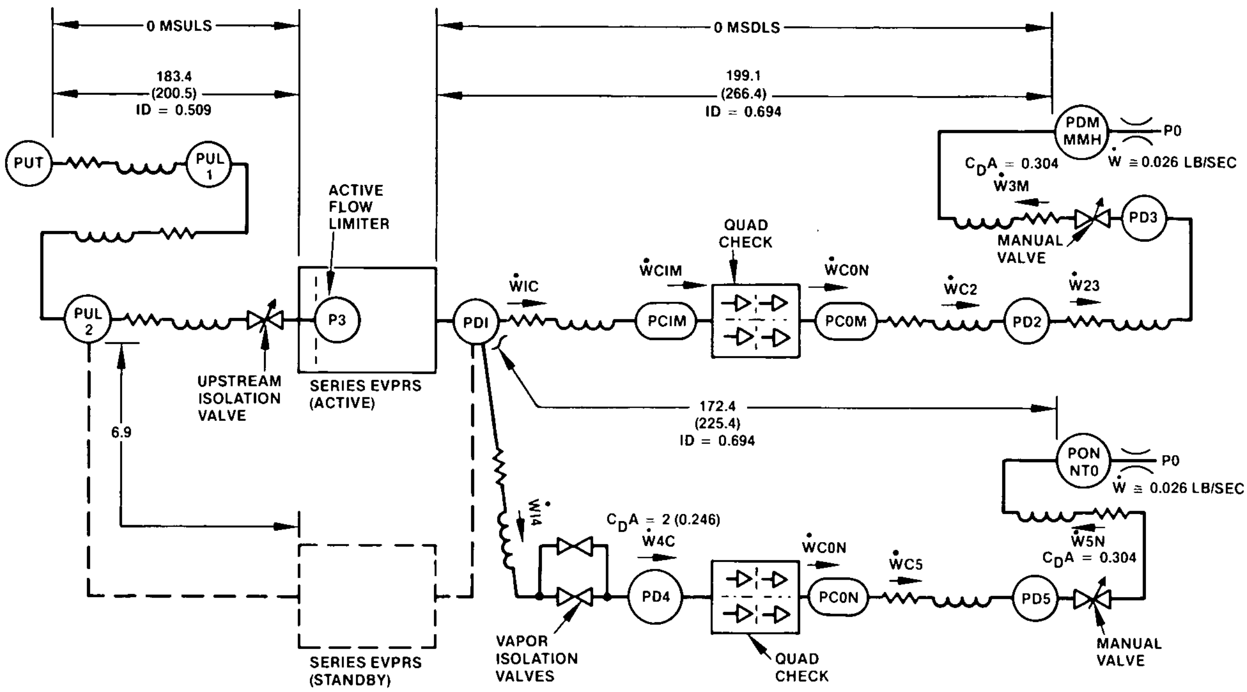


FIGURE 13. OMS DYNAMIC SIMULATION MODEL

Table 3 lists three dynamic simulation conditions, including one abnormal pre-launch case.

Table 3. OMS Dynamic Simulations

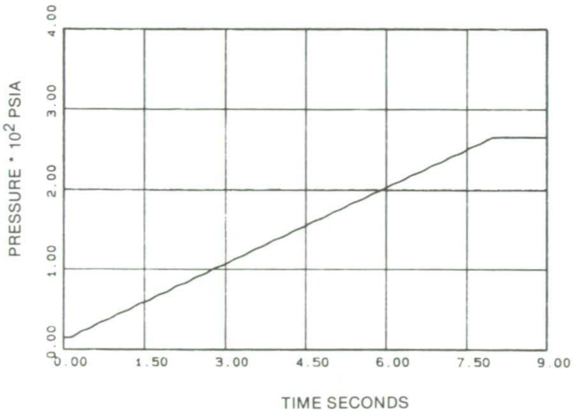
CASE	He ATM	PRESSURE (PSIA)	ULLAGE M^3	ULLAGE (FT^3)	STEPFLOW GHe SCMM	STEPFLOW GHe (SCFM)	GAINS K_p	GAINS K_d	GAINS K_I	SIMULATE OPERATION
1	340	(5000)	0.17	(6)	—	—	20	1	20	INITIAL PRESSURIZATION: 8 SEC RAMP
2	340	(5000)	0.17	(6)	9.0	(320)	20	1	20	STEP FLOW ON AND OFF
3*	40.8	(600)	0.17	(6)	9.0	(320)	20	1	20	STEP FLOW ON AND OFF

*ABNORMAL PRE-LAUNCH CONDITION SIMULATION

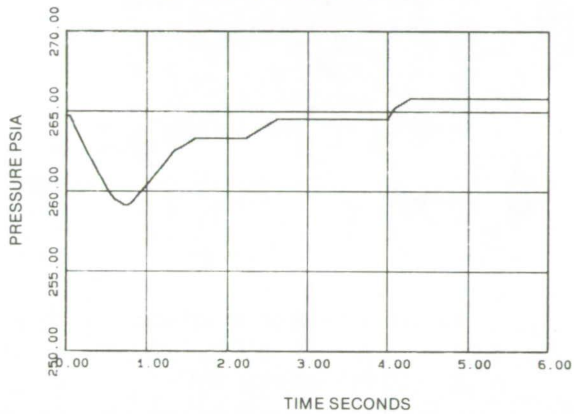
Case 1, initial pressurization by linearly ramping the output pressure from 0 to 18 atm (0 to 265 psi) in 8 seconds, is shown in Figure 14a. The inlet pressure is at the maximum level, 340 atm (5000 psi), and a small ullage of 0.17 cubic meter (6 cubic feet) exists.

Case 2, a step flow demand for 4 seconds, is shown in Figure 14b. Again the inlet pressure is 340 atm (5000 psi), the ullage is 0.17 cubic meters (6 cubic feet) and the steady-state flow rate is 9.0 SCMM (320 SCFM) GHe.

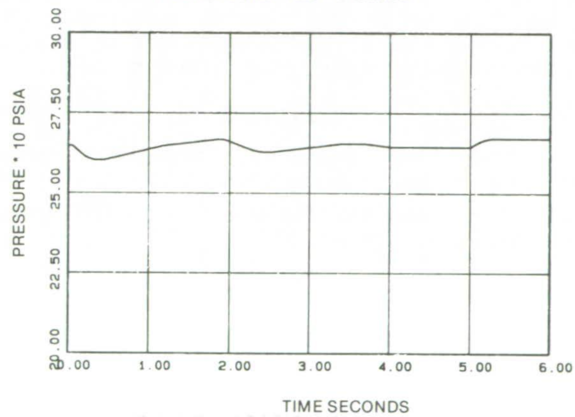
Case 3, a minimum 40.8 atm (600 psi) inlet pressure step flow demand simulation, is shown in Figure 14c. The ullage is 0.17 cubic meter (6 cubic feet) and the steady state flow rate is 9.0 SCMM (320 SCFM).



a. CASE 1 INITIAL PRESSURIZATION



b. CASE 2 STEP FLOW DEMAND



c. CASE 3 STEP FLOW DEMAND (ABNORMAL GROUND TEST CONDITIONS)

FIGURE 14. OMS DYNAMIC SIMULATIONS

Case No. 3, Figure 14c is obviously an abnormal condition, as the minimum inlet pressure always coexists with maximum tank ullage during in-space utilization of the OMS. It was simulated on the basis that ground testing could conceivably be performed under these conditions.

As noted in Table 3, it was not necessary to change the PID gains (K_p, K_d, K_I) to achive stability and regulated accuracy in these (and many other) simulations.

BREADBOARD DEMONSTRATION UNITS

Prior to releasing the EVPR design for prototype fabrication it was determined prudent to conduct breadboard demonstration tests on two of the most critical design elements of the EVPR: the ROTAX flexure drive assembly, and the brushless DC motor assembly.

The ROTAX breadboard, Eaton drawing No. SK 7615, was fabricated to verify the cycle life of the assembly and the non-linear ROTAX lift versus rotation characteristic. The breadboard ROTAX test fixture is pictured in Figure 15. The lower part of the breadboard contains a permanent magnet that attracts a ferromagnetic plate attached to the ROTAX shaft. This simulates the closing bias and pressure unbalance loading on the ROTAX cables when used in the EVPR.

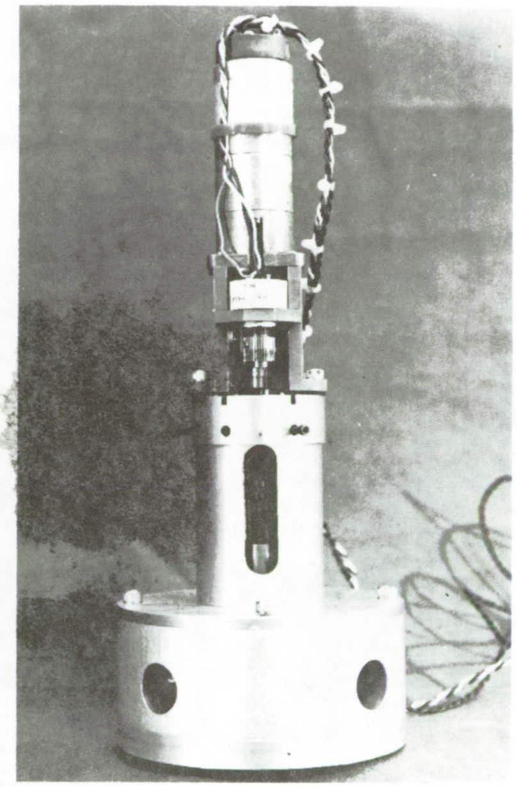


FIGURE 15. ROTAX BREADBOARD TEST FIXTURE

Figure 16 indicates that the total vertical load of fixture SK 7615, as measured by an Instron mechanical testing system, was a reasonably accurate representation of the analyzed value.

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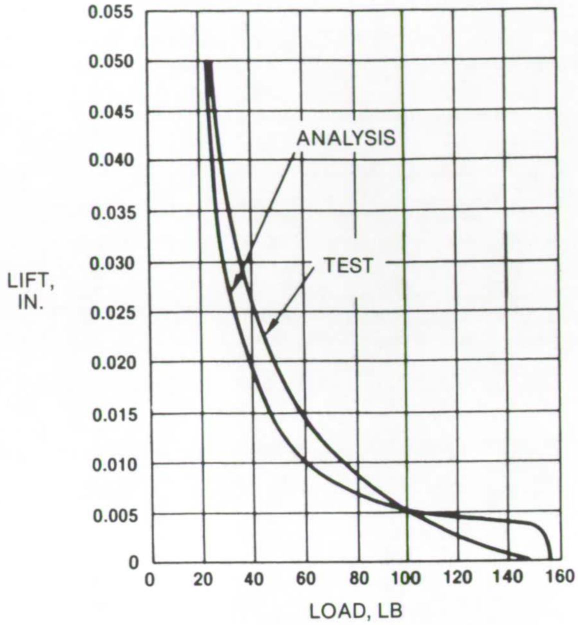

FIGURE 16. ROTAX LOAD CHARACTERISTIC

The ROTAX was cycled for 250,000 cycles without failure, far exceeding the 20,000 cycle life requirement for the EVPR. Inspection of SN data for the 321 CRES cables shows that infinite life can be projected for the ROTAX in this application. The measured lift characteristic of the ROTAX was within 5% of the calculated lift.

The breadboard motor fixture, Eaton drawing No. SK 7617, was fabricated to verify the 0.576 NM (5 in-lb) steady state torque output design requirement. Testing of the breadboard motor, pictured in Figure 17, produced the results shown in Table 4.

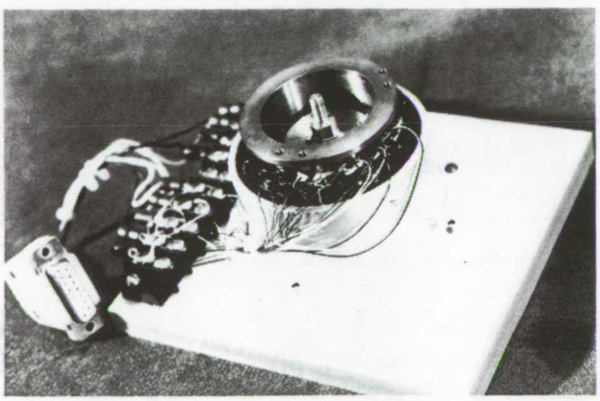

FIGURE 17. MOTOR BREADBOARD TEST FIXTURE

TABLE 4. BREADBOARD MOTOR TEST RESULTS

PARAMETER	MEASURED VALUE
RESISTANCE, 21 °C (70 °F)	16.2 OHMS
PEAK INDUCTANCE, 1 KHz	7.5 MH
PEAK TORQUE, 1.2 AMPS	0.576 NM (5.0 IN-LBS)
MOTOR WEIGHT	0.444 KG (0.98 LBS)
COGGING TORQUE	0.029 NM (4 IN-OZ)
PEAK POWER, 21 °C (70 °F)	23.6 WATTS

PROTOTYPE EVPR SYSTEM TESTS

As of the date of submittal of this paper nearly all protoype EVPR parts had been fabricated and testing was about to commence, Figure 18 is a photograph of the EVPR parts prior to assembly.

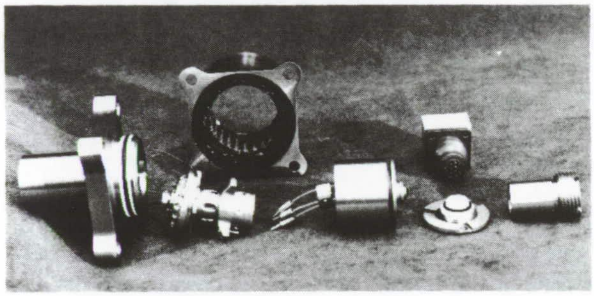

FIGURE 18. EVPR COMPONENTS

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